SUSTAINABLE, JUST AND PRODUCTIVE WATER RESOURCES DEVELOPMENT IN WESTERN NEPAL UNDER CURRENT AND FUTURE CONDITIONS

USAID's *Digo Jal Bikas Project*

ANNEXES

Submitted to

United States Agency for International Development (USAID)
Kathmandu, Nepal

Submitted by

International Water Management Institute (IWMI), Nepal Office
Lalitpur-3, Durbar Tole, Pulchowk, Kathamandu, Nepal
T: (+977-1) 5542306/5543141 | F: (+977-1) 5543511

November, 2019

Acknowledgements

This study was made possible by the generous support of the American people through the United States Agency for International Development (USAID) under the *Digo Jal Bikas* (DJB) project. The research work was led by the International Water Management Institute (IWMI) with support from Duke University, USA, and Kathmandu University (KU). The Nepal Water Conservation Foundation (NWCF) provided support for field data collection from households. This research was carried out as part of the CGIAR Research Program on Water, Land and Ecosystems (WLE) and supported by Funders contributing to the CGIAR Trust Fund (https://www.cgiar.org/funders/).

Project

This research study was initiated under the bilateral Grant Agreement between the International Water Management Institute (IWMI) and the United States Agency for International Development (USAID) [Grant Award Number: AID-367-IO-16-00002].

Collaborators

International Water Management Institute (IWMI)

Duke University

Kathmandu University

Nepal Water Conservation Foundation (NWCF)

Funding support

United States Agency for International Development (USAID)

Cover photo

The West Seti River in Karnali Basin at Dipayal, Silgadi (*photo:* Sanita Dhaubanjar/IWMI).

List of Annexes

Annex 4-3: Shrestha, G., Clement, F. (2019). Social capital and collective water resource governance in Far-West Nepal: A gendered perspective. Journal of South Asian Development. In preparation.

Annex 5-1: Bastakoti R.C., Karki E., Thapa B.R., Pandey V.P. (2019). Dealing with variations in access to water: An assessment of challenges and coping strategies in Western Nepal. Climate and Development (Under Review).

Annex 5-2: Pandey V.P., Sharma A., Dhaubanjar S., Bharati L., Joshi I.R. (2019). Climate shocks and responses in Karnali-Mahakali Basins, Western Nepal. Climate, *7*, 92. (https://www.mdpi.com/2225-1154/7/7/92)

Annex 6-1: Tachamo Shah, R.D., Sharma, S. et al. (2019). Water-diversion induced changes in aquatic biodiversity in monsoon-dominated rivers of Western Himalayas in Nepal: Implications for Environmental Flows. Ecological Indicators, 108: 105735. (https://doi.org/10.1016/j.ecolind.2019.105735)

Annex – 7.1: Pakhtigian E.L., Jeuland M., Dhaubnjar S., Pandey V.P. (2019). Balancing intersectoral demand in basin-scale planning: The case of Nepal's western river basins. Water Resources Economics. In Press. https://doi.org/10.1016/j.wre.2019.100152

Annex – 7.2: Pakhtigian, E. L., Jeuland, M., Bharati, L., & Pandey, V. P. (2019). The role of hydropower in visions of water resources development for rivers of Western Nepal. *International Journal of Water Resources Development*, 1-28. (https://www.tandfonline.com/doi/abs/10.1080/07900627.2019.1600474?journalCode=cijw20)

Annex – 7.3: Pakhtigian, E. L., & Jeuland, M. (2019). Valuing the Environmental Costs of Local Development: Evidence from Households in Western Nepal. *Ecological Economics*, *158*, 158-167. (https://www.sciencedirect.com/science/article/pii/S0921800918308085)

Annex – 7.4: Sood, A., Pakhtigian, E.L., Bekchanov, M. & Jeuland, M. (2019). Hydro-economic Modeling Framework to Address Water-Energy-Environment-Food Nexus Questions at the River Basin Scale.

Annex 2-1

Annex 2-1: Description of methodology for bio-physical and hydro-climatic characterization

A2-1.1. Methodological Framework

Figure 2-2 (main report) depicts flow chart of the methodological framework adopted to evaluate current and future bio-physical and hydro-climatic characteristics of the Karnali-Mohana (KarMo) and Mahakali basins. First, existing datasets were compiled, quality checked and assessed for bio-physical characterization of current conditions. Parallel efforts were undertaken to set up hydrological models for the two basins and prepare bias-corrected ensemble climate projections. The calibrated and validated models were forced with the projected future climate to simulate hydrological futures. The model simulations were used to evaluate changes in spatio-temporal distribution in water balance components under current and future conditions.

A2-1.2. Biophysical characterization

Various geo-spatial and time-series data were acquired to characterize topography, soil types, land use/land cover (LULC), hydro-climatology and development plans for water infrastructure projects in the study basins. **Table A2-1-1** summarises the spatial and time-series datasets collected from local and global sources. The methodologies used to prepare and quality control these datasets are described elsewhere (**Annex-B, Year-End Report (i.e., April 2017), Year-1**). These datasets were analysed to develop a thorough understanding of current biophysical conditions in the basins. All datasets gathered under the project will be made available publicly through IWMI Water Data Portal (http://www.iwmi.cgiar.org/2018/06/water-data-portal/).

Table A2-1-1: *Data type, properties and sources used in this study.*

Dataset [Unit]	Data Type	Data Description/ Properties	Data Source	Resolution (Time frame)
Terrain [m]	Spatial grids	Digital Elevation Model (DEM)	NASA JPL (2009)	30m x 30m grids (for 2009)
Soil [-]	Spatial vectors	Soil classification and physical properties (e.g., texture, porosity, field capacity, wilting point, saturated conductivity and soil depth)	FAO (2007); Dijkshoorn and Huting (2009)	1:1 million map (from multiple years)
Land use/cover (LULC) [-]	Spatial grids	Landsat land use/cover classification (9 classes)	ICIMOD (2012); ESA (2016)	30m x 30m grids (for 2010)
Precipitation [mm]	Time-series and	Daily observed precipitation	Department of Hydrology and Meteorology	36 DHM stations; 1 IMD station and 30

	spatial grids		(DHM), Nepal; Indian Meteorological Department (IMD), and TRMM	IMD grids, (1981-2013); and 36 TRMM grids (0.25° x 0.25°)
Temperature [°C]	Time-series	Daily observed minimum and maximum temperature	DHM, Nepal	16 DHM stations and 4 IMD grids (1981-2013)
Relative humidity [-]	Time-series	Daily observed relative humidity in morning and evening	DHM, Nepal	15 stations (1981-2013)
Sunshine hours [hrs]	Time-series	Daily observed sunshine hours	DHM, Nepal	5 stations (1981-2013)
Wind speed [m/s]	Time-series	Daily observed mean wind speed	DHM, Nepal	7 stations (1981-2013)
River discharge [m^3/s]	Time-series	Daily observed streamflow	DHM, Nepal	10 stations (1981-2013)
Future Precipitation [mm] Temperature [°C]	Time-series extracted from spatial grids	Daily projected values	19 Regional Climate Models, as detailed in Dhaubanjar et al. (2019)	0.44° x 0.44° (1981 – 2100)

TRMM: National Aeronautics and space Administration (NASA) Tropical Rainfall Measuring Mission (TRMM) 3842v7.

The spatial coverage of the observed hydro-climatic time-series datasets is presented in **Figure 2-3 (main report)**. Data from 69 meteorological stations and 35 hydrological stations were purchased from the Nepalese Department of Hydrology (DHM). Additionally, data available at the Indian Meteorology Department (IMD) was reviewed. One IMD meteorological station and four IMD temperature grids and 30 IMD precipitation grids were obtained as relevant for this study. As can be seen in **Figure 2-3 (main report)**, the network of meteorological stations in Western Nepal is sparse, especially in the northern mountainous regions. Satellite based meteorological data are increasingly being applied as an alternative to fill data gaps in poorly gauged river systems (Ghaju and Alfredsen 2012; Müller and Thompson 2013; Bajracharya et al. 2018). Thirty-six grids from NASA's TRMM 3B42v7 dataset shown in **Figure 2-3 (main report)** were extracted to represent areas with no station data.

Observed time-series data from stations were subject to quality assessment after which only a subset of available stations was selected for use in this study. First erroneous values such as spurious peaks or sudden drops and typographic errors were identified for six hydro-meteorological parameters (Discharge – Q, Precipitation - P, Temperature – T, Relative humidity – RH, wind speed - WS and sunshine hours - SH) from station datasets. Then stations were ranked based on continuity in data characterized by the extent of missing data and consistency as seen in the single mass curve. Based on availability of all time-series datasets, 1980-2015 was selected as time-frame with reasonable data available across all stations.

Hydropower plants and irrigation canals are important infrastructures affecting hydrological cycles. Hydropower projects in various stages of development were identified from multiple reports and the Department of Electricity Development (DoED) website tracking hydropower licenses. Further details about the projects were compiled from additional sources. Some projects had different details listed in different sources. In such cases, details reported in the DoED website was given precedence followed by those in national master plan studies. If multiple licenses were available in the DoED website for the same project, details for the largest was selected. From 193 identified projects in the project area, all storage projects and run-of-river projects with installed capacity greater than 0.5 MW are shortlisted for consideration in this study. Similarly, for irrigation projects, of the 159 projects identified in project area, only projects with net command area greater than 100 ha are short listed.

A2-1.3. Hydrological model set-up

Two hydrological models were developed in the Soil and Water Assessment Tool - SWAT (Arnold et al. 1998) for KarMo and Mahakali basins. SWAT is a process-based hydrological model capable of simulating hydrology, sediment transport, vegetation growth and management practices in complex basins with varying soils, land use/cover and management conditions (Arnold et al. 1998; Srinivasan et al. 1998). Conceptually, SWAT divides a basin into sub-basins and further into Hydrologic Response Units (HRUs). Each HRU represents a unique combination of a soil, land use/cover and slope type within a sub-watershed. Such representation captures spatial heterogeneity giving a better physical description of the water balance. Spatially distributed data (for topography, land use/cover, and soil) and daily time series data (for meteorological variables) summarized in were converted to SWAT formats and used as inputs to set-up the models.

The model setup for Chamelia in Mahakali and KarMo are described in detail in Pandey et al. (2019a) (**Annex 2-6**) and Pandey et al. (2019b) (**Annex 2-7**) and they are briefly summarized here under. For the KarMo model, the basin was divided into 111 sub-basins (**Figure A2-1-1**) and 2,122 Hydrologic Response Units (HRUs) to sufficiently capture spatial heterogeneity. The multi-parameter and multi-site calibration approach was used. Calibration and validation was carried out at 10 hydrological stations along five tributaries of the KarMo (**Figure A2-1-1**). Out of 10 stations, three (Q215; Q250 and Q280) are in the Karnali-main river, two (Q265 and Q270) in Bheri; three (Q259.2, Q256.5 and Q260) in Seti; one (Q 220) in Tila; one (Q 283.3) in Mohana. The calibrated and validation periods considered are 1995-2002 and 2003-2009, respectively, for six stations whereas varying periods for other stations based on availability of good quality and continuous time series.

Only a third of the Mahakali basin falls in Nepal with the remaining area is in India. Hydrological data from the Indian side of Mahakali was not accessible at the time of the study. Owing to this limitation in hydrological data for Mahakali, a SWAT model was calibrated only for Chamelia, the largest tributary of Mahakali within Nepalese borders with a catchment area of 1,603 km^2. Three discharge stations are available in the Chamelia watershed (**Figure 2-22, main report**) with good quality data providing sufficient basis for developing a credible model. To better represent heterogeneity, the Chamelia watershed was discretized into 16 sub-watersheds (**Figure 2-22, main report**) and 225 HRUs. Calibration and validation periods considered were 2001-2007 and

2008-2013, respectively. In case of Panjewanya station (Q125), calibration and validation periods were 2001-2005 and 2006-2009, respectively due to lack of sufficient data.

For both models, a warm up period of three years was used to develop appropriate soil and groundwater conditions (Fontaine et al. 2002). The models were calibrated in three stages: i) Sensitivity analysis; ii) Auto-calibration; and iii) Manual calibration. Sensitivity analysis was carried out using SWAT-CUP, which combines the Latin Hypercube (LH) and one-factor-at-a-time (OAT) sampling (van Griensven 2005). After sensitivity analysis, SWAT-CUP was used for auto-calibration. Each model was run for 1,000 iterations initially to narrow down the range of values for the sensitive parameters. Then auto-calibration results were further subjected to manual calibration based on knowledge of the basin and experience of the modelling team. Observed and simulated flows were visually compared in terms of the hydrographs (peak, time to peak, shape of the hydrograph and baseflow); scatter plots; flow duration curve; statistical parameters, and water accumulation to evaluate and improve model performance during manual calibration. The statistical parameters considered for the model evaluation were mean, coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), and percent bias (PBIAS).

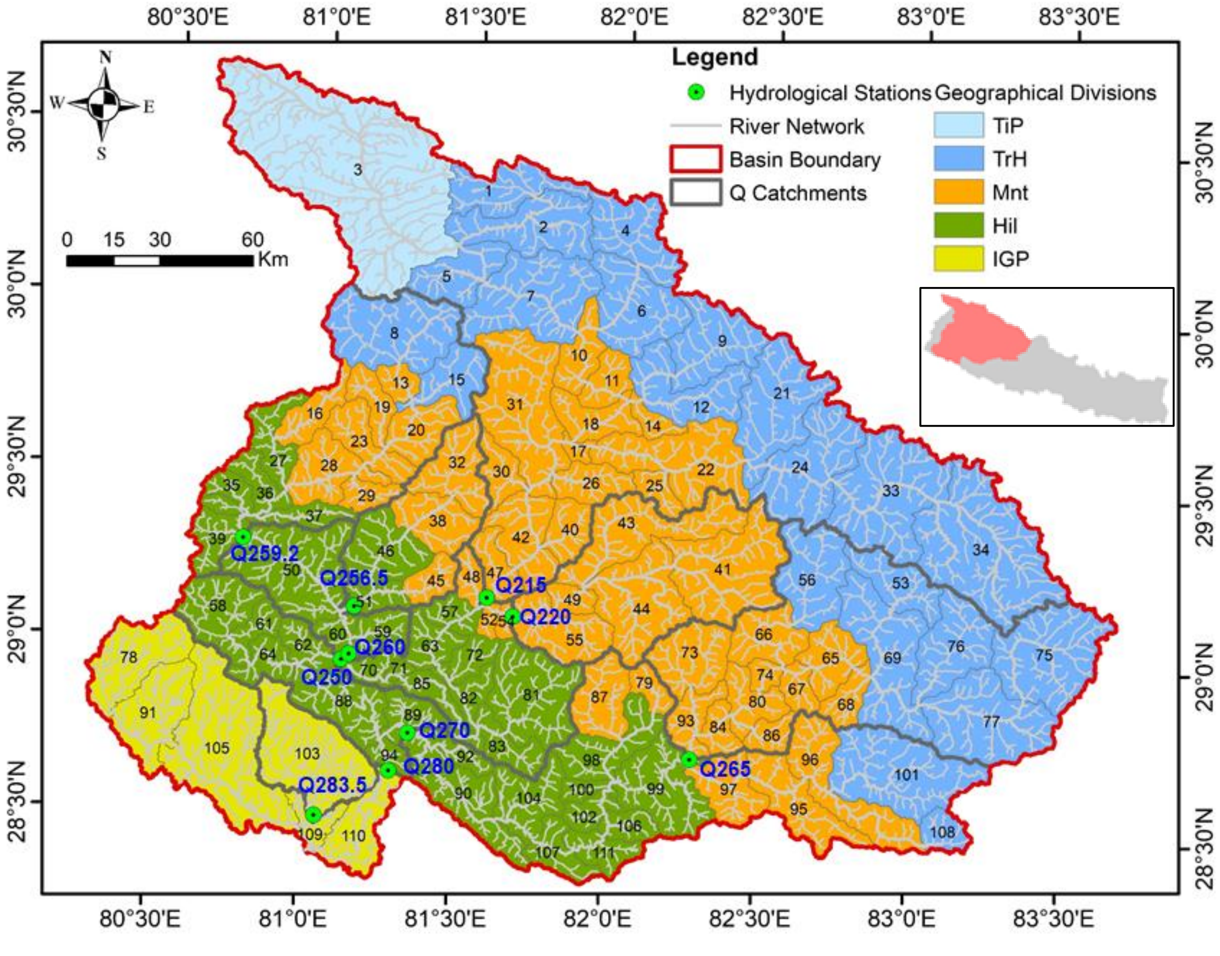


Figure A2-1-1: *SWAT sub-watersheds and model calibration stations along with geographical divisions of the KarMo basin. TiP is Tibetan Plateau; TrH is Trans-Himalaya; Mnt is Mountain; Hil is Hill; IGP is Indo-Gangetic Plain.*

A2-1.4. Climate Projection and Impact Assessment

We adopted the climate futures framework to generate application specific climate projections that capture the risks relevant to long term water-resources planning in the KarMo basin. **Figure A2-1-2** shows the workflow adapted from Clarke et al. (2011). Nineteen RCMs available in COordinated Regional Downscaling EXperiment for South Asia (CORDEX-SA) platform were used to generate climate projections. The RCMs used in the study are described in **Table A2-1-2**. RCMs were standardized and spatio-temporal averages evaluated for the northern Mountains, mid Hills and southern Terai regions of Western Nepal.

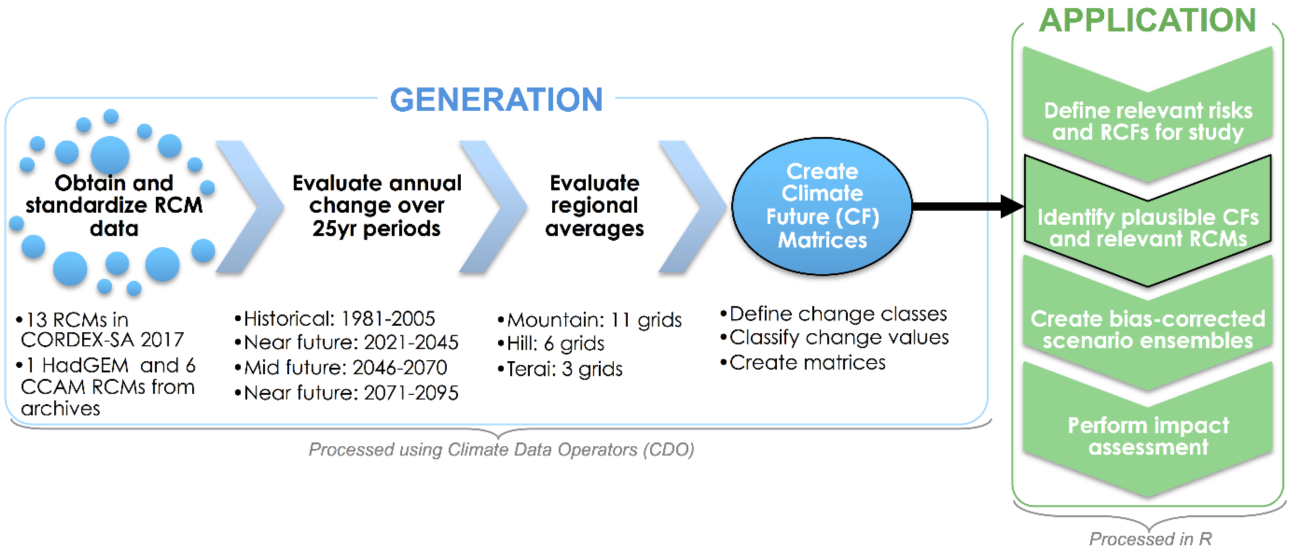


Figure A2-1-2: *Methodology for generating application specific climate projections using the climate futures framework Clarke et al. (2011).*

Table A2-1-2: *Description of the 19 CORDEX-SA RCMs in this study. All RCMs have 0.44° spatial resolution.*

	Short Name [GCM_RCM]	Driving GCM	CORDEX-SA RCM Description	RCM Modeling Center	Timeframe	Coordinate System
1.	ACCESS_CCAM	ACCESS1.0	CSIRO-CCAM-1391M: Conformal Cubical Atmospheric Model (McGregor and Dix 2001)	Commonwealth Scientific and Industrial Research Organization (CSIRO), Marine and Atmospheric Research, Melbourne, Australia	Hist: 1970-2005 RCP4.5/8.5: 2006-2099	regular
2.	CNRM_CCAM	CNRM-CM5			Hist: 1970-2005 RCP4.5/8.5: 2006-2099	regular
3.	GFDL_CCAM	GFDL-CM3			Hist: 1970-2005 RCP4.5: 2006-2070 RCP8.5: 2006-2099	regular

4.	MPI_CCAM	MPI-ESM-LR			Hist: 1970-2005 RCP4.5/8.5: 2006-2099	regular
5.	NorESM_CCAM	NorESM-M			Hist: 1970-2005 RCP4.5: 2006-2099 RCP8.5: None	regular
6.	HadGEM_RA	HadGEM2-AO	HadGEM3-RA: HadGEM3 Regional Atmospheric Model (Moufouma-Okia and Jones 2014)	Met Office Hadley Centre (MOHC), UK	Hist: 1970-2005 RCP4.5/8.5: 2006-2100	curvilinear rotated_ latitude_longitude
7.	CNRM_RCA4	CNRM-CM5	SMHI-RCA4: Rossby Centre regional atmospheric model version 4 (Samuelsson et al. 2011)	Rosssy Centre, Swedish Meteorological and Hydrological Institute (SMHI), Sweden	Hist: 1951-2005 RCP: 2006-2100	rotated pole
8.	ICHEC_RCA4	ICHEC-EC-EARTH			Hist: 1970-2005 RCP: 2006-2100	rotated_latitude_ longitude
9.	IPSLMR_RCA4	IPSL-CM5A-MR			Hist: 1951-2005 RCP: 2006-2100	rotated_pole
10.	MIROC5_RCA4	MIROC-MIROC5			Hist: 1951-2005 RCP: 2006-2100	rotated_pole
11.	MPI_RCA4	MPI-ESM-LR			Hist: 1951-2005 RCP: 2006-2100	rotated_pole
12.	NOAA_RCA4	NOAA-GFDL-GFDL-ESM2M			Hist: 1951-2005 RCP: 2006-2100	rotated_pole
13.	MPI_REMO	MPI-ESM-LR	MPI-CSC-REMO2009: MPI	Climate Service Center	Hist: 1970-2005	regular

			Regional model 2009 (Teichmann et al. 2013)	(CSC), Germany	RCP: 2006-2100	
14.	CanESM2_RegCM4	CCCma-CanESM2	IITM-RegCM4: The Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climatic Model version 4 (Giorgi et al. 2012)	Centre for Climate Change Research (CCCR), Indian Institute of Tropical Meteorology (IITM), India	Hist: 1951-2005 RCP4.5/8.5: 2006-2099	rotated_mercator
15.	CNRM_RegCM4	CNRM-CM5			Hist: 1951-2005 RCP4.5: 2006-2099 RCP8.5: 2006-2085	rotated_mercator
16.	CSIRO_RegCM4	CSIRO-Mk3.6			Hist: 1951-2005 RCP4.5/8.5: 2006-2099	rotated_mercator
17.	IPSLLR_RegCM4	IPSL-CM5A-LR			Hist: 1951-2005 RCP4.5/8.5: 2006-2099	rotated_mercator
18.	MPIMR_RegCM4	MPI-ESM-MR			Hist: 1951-2005 RCP4.5/8.5: 2006-2099	rotated_mercator
19.	NOAA_RegCM4	NOAA-GFDL-GFDL-ESM2M			Hist: 1970-2005 RCP: 2006-2099	curvilinear rotated_mercator

For each region, projected changes in annual temperature and precipitation were classified into qualitative categories of changes in precipitation and temperature to generate a *climate future (CF) matrix*. **Table A2-1-3** presents the classes defined subjectively, modifying the original ranges defined for the Australian framework (Clarke et al. 2011) to consider the natural climate variability in Western Nepal and local demarcations of climate risks. Considering two Representative Concentration Pathways (RCPs, 4.5 and 8.5) and three future periods (near-future (NF; 2021-2045), mid-future (MF; 2046-2070), and far-future (FF; 2071-2095)), six climate future matrices were developed representing 6 climate scenarios in each region. In this study, RCP4.5 is selected as a medium stabilizing scenario and RCP8.5 as a very high emission scenario. RCP4.5 refers to stabilization without overshoot pathway leading to 4.5 W/m2 (~650 ppm CO^2) at stabilization after 2100; where as RCP8.5 refers to rising radiative forcing pathways leading to 8.5 W/m2 (~1370 ppm CO^2) by 2100 (van Vuuren et al. 2011).

Table A2-1-3: *Qualitative classifications of projected changes in precipitation and temperature for Western Nepal.*

Δ Precipitation Classes		Δ Temperature Classes	
Description	**Range**	**Description**	**Range**
Significantly Drier	Δpr < -25%	Colder	Δt < 0ºC
Much Drier	-25% ≤ Δpr < -15%	Slightly Warmer	0 ≤ Δt < 0.5 ºC
Drier	-15% ≤ Δpr < -10%	Warmer	0.5 ºC ≤ Δt < 2.0 ºC
Little change	-10% ≤ Δpr < 10%	Hotter	2.0 ºC ≤ Δt < 3.5 ºC
Wetter	10% ≤ Δpr < 15%	Much Hotter	Δt ≥ 3.5 ºC
Much Wetter	15% ≤ Δpr < 25%		
Significantly Wetter	Δpr ≥ 25%		

Next, the CF matrices were applied to generate daily time series projections at a subset of meteorological stations with relatively good quality data input in the SWAT model. To prepare projections at desired station, the climate future matrix for the relevant region and climate scenario were queried to identify all RCMs that represent two risk cases and one consensus case summarized below:

- Low-risk: (Δtmax: Slightly Warmer OR Warmer) + (Δpr: Wetter OR Much Wetter)
- Consensus: CF with maximum number of models in the matrix
- High-risk: (Δtmax: Hotter OR Much Hotter) + (Δpr: Much Drier OR Significantly Drier)

Considering long-term water infrastructure development, stakeholder interaction workshop revealed low-risk future as one where relatively more water is available compared to historical averages. This allowing for higher storage in reservoirs and subsequent distribution, but not significantly more water so as to increase the risk of floods and landslides Conversely, high-risk scenario was defined as one where there is decline in average water availability.

Daily time-series data were extracted from all RCMs that were selected as under each case for each future period and RCP. Raw RCM time series were then bias-corrected using the quantile mapping (QM) method (Gudmundsson et al. 2012; Teutschbein and Seibert 2012) implemented in R using the qmap package. QM corrects quantiles of RCM data to match with that of observed ones by creating suitable transfer functions. The bias corrected times series from the selected RCMs for each station were combined to create equally weighted multi-model ensemble time series for each climate scenario. The performance of bias correction was evaluated using: the Nash–Sutcliffe Efficiency coefficient (NSE), the percentage bias (PBIAS) and the coefficient of determination (R^2) at seasonal (winter - DJF, pre-monsoon - MAM, monsoon - JJAS), post-monsoon-ON) and annual scales. NSE and R^2 values close to 1 and PBIAS close to 0 indicate good performance, i.e., simulated values are statistically close to the observed. The method for generation of application-specific climate projections is described in detail in Dhaubanjar et al. (2019). The projected future CC and its impact were analysed based on these ensembles.

A simpler approach was taken for CC impact assessment for Chamelia basin owing to its smaller size and limited number of stations available. Five of the RCMs listed in **Table A2-1-2** were used, viz. ACCESS_CCAM, CNRM_CCAM, MPI_CCAM, MPI_REMO and ICHEC_RCA4. Projections from the five RCMs were extracted for the three meteorological stations in Chamelia under RCP 4.5 and 8.5 and the three future time frames. Raw projections were bias corrected using QM and averaged to generate ensemble projections for use in the SWAT models. The climate projections for Chamelia are discussed in detail in Pandey et al. (2019b). Only the SWAT simulated impact of CC on water availability in Chamelia are analysed and discussed.

References

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic modeling and assessment part I: Model development. J Am Water Resour Assoc 34:73–89.

Bajracharya AR, Bajracharya SR, Shrestha AB, Maharjan SB (2018) Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal. Sci Total Environ 625:837–848. doi: 10.1016/j.scitotenv.2017.12.332

Clarke JM, Whetton PH, Hennessy KJ (2011) Providing Application-specific Climate Projections Datasets: CSIRO's Climate Futures Framework. MODSIM2011, 19th Int Congr Model Simul 2683–2687. doi: 10.13140/2.1.1915.2649

Dhaubanjar S., Pandey V.P., Bharati L (2019). Climate Futures for Western Nepal based on Regional Climate Models in the CORDEX-SA. International Journal of Climatology. https://doi.org/10.1002/joc.6327

Dijkshoorn K, Huting J (2009) Soil and Terrain database for Nepal. ISRIC – World Soil Information, Wageningen

ESA (2016) 300 m annual global land cover map from 2015 [Dataset]. By European Space Agency (ESA). In: Clim. Chang. Initiat. - L. Cover Proj. http://maps.elie.ucl.ac.be/CCI/viewer/download.php. Accessed 31 Aug 2016

FAO (2007) FAO/UNESCO Digital Soil Map of the World [Dataset]. By Food and Agriculture Organization of the United Nations (FAO). http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/. Accessed 27 Mar 2013

Fontaine TA, Cruickshank TS, Arnold JG, Hotchkiss RH (2002) Development of a snowfall-snowmelt routine for mountainous terrain for the soil water assessment tool (SWAT). J Hydrol. doi: 10.1016/S0022-1694(02)00029-X

Ghaju S, Alfredsen K (2012) Evaluation of Satellite Based Precipitations and Their Applicability for Rainfall Runoff Modelling in Narayani Basin of Nepal. J Hydrol Meteorol 8:22. doi: http://dx.doi.org/10.3126/jhm.v8i1.15569

Giorgi F, Coppola E, Solmon F, et al (2012) RegCM4: Model description and preliminary tests over multiple CORDEX domains. Clim Res 52:7–29. doi: 10.3354/cr01018

Gudmundsson L, Bremnes JB, Haugen JE, Engen-Skaugen T (2012) Technical Note: Downscaling RCM precipitation to the station scale using statistical transformations – A comparison of methods. Hydrol Earth Syst Sci 16:3383–3390. doi: 10.5194/hess-16-3383-2012

ICIMOD (2012) Land Cover of Nepal 2010 [Dataset]. By International Center for Integrated Mountain Development (ICIMOD). In: Reg. Database Syst. http://rds.icimod.org/Home/DataDetail?metadataId=9224. Accessed 1 Jan 2015

McGregor JL, Dix MR (2001) The CSIRO Conformal-Cubic Atmospheric GCM. Fluid Mech its Appl 61:197–202. doi: 10.1007/978-94-010-0792-4_25

Moufouma-Okia W, Jones R (2014) Resolution dependence in simulating the African hydroclimate with the HadGEM3-RA regional climate model. Clim Dyn 44:609–632.

Müller MF, Thompson SE (2013) Bias adjustment of satellite rainfall data through stochastic modeling: Methods development and application to Nepal. Adv Water Resour 60:121–134. doi: 10.1016/j.advwatres.2013.08.004

NASA JPL (2009) ASTER Global Digital Elevation Model V002 [Data set]. In: Nasa Jpl. https://doi.org/10.5067/ASTER/ASTGTM.002. Accessed 27 Mar 2013

Pandey VP, Dhaubanjar S, Bharati L, Thapa BR (2019a) Hydrological response of Chamelia watershed in Mahakali Basin to climate change. Sci Total Environ 650:365–383. doi: 10.1016/j.scitotenv.2018.09.053

Pandey VP, Dhaubanjar S, Bharati L, Thapa BR (2019b) Modelling hydrology in large basins using multi-site calibration approach: A case of Karnali-Mohana basin, Western Nepal. Manuscr Submiss

Samuelsson P, Jones CG, Willén U, et al (2011) The Rossby Centre Regional Climate model RCA3: Model description and performance. Tellus, Ser A Dyn Meteorol Oceanogr 63:4–23. doi: 10.1111/j.1600-0870.2010.00478.x

Srinivasan R, Ramanarayanan TS, Arnold JG, Bednarz ST (1998) Large area hydrologic modeling and assessment part II: Model application. J Am Water Resour Assoc. doi: 10.1111/j.1752-1688.1998.tb05962.x

Teichmann C, Eggert B, Elizalde A, et al (2013) How does a regional climate model modify the projected climate change signal of the driving GCM: A study over different CORDEX regions using REMO. Atmosphere (Basel) 4:214–236. doi: 10.3390/atmos4020214

Teutschbein C, Seibert J (2012) Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. J Hydrol 457:12–29. doi: 10.1016/j.jhydrol.2012.05.052

van Griensven A (2005) Sensitivity, auto-calibration, uncertainty and model evaluation in SWAT 2005.

van Vuuren DP, Edmonds J, Kainuma M, et al (2011) The representative concentration pathways: An overview. Clim Change 109:5–31. doi: 10.1007/s10584-011-0148-z

Annex 2-2

Annex 2-2: Advance Climate Future Matrix Visuals for Western Nepal

Figure A2-2-1 shows the number of models that project values in each of the Δpr and Δtmax classes are

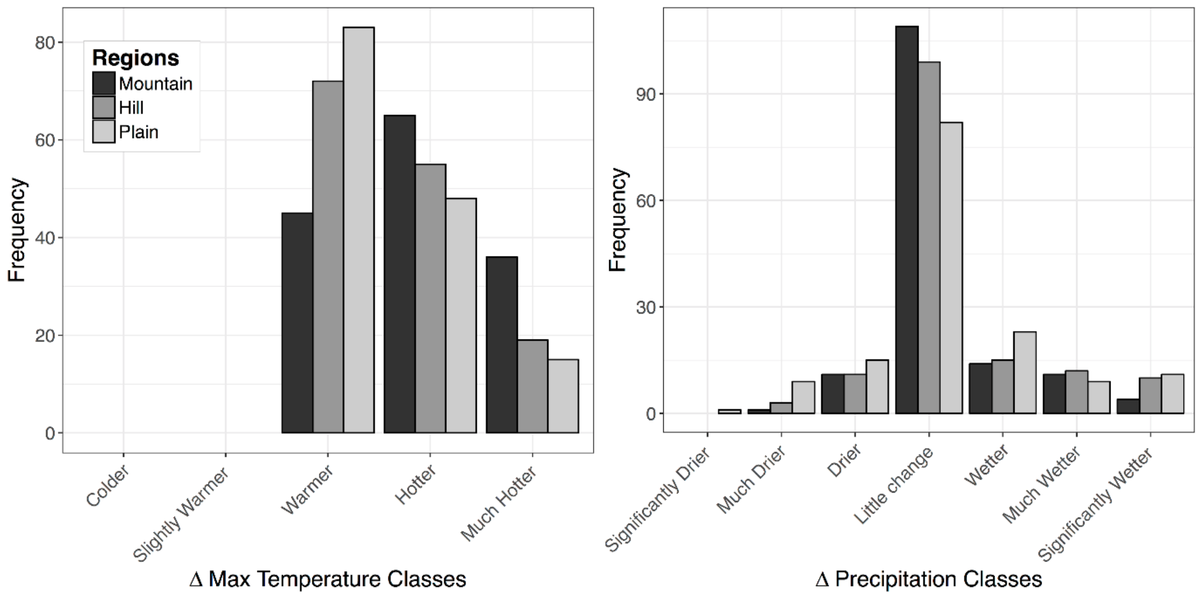


Figure A2-2-1: *Number of models projecting values in each Δtmax (left) and Δpr (right) classes defined in Table 4 for the three regions considering model projections under both RCPs for all future timeframes.*

Figure A2-2-2 and **Figure A2-2-3** present CF matrices under RCP4.5_Near and RCP8.5_Far scenarios for plain and mountain, respectively. In both regions, the 19 RCMs concentrate around the "Warmer"+"Little Change" CF in RCP 4.5_Near and spread out further for RCP 8.5_Far. Even projection based on the same RCM but driven by different GCMs move in different direction. For example, see points for MPI_RCA4, MIROC5_RCA4 and IPSLMR_RCA4 that belong to the RCA4 RCM family. For both mountain and plain, MPI_RCA4 projections move towards the upper right – "Drier"+"Hotter" corner, while that for MIROC5_RCA4 and IPSLMR_RCA4 move towards the lower right – "Wetter"+"Hotter" corner. The trends for individual RCMs are also not generalizable across the three regions. In **Figure A2-2-2*A*** and ***B*** for the plains, HadGEM_RA projects "Significantly Wetter" conditions but in **Figure A2-2-3*B*** for the mountains, HadGEM_RA projects "Drier" conditions. This suggests that GCM behaviours dominate RCMs outputs, also noted by Sanjay et al. (2017). The matrix-based visualization allows for easy tracking of changes in Δpr and Δtmax over the different scenarios for individual RCMs as well as their ensemble behaviour. Animated GIFs show the relative progression of RCM points for the plains towards higher precipitation changes (both positive and negative) for higher RCPs and futures. For the mountains, the movement is more pronounced along the temperature axis, where by all RCMs fall under the "Much Hotter" category for RCP 8.5_Far **(Figure A2-2-3B**).

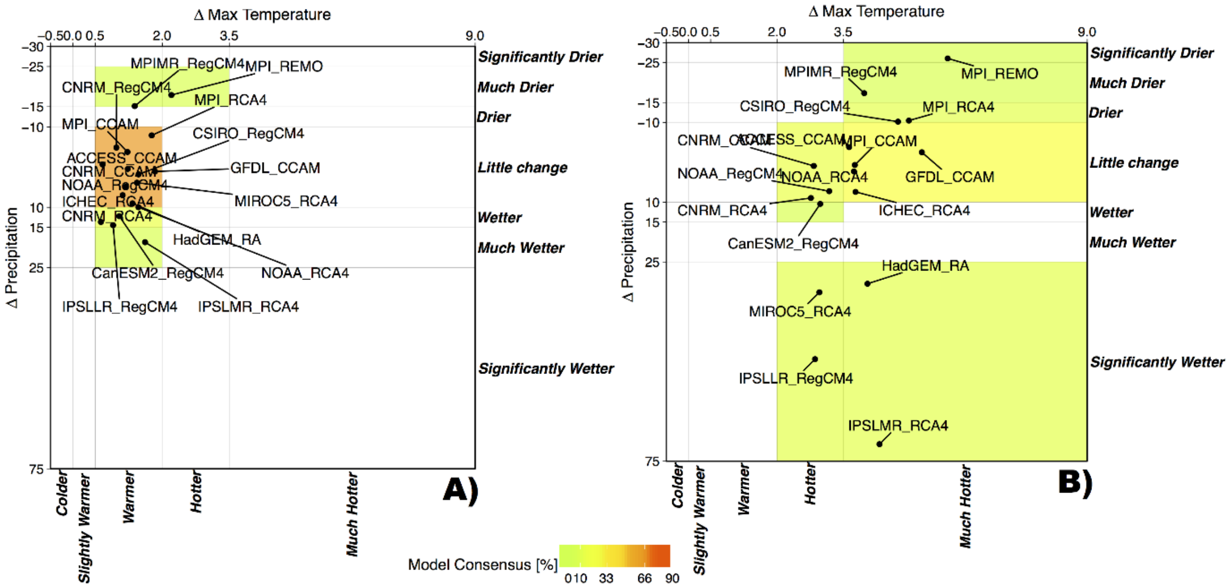


Figure A2-2-2: *Advanced Climate Future Matrix visuals for Terai PLAIN under A) RCP 4.5 near future (2021-2045) and B) RCP 8.5 far future (2070-2095) on the right. See Table A2-1-2 (Annex A2-1) for RCM description.*

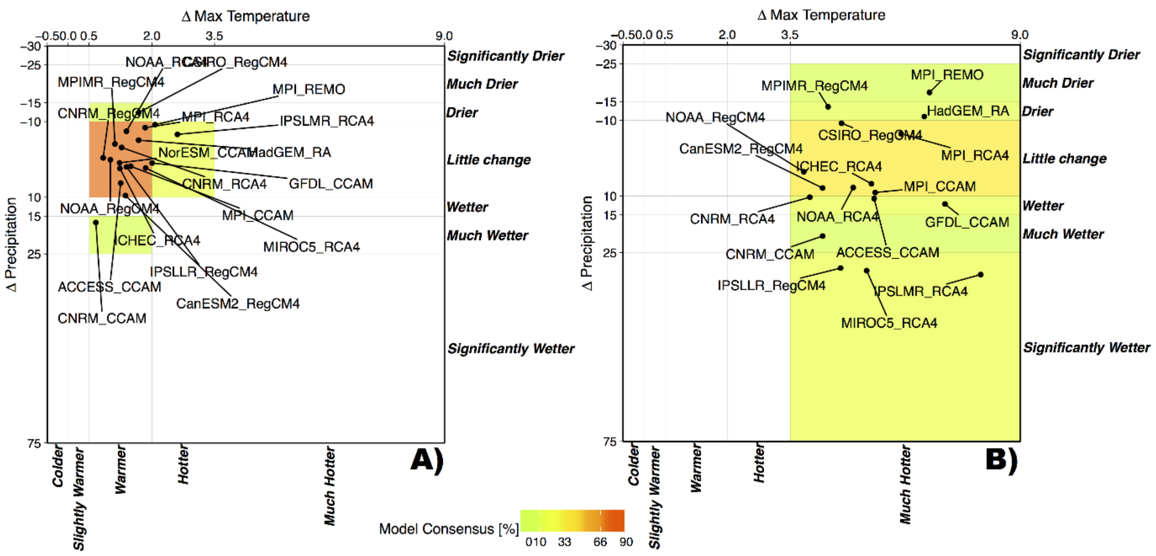


Figure A2-2-3: *Advanced Climate Future Matrix visuals for MOUNTAIN under A) RCP 4.5 near future (2021-2045) and B) RCP 8.5 far future (2070-2095) on the right. See Table A2-1-2 (Annex A2-1) for RCM description.*

Figure A2-2-4 visualizes the role of CF matrices in generating application-specific climate scenarios for Karnali by comparing the ranges in Δpr and Δtmax in all available RCMs to that of the ensembles representing the 18 scenarios. The ensemble means are shown by the bar charts and listed at the top, while the error bars show the ranges. The value ranges are narrower for the scenarios than for "All RCMs" as the scenarios selectively group models that agree in projections. The low and high-risk scenarios have even narrower ranges because they comprise of fewer RCMs. Especially for Δpr, it is clear that each climate scenario only samples a portion of the full range of available projections. While Δpr values for all RCMs across all regions and scenarios range from -26.1 to 70.7%, the ensemble means for the scenarios are between -2.8 to 8.9%. The low-risk scenario ensembles across all regions and scenarios have mean Δpr values between 10.5 to 18.2%, consensus between -9.7 to 10.0% and high-risk between -26.1 to -16.0%.

Similarly, for Δtmax, when considering specifically the far future, Δtmax across all regions ranges between 0.9 to 5.9 ºC for all RCM, 0.6 to 0.2 ºC for low-risk, 0.6 to 6.1 ºC for consensus and 4.1 to 6.8 ºC for high-risk. Using an ensemble with all RCMs would in essence only simulate climate scenario with small changes in precipitation as seen for the consensus RCF because climate signals from different RCMs cancel out. Application of CF matrix as a RCM selection criterion prior to ensemble generation allows practitioners to create ensembles that match the climate risk of their interest lending well to a scenario-based impact analysis. Analysis that considers RCM selection consciously can provide more robust climate inputs in comparison to random use of RCMs without characterizing the nature of the projections.

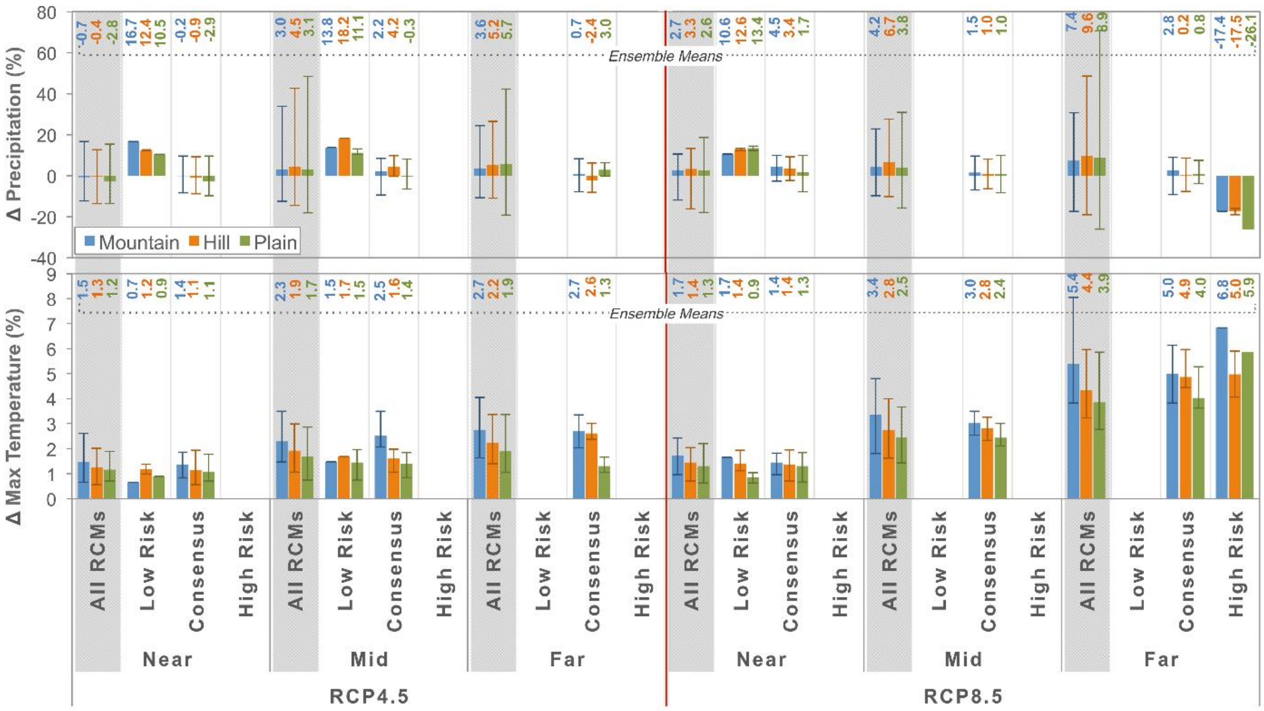


Figure A2-2-4: *Region-wise means (bars) and ranges (error bars) in long-term annual average Δpr and Δtmax for all available RCMs (greyed) and representative RCM ensembles for the 18 different climate scenarios combining 2 RCPs (4.5 and 8.5), 3 futures (near, mid, far) and three RCFs (low risk, consensus, high risk). Numbers at the top of graph indicate mean value for each scenario ensemble.*

References

Sanjay J, Krishnan R, Shrestha AB, et al (2017) Downscaled climate change projections for the Hindu Kush Himalayan region using CORDEX South Asia regional climate models. Adv Clim Chang Res 8:185–198. doi: 10.1016/j.accre.2017.08.003

Annex 2-3

Annex 2-3: Evaluation of RCM Biases Across Seasons and Regions in the Western Nepal

Figure A2-3-1 presents historical long-term average seasonal total precipitation and maximum temperature based on observed data (black bar), the raw scenario ensembles (dashed lines) and bias-corrected ensembles (colored bars). Similarly, the solid lines in **Figure A2-3-1** show the bias-corrected future RCM ensembles. Future temperatures are higher than historical values across all seasons and stations with highest warming seen in the mountain stations 202 and 303. There is no discernible trend in precipitation.

The deviation of the historical raw RCM ensembles (dashed lines) from the historical observed values indicate a spatial trend in bias. The bias in precipitation is more complex than temperature bias, potentially due to the complexities of the governing orographic processes of cloud formation. Consistent with literature, the raw ensembles in **Figure 2-3-1*A*** show wet biases for mountain stations, both wet and dry biases for hill stations and dry biases for the lower elevation plain stations. Stations 104 (1848 m) and 514 (2100 m) classified as hilly station due to their latitude-longitude lie in relatively high elevations. It is interesting to note that station 104 in particular shows biases expected for the mountain region. Ghimire et al. (2015) also find that RCM precipitation bias varies from -20 to 20% between 0-6000 m. Precipitation bias also shows a seasonal trend. In the mountain and hill, there is wet bias across all seasons for majority of the scenarios. But in the plain, there is a dry bias in the monsoon (JJAS) and wet bias in winter (DJF). In **Figure 2-3-1*B*,** for long-term average maximum temperature, the raw historical ensemble values lie below the historical observed bar in black across all stations showing systematic cold bias across all seasons and scenarios. Higher biases are seen for the mountain stations than the hill and plain stations. Refer to Dhaubanjar et al. (2019) (i.e., **Annex 2-8**) for further details on evaluation of RCM biases; efficacy of QM for bias correction; and the range of changes. Furthermore, **Table A2-3-1** shows the range in seasonal and annual average changes in precipitation and maximum temperature.

Figure A2-3-2 further explores the future climate projections in terms of range of projected changes with respect to the bias-corrected historical values. **Table A2-3-1** summarizes the range in seasonal and annual average changes seen across each region in the figure. Trends in annual Δpr and Δtmax across the various scenarios are similar for the stations in the same region. The average annual Δpr ranges from -14.1 to 16.7%, for mountain, -10.3 to 20.7% for hill and -23.8 to 16.4% for plain. Across all regions average seasonal Δpr values (-51.6 to 196.8%) are much higher and variable than annual values (-23.8 to 20.7%). Increasing trends in average annual Δtmax across the climate scenarios and stations are similar. The average annual Δtmax, ranging from 0.5 to 5.3 ^{o}C across the mountains and 0.8 to 4.5 ^{o}C across the hills and plains are well representative of seasonal changes. These spatial variations are consistent with prior observation based on raw RCM data that Δpr appears more prominent in the terai while Δtmax is more prominent in the mountains.

Δtmax is more similar across stations in hills and terai than Δpr. Average Δpr has a wide range in all three regions. However, in **Figure A2-3-2*A*** the median Δpr across all seasons, scenarios and stations lie close to zero, with whiskers extending in both positive and negative directions. Reasonably, the medians for low-risk scenarios are generally skewed above zero while the single high-risk scenario is negatively skewed. Winter (DJF), pre-monsoon (MAM) and post-monsoon (ON) precipitation projections fluctuate more than monsoon (JJAS), suggested by the higher mean Δpr values and whiskers extending beyond 100% for these seasons.

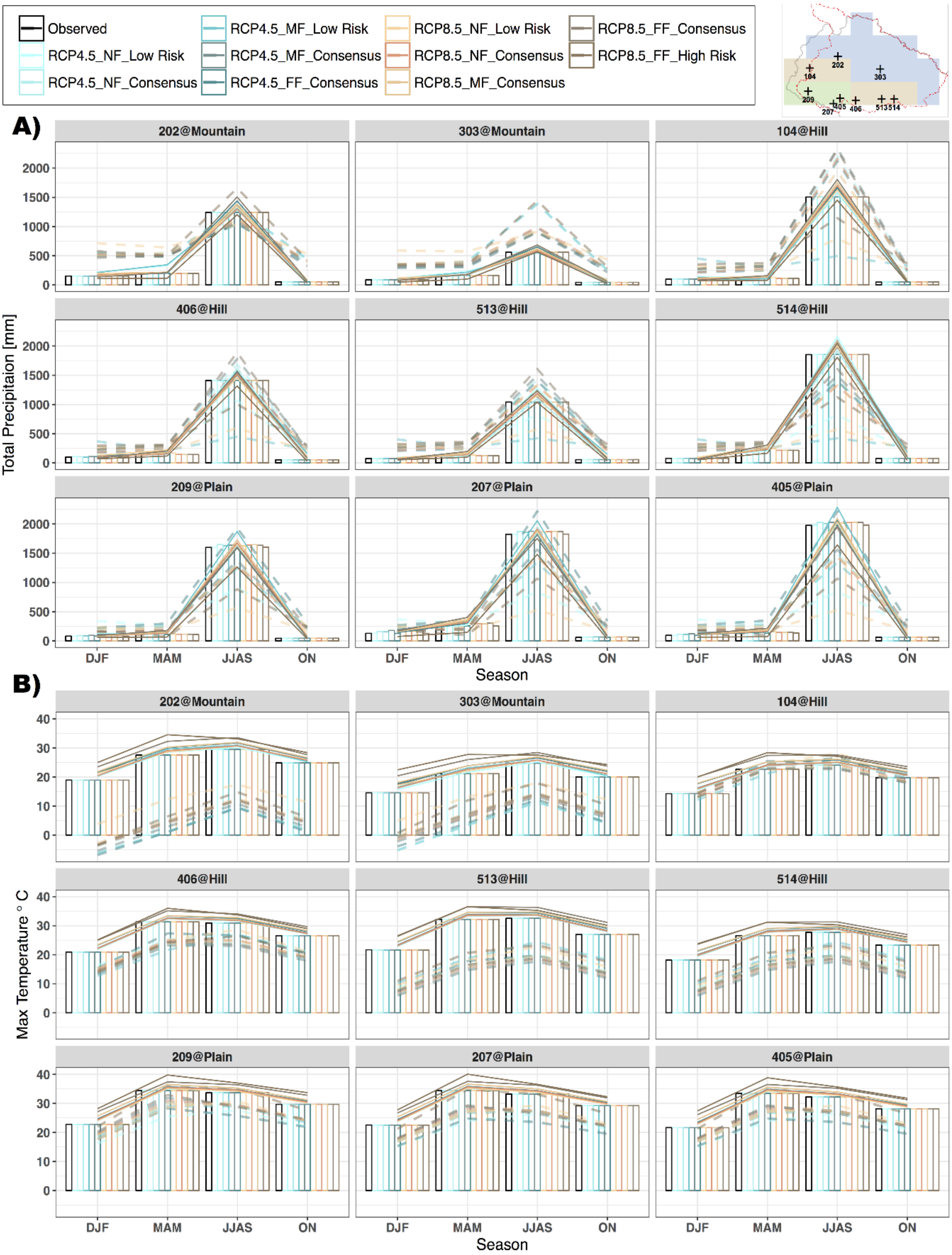


Figure A2-3-1: *Comparison of long-term seasonal averages for A) total precipitation and B) maximum temperature in historical and future time frame across the nine meteorological stations. Observed historical station data and bias corrected historical RCM ensembles are shown as bar plots. Raw historical RCM ensembles are shown in dashed lines and bias corrected future RCM ensembles are in solid lines. Colors differentiate the observed (in black), five RCP 4.5 scenarios (in shades of blue) and five RCP 8.5 scenarios (in shades of brown). Inset in top right corner shows station locations in Karnali.*

Table A2-3-1: *Range in seasonal and annual average Δpr and Δtmax values across nine meteorological stations in the three regions*

Mean Δpr [%]	DJF	MAM	JJAS	ON	Annual
Mountain (202, 303)	-45.7 to 43.2%	-41.8 to 73.8%	-3.1 to 22.3%	-51.6 to 104%	-14.1 to 16.7%
Hill (104, 406, 513, 514)	-32.5 to 47.7%	-29.7 to 54.5%	-6.9 to 22.9%	-45.7 to 196.8%	-10.3 to 20.7%
Plain (209, 207, 405)	-41.1 to 62.5%	-46.8 to 54.3%	-21 to 14.8%	-46.5 to 123.4%	-23.8 to 16.4%
Mean Δtmax [oC]	**DJF**	**MAM**	**JJAS**	**ON**	**Annual**
Mountain (202, 303)	1.1 to 8.0ºC	0.5 to 7.0 ºC	0.4 to 4.1 ºC	0.1 to 4.2 ºC	0.5 to 5.3 ºC
Hill (104, 406, 513, 514)	0.9 to 5.8 ºC	1.0 to 5.8 ºC	0.7 to 3.8 ºC	0.6 to 4.1 ºC	0.8 to 4.5 ºC
Plain (209, 207, 405)	1.1 to 5.8 ºC	0.6 to 5.7 ºC	0.6 to 3.4 ºC	0.5 to 4.0 ºC	0.8 to 4.5 ºC

Highest changes are seen in post-monsoon (ON), with averages Δpr as high as 196% projected for the hill and as low as -51.6% in the mountain. While absolute changes in post-monsoon, winter and pre-monsoon precipitation do not appear significant compared to the monsoon in **Figure A2-3-1*A***, the high range in percentage changes and low medians in **Figure A2-3-2*A*** suggest a shift in rainfall pattern. The mean, median and overall distribution of Δpr suggest prolonged monsoon and frequent sporadic rain events even in drier months. In **Figure A2-3-2*B***, Δtmax has a clear spatiotemporal trend with higher values and spread seen in the mountain stations, for higher futures and RCPs. Majority of means and medians lie above zero providing strong indication of temperature rise all year-round. Average Δtmax across all regions is highest at 8 ºC in the winter (DJF) and lowest at 0.4 ºC in the monsoon (JJAS) both for the mountains.

Presented projections at the nine stations reiterate the spatio-temporal variation in climate even over short distances in heterogeneous terrains. The bias-corrected Δpr project highest values and spread for the post-monsoon season (JJAS), especially in the hills, indicating a potential shift in rainfall pattern with prolonged monsoon and sporadic intense rain events likely even in drier months. Average seasonal Δpr values (-51.6 to 196.8%) are much higher and variable than annual values (-23.8 to 20.7%). The average annual Δtmax, ranging around 0.5-5.3°C across the mountains and 0.8 to 4.5°C across the hills and plains are well representative of seasonal changes. Farther in the future, the hills and plains may see most fluctuation in precipitation while the mountains see highest increase in temperature. The lack of definite direction in precipitation change will be key challenge in management of climate risks. Scientific advances leading to increase in reliability and resolution of satellite-based climate data and RCMs will be key to ensure future climate assessments can better capture the variations induced by complex topography and microclimates across the over 50,000 km^2 span of Western Nepal.

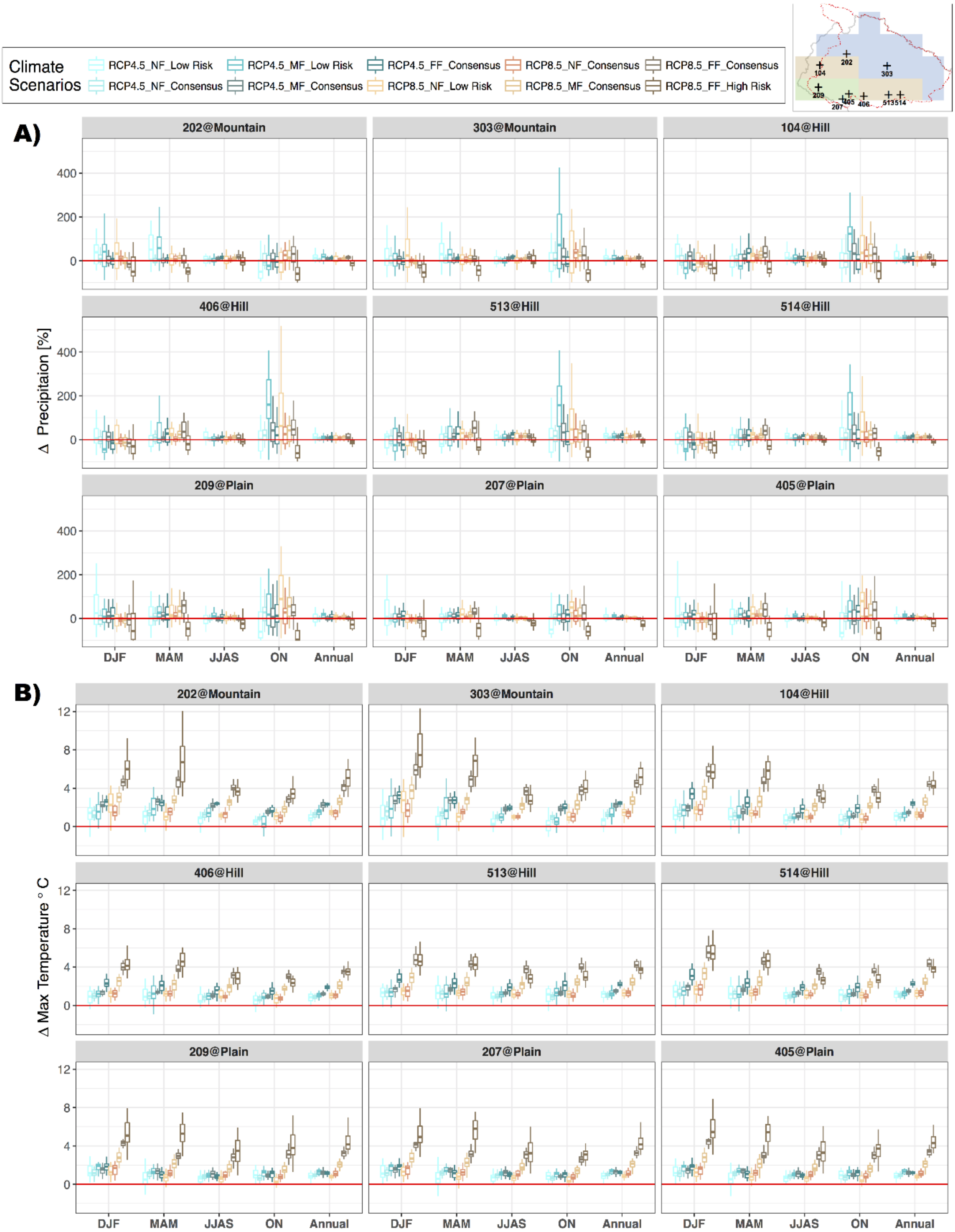


Figure A2-3-2: *Projected changes in of long-term seasonal averages for A) total precipitation in [%] and B) maximum temperature in [°C] for the 10 climate scenarios at nine meteorological stations. Change evaluated with respect to historical RCM ensemble corresponding to each climate scenario. Edges of the box plot indicates interquartile range (IQR), interior line indicates median and whiskers indicate lower of +/- 1.5*IQR or max/min data values. Colors differentiate the five RCP 4.5 scenarios (in shades of blue) and five RCP 8.5 scenarios (in shades of brown).*

References

Ghimire S, Choudhary A, Dimri AP (2015) Assessment of the performance of CORDEX-South Asia experiments for monsoonal precipitation over the Himalayan region during present climate: Part I. Clim Dyn 2–4. doi: DOI 10.1007/s00382-015-2747-2

Dhaubanjar S, Pandey VP, Bharati L (2019) Climate futures for Western Nepal based on regional climate models in the CORDEX-SA. Int J Climato, In Press.

Annex 2-4

Annex 2-4: Evaluation of hydrological model performance for the Karnali-Mohana (KarMo) basin

A SWAT model was developed for the KarMo basin using the spatial and time-series datasets presented in the **Section 2.4.1 (main report)**. Multi-station calibration approach was adopted to better represent spatial heterogeneity in the KarMo basin. The KarMo SWAT model was calibrated and validated at 10 hydrological stations shown in **Figure 2-10 (main report)** and summarized in **Table A2-4-1**. Three years were used as warm-up period before the start of calibration period. The shape and pattern of observed and simulated hydrograph and flow duration curve (FDC) as well as statistical parameters were used to evaluate model performance at each of the 10 stations.

Model simulations were analysed considering spatio-temporal changes across five major tributaries (Seti, Karnali-main, Tila, Bheri and Mohana) and five geographic divisions (of northern Trans-Himalayas (TrH), Mountains (Mnt), Hills (Hil), and southern Terai flatland, which is a part of Indo-Gangetic Plan (IGP)) of Karnali and Mohana. Two stations (IDs: 265 and 270) are in Bheri watershed; three (IDs: 259.2, 256.5 and 260) in Seti; one (ID: 220) in Tila; one (ID: 283.3) in Mohana; and three (IDs: 215; 250 and 280) in the Karnali main river. At each station, a summary plot with simulated and observed hydrographs, scatter plot, flow duration curve, and model performance statistics was prepared. Please refer **Annex 2-7** for details.

Table A2-4-1: Hydrological stations considered for model calibration and validation in KarMo basin

Station Index	River Name [Area, km^2]	Location	Coordinate		Period	
			Lat [N]	Lon [E]	Calibration	Validation
215	Humla Karnali [15,200]	Lalighat	29.159	81.591	1995 – 2001	2002 - 2004
220	Tila [1,870]	Nagma	29.107	81.680	1995 – 2002	2003 - 2009
250	Karnali [21,240]	Benighat	28.961	81.119	1995 – 2002	2003 - 2009
256.5	Budhi Ganga[1,576]	Chitra	29.163	81.216	2001 – 2005	2006 – 2008
259.2	West Seti [4,420]	Ghopa Ghat	29.300	80.775	1995 – 2002	2003 - 2009
260	Seti [7,460]	Bangna	28.978	81.144	1995 – 1999	2001 - 2008
265	Thulo Bheri[6,720]	Rimna	28.713	82.283	1995 – 2002	2003 - 2009
270	Bheri [12,290]	Jamu	28.756	81.350	1995 – 2002	2003 - 2009
280	Karnali [42,890]	Chisapani	28.644	81.292	1995 – 2002	2003 - 2009
283.5	Pathariya [983]	Chhachharawa	28.504	81.054	2001 – 2004	2000 - 2007

A2-4-1. Model performance for Bheri watershed

Simulated hydrographs at the two stations in Bheri watershed are comparable to the observed ones for daily as well as monthly time series (**Figure A2-4-1 and Figure A2-4-2**). Values of model performance indicators (R^2, NSE, and PBIAS) are also good. The model performance at Jamu (**Figure A2-4-2**) is comparable for calibration and validation period but that at Rimna worsens in the validation period. At both stations, peak flows appear to be underestimated but dry flow is well estimated resulting in negative PBIAS.

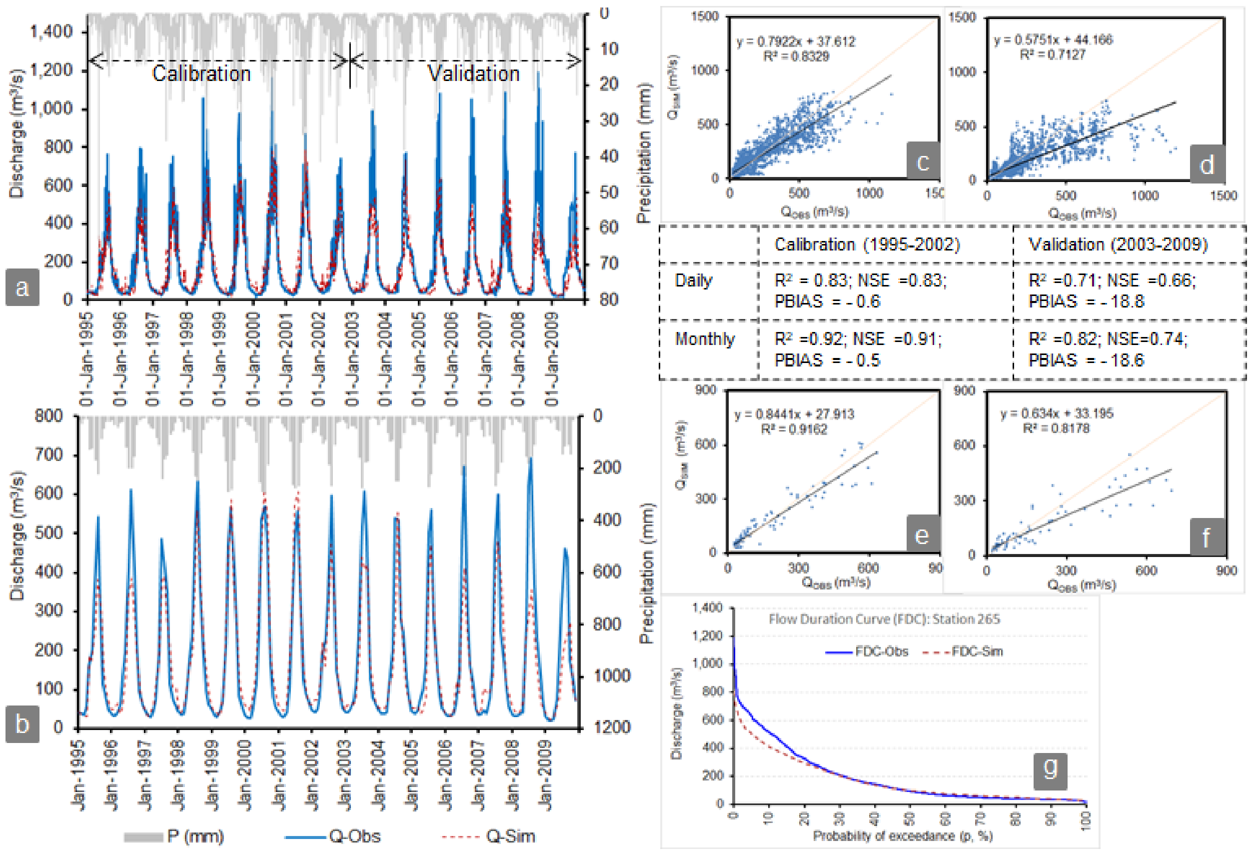


Figure A2-4-1*: Model performance at Q265 (Rimna Station; Thuli Bheri) – a) Observed and simulated daily hydrographs; b) Observed and simulated monthly hydrographs; c & d) Scattered plots for daily flow calibration and validation; e & f) Scattered plots for monthly flow calibration and validation; and g) Flow duration curve (FDC, daily).*

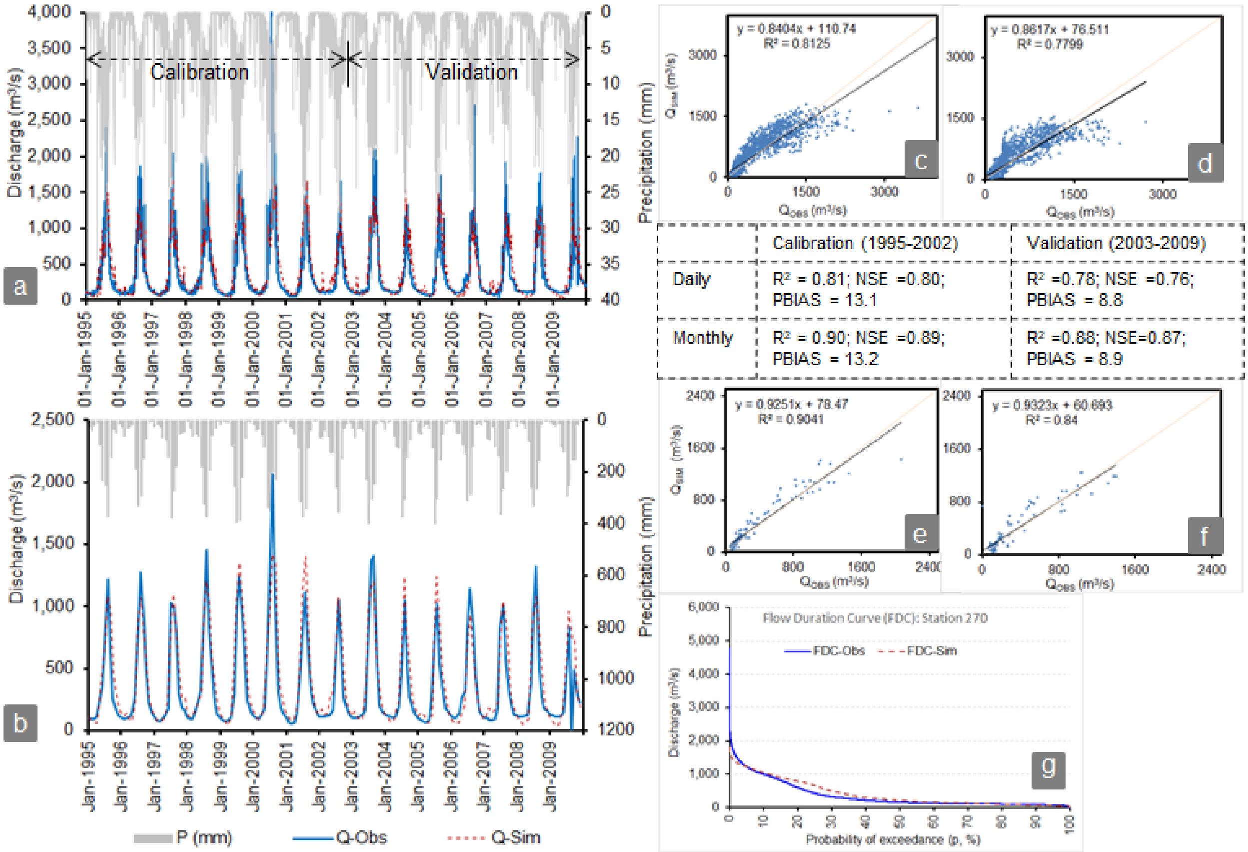


***Figure A2-4-2**: Model performance at Q270 (Jamu Station; Bheri River) – a) Observed and simulated daily hydrographs; b) Observed and simulated monthly hydrographs; c & d) Scattered plots for daily flow calibration and validation; e & f) Scattered plots for monthly flow calibration and validation; and g) Flow duration curve (FDC, daily).*

The calibrated parameter values applied for sub-basins above these two hydrological stations are provided in **Table A2-4-2** and **Table A2-4-3**.

***Table A2-4-2**: Calibrated SWAT parameters at Rimna (Station ID = 265) station in decreasing order of sensitivity. [Ratio] indicates the value is multiplier.*

Parameter*	Definition	Unit	Process (Data file)*	Level*	Range	Initial value	Calibrated value
LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0 – 180	0	80
TLAPS	Temperature lapse rate	°C/km	Topographic effect (.sub)	Sub-basin	-10 – 10	-5.6	-5.2
GWQMN	Threshold depth of water in shallow aquifer for groundwater return flow to occur	mm	Soil (.gw)	HRU	0 – 5000	1000	200
CN2	SCS runoff curve number for moisture condition II	-	Runoff (.mgt)	HRU	35 – 98	Varies	1.25 (Ratio)
ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0 – 1	0.048	0.6
CH_N2	Manning's "n" value for the main channel	-	Channel (.rte)	Reach	0 – 1	0.014	0.8
CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/hr	Channel (.rte)	Reach	0 – 500	0	400
SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0 – 3500	Varies	0.4 (Ratio)
ESCO	Soil evaporation compensation factor	-	Evaporation (.hru)	HRU	0 – 1	0.95	0.98
CANMX	Maximum canopy storage	mm	Runoff (.hru)	HRU	0 – 100	0	85
GW_DELAY	Delay time for aquifer recharge	days	Groundwater (.gw)	HRU	0 – 500	31	70
SOL_K	Saturated soil conductivity	mm/hr	Soil (.sol)	HRU	0 – 2000	Varies	0.3 (Ratio)
SOL_AWC	Available water storage capacity of the soil layer	-	Soil (.sol)	HRU	0 – 1	Varies	0.4 (Ratio)
EPCO	Plant uptake compensation factor	-	Evaporation (.hru)	HRU	0 – 1	1	0.1

***Table A2-4-3**: Calibrated SWAT parameters at Jamu (Station ID = 270) station in decreasing order of sensitivity. [Ratio] indicates the value is multiplier.*

Parameter*	Definition	Unit	Process (Data file)*	Level*	Range	Initial value	Calibrated value
LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0 – 180	0	60
CN2	SCS runoff curve number for moisture condition II	-	Runoff (.mgt)	HRU	35 – 98	Varies	1.10 (Ratio)
ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0 – 1	0.048	0.66
CH_N2	Manning’s “n” value for the main channel	-	Channel (.rte)	Reach	0 – 1	0.014	0.55
CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/hr	Channel (.rte)	Reach	0 – 500	0	120
SOL_AWC	Available water storage capacity of the soil layer	-	Soil (.sol)	HRU	0 – 1	Varies	0.4 (Ratio)
GW_DELAY	Delay time for aquifer recharge	days	Groundwater (.gw)	HRU	0 – 500	31	50
ESCO	Soil evaporation compensation factor	-	Evaporation (.hru)	HRU	0 – 1	0.95	0.2
GWQMN	Threshold depth of water in shallow aquifer for groundwater return flow to occur	mm	Soil (.gw)	HRU	0 – 5000	1000	200
SOL_K	Saturated soil conductivity	mm/hr	Soil (.sol)	HRU	0 – 2000	Varies	0.5 (Ratio)
SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0 – 3500	Varies	0.7 (Ratio)

A2-4-2 Model performance for Seti watershed

Model performance in Seti watershed was evaluated at three hydrological stations (Q259.2, Q256.5, and Q260) as shown in **Figure 2-10 (main report)**.

In case of Q259.2 (Ghopa Ghat station), calibration and validation were carried out for the period of 1995-2002 and 2003-2009, respectively. The R^2, NSE and PBIAS for daily calibration are 0.77, 0.77 and -4.8%, respectively, for daily flow simulation and much better for monthly simulation (**Figure A2-4-3**). The observed and simulated hydrographs at all three stations, for daily as well as monthly flows, are very much comparable. FDC is well reproduced. Performance at other two stations also look reasonable (**Figure A2-4-4** and **Figure A2-4-5**). Therefore, the model is capable of reproducing hydrological regime and average flow conditions within the Seti watershed.

The calibrated parameter values applied in the sub-basins above the three hydrological stations are provided in **Tables A2-4-4, A2-4-5** and **A2-4-6**.

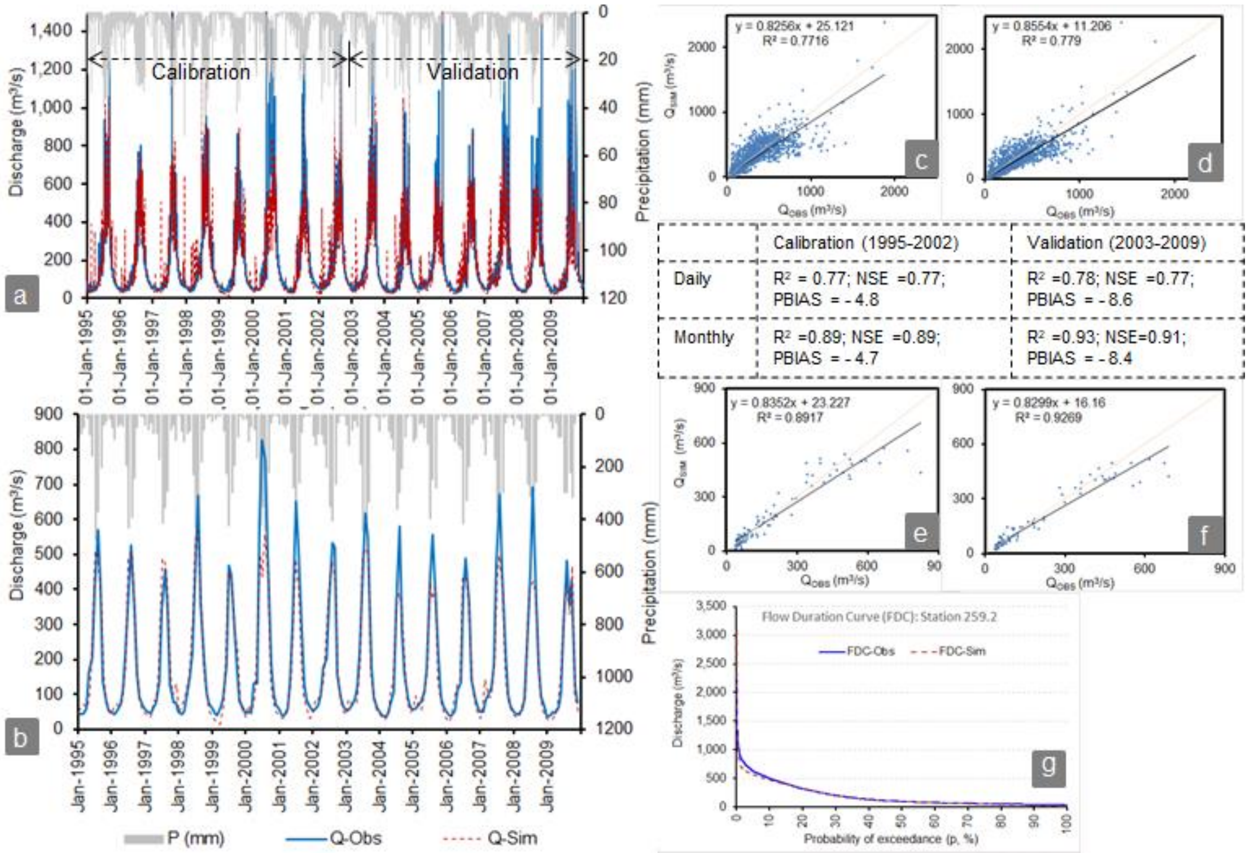


***Figure A2-4-3**: Model performance at Q259.2 (Ghopa Ghat station; Seti River) – a) Observed and simulated daily hydrographs; b) Observed and simulated monthly hydrographs; c & d) Scattered plots for daily flow calibration and validation; e & f) Scattered plots for monthly flow calibration and validation; and g) Flow duration curve (FDC, daily).*

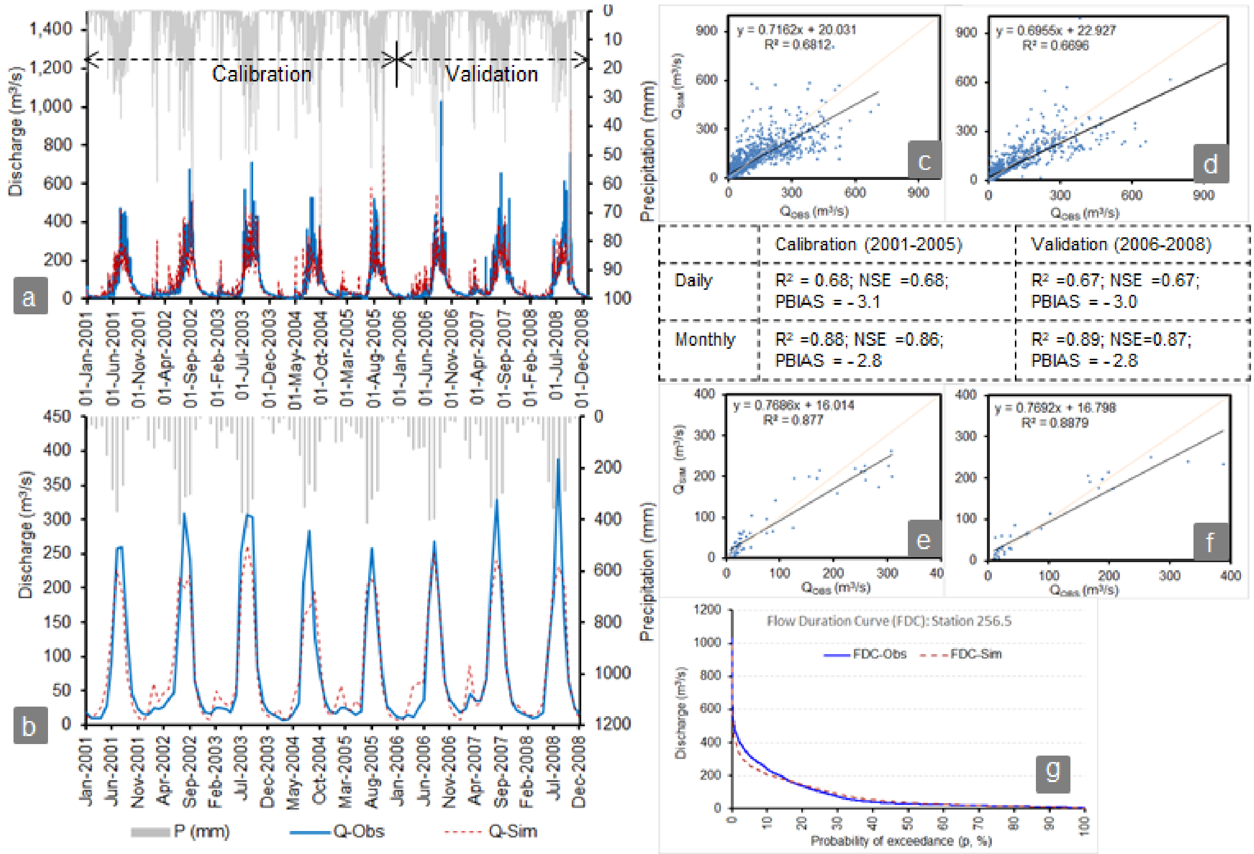


Figure A2-4-4*: Model performance at Q256.5 (Chitra station; Budhi Ganga River) – a) Observed and simulated daily hydrographs; b) Observed and simulated monthly hydrographs; c & d) Scattered plots for daily flow calibration and validation; e & f) Scattered plots for monthly flow calibration and validation; and g) Flow duration curve (FDC, daily).*

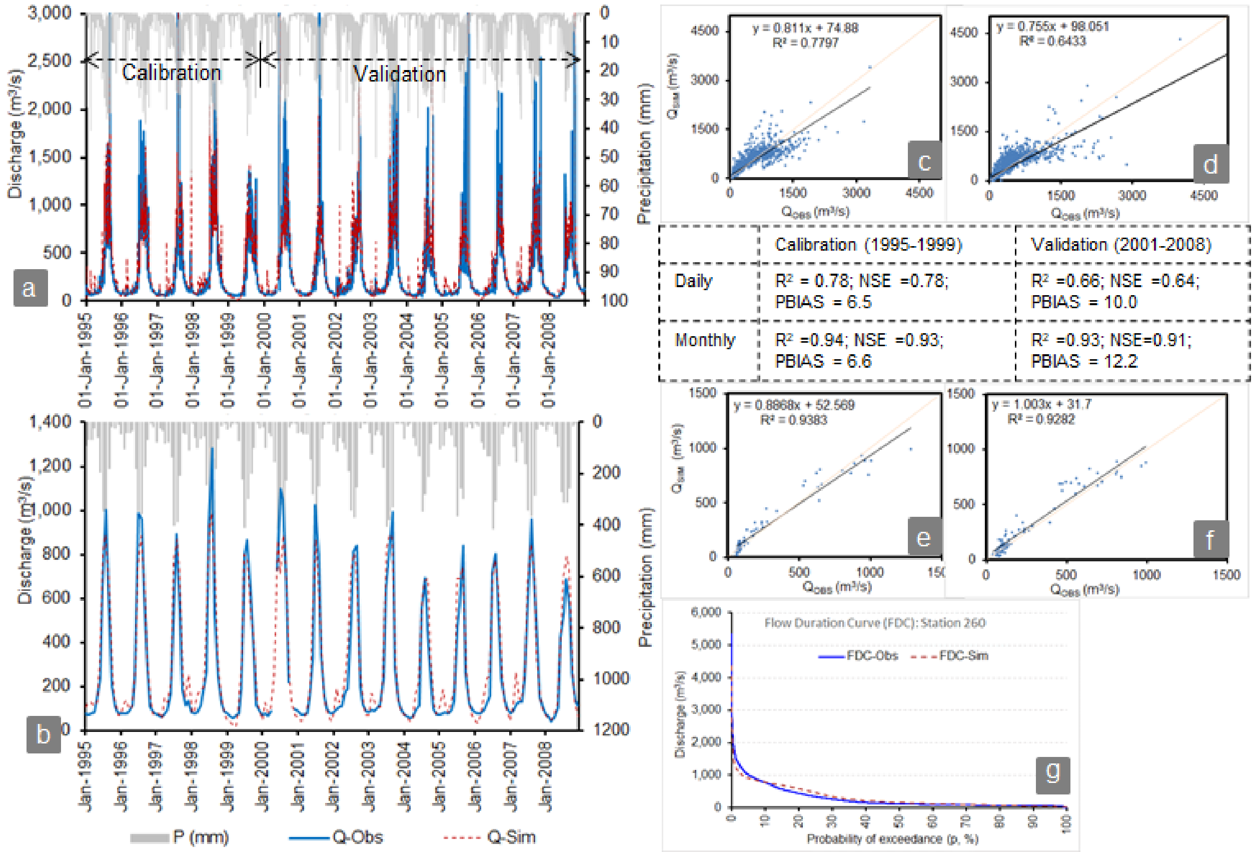


Figure A2-4-5: *Model performance at Q260 (Bangna station; Seti River) – a) Observed and simulated daily hydrographs; b) Observed and simulated monthly hydrographs; c & d) Scattered plots for daily flow calibration and validation; e & f) Scattered plots for monthly flow calibration and validation; and g) Flow duration curve (FDC, daily).*

Table A2-4-4*: Calibrated SWAT parameters at Ghopa Ghat (Station ID = 259.2) station in decreasing order of sensitivity. [Ratio] indicates the value is multiplier.*

Parameter*	Definition	Unit	Process (Data file)*	Level*	Range	Initial value	Calibrated value
ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0 – 1	0.048	0.8
CN2	SCS runoff curve number for moisture condition II	-	Runoff (.mgt)	HRU	35 – 98	Varies	1.25 (Ratio)
LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0 – 180	0	60
PLAPS	Precipitation lapse rate	mm/km	Topographic effect (.sub)	Sub-basin	-1000 – 1000	0	200
CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/hr	Channel (.rte)	Reach	0 – 500	0	104
CH_N2	Manning's "n" value for the main channel	-	Channel (.rte)	Reach	0 – 1	0.014	0.25
CANMX	Maximum canopy storage	mm	Runoff (.hru)	HRU	0 – 100	0	50
GW_DELAY	Delay time for aquifer recharge	days	Groundwater (.gw)	HRU	0 – 500	31	15
SOL_AWC	Available water storage capacity of the soil layer	-	Soil (.sol)	HRU	0 – 1	Varies	0.4 (Ratio)
GWQMN	Threshold depth of water in shallow aquifer for groundwater return flow to occur	mm	Soil (.gw)	HRU	0 – 5000	1000	100
TLAPS	Temperature lapse rate	°C/km	Topographic effect (.sub)	Sub-basin	-10 – 10	-5.6	-7.1
GW_REVAP	Groundwater revap coefficient	-	Groundwater (.gw)	HRU	0.02 – 0.2	0.02	0.2
REVAPMN	Threshold depth of water in shallow aquifer for revap to occur	mm	Groundwater (.gw)	HRU	0 – 500	750	50
SOL_K	Saturated soil conductivity	mm/hr	Soil (.sol)	HRU	0 – 2000	Varies	0.6 (Ratio)
SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0 – 3500	Varies	2 (Ratio)

***Table A2-4-5**: Calibrated SWAT parameters at Chitra (Station ID = 256.5) station in decreasing order of sensitivity. [Ratio] indicates the value is multiplier.*

Parameter*	Definition	Unit	Process (Data file)*	Level*	Range	Initial value	Calibrated value
CN2	SCS runoff curve number for moisture condition II	-	Runoff (.mgt)	HRU	35 – 98	Varies	1.21 (Ratio)
LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0 – 180	0	35
PLAPS	Precipitation lapse rate	mm/km	Topographic effect (.sub)	Sub-basin	-1000 – 1000	0	75
CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/hr	Channel (.rte)	Reach	0 – 500	0	20
CH_N2	Manning's "n" value for the main channel	-	Channel (.rte)	Reach	0 – 1	0.014	0.1
GW_DELAY	Delay time for aquifer recharge	days	Groundwater (.gw)	HRU	0 – 500	31	8
SOL_K	Saturated soil conductivity	mm/hr	Soil (.sol)	HRU	0 – 2000	Varies	0.4 (Ratio)
TLAPS	Temperature lapse rate	°C/km	Topographic effect (.sub)	Sub-basin	-10 – 10	-5.6	-7.5
SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0 – 3500	Varies	0.7 (Ratio)
ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0 – 1	0.048	0.5
SOL_AWC	Available water storage capacity of the soil layer	-	Soil (.sol)	HRU	0 – 1	Varies	0.3 (Ratio)
CANMX	Maximum canopy storage	mm	Runoff (.hru)	HRU	0 – 100	0	50
CH_N1	Manning's "n" value for the tributary channel	-	Runoff (.sub)	Sub-basin	0.01-30	0.014	10
ESCO	Soil evaporation compensation factor	-	Evaporation (.hru)	HRU	0 – 1	0.95	0.99
REVAPMN	Threshold depth of water in shallow aquifer for revap to occur	mm	Groundwater (.gw)	HRU	0 – 500	750	130

***Table A2-4-6**: Calibrated SWAT parameters at Bangna (Station ID = 260) station in decreasing order of sensitivity. [Ratio] indicates the value is multiplier.*

Parameter*	Definition	Unit	Process (Data file)*	Level*	Range	Initial value	Calibrated value
CN2	SCS runoff curve number for moisture condition II	-	Runoff (.mgt)	HRU	35 – 98	Varies	1.15 (Ratio)
LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0 – 180	0	40
ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0 – 1	0.048	0.5
SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0 – 3500	Varies	0.61 (Ratio)
CANMX	Maximum canopy storage	mm	Runoff (.hru)	HRU	0 – 100	0	63
ESCO	Soil evaporation compensation factor	-	Evaporation (.hru)	HRU	0 – 1	0.95	0.99
CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/hr	Channel (.rte)	Reach	0 – 500	0	200
TLAPS	Temperature lapse rate	°C/km	Topographic effect (.sub)	Sub-basin	-10 – 10	-5.6	-7.1
SOL_AWC	Available water storage capacity of the soil layer	-	Soil (.sol)	HRU	0 – 1	Varies	0.5 (Ratio)
REVAPMN	Threshold depth of water in shallow aquifer for revap to occur	mm	Groundwater (.gw)	HRU	0 – 500	750	261

A2-4-3 Model performance for Mohana watershed

The model performance was evaluated at one station (Q283.5) located in Pathriya, a tributary of Mohana.for daily as well as monthly flows. Reliable data is only available for the short span of 2001-2003 available at this station. Due to the seasonal flash floods in the region, hydrological stations in Mohana are difficult to maintain as per our personal communication with DHM. The model performance, as indicated by statistical indicator, for monthly simulation seems reasonable (**Figure A2-4-6**); however, flow pattern for the calibration and validation period is nicely reproduced. In case of daily simulation, R2 and NSE are below 0.6 for calibration period (2001-2002) and even worse for validation period (Jan-Dec, 2003). The scattering of simulated-observed dots is very high, which indicates, less reliability in simulated flow pattern across all the seasons even though long-term average is reproduced reasonably. However, considering the issues in hydrological data collection in the southern rivers like Mohana, the performance is considered acceptable. The calibration parameter values at the time of SWAT model calibration are reported in **Table A2-4-7**.

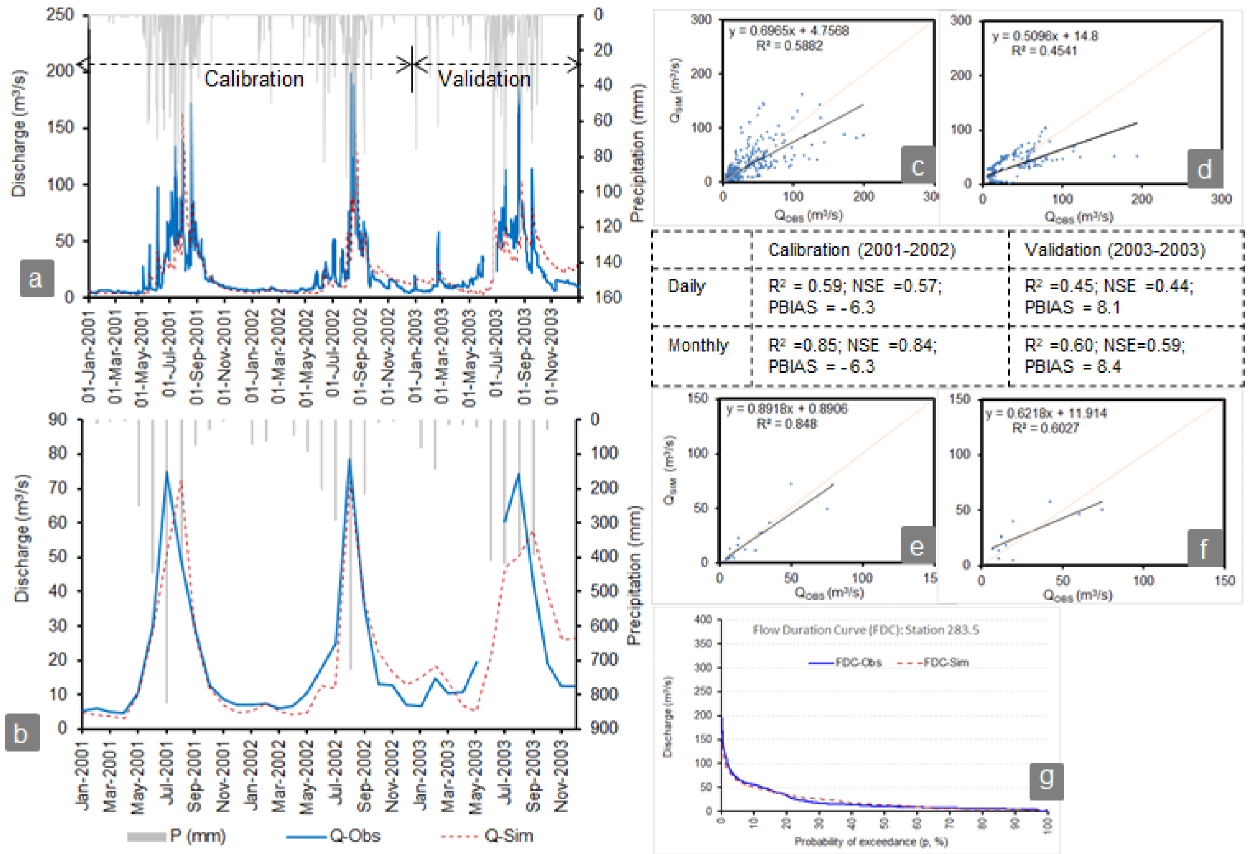


***Figure A2-4-6**: Model performance at Q283.5 (Chhachharawa station; Pathariya River) – a) Observed and simulated daily hydrographs; b) Observed and simulated monthly hydrographs; c & d) Scattered plots for daily flow calibration and validation; e & f) Scattered plots for monthly flow calibration and validation; and g) Flow duration curve (FDC, daily).*

***Table A2-4-7**: Calibrated SWAT parameters at Chhachharawa (Station ID = 283.5) station in decreasing order of sensitivity.*

Parameter*	Definition	Unit	Process (Data file)*	Level*	Range	Initial value	Calibrated value
CN2	SCS runoff curve number for moisture condition II	-	Runoff (.mgt)	HRU	35 – 98	Varies	0.6 (Ratio)
ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0 – 1	0.048	0.95
LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0 – 180	0	25
CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/hr	Channel (.rte)	Reach	0 – 500	0	500
GW_DELAY	Delay time for aquifer recharge	days	Groundwater (.gw)	HRU	0 – 500	31	200
CANMX	Maximum canopy storage	mm	Runoff (.hru)	HRU	0 – 100	0	5
ESCO	Soil evaporation compensation factor	-	Evaporation (.hru)	HRU	0 – 1	0.95	0.99
PLAPS	Precipitation lapse rate	mm/km	Topographic effect (.sub)	Sub-basin	-1000 – 1000	0	50
TLAPS	Temperature lapse rate	°C/km	Topographic effect (.sub)	Sub-basin	-10 – 10	-5.6	-9.5
GWQMN	Threshold depth of water in shallow aquifer for groundwater return flow to occur	mm	Soil (.gw)	HRU	0 – 5000	1000	5000
SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0 – 3500	Varies	0.6 (Ratio)
GW_REVAP	Groundwater revap coefficient	-	Groundwater (.gw)	HRU	0.02 – 0.2	0.02	0.2
RCHRG_DP	Deep aquifer percolation fraction	-	Groundwater (.gw)	HRU	0 – 1	0.05	0.1
REVAPMN	Threshold depth of water in shallow aquifer for revap to occur	mm	Groundwater (.gw)	HRU	0 – 500	750	100
EPCO	Plant uptake compensation factor	-	Evaporation (.hru)	HRU	0 – 1	1	0.1
SOL_K	Saturated soil conductivity	mm/hr	Soil (.sol)	HRU	0 – 2000	Varies	2.0 (Ratio)
CH_N1	Manning's "n" value for the tributary channel	-	Runoff (.sub)	Sub-basin	0.01-30	0.014	0.6
SHALLST	Initial depth of water in shallow aquifer	mm	Groundwater (.gw)	HRU	0 – 50000	1000	500

A2-4-4 Model performance for Tila watershed

The model performance at Tila river is evaluated at Q220 station (please refer **Figure 2-10 in main report** for location). The model performance is shown in **Figure A2-4-7** and calibrated parameter values are reported in **Table A2-4-8**. The hydrograph pattern (monthly and daily), flow duration curve, and statistical indicators (R^2, NSE, and PBIAS) suggests that the model is capable of reproducing hydrological pattern and average flow conditions in the Tila watershed.

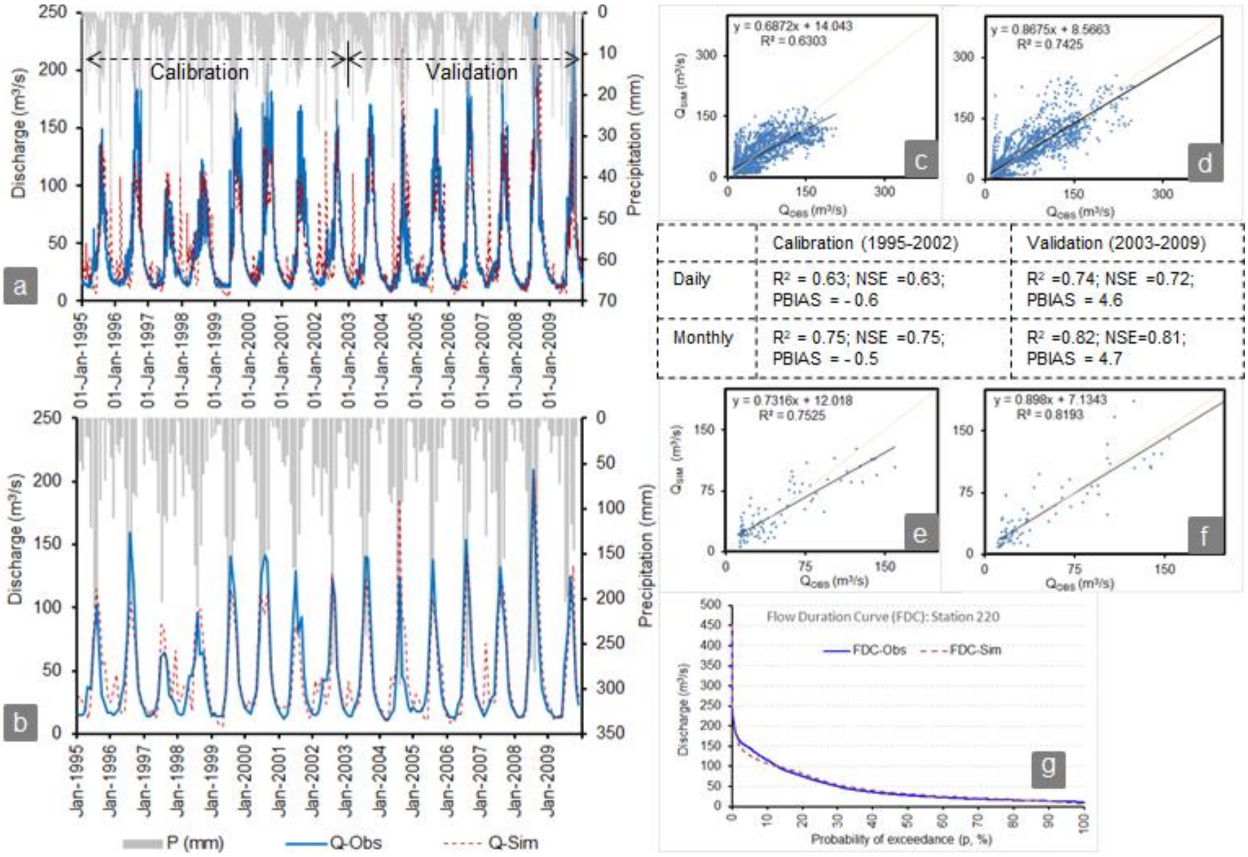


Figure A2-4-7*: Model performance at Q220 (Nagma station; Tila River) – a) Observed and simulated daily hydrographs; b) Observed and simulated monthly hydrographs; c & d) Scattered plots for daily flow calibration and validation; e & f) Scattered plots for monthly flow calibration and validation; and g) Flow duration curve (FDC, daily).*

***Table A2-4-8**: Calibrated SWAT parameters at Nagma (Station ID = 220) station in decreasing order of sensitivity. [Ratio] indicates the value is multiplier.*

Parameter*	Definition	Unit	Process (Data file)*	Level*	Range	Initial value	Calibrated value
CN2	SCS runoff curve number for moisture condition II	-	Runoff (.mgt)	HRU	35 – 98	Varies	1.22 (Ratio)
LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0 – 180	0	70
CANMX	Maximum canopy storage	mm	Runoff (.hru)	HRU	0 – 100	0	3
CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/hr	Channel (.rte)	Reach	0 – 500	0	450
ESCO	Soil evaporation compensation factor	-	Evaporation (.hru)	HRU	0 – 1	0.95	0.99
ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0 – 1	0.048	0.40
TLAPS	Temperature lapse rate	°C/km	Topographic effect (.sub)	Sub-basin	-10 – 10	-5.6	-2.0
GW_DELAY	Delay time for aquifer recharge	days	Groundwater (.gw)	HRU	0 – 500	31	80
SOL_AWC	Available water storage capacity of the soil layer	-	Soil (.sol)	HRU	0 – 1	Varies	0.3 (Ratio)
SOL_K	Saturated soil conductivity	mm/hr	Soil (.sol)	HRU	0 – 2000	Varies	0.3 (Ratio)
SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0 – 3500	Varies	0.6 (Ratio)

A2-4-5 Model performance for Karnali-Main

The model performance at three hydrological stations (Q215, Q250 and Q280) along the Karnali main river were evaluated. The model performance at those stations are shown in **Figures A2-4-8, A2-4-9, and A2-4-10**. The calibrated model parameters are summarized in **Tables A2-4-9, A2-4-10, and A2-4-11**. For all three cases, hydrograph patterns and flow duration curve are well reproduced and model performance indicators (R^2, NSE and PBIAS) are reasonably good. Considering the aforementioned observations, the model is adequate to reproduce average flow conditions in the Karnali-main watershed.

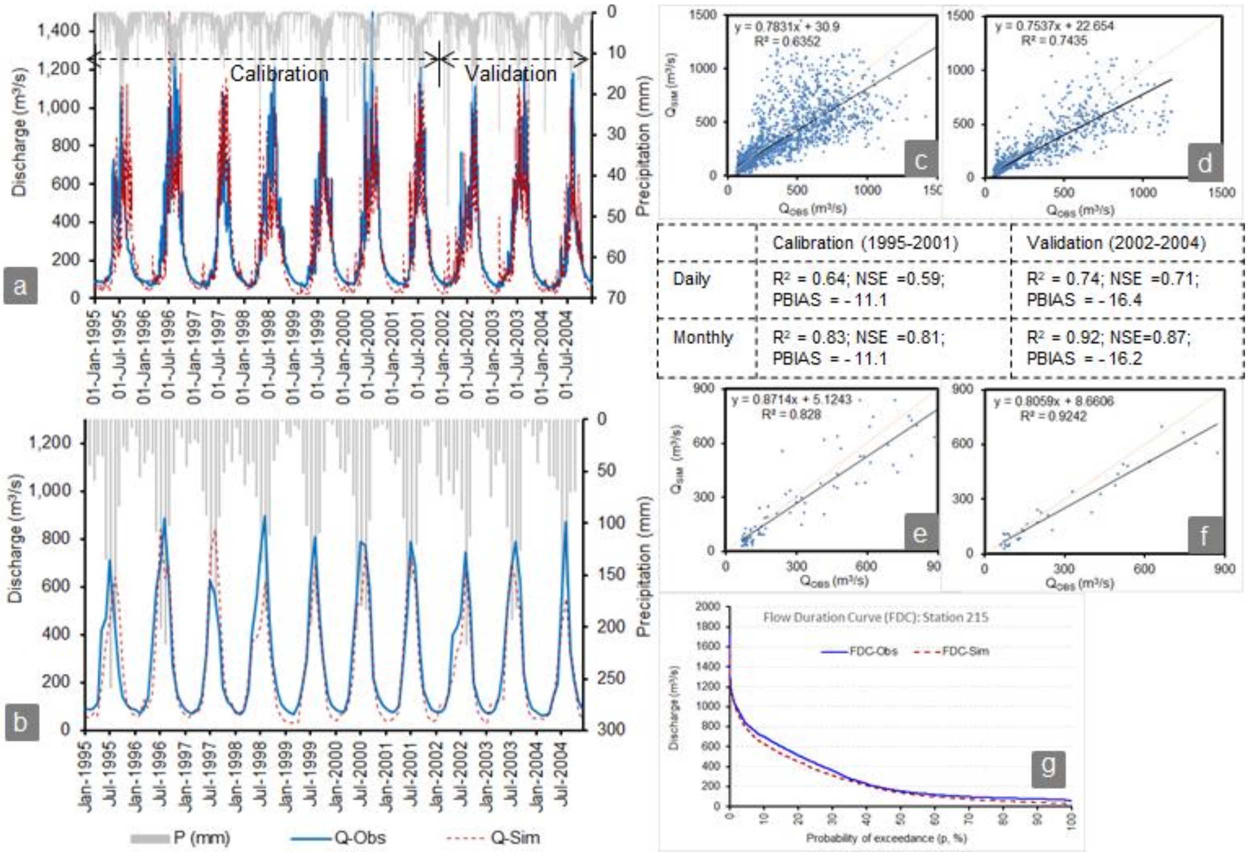


***Figure A2-4-8**: Model performance at Q215 (Karnali River) – a) Observed and simulated daily hydrographs; b) Observed and simulated monthly hydrographs; c & d) Scattered plots for daily flow calibration and validation; e & f) Scattered plots for monthly flow calibration and validation; and g) Flow duration curve (FDC, daily).*

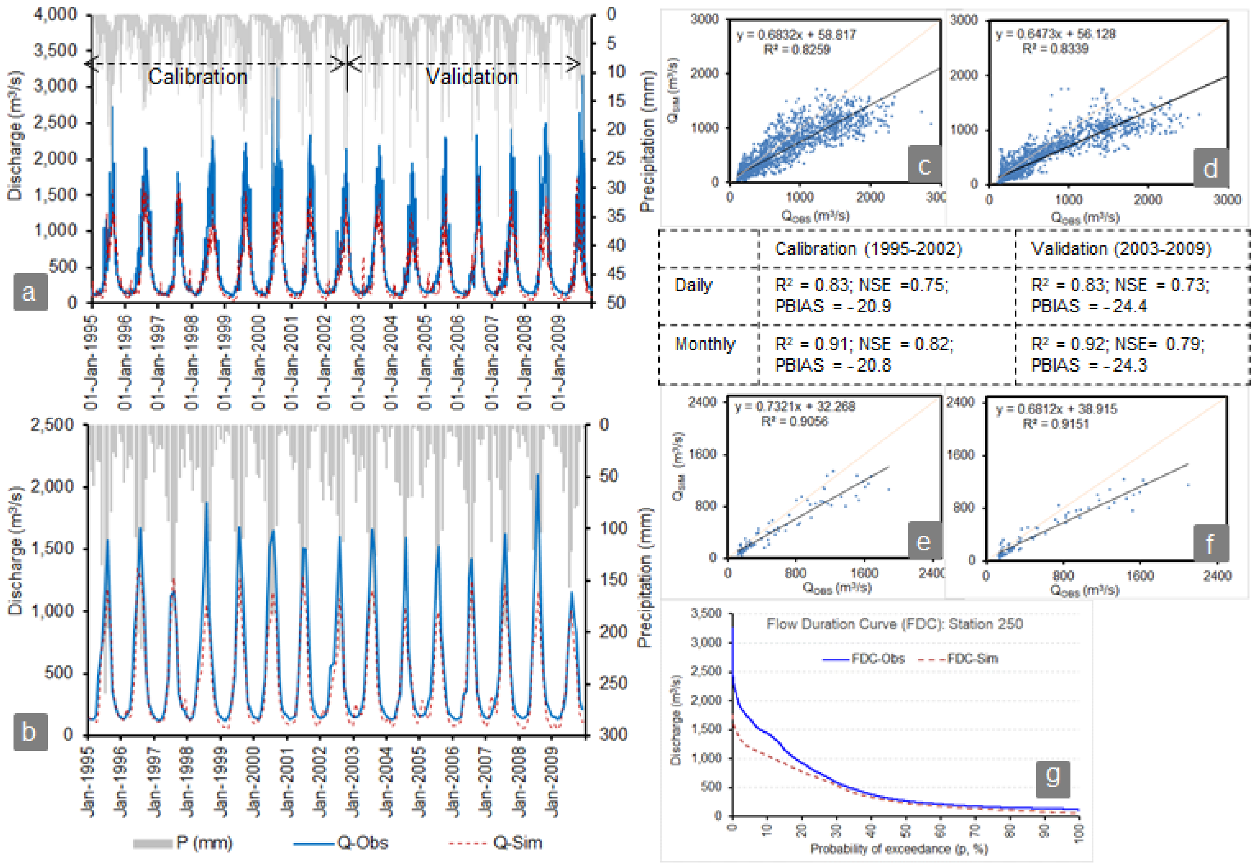


***Figure A2-4-9**: Model performance at Q250 (Karnali River) – a) Observed and simulated daily hydrographs; b) Observed and simulated monthly hydrographs; c & d) Scattered plots for daily flow calibration and validation; e & f) Scattered plots for monthly flow calibration and validation; and g) Flow duration curve (FDC, daily).*

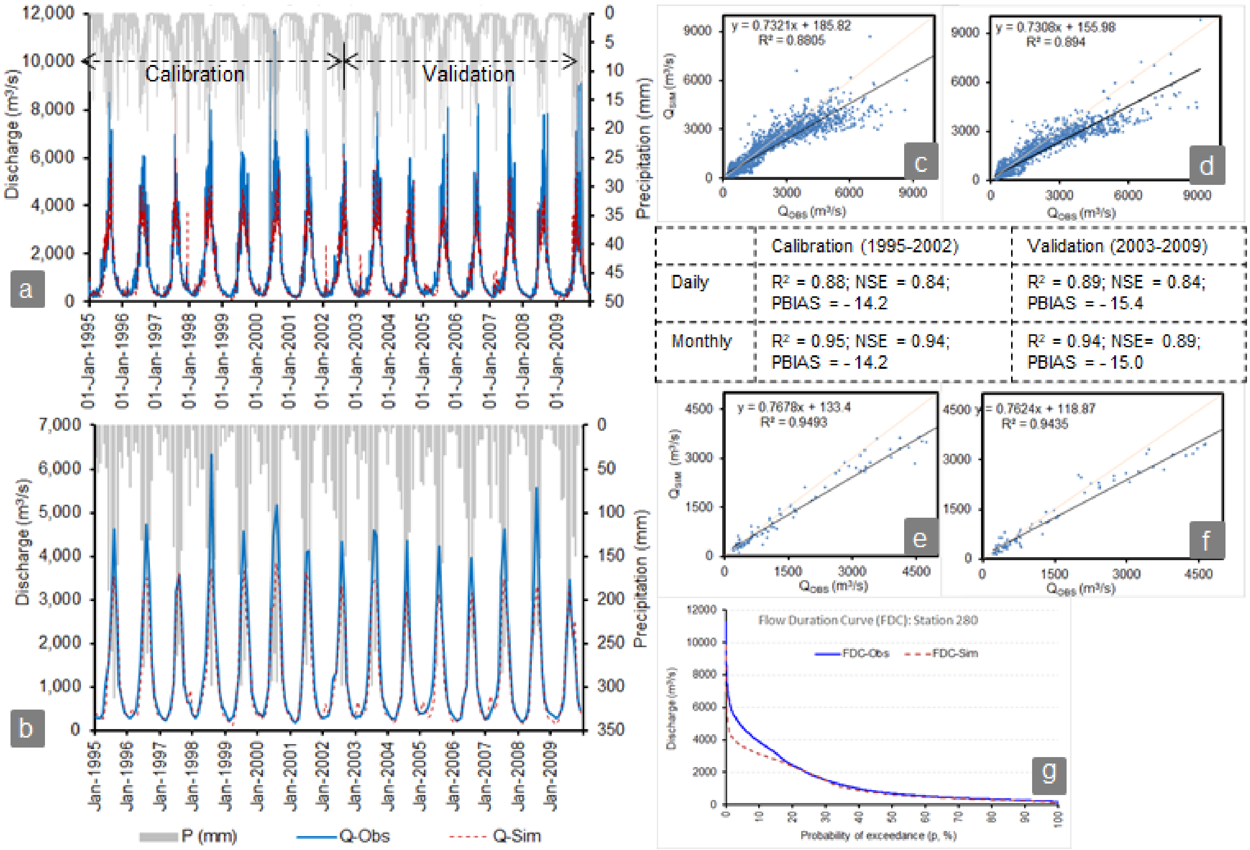


Figure A2-4-10: *Model performance at Q280 (Karnali River) – a) Observed and simulated daily hydrographs; b) Observed and simulated monthly hydrographs; c & d) Scattered plots for daily flow calibration and validation; e & f) Scattered plots for monthly flow calibration and validation; and g) Flow duration curve (FDC, daily).*

Table A2-4-9*: Calibrated SWAT parameters at Lalighat (Station ID = 215) station in decreasing order of sensitivity. Ratio] indicates the value is multiplier.*

Parameter*	Definition	Unit	Process (Data file)*	Level*	Range	Initial value	Calibrated value
ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0 – 1	0.048	0.10
LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0 – 180	0	15
CN2	SCS runoff curve number for moisture condition II	-	Runoff (.mgt)	HRU	35 – 98	Varies	1.1 (Ratio)
TLAPS	Temperature lapse rate	°C/km	Topographic effect (.sub)	Sub-basin	-10 – 10	-5.6	-7.1
GWQMN	Threshold depth of water in shallow aquifer for groundwater return flow to occur	mm	Soil (.gw)	HRU	0 – 5000	1000	500
SOL_K	Saturated soil conductivity	mm/hr	Soil (.sol)	HRU	0 – 2000	Varies	0.6 (Ratio)
CH_N2	Manning's "n" value for the main channel	-	Channel (.rte)	Reach	0 – 1	0.014	0.50
GW_DELAY	Delay time for aquifer recharge	days	Groundwater (.gw)	HRU	0 – 500	31	80
CANMX	Maximum canopy storage	mm	Runoff (.hru)	HRU	0 – 100	0	60
SOL_AWC	Available water storage capacity of the soil layer	-	Soil (.sol)	HRU	0 – 1	Varies	0.5 (Ratio)
SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0 – 3500	Varies	0.6 (Ratio)

Table A2-4-10*: Calibrated SWAT parameters at Benighat (Station ID = 250) station in decreasing order of sensitivity. [Ratio] indicates the value is multiplier.*

Parameter*	Definition	Unit	Process (Data file)*	Level*	Range	Initial value	Calibrated value
GW_DELAY	Delay time for aquifer recharge	days	Groundwater (.gw)	HRU	0 – 500	31	5

CN2	SCS runoff curve number for moisture condition II	-	Runoff (.mgt)	HRU	35 – 98	Varies	1.25 (Ratio)
GWQMN	Threshold depth of water in shallow aquifer for groundwater return flow to occur	mm	Soil (.gw)	HRU	0 – 5000	1000	40
PLAPS	Precipitation lapse rate	mm/km	Topographic effect (.sub)	Sub-basin	-1000 – 1000	0	500
ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0 – 1	0.048	0.90
LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0 – 180	0	100
SOL_AWC	Available water storage capacity of the soil layer	-	Soil (.sol)	HRU	0 – 1	Varies	0.4 (Ratio)
TLAPS	Temperature lapse rate	°C/km	Topographic effect (.sub)	Sub-basin	-10 – 10	-5.6	0
SOL_K	Saturated soil conductivity	mm/hr	Soil (.sol)	HRU	0 – 2000	Varies	2.0 (Ratio)
CANMX	Maximum canopy storage	mm	Runoff (.hru)	HRU	0 – 100	0	80
ESCO	Soil evaporation compensation factor	-	Evaporation (.hru)	HRU	0 – 1	0.95	0.99
CH_N2	Manning's "n" value for the main channel	-	Channel (.rte)	Reach	0 – 1	0.014	0.56
CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/hr	Channel (.rte)	Reach	0 – 500	0	480
RCHRG_DP	Deep aquifer percolation fraction	-	Groundwater (.gw)	HRU	0 – 1	0.05	0.01

Table A2-4-11*: Calibrated SWAT parameters at Chisapani (Station ID = 280) station in decreasing order of sensitivity. [Ratio] indicates the value is multiplier.*

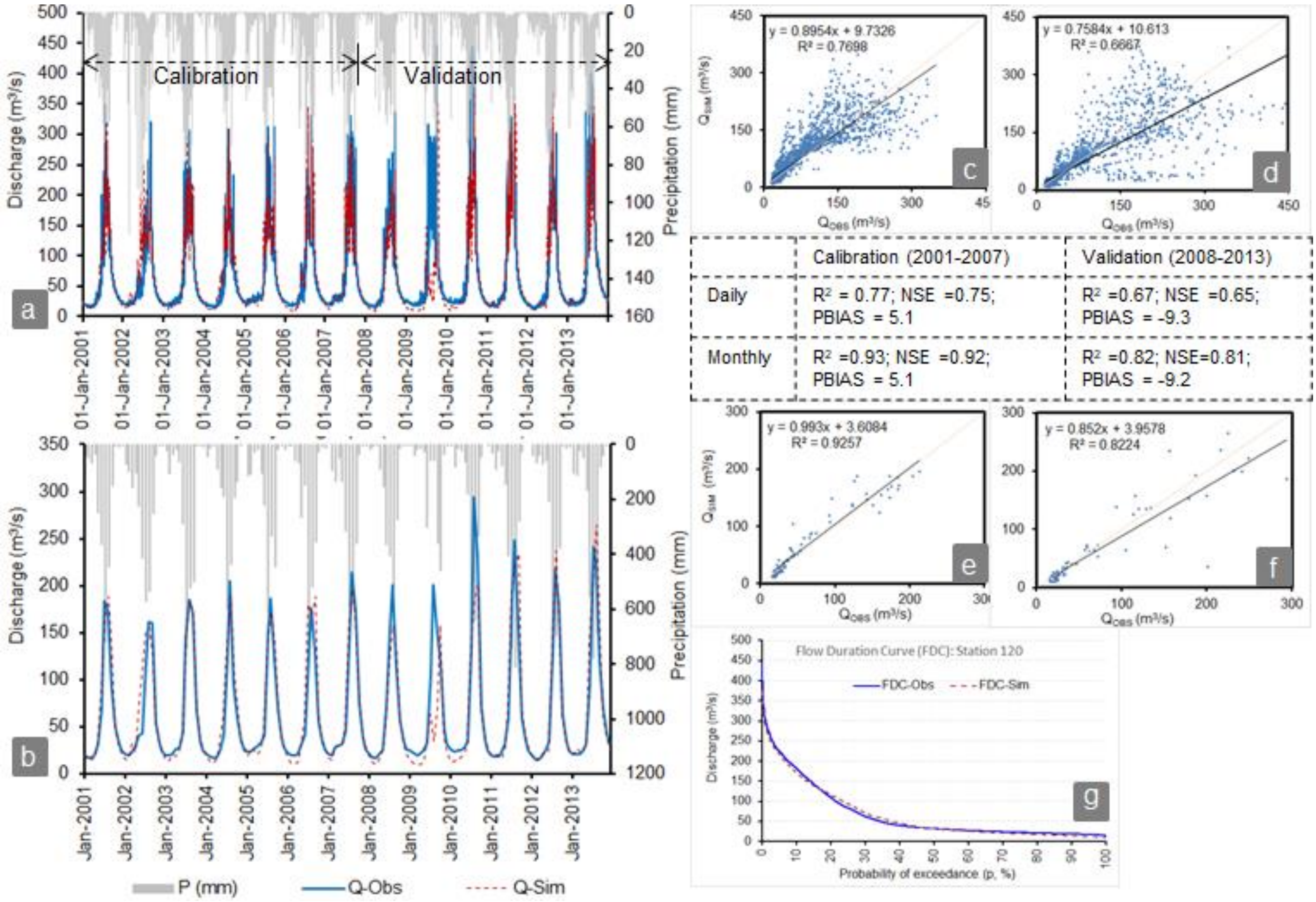
Parameter*	Definition	Unit	Process (Data file)*	Level*	Range	Initial value	Calibrated value
ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0 – 1	0.048	0.90
CANMX	Maximum canopy storage	mm	Runoff (.hru)	HRU	0 – 100	0	70
CN2	SCS runoff curve number for moisture condition II	-	Runoff (.mgt)	HRU	35 – 98	Varies	1.1 (Ratio)

SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0 – 3500	Varies	0.61 (Ratio)
ESCO	Soil evaporation compensation factor	-	Evaporation (.hru)	HRU	0 – 1	0.95	0.99
CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/hr	Channel (.rte)	Reach	0 – 500	0	104

Annex 2-5

Annex 2-5: Evaluation of hydrological model performance for the Mahakali basin

Owing to lack of data for the entire Mahakali basin, a hydrological model was only calibrated for Chamelia sub-basin in the Nepali side of Mahakali. Model parameters related to runoff, evapotranspiration, groundwater and soil water were adjusted to represent observed hydrological patterns at the three hydrological stations (please refer **Figure 2-22, main report**, for location of the stations). The model performance at Q120 (at Karkalegaon) in the Chamelia river is shown in **Figure A2-5-1**.



	Calibration (2001-2007)	Validation (2008-2013)
Daily	R^2 = 0.77; NSE = 0.75; PBIAS = 5.1	R^2 = 0.67; NSE = 0.65; PBIAS = -9.3
Monthly	R^2 = 0.93; NSE = 0.92; PBIAS = 5.1	R^2 = 0.82; NSE = 0.81; PBIAS = -9.2

Figure A2-5-1: *Comparison of observed versus simulated stream flows at Karkalegaon (Index = Q120; River = Chamelia) station: a) Hydrograph for daily simulation, b) Hydrograph for monthly simulation, c &d) Scattered plots for daily calibration and validation, e & f) Scattered plots for monthly flow calibration and validation, e) Flow duration curve (FDC, daily).*

The calibrated parameters for Chamelia at station Q120 are shown in **Table A2-5-1** while performance at other stations are discussed in Pandey et al. (2019b) (**Annex 2-6)**. Sensitive parameters were not consistent throughout the sub-watersheds. However, the runoff curve number (CN2), groundwater delay (GW_DELAY) and baseflow recession factor (ALPHA_BF) were among the most sensitive parameters at all three stations, albeit with varying levels of influence.

Table A2-5-1: *Calibrated SWAT parameters at Karkale Gaon (Chamelia, station Q120) in Chamelia, Mahakali (in decreasing order of sensitivity)*

Parameter	Definition	Unit	Process (Data file)*	Level*	Recommended Range	Default value	Calibrated value
CN2	SCS runoff curve number for moisture condition II	-	Runoff (.mgt)	HRU	35 – 98	Varies	1.2 (Ratio)
CANMX	Maximum canopy storage	mm	Runoff (.hru)	HRU	0 – 100	0	98
CH_N1	Manning's "n" value for the tributary channel	-	Runoff (.sub)	Sub-basin	0.01-30	0.014	0.5
ESCO	Soil evaporation compensation factor	-	Evaporation (.hru)	HRU	0 – 1	0.95	0.2
GW_DELAY	Delay time for aquifer recharge	days	Groundwater (.gw)	HRU	0 – 500	31	5
CH_N2	Manning's "n" value for the main channel	-	Channel (.rte)	Reach	0 – 1	0.014	0.15
CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/hr	Channel (.rte)	Reach	0 – 500	0	300
TLAPS	Temperature lapse rate	°C/km	Topographic effect (.sub)	Sub-basin	-10 – 10	-5.6	-7.9
ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0 – 1	0.048	0.25
LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0 – 180	0	80
SOL_K	Saturated soil conductivity	mm/hr	Soil (.sol)	HRU	0 – 2000	Varies	0.2 (Ratio)
SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0 – 3500	Varies	2 (Ratio)

There are good agreements between the simulated and observed streamflow values at all the three hydrological stations for both calibration and validation periods. **Figure A2-5-1** shows the model performance at station Q120. The model simulates the hydrological regime for daily as well as monthly flows reasonably well, reproducing flow duration curve (FDC), and keeping statistical parameters within reasonable range. Difference between observed and simulated average annual values for calibration, validation and overall (calibration + validation) periods are less than 15% at all three stations. Of the three hydrological stations, st120 lies on the main stem of Chamelia, covering most of the watershed, and shows the best performance. Based on the general performance ratings criteria developed by Moriasi et al. (2007), for both monthly and daily time steps, model calibration results are "very good (NSE>0.65)" for the stations Q120 and Q115 and "adequate (NSE = 0.54 to 0.65)" for the station Q125. For the validation period, the daily and monthly NSE range between 0.33 to 0.65 and 0.68 to 0.81 across the three stations, with relatively poorer performance at Q115.

A closer look into the hydrograph and scatter plots during calibration indicates that the model estimates low flows and long-term average reasonably well for both daily and monthly simulations. However, the scatter points are spread out further for high flows indicating that the model is poorer at simulating high peaks (or high flows). The equation of the linear fit shows that model is under-estimating flow at both daily and monthly scale. During validation, the scatter plot shows higher spread even for average-flows indicating that the model performance is poor for both high-flows as well as average flows even if low flow is reasonably reproduced. Overall, the model is better suited for low-flows estimation and water resources assessment and needs further calibration for use in flood-forecasting and extreme analysis. As the goal of this modeling is to assess water availability and its distribution in the long run, the model is considered adequate to serve the purpose.

References

Moriasi DN, Arnold JG, Van Liew MW, et al (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASABE. doi: 10.13031/2013.23153

Pandey VP, Dhaubanjar S, Bharati L, Thapa BR (2019b) Hydrological response of Chamelia watershed in Mahakali Basin to climate change. Sci Total Environ 650:365–383. doi: 10.1016/j.scitotenv.2018.09.053

Annex 2-6

Science of the Total Environment 650 (2019) 365–383

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Hydrological response of Chamelia watershed in Mahakali Basin to climate change

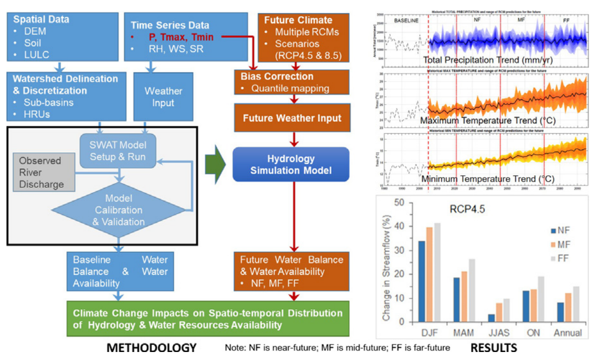
Vishnu Prasad Pandey *, Sanita Dhaubanjar, Luna Bharati, Bhesh Raj Thapa

International Water Management Institute (IWMI), Nepal Office, Lalitpur, Nepal

HIGHLIGHTS

- The first study evaluating spatio-temporal distribution in water availability to climate change in Chamelia.
- Maximum temperature under RCP scenarios and for three future periods are projected to increase in a range of 0.9-3.4°C).
- Streamflow is projected to increase gradually from near to far future under both RCPs, e.g. 12.2% in mid-future & RCP4.5

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 9 April 2018
Received in revised form 4 September 2018
Accepted 4 September 2018
Available online 05 September 2018

Editor: Ouyang Wei

Keywords:
Chamelia watershed
Climate change
Hydrological modeling
Mahakali
SWAT
Water resources

ABSTRACT

Chamelia (catchment area = 1603 km^2), a tributary of Mahakali, is a snow-fed watershed in Western Nepal. The watershed has 14 hydropower projects at various stages of development. This study simulated the current and future hydrological system of Chamelia using the Soil and Water Assessment Tool (SWAT). The model was calibrated for 2001–2007; validated for 2008–2013; and then applied to assess streamflow response to projected future climate scenarios. Multi-site calibration ensures that the model is capable of reproducing hydrological heterogeneity within the watershed. Current water balance above the Q120 hydrological station in the forms of precipitation, actual evapotranspiration (AET), and net water yield are 2469 mm, 381 mm and 1946 mm, respectively. Outputs of five Regional Climate Models (RCMs) under two representative concentration pathways (RCPs) for three future periods were considered for assessing climate change impacts. An ensemble of bias-corrected RCM projections showed that maximum temperature under RCP4.5 (RCP8.5) scenario for near-, mid-, and far-futures is projected to increase from the baseline by 0.9 °C (1.1 °C), 1.4 °C (2.1 °C), and 1.6 °C (3.4 °C), respectively. Minimum temperature for the same scenarios and future periods are projected to increase by 0.9 °C (1.2 °C), 1.6 °C (2.5 °C), and 2.0 °C (3.9 °C), respectively. Average annual precipitation under RCP4.5 (RCP8.5) scenario for near-, mid-, and far-futures are projected to increase by 10% (11%), 10% (15%), and 13% (15%), respectively. Based on the five RCMs considered, there is a high consensus for increase in temperature but higher uncertainty with respect to precipitations. Under these projected changes, average annual streamflow was simulated to increase gradually from the near to far future under both RCPs; for instance, by 8.2% in near-, 12.2% in mid-, and 15.0% in far-future under RCP4.5 scenarios. The results are useful for planning water infrastructure projects, in Chamelia and throughout the Mahakali basin, to ensure long-term sustainability under climate change.

* Corresponding author.
E-mail address: v.pandey@cgiar.org (V.P. Pandey).

https://doi.org/10.1016/j.scitotenv.2018.09.053
0048-9697/

1. Introduction

River basins across the globe are experiencing varying degrees of impacts from climate change (Kim and Kaluarachchi, 2009; Zhu and Ringler, 2012; Kure et al., 2013; Manandhar et al., 2013; Khadka et al., 2014; Shrestha and Htut, 2016; Versini et al., 2016; etc.). Snow-fed watersheds are considered even more vulnerable (Barnett et al., 2005; Immerzeel et al., 2013). The Intergovernmental Panel on Climate Change (IPCC), based on Coupled Model Intercomparison Project (CMIP5), has defined a series of Representative Concentration Pathways (RCP) for future climate projections (Van Vuuren et al., 2011). As per the RCP scenarios, temperature is projected to rise with high confidence and summer monsoon precipitation is projected to rise across South Asia with medium confidence (IPCC, 2013). These changes may alter the hydrologic systems (Bolch et al., 2012) leading to (but not limited to) disappearance of natural springs, loss or functional change in wetlands, increased variability in streamflow, and glacier retreat (Bates et al., 2008). This may consequently cause losses in transient groundwater storage (Andermann et al., 2012), agricultural productivity and yield, rural and urban livelihoods due to intermittent water supply, industrial productivity, and overall economy (Dixit et al., 2009; WECS, 2011; IWMI, 2014).

Water has been identified as the key resource for development and economic growth of Nepal (WECS, 2011). Because of possible impacts on future water availability and spatio-temporal distribution, climate change (CC) is frequently discussed in national development discourse in Nepal (Dixit et al., 2009). The climatic trends in Nepal reveal significant warming in recent decades (Devkota and Gyawali, 2015) and CC scenarios for Nepal across multiple general circulation models (GCMs) show considerable convergence on continued warming, with averaged mean temperature projected to increase by 1.2 °C and 3 °C by 2050 and 2100, respectively (World Bank, 2009). Studies in Nepalese basins such as Koshi have shown a large increase in intra- and inter-annual variability in climate and streamflows (Bharati et al., 2014, 2016). Another study (Manandhar et al., 2013) has shown that average annual and seasonal streamflows are expected to increase with a rise in temperature in the Kali Gandaki basin. As water is the crucial resource for socio-economic development of Nepal, it is imperative to understand likely impacts of CC on future water availability and incorporate them in future water resource planning. However, studies on projected future climate scenarios and associated impacts on spatio-temporal distributions and availability of water resources are limited, particularly in western Nepal. This study therefore considers evaluating climate change impacts on hydrological responses of Chamelia, a snow-fed tributary at the headwaters of Mahakali River Basin in Western Nepal (Fig. 1). This is the first study of this nature in the watershed, and it is important especially given the context of several planned hydropower projects.

The Mahakali basin, as delineated at a point (latitude = 28°28′42″; longitude = 80°31′38″) below the Nepal-India border in the Digo Jal Bikas Project, covers 17,377 km^2. Mahakali is a transboundary basin with about two-thirds of the basin falling in India and the rest in Nepal. The Mahakali river forms the border between India and Nepal and then joins Ganges basin in India (Fig. 1). Chamelia is the largest watershed in the Nepalese side of the Mahakali Basin, covering an area of 1603 km^2. Any intervention in the form of water infrastructure or management is expected to have impacts on downstream communities in both Nepal and India. Chamelia is also highly vulnerable to CC in comparison to other mid-hill watersheds in Nepal (Siddiqui et al., 2012). The watershed has been a center for hydropower development in recent

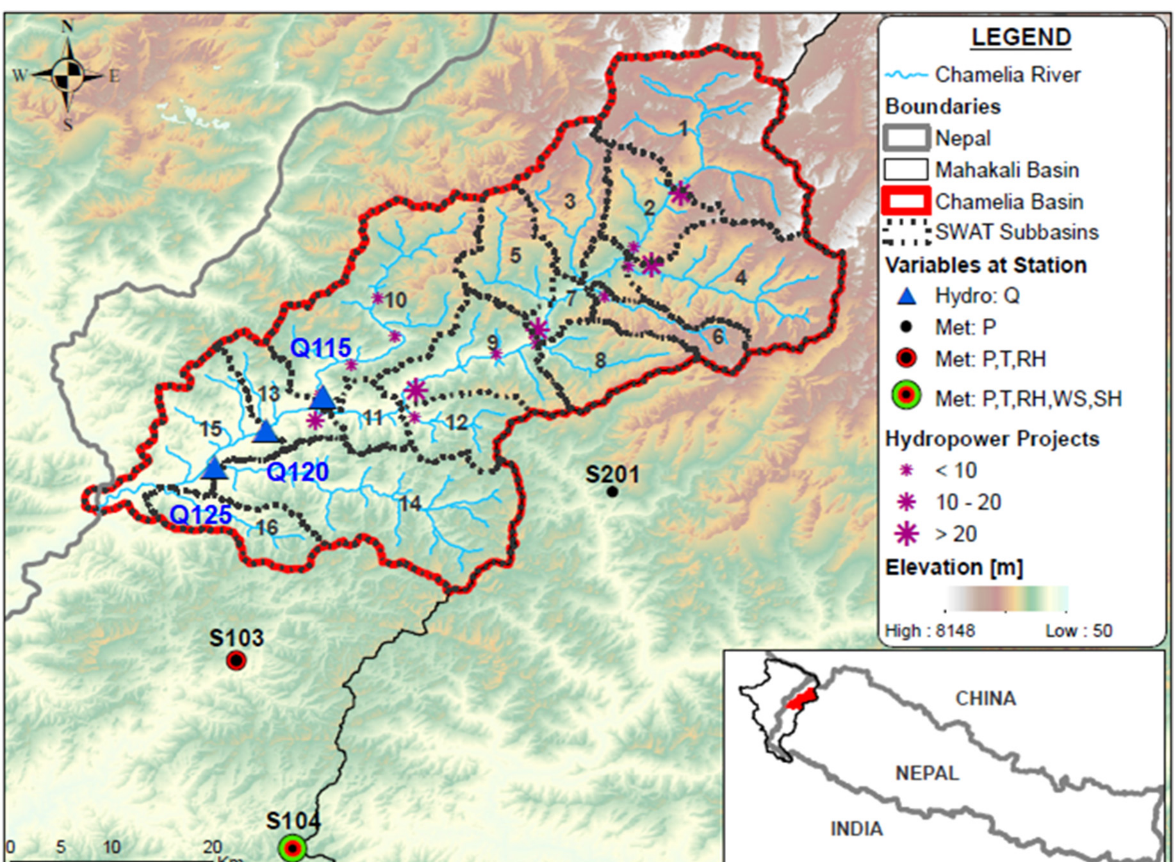


Fig. 1. Topography, river network, hydro-meteorological stations, and planned hydropower projects in Chamelia watershed. Inset shows location of Chamelia in western Nepal. "*" represents hydropower projects in various stages of development, with symbol size indicating production capacity of hydropower projects in megawatts (MW).

years. According to the data from Department of Electricity Development (DoED) Chamelia has 14 hydropower projects in various stages of development, with individual capacity ranging from 1 to 40 megawatts (MW), and a total capacity of 214 MW; 56.5 MW are either operational or under construction (IWMI, 2017). Some small-scale irrigation projects also exist in the watershed. CC may affect various aspects of such water infrastructure projects, all of which are manifested through hydrological alterations. Though CC is already experienced in the South Asian region (IPCC, 2013), no prior study has evaluated the extent of change and consequences on water availability in the Chamelia watershed. A quantification of spatial and temporal change in water availability across the basin is a key information to discuss implication of CC across the multiple sectors under the Nepalese water-energy-food nexus (Rasul, 2016).

This study aims to address this missing quantification of CC impacts on water availability in the Chamelia watershed, a tributary of Mahakali. We have three-fold objectives: i) to assess current spatio-temporal variations in water availability; ii) to project future temperature and rainfall; and iii) to assess the impacts of projected changes in temperature and rainfall on water availability. We simulate the current hydrology of Chamelia watershed using the Soil and Water Assessment Tool (SWAT); project future climate based on multiple Regional Circulation Models (RCMs); and then assess the response of the sub-watersheds to projected climate. Specifically, projected temperature and rainfall are generated using quantile mapping bias-correction of five RCM outputs. Change in climate and water availability is evaluated for three future periods: near-future (NF: 2021–2045), mid-future (MF: 2046–2070), and far-future (FF: 2071–2095), with respect to simulation for the baseline (1980–2005).

2. Methodology and data

Overall methodological framework adopted in this study is depicted in Fig. 2. Broadly, it consists of data preparation, model setup, model calibration and validation, current hydrological characterization, future climate projection, and CC impacts assessment on water availability using the validated SWAT model. The methodology is elaborated in the following sub-sections.

2.1. SWAT theory

SWAT is a process-based hydrological model that can predict impacts of climatic and non-climatic changes on water, sediment and agricultural chemical yields in complex basins with varying soils, land use/cover and management conditions (Arnold et al., 1998; Srinivasan et al., 1998). The main components of the model pertinent to hydrological analysis include: climate, hydrology, plant growth, land management, channel and reservoir routing.

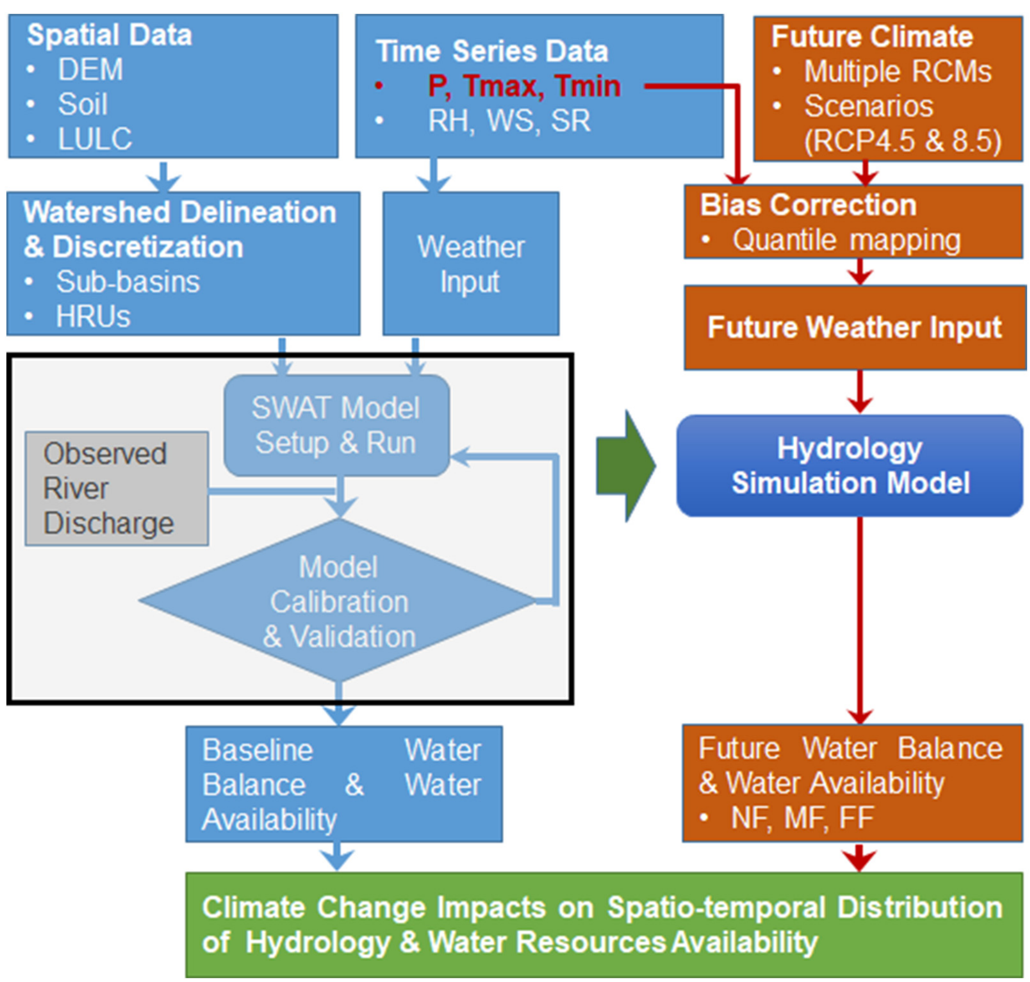


Fig. 2. Methodological framework adopted in this study. Blue indicates processes related to hydrological modeling while orange indicates processes related to climate projection and impacts. Both contribute to the end goal to evaluate climate change impacts shown in green. DEM is digital elevation model; LULC is land use/cover; P is precipitation; Tmax and Tmin are maximum and minimum temperatures; RH is relative humidity; WS is wind speed; SR is solar radiation; RCP is representative concentration pathways; RCMs is regional climate models; SWAT is soil and water assessment tool; NF is near-future; MF is mid-future; FF is far-future. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Conceptually, SWAT is semi-distributed and divides a basin into sub-basins. Each sub-basin is connected through a stream channel and further divided into Hydrologic Response Units (HRUs). HRU is a unique combination of a soil, land use/cover (LULC) and slope type in a sub-watershed. SWAT simulates hydrology, vegetation growth, and management practices at the HRU level. The hydrological processes explicitly modeled within each HRU are: soil water balance, surface runoff, infiltration, evapotranspiration (ET), canopy storage, plant uptake, percolation, return flow, recharge (shallow and deep aquifers), lateral flow, seepage, baseflow (from shallow aquifer) and groundwater pumping (Neitsch et al., 2011; Srinivasan, 2012). Since the model maintains a continuous water balance, the subdivision of the basin into unique HRUs, enables it to reflect differences in evapotranspiration for various LULCs and soils. Thus runoff is predicted separately for each sub-basin and routed to obtain the total runoff at the basin outlets. This provides a better physical description of the water balance. Detailed descriptions of the model can be found in Arnold et al. (1998), Srinivasan et al. (1998), and Neitsch et al. (2011).

2.2. Spatial data preparation

Three types of spatial data are required as input to SWAT model: digital elevation model (DEM), LULC, and soil type. Spatial distribution in topography in this study is represented by the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (GDEM V2) with 1-arc second resolution (approximately 30 m at the equator) (NASA JPL, 2009). ASTER GDEM, shown in Fig. 1, was jointly developed by the Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). A threshold area of 1000 ha was defined to create river network based on the ASTER DEM. As per the DEM, topography across the Chamelia watershed varies from 505 to 7090 m (Fig. 1).

The LULC in Fig. 3a is prepared based on a map from ICIMOD (2010). There are nine LULC types in the study area. Forest (40%) and rainfed agriculture (28%) are the dominant types accounting for more than two-thirds of the Chamelia watershed (Fig. 3a). Snow/glacier covers 6.3% of the watershed.

The soil type data is prepared based on the data developed by SOTER program (Dijkshoorn and Huting, 2009). There are seven types of soil in the watershed (Fig. 3b); the dominant among them are Eutric Regosols (23.8%), Eutric Cambisols (24.5%), and Gelic Cambisols (22.0%). The properties of each soil type are defined by hydraulic conductivity, appearance and depth.

2.3. Time series data preparation

There are no meteorological stations within the study watershed. Meteorological data from three stations close to the study watershed (Fig. 1) were obtained from the Department of Hydrology and Meteorology (DHM). Discharge data are available at three stations located within the catchment (Fig. 1). Rainfall and temperature data were formatted as per SWAT's input template and were used in the original units of mm and °C. SWAT requires daily relative humidity in fraction, however, two sets of observed data per day (morning and evening) were available in percentage. The average of the two data was taken and converted into fraction. SWAT requires solar radiation in $MJ/m^2/day$ but observations are available in sunshine hours. The conversion from sunshine hours to solar radiation ($MJ/m^2/day$) was made using the Angstrom-Prescott (AP) model (Allen et al., 1998). SWAT requires wind speed in m/s, however, observed data were available in km/h. They were converted into m/s. All time-series data were quality checked for extent of missing values, typographic issues and coding errors. Overlaps in timeframes across all datasets were assessed to identify calibration and validation periods as periods with the best observed data.

2.4. SWAT model setup

ArcSWAT2012 was used as the interface to setup the model for Chamelia. To better represent heterogeneity, the watershed was discretized into 16 sub-watersheds as shown in Fig. 1. The watersheds were further discretized into 225 HRUs. The average size of the sub-watershed is 100.2 km^2, varying from 33.2 to 233.5 km^2. Multiple HRUs were defined using LULC (2%), soil type (5%) and slope (10%). Slopes for the purpose of defining HRUs were divided into four classes (0–3%; 3–15%; 15–30%; and >30%). Ten elevation bands, at intervals of 500 m, were defined to model the process of snowmelt and orographic distribution of temperature and precipitation. Weather input was fed in the form of daily rainfall (3 stations), maximum and minimum temperatures (2 stations), relative humidity (2 stations), wind speed (1 station) and sunshine hours (1 station) (Table 1). Daily time series of weather were used. SCS curve number method was used to estimate surface runoff, where daily curve number is estimated based on a function of soil moisture. The Penman-Monteith method was used to estimate potential evapotranspiration (PET). Variable storage method was applied to route flow in the channels. No point discharge was defined.

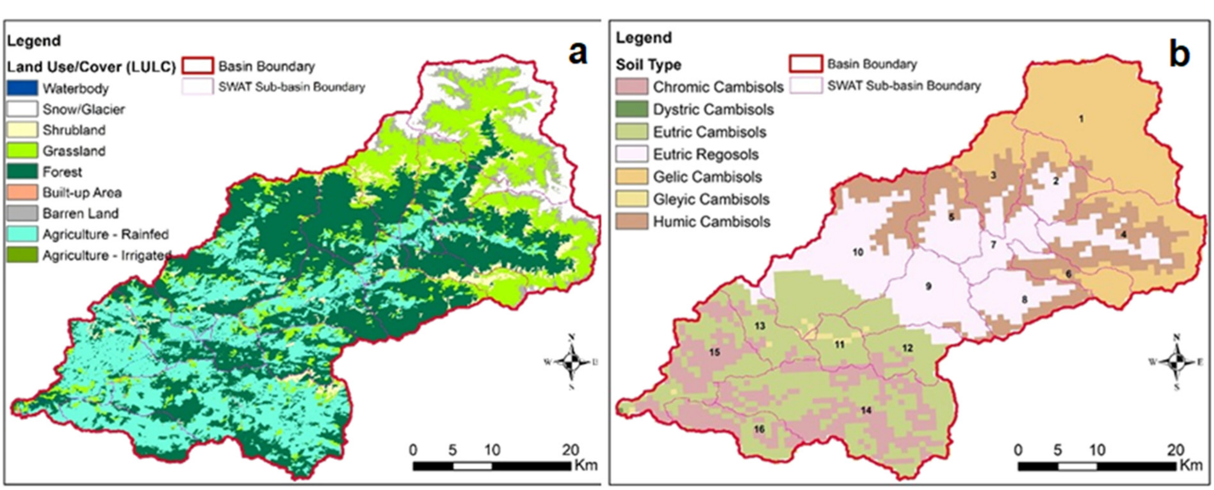


Fig. 3. Spatial distribution in – a) land use/cover, and soil type (b) – within Chamelia.

Table 1
Description of hydro-meteorological data used in this study.

Index	Lat.	Lon.	Elevation (masl)	S. name	River	Drainage (km^2)	Variables	Duration
115	29.702	86.607	784	Harsing Bagar	Naugraha Gad	203	Q	2001–2013
120	29.672	80.558	724	Karkale Gaon	Chamelia River	1150	Q	2001–2013
125	29.638	80.514	580	Panjewanya	Jamari Gad	228	Q	2001–2009
103	29.467	80.533	1266	Patan (West)	–	–	P, T, RH	2001–2013
104	29.300	80.583	1848	Dadeldhura	–	–	All	2001–2013
201	29.617	80.867	1456	Pipalkot	–	–	P	2001–2013

Note: masl is “meters above mean sea level”; Index is “station number of Department of Hydrology and Meteorology, Nepal”; Lat. Is “latitude”; Lon. Is “longitude”; S. is “station”; Q is “river discharge”; P is “precipitation”; T is “temperature”; RH is “relative humidity”; all means all five meteorological variables (P, T, RH, sunshine hours, and wind speed).

2.5. Model calibration and validation

Calibration is the parameterization of a model to a given set of conditions, thereby reducing the prediction uncertainty (Arnold et al., 2012). SWAT model for Chamelia watershed was calibrated and validated at three hydrological stations (Table 1; Fig. 1) with daily observed streamflow data. The multi-site calibration approaches are considered as better one against the single site calibration as demonstrated in Hasan and Pradhanang (2017). The hydrological data at the three stations were evaluated using exploratory analysis tools such as hydrographs, mass curves, and data reading. Data availability varied at each station so periods with consistent and good quality data with no or negligible missing data were identified for each station independently. At stations Q120 and Q115, timeframe of 2001–2013 was selected with calibration and validation periods of 2001–2007 and 2008–2013, respectively. At Q125, 2001–2009 was selected with calibration and validation periods of 2001–2005 and 2006–2009, respectively. A warm up period of 3 years was used to develop appropriate soil and groundwater conditions before calibration (Fontaine et al., 2002). The model was calibrated in three stages: i) Sensitivity analysis, ii) Auto-calibration in SWAT-CUP, and iii) manual calibration. Sensitivity was analysed using global sensitivity approach, wherein, one parameter value is changed at a time while keeping others constant. Auto-calibration was run for 1000 iterations with parameter ranges recommended in SWAT documentations (Neitsch et al., 2011). Although the range of values for the sensitive parameters was narrowed down during auto-calibration, the simulated and observed hydrographs did not match well. Then manual calibration was performed on the results of the auto-calibration by tweaking relevant model parameters to match the simulated hydrograph to the observed.

During manual calibration, adjustments were initially made to the most sensitive parameters and then to the less sensitive ones. Parameters other than those identified during the sensitivity analysis were also adjusted for more realistic values leading to better performance of the model. Visual inspection of the hydrographs (peaks, time to peak, shape of the hydrograph and baseflow); scattered plots; flow duration curve; statistical parameters; and water balance comparison (observed verses simulated) at daily, monthly and annual scales were used as the basis for evaluating model performance. Following statistical parameters were considered for performance evaluation: coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and change in mean values. Details of these methods are available in Nash and Sutcliffe (1970), Gupta et al. (1999), and Moriasi et al. (2007). The model performance was evaluated for both monthly and daily simulations. Due care was given to keep physically based parameters within a reasonable range (Table 4) throughout the calibration process.

2.6. Uncertainty assessment

Predictive uncertainty was assessed using SUFI-2 algorithm (Abbaspour et al., 2007), which defines uncertainty as the discrepancy between measured and simulated variables. The predictive uncertainties reflect all sources of uncertainty, i.e. conceptual model, forcing inputs (e.g. rainfall), and parameter (Rostamian et al., 2008). The uncertainty of input parameters in SUFI-2 is depicted as a uniform distribution, while model output uncertainty is quantified using 95% prediction uncertainty (95PPU) band and associated measures (i.e., p-factor and r-factor). The p-factor is the percentage of data bracketed in the 95PPU band and measures the portion of uncertainty the model is capturing. The r-factor, calculated as a ratio of mean width of the 95PPU band and standard deviation, on the other hand, captures the goodness of calibration; smaller the 95PPU band better the calibration result. The 95PPU plot, p-factor and r-factor were obtained using SWAT-CUP.

2.7. Future climate projections

The IPCC represent possible futures in the form of representative concentration pathways (RCPs). Four RCP pathways are developed for the climate modeling community as a basis for long-term and near-term modeling experiments. They are RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (Van Vuuren et al., 2011). It is the innovative collaboration between integrated assessment modelers, climate modelers, terrestrial ecosystem modelers and emission inventory experts. RCM outputs are generally only available for RCP4.5 and 8.5 and occasionally for RCP2.6. In this study, RCP4.5 is selected as a medium stabilizing scenario and RCP8.5 as a very high emission scenario. RCP4.5 refers to stabilization without overshoot pathway leading to 4.5 W/m^2 (~650 ppm CO_2) at stabilization after 2100; where as RCP8.5 refers to rising radiative forcing pathways leading to 8.5 W/m^2 (~1370 ppm CO_2) by 2100.

Outputs from five RCMs (Table 2) were used in this study as representative future climates. They are combinations of four unique Global Circulation Models (GCMs) downscaled dynamically by three unique RCMs. Three CCAM models and one REMO model were selected based on review of past studies in South Asia (Saeed and Suleri, 2015; Li et al., 2016; Mukherjee et al., 2017). Additionally, the ICHEC-RCA4 model was selected as it showed closest correspondence to observed precipitation in rigorous assessment of the past performance of 11 RCMs for in the Hindu Kush Himalayas carried out by Ghimire et al. (2015). The five RCMs and their un-weighted average ensemble were used as future climate inputs. Using such multi-model ensembles can reduce the overall uncertainty in model predictions (Scinocca et al., 2015). Precipitation data from ICHEC-RCA4 and REMO were in $kg/m^2/s$ unit, which were converted into millimeters (mm) before further use. For RCMs with 365-day calendars, an additional day in leap years was filled with data from the preceding day. RCM gridded data were processed using the Climate Data Operators (CDO). Future climate time series (daily precipitation and min/max temperature) were extracted from these RCMs at the three meteorological stations.

Bias correction of raw RCM outputs is highly recommended for hydrological applications, especially for applications at finer spatial scales (Teutschbein and Seibert, 2012; Wilby, 2010; Wood et al., 2004). A paper comparing multiple bias correction methods considering outputs of multiple RCMs for Western Nepal undertaken by the authors is under development. Quantile mapping (QM) has emerged as a better technique for bias correction for improving the past performance of RCMs

Table 2
Description of RCMs considered in this study.

SN	Unique name	CORDEX South Asia RCM	RCM description (source)	Contributing CORDEX modeling center	Driving GCM	Calendar	Unit: P [T]
1	ACCESS_CCAM	CSIRO-CCAM-1391 M	ConformalCubi Atmospheric Model - CCAM (McGregor and Dix, 2001)	Commonwealth Scientific and Industrial Research Organisation (CSIRO)	ACCESS1.0	365 days	mm [K]
2	CNRM_CCAM	CSIRO-CCAM-1391 M	ConformalCubi Atmospheric Model - CCAM (McGregor and Dix, 2001)	Commonwealth Scientific and Industrial Research Organisation (CSIRO)	CNRM-CM5	365 days	mm [K]
3	MPI.ESM_CCAM	CSIRO-CCAM-1391 M	ConformalCubi Atmospheric Model - CCAM (McGregor and Dix, 2001)	Commonwealth Scientific and Industrial Research Organisation (CSIRO)	MPI-ESM-LR	365 days	mm [K]
4	MPI.E.MPI_REMO	MPI-CSC-REMO2009	MPI Regional model 2009 (Teichmann et al., 2013)	Climate Service Center (CSC), Germany	MPI-ESM-LR	366 days	$kg/m^2/s$ [K]
5	ICHEC_RCA4	SMHI-RCA4	Rossby Centre regional atmospheric model version 4 -RCA4 (Samuelsson et al., 2011)	Rossby Centre, Swedish Meteorological and Hydrological Institute (SMHI), Sweden	ICHEC-EC-EARTH	366 days	$kg/m^2/s$ [K]

Note: P is precipitation; T is temperature; RCM is regional circulation model; GCM is Global Circulation Model; CORDEX is coordinated regional climate downscaling experiment.

(Berg et al., 2012; Chen et al., 2013; Lutz et al., 2016; Teutschbein and Seibert, 2012). This study considers future climate data at three meteorological stations bias-corrected using QM method (Gudmundsson et al., 2012).

QM corrects quantiles of raw RCM data to match with that of observed ones using transfer functions. When the distribution is expected to change (i.e., more extreme rainfall events, change in wet/dry days), extra complexity is warranted in bias-correction, and so the choice of QM is necessary at finer (e.g., daily) resolutions (Shrestha et al., 2017a, b). Both distribution-based and empirical QM are used in correcting precipitation and temperature. In this study, empirical QM was implemented in R using Gudmundsson et al.'s (2012) qmap package, where regularly spaces quantiles are approximated by linear functions.

2.8. Climate change impact assessment

The calibrated and validated SWAT model was forced with the bias corrected projections for daily precipitation and temperatures (maximum and minimum). Simulations of futures were undertaken based on five RCM outputs as well their ensemble. The ensemble inputs were prepared by taking an average of the five selected RCMs for each daily time step. Studies comparing past-performance of RCMs for the South Asian domain find that multi-modal ensembles often perform better than individual RCMs with lower biases and standard deviations (Choudhary and Dimri, 2017; Ghimire et al., 2015; Sanjay et al., 2017). IPCC reports (Knutti et al., 2010a; Knutti et al., 2010b; Wilby, 2010) also encourage thoughtful usage of multi-modal ensembles.

With two RCPs and five RCMs and an ensemble, 12 different future scenarios were generated and run in the SWAT model. The simulated streamflows based on the future projection were then synthesized in terms of long-term annual average and seasonal values for the three future periods: near-future (2021–2045), mid-future (2046–2070), and far-future (2071–2095). Finally, change in streamflow at annual and seasonal scales with respect to simulated baseline values are reported as an impact of CC on water resources availability. To characterize spatial variation, change in sub-basin level values of key water balance components is also shown.

2.9. Data and sources

Spatial and time-series data reflecting biophysical, hydro-climatic and future climatic contexts required in this study were collected from local and global sources. Information related to existing and planned water infrastructures within the watershed were obtained from literature. The details of data required by SWAT, their description, and sources are provided in Table 3 below.

3. Results and discussion

3.1. Hydrological model development

A hydrological model for Chamelia was set up, calibrated and validated in SWAT. Model parameters related to runoff, evapotranspiration, groundwater and soil water were adjusted to represent observed hydrological patterns at the three hydrological stations shown in Fig. 1.

Table 3
Data and sources used in this study.

Dataset [unit]	Data type	Data description/properties	Data source	Resolution (time frame)
Terrain [m]	Spatial grids	Digital elevation model (DEM)	NASA JPL (2009)	30 m × 30 m grids (for 2009)
Soil [–]	Spatial vectors	Soil classification and physical properties (e.g., texture, porosity, field capacity, wilting point, saturated conductivity and soil depth)	Dijkshoorn and Huting (2009)	1:1 million map (from multiple years)
Land use/cover (LULC) [–]	Spatial grids	Landsat land use/cover classification (9 classes)	ICIMOD (2010)	30 m × 30 m grids (for 2010)
Precipitation [mm]	Time-series	Daily observed precipitation	Department of Hydrology and Meteorology (DHM), Nepal	3 stations (2001–2013)
Temperature [°C]	Time-series	Daily observed minimum and maximum temperature	DHM, Nepal	2 stations (2001–2013)
Relative humidity [–]	Time-series	Daily observed mean relative humidity	DHM, Nepal	2 stations (2001–2013)
Sunshine hours [h]	Time-series	Daily observed sunshine hours	DHM, Nepal	1 stations (2001–2013)
Wind speed [m/s]	Time-series	Daily observed mean wind speed	DHM, Nepal	1 stations (2001–2013)
River discharge [m^3/s]	Time-series	Daily observed streamflow	DHM, Nepal	3 stations (2001–2013)
Future precipitation [mm] Temperature [°C]	Time-series extracted from spatial grids	Daily projected values	5 Regional Climate Models detailed in Table 2	0.44° × 0.44° (1970–2100)

The calibrated parameters are shown in Table 4. Sensitive parameters were not consistent throughout the sub-watersheds. However, the runoff curve number (CN2), groundwater delay (GW_DELAY) and baseflow recession factor (ALPHA_BF) were among the most sensitive parameters at all three stations, albeit with varying levels of influence.

The default values of SWAT parameters underestimated the baseflow in most cases. Therefore, CN2, one of the sensitive parameters that plays a key role in increasing the infiltration and subsequently the groundwater contribution to baseflow, was fine-tuned. The value of ALPHA_BF, which affects the shape of the receding limb of hydrograph, was changed based on visual assessment of the slope of the receding limb. Similarly, other flow related parameters such as soil evaporation compensation factor (ESCO), threshold depth of water in the shallow aquifer to trigger return flow (GWQMN), soil depth (SOL_Z), available water capacity of the soil (SOL_AWC), saturated hydraulic conductivity (SOL_K), effective hydraulic conductivity in main channel (CH_K2), lateral flow travel time (LATTIME), and channel Manning's number (CH_N2), among others, were adjusted to not only match the simulated and observed flows at daily and monthly scale but also to reasonably approximate the water balance components. Defining elevation bands allowed for variable temperature laps rate (TLAPS), which played an important role in replicating the spatial distribution of temperature, as seen in other studies as well (e.g., Rahman et al., 2012).

3.1.1. Model performance

Results show a good agreement between the simulated and observed streamflow values at all the three hydrological stations for both calibration and validation periods (Figs. 4–6). The model simulates reasonably well the hydrological regime for daily as well as monthly flows, reproducing flow duration curve (FDC), and keeping statistical parameters within reasonable range (Figs. 4–6) as discussed in Liu and de Smedt (2004) and Moriasi et al. (2007). Additionally, the hydrological response pattern follows the rainfall pattern at all the stations, for both daily and monthly simulations. As can be expected monthly simulation has better performance compared to daily. Difference between observed and simulated average annual values for calibration, validation and overall (calibration + validation) periods are <15% at all three stations (Table 5). Based on the general performance ratings

Table 4
Calibrated SWAT parameters at three hydrological stations (in decreasing order of sensitivity).

Station (river)	Parameter	Definition	Unit	Process (data file)[a]	Level[a]	Recommended range	Default value	Calibrated value
Karkale Gaon (Chamelia), Q120	CN2	SCS runoff curve number for moisture condition II	–	Runoff (.mgt)	HRU	35–98	Varies	1.2 (ratio)
	CANMX	Maximum canopy storage	mm	Runoff (.hru)	HRU	0–100	0	98
	CH_N1	Manning's "n" value for the tributary channel	–	Runoff (.sub)	Sub-basin	0.01–30	0.014	0.5
	ESCO	Soil evaporation compensation factor	–	Evaporation (.hru)	HRU	0–1	0.95	0.2
	GW_DELAY	Delay time for aquifer recharge	days	Groundwater (.gw)	HRU	0–500	31	5
	CH_N2	Manning's "n" value for the main channel	–	Channel (.rte)	Reach	0–1	0.014	0.15
	CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/h	Channel (.rte)	Reach	0–500	0	300
	TLAPS	Temperature lapse rate	°C/km	Topographic effect (.sub)	Sub-basin	−10–10	−5.6	−7.9
	ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0–1	0.048	0.25
	LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0–180	0	80
	SOL_K	Saturated soil conductivity	mm/h	Soil (.sol)	HRU	0–2000	Varies	0.2 (ratio)
	SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0–3500	Varies	2 (ratio)
Harsing Bagar (Naugraha Gad), Q115	CN2	SCS runoff curve number for moisture condition II	–	Runoff (.mgt)	HRU	35–98	Varies	1.15 (ratio)
	ESCO	Soil evaporation compensation factor	–	Evaporation (.hru)	HRU	0–1	0.95	0.4
	CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/h	Channel (.rte)	Reach	0–500	0	450
	ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0–1	0.048	0.2
	CH_N2	Manning's "n" value for the main channel	–	Channel (.rte)	Reach	0–1	0.014	0.2
	TLAPS	Temperature lapse rate	°C/km	Topographic effect (.sub)	Sub-basin	−10–10	−5.6	−9.5
	LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0–180	0	30
	SOL_K	Saturated soil conductivity	mm/h	Soil (.sol)	HRU	0–2000	Varies	0.5 (ratio)
	SOL_AWC	Available water storage capacity of the soil layer	–	Soil (.sol)	HRU	0–1	Varies	0.5 (ratio)
	SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0–3500	Varies	2.0 (ratio)
	GW_DELAY	Delay time for aquifer recharge	days	Groundwater (.gw)	HRU	0–500	31	90
	CANMX	Maximum canopy storage	mm	Runoff (.hru)	HRU	0–100	0	80
	EPCO	Plant uptake compensation factor	–	Evaporation (.hru)	HRU	0–1	1	0.6
	OV_N	Manning's n value for overland flow	–	HRU (.hru)	HRU	0.01–30	Varies	0.16 (ratio)
Panjewanya (Gamari Gad), Q125	GW_DELAY	Delay time for aquifer recharge	days	Groundwater (.gw)	HRU	0–500	31	60
	TLAPS	Temperature lapse rate	°C/km	Topographic effect (.sub)	Sub-basin	−10–10	−5.6	0
	SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0–3500	Varies	2.0 (ratio)
	GWQMN	Threshold depth of water in shallow aquifer to occur groundwater return flow	mm	Soil (.gw)	HRU	0–5000	1000	4900
	ESCO	Soil evaporation compensation factor	–	Evaporation (.hru)	HRU	0–1	0.95	0.99
	CN2	SCS runoff curve number for moisture condition II	–	Runoff (.mgt)	HRU	35–98	Varies	0.98 (ratio)
	CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/h	Channel (.rte)	Reach	0–500	0	450
	ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0–1	0.048	0.2
	LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0–180	0	40
	SOL_K	Saturated soil conductivity	mm/h	Soil (.sol)	HRU	0–2000	Varies	0.15 (Ratio)
	CH_N2	Manning's "n" value for the main channel	–	Channel (.rte)	Reach	0–1	0.014	0.15
	EPCO	Plant uptake compensation factor	–	Evaporation (.hru)	HRU	0–1	1	0.2
	SHALLST	Initial depth of water in shallow aquifer	mm	Groundwater (.gw)	HRU	0–50,000	1000	300

[a] For detailed explanation of the parameters, please refer to Arnold et al. (2012). Recommended and default values are as per SWAT documentation (Neitsch et al., 2011).

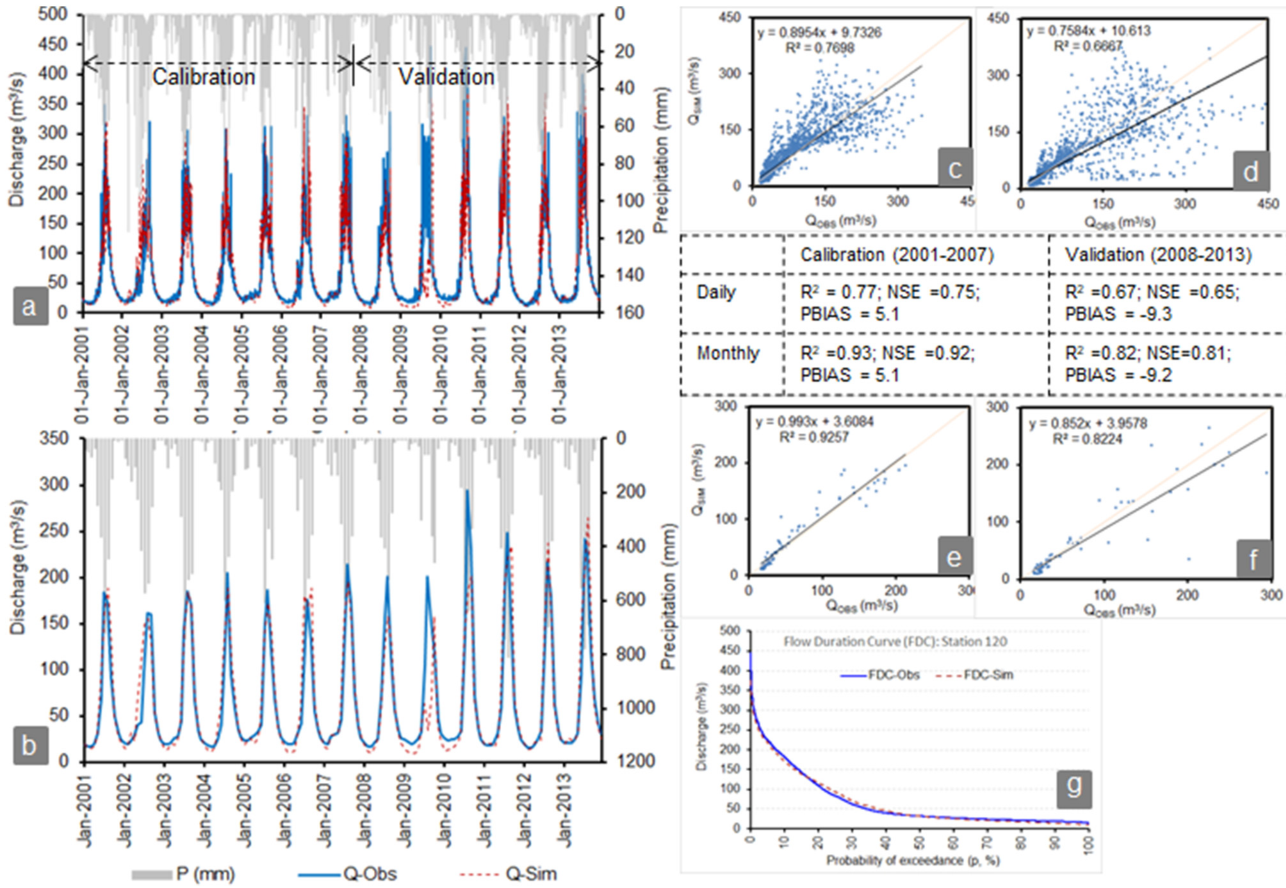


Fig. 4. Comparison of observed versus simulated stream flows at Karkalegaon (Index = Q120; River = Chamelia) station: a) Hydrograph for daily simulation, b) hydrograph for monthly simulation, c & d) scattered plots for daily calibration and validation, e & f) scattered plots for monthly flow calibration and validation, g) flow duration curve (FDC, daily).

criteria developed by Moriasi et al. (2007), for both monthly and daily time steps, model calibration results are "very good (NSE > 0.65)" for the stations Q120 and Q115 and "adequate (NSE = 0.54 to 0.65)" for the station Q125. For the validation period, the daily and monthly NSE range between 0.33 to 0.65 and 0.68 to 0.81 across the three stations, with relatively poorer performance at Q115.

A closer look into the hydrograph and scatter plots during calibration indicates that the model estimates low flows and long-term average reasonably well for both daily and monthly simulations. However, the scatter points are spread out further for high flows indicating that the model is poorer at simulating high peaks (or high flows). The equation of the linear fit shows that model is under-estimating flow at both daily and monthly scale. During validation, the scatter plot shows higher spread even for average-flows indicating that the model performance is poor for both high-flows as well as average flows even if low flow is reasonably reproduced. Overall, the model is better suited for low-flows estimation and water resources assessment and needs further calibration for use in flood-forecasting and extreme analysis. As the goal of this modeling is to assess water availability and its distribution in the long run, the model is considered adequate to serve the purpose.

Observed variation in performance across the hydrological stations can partly be attributed to limitations in the hydro-meteorological inputs. Studies have identified spatial variability in errors in rainfall, streamflow, soils map, and land use/cover inputs caused by various reasons, including poor sampling strategies. In this study, none of the selected meteorological stations lie directly inside Chamelia watershed. To account for variation in topography among the meteorological stations and within Chamelia watershed, values of meteorological variables were distributed spatially and topographically by assigning elevation bands in SWAT. Ten elevation bands, at intervals of 500 m, were defined to model the process of snowmelt and orographic distribution of temperature and precipitation. Of the three hydrological stations, st120 lies on the main stem of Chamelia, covering most of the watershed, and shows the best performance. Stations st115 and st125, on the other hand, are 1st order tributaries and drain smaller sub-watersheds within Chamelia. Therefore, streamflows generated at these stations will be more sensitive to errors in meteorological inputs, contributing to the poorer model performance.

In addition, accurate information on the snow and glaciers, coverage area, depth, and depletion rate is not available for the high altitude areas in the watershed. Considering potential uncertainties and limitations in the input data, the performance of the model in calibration and validation can be considered acceptable to simulate streamflow in the watershed. As seen in Fig. 1, most licensed hydropower projects lie upstream of the st120 station. The "very good" model performance at this station is key for assessment of impact due to these projects. Multi-site calibration (at three hydrological stations) assures that the model is capable of reproducing hydrological heterogeneity within the Chamelia watershed with higher reliability at stations of greater importance.

3.1.2. Predictive uncertainty of the model

Uncertainty is an inherent part of hydrological modeling (Latif, 2011) due to input data, model structure, and model parameters, among others (Leta et al., 2015). Exploratory data analysis was used to help reduce uncertainties in input data. This study adopted SUFI-2 algorithm, plotted 95PPU band, and then quantified the predictive uncertainty using p-factor and r-factor as described in Abbaspour et al. (2007). Other studies such as Rostamian et al. (2008), Shrestha et al.

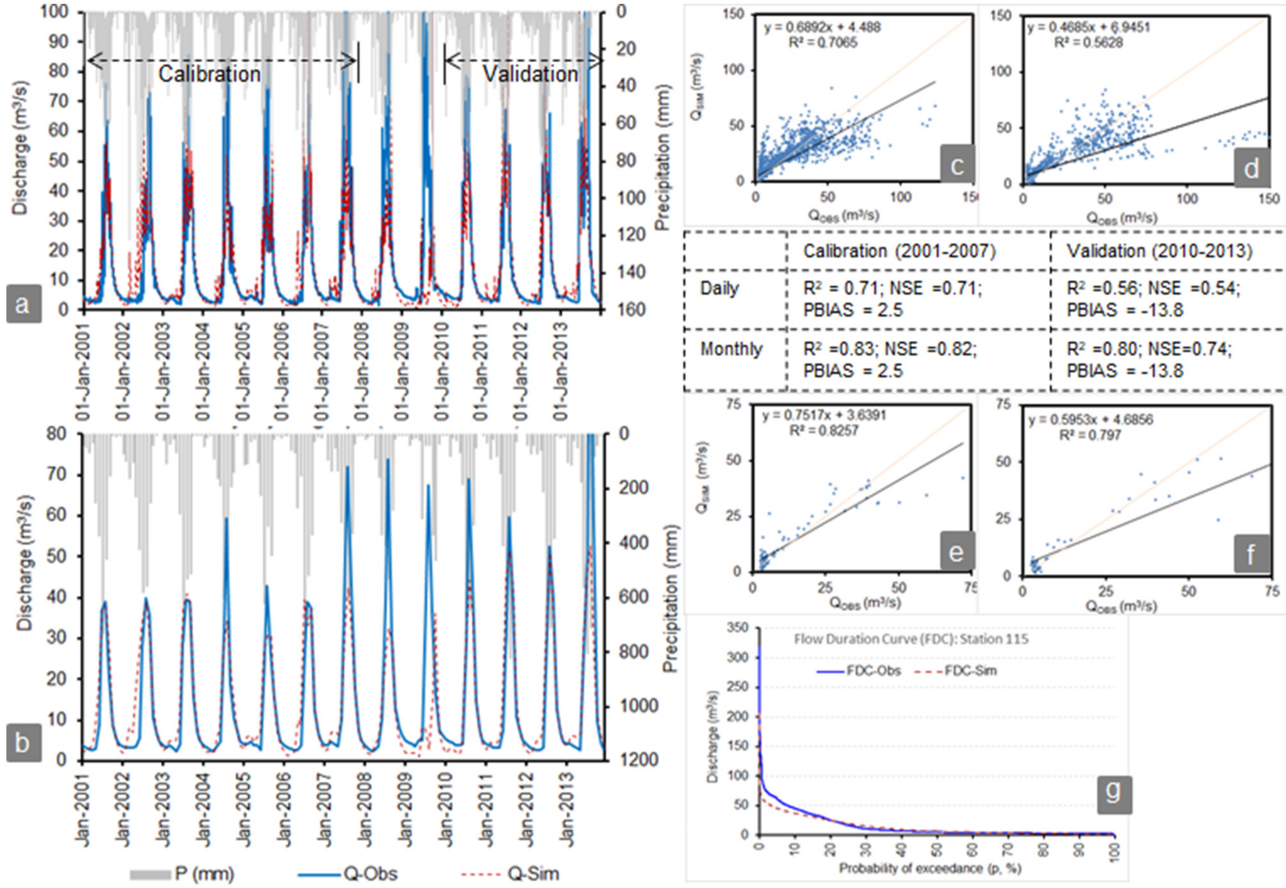


Fig. 5. Comparison of observed versus simulated stream flows at Harsing Bazar (Index = Q115; River = Naugraha Gad) station: a) Hydrograph for daily simulation, b) hydrograph for monthly simulation, c & d) scattered plots for daily calibration and validation, e & f) scattered plots for monthly flow calibration and validation, g) flow duration curve (FDC, daily).

(2017a), Shrestha et al. (2017b) and Krishnan et al. (2018) have also used similar approach. The ideal model would have a p-factor approaching to 100%, i.e. all observed data fall within the 95PPU band, and r-factor approaching to zero, i.e. predictive uncertainty is less than variability in observed data. Generally, higher p-factor can be obtained with an increased r-factor as wider bandwidths are more flexible to capture observed variations. But higher bandwidth indicates higher predictive uncertainties. The r-factor of less than one generally indicates a good calibration (Rostamian et al., 2008).

The daily hydrographs with 95PPU bands for all the three stations are shown in Annex-1. The 95PPU band is widest for Q120 with majority of the observations covered. At stations Q115 and Q125, the 95PPU bands are much narrower specially for high flow period. Both the p- and r-factors for the calibration at Q120 (catchment = 1150 km^2) were 0.91 and 0.79, respectively. It means 91% of the observed data points are within the 95PPU simulation bands and therefore the model predictions capture observations well. Similarly, for Q115 (catchment = 203 km^2), the p- and r-factors are 0.76 and 0.52. For Q125 (catchment = 228 km^2), p- and r-factors are 0.68 and 0.46, respectively. While Q115 and Q125 have lower prediction uncertainties than Q120, their ability to simulate observed data is low. Overall at the three stations (Q115, Q120, and Q125), the r-factor is in a range of 0.46–0.79 and p-factor in a range of 0.68–0.91. The model is therefore considered well calibrated and reasonably captures uncertainties.

More aggressive methods for disaggregating and quantifying the contribution of various sources (structure, parameter, input) towards total predictive uncertainty exist (Saltelli et al., 2006). However, all input datasets have limitations due to data availability quality, length and resolution. Observed hydro-meteorological data for Chamelia is only of acceptable quality for 12 years and none of the meteorological stations used are physically within the basin as shown in Fig. 1. Spatial data sets are coarse, often remotely based with limited field based verification. Hence input data uncertainty is potentially larger than parameter uncertainty. The lack of longer and higher quality observed datasets is a key barrier that did not provide a sufficient basis for a more rigorous analysis of propagation of input errors in the model and subsequent evaluation of model structure and parameter uncertainty. Hence only the standard SUFI-2 approach was used here to evaluate total predictive uncertainty.

3.2. Characterization of current hydrology

Current hydrology of the Chamelia watershed was characterized using simulated results from the SWAT model developed in this study. Four major hydrological components were considered for the analysis, namely, precipitation, actual evapotranspiration (ET), net water yield and the change in storage (Δ storage). The 'Δ storage' is a collective term including groundwater recharge, change in soil moisture storage in the vadose zone and other transmission losses in the system. Net water yield is the streamflow generated at the sub-basin outlet. Streamflow is the sum of surface runoff, lateral flow, and groundwater flow, with deductions for losses and abstractions.

Annual average precipitation, actual ET and net water yield of the basin at Q120 station for the simulation period (2001–2013) were 2469 mm, 381 mm and 1946 mm, respectively. The values, however, vary within each sub-basin (Fig. 7; please refer Fig. 1 for the sub-basins location). There is spatial heterogeneity in all the water balance components (Fig. 7). Net water yield shows a minimum value of

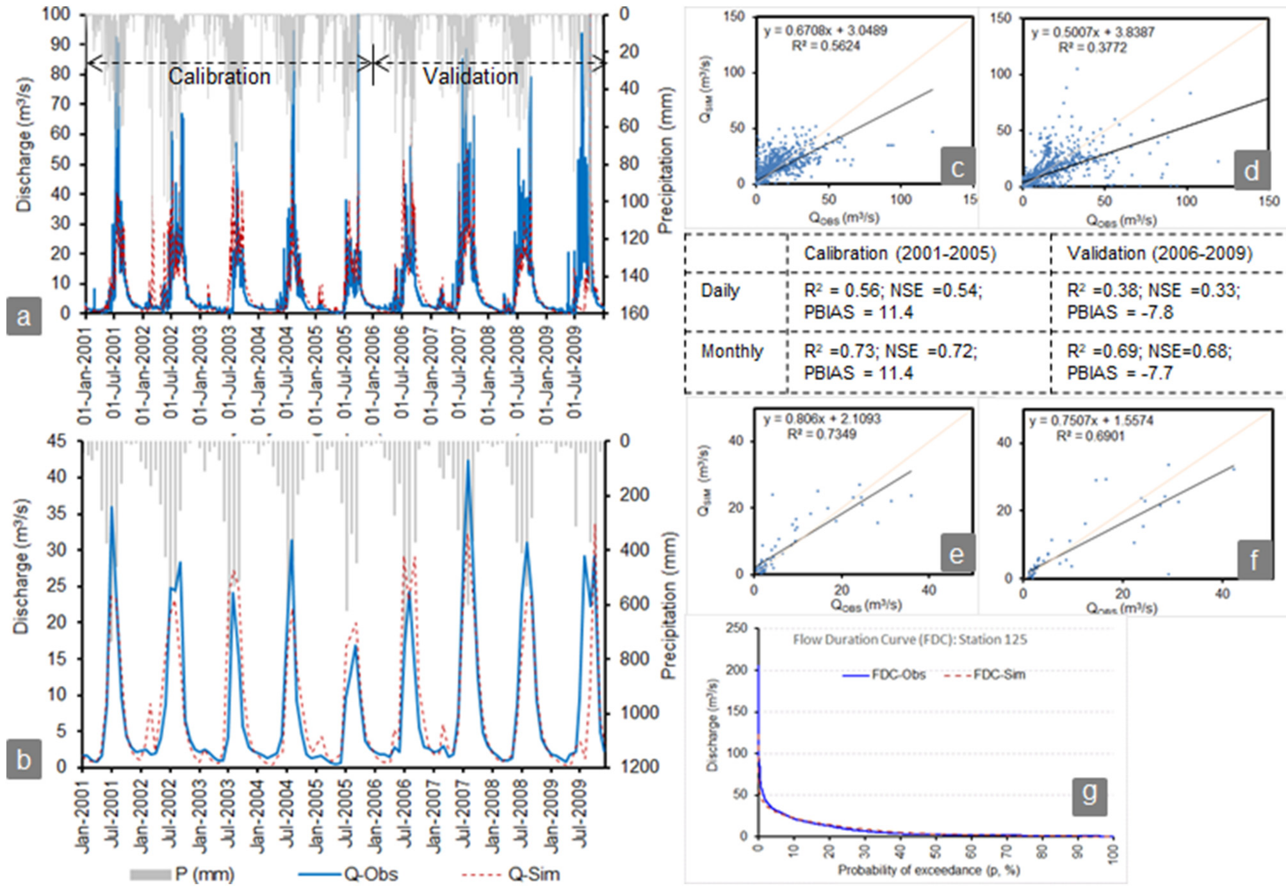


Fig. 6. Comparison of observed versus simulated stream flows at Panjewanya (Index = Q125; River = Jamari Gad) station: a) Hydrograph for daily simulation, b) hydrograph for monthly simulation, c & d) scattered plots for daily calibration and validation, e & f) scattered plots for monthly flow calibration and validation, g) flow duration curve (FDC, daily).

589 mm in the sub-basin 16, a tributary joining Chamelia near the outlet of the watershed and the maximum of 2152 mm in sub-basin 6, a tributary joining Chamelia near headwaters of the watershed (see Fig. 1 for sub-basin locations). Net water yield is greater than actual ET in most of the sub-basins in the upstream, represented by low sub-basin numbers. Low ET is reasonable as these sub-basins lie at higher elevations with low temperature. As ET depends largely on precipitation, land use/cover and temperature, it was estimated higher in forested areas. In case of actual ET, sub-basin 1 has the minimum value of 9 mm and sub-basin 11 has the highest values of 766 mm. Precipitation contributes to storage only in upstream basins in steep terrain while in downstream basins, storage contributes a baseflow. This indicates that aquifer recharge is largely happening in the hills. Furthermore, watersheds with more snow cover in upstream showed lower contribution of baseflow than other watersheds, which is consistent with literatures (e.g., Hasan and Pradhanang, 2017). On the other hand, watersheds in the downstream show more contribution from baseflow, which is likely due to interflow of water infiltrated in the upstream. These discussions indicate that the hydrological characteristics simulated by the model are reasonable.

Additionally, Fig. 8 shows a large temporal variation in the water balance components in the Chamelia watershed. Net water yield and actual ET are highest in the monsoon season and lowest in the dry season, as expected. 'Δ storage' is negative in monsoon with −134.5 mm in July (the wettest month) indicating recharge and positive in the dry season with 43.5 mm in December indicating groundwater contribution to streamflow. Relatively large value of the 'Δ storage' in monsoon season could be attributed to high groundwater recharge, which ultimately yields to high groundwater contribution to streamflow during the dry periods.

Table 5
Comparison of mean and standard deviations of observed and simulated average annual streamflows.

Station index	Period	Mean streamflow (m^3/s)			Standard deviation (m^3/s)		
		Obs.	Sim.	% Diff.	Obs.	Sim.	Diff.
st115	Calibration	13.29	13.63	2.6	2.5	1.7	−0.8
	Validation	17.55	15.13	−13.8	4.8	2.1	−2.7
	Overall	15.11	13.46	−10.9	3.6	2.6	−1.0
st120	Calibration	62.12	65.3	5.1	4.8	2.9	−1.9
	Validation	70.94	64.39	−9.2	7.0	6.0	−1.0
	Overall	66.19	64.88	−2.0	7.3	10.5	3.2
st125	Calibration	6.84	7.62	11.4	1.8	1.2	−0.6
	Validation	9.05	8.35	−7.7	2.0	2.1	0.1
	Overall	7.82	7.95	1.7	2.1	1.6	−0.5

Notes: Obs. is observed; Sim. is simulated; Diff. is difference.

3.3. Future climate projection

Raw projections extracted from the five selected RCMs for historical baseline (1980–2005) are presented in Annex-2. The raw data for both maximum and minimum temperatures showed under-estimation throughout the year. In case of maximum temperature, there was slight over-estimation for the moths of March, April, May and June. In case of precipitation, the raw RCM data showed over-estimation for most of the months, except February, March, and April (Annex-2. B). The raw RCM

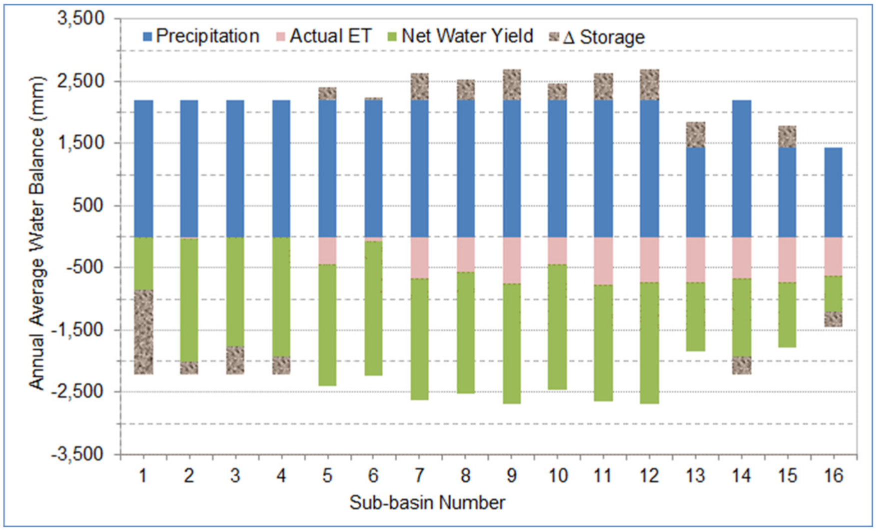


Fig. 7. Sub-basin wise long-term annual average water balance from SWAT model simulations (2001–2013) in Chamelia. See Fig. 1 for location of sub-basin within the watershed, low numbers represent upstream basins. ET is evapotranspiration.

daily projections were bias-corrected using quantile-mapping method to remove seen biases. The statistical parameters before and after bias-correction at climate station st103 are shown in Annex-3. Comparative plots and performance statistics show that R^2 is improved to a great extent by bias correction. For ensemble outputs as an example, R^2 values have increased from −1.67 to 0.65 for precipitation, from 0.37 to 0.90 for maximum temperature, and from 0.59 to 0.95 for minimum temperature. Other statistical indicators have also improved to a reasonable level after bias correction (Annex-3).

Projected precipitation and min/max temperature extracted at the three selected meteorological stations from five RCMs (Table 3) under RCP4.5 and RCP8.5 scenarios were bias-corrected. Three future timeframes were considered: near future (NF, 2021–2045), mid-future (MF, 2046–2070), and far-future (FF, 2071–2095). The period of 1980–2005 was considered as climate baseline. The future climate projections are discussed here are based on the downscaled RCM values at a meteorological station (Index = 103) because of proximity to the watershed.

3.3.1. Projected precipitation

Annual total precipitation for the climate baseline and future periods show no obvious trend (Fig. 9). Projected range of annual total precipitation for the three future periods are 1080–1732 (NF); 821–2560 mm (MF); and 670–1743 mm (FF); respectively. It indicates an increase in the uncertainty range when we progress further with the future.

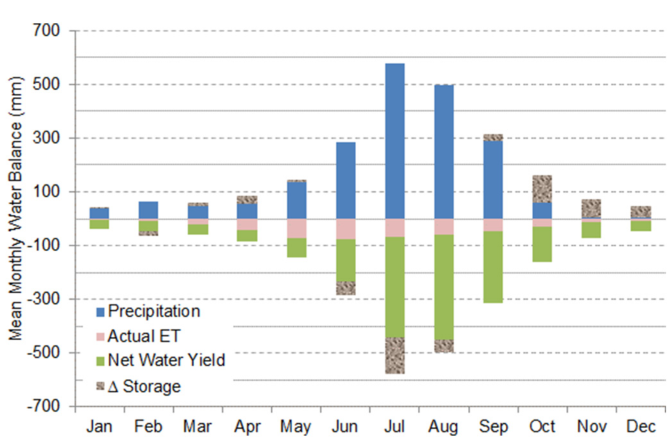


Fig. 8. Mean monthly water balance from model simulation (2001–2013) in Chamelia watershed. ET is evapotranspiration.

The range of changes in projected total precipitation by the five RCMs is presented in Fig. 10. It is clear that the annual ranges are not representative of the seasonal changes as the negative and positive changes across the seasons are averaged out in the annual values. As can be expected, the three CCAM models based on the same dynamic downscaling show similar behaviours and ranges. Studies have shown that precipitation trends in RCMs are dominated by the driving RCMs rather than the driving GCMs in South Asia (ul Hasson, 2016). ICHEC_RCA4 shows high spread in predictions with wet bias while the REMO model appears to predict drier conditions. This is in line with finding from Ghimire et al. (2015), where South Asian RCMs show positive wet bias for mid elevations. However, the medians for most cases in Fig. 10 lie within the ±50% range, suggesting that the RCMs predict increase in annual precipitation for some years and decrease in others. For these cases, medians (line in the box plot) and the means (x in the box plot) lie close to each other and close to the 0 line for the pre-monsoon and monsoon months. Such a lack of skewness in data indicates that increase and decrease in precipitation are projected equally across the years for DJF, MAM, JJAS. For post-monsoon months (ON), medians lie below the means indicating the projections are negatively skewed.

Considering the range of predictions as a measure of uncertainty, the annual and monsoon (JJAS) precipitations show the least uncertainty. Post-monsoon (ON) precipitation shows the high level of uncertainty for all the scenarios and futures considered. Even the projections by different RCMs do not vary much for the annual and monsoon season projections but vary significantly for other seasons. The higher prediction range indicates a more erratic behaviour of rainfall and its intensity at a seasonal scale. It should be additionally noted that the use of three CCAM-based models is bound to highlight the trends seen in CCAM model as more likely. A higher number and variety of RCMs would allow for an objective discussion of uncertainty and consensus in predictions seen across RCMs.

Table 6 summarizes the projected changes in average annual and seasonal precipitation values for RCP4.5 and RCP 8.5 scenarios based on the ensemble of five RCMs. Average annual values are projected to increase consistently over three future periods, however, the rate of change varies over the years (Table 6). Taking an example of RCP4.5 scenarios, average annual precipitation is projected to increase by 10% in NF and 13% in FF; however, it varies over the years from −10 to 30%

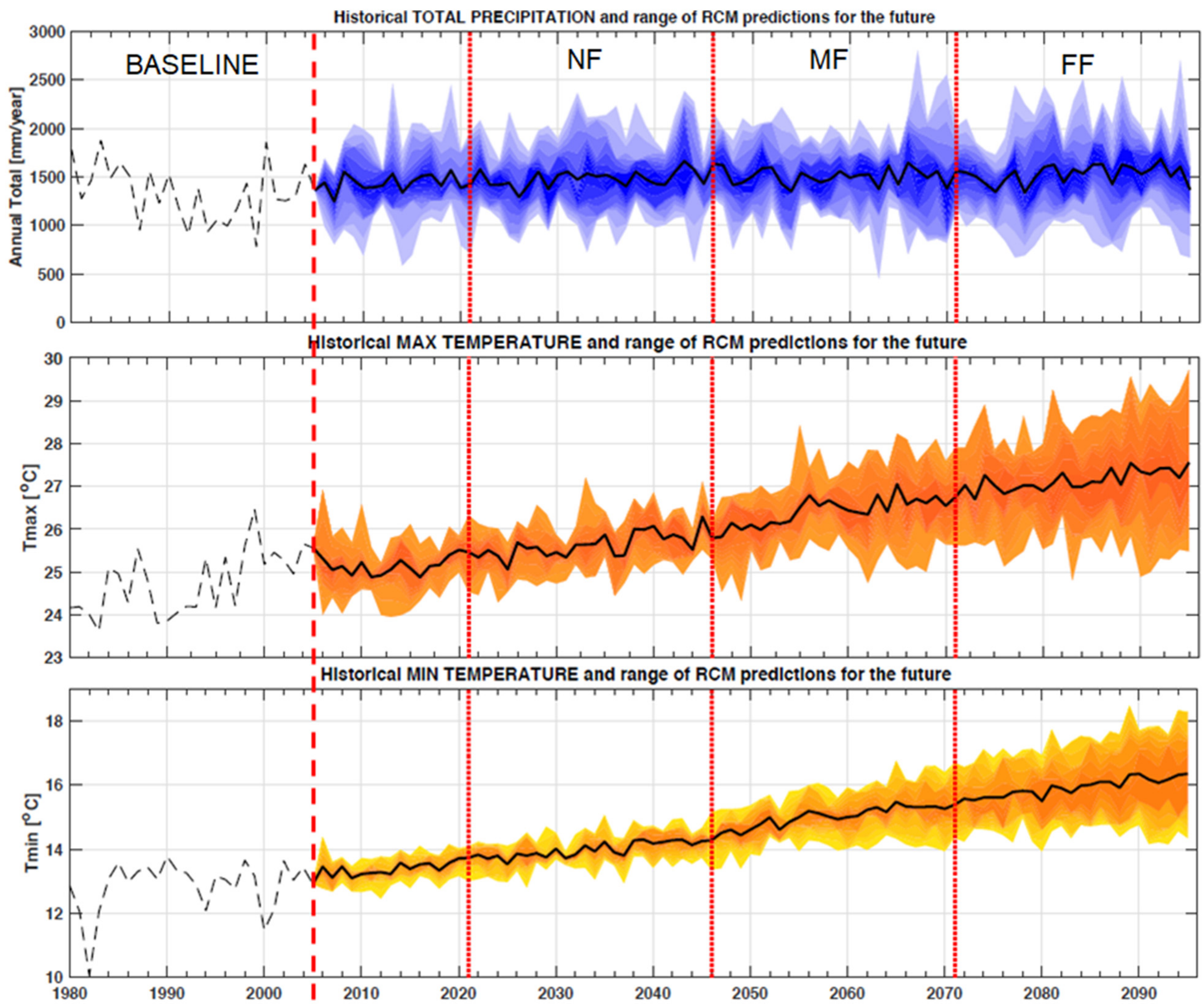


Fig. 9. Trends in long-term average annual total precipitation and max/min temperature at station 103. Baseline period shows observed data while future timeframes show range of bias-corrected projections from different RCMs for both RCP scenarios. NF, MF and FF refer to near-, mid- and far-futures, respectively. The dark line shows ensemble of the 5 RCMs for the two scenarios. Shaded areas indicate range in the projections.

for NF and − 5 to 34% for FF. The rate of increase is even higher for RCP8.5 scenarios.

We further analysed whether the annual increase applies to all the seasons. Table 6 shows that only MAM season follows consistent increasing trends from NF to FF as the case of annual values; albeit, the rate of change is higher for MAM season compared to the annual ones. Other seasons do not show a consistent gradual increasing or decreasing trends from NF to FF; however, all the seasons show an increasing trend from NF to MF. The range of projection bracket increases when we move from NF to MF, suggesting again for higher degree of uncertainly in projection when we move towards far future.

Such trends suggest that the RCMs show consensus that future change will likely increase amount of winter rain (from westerlies) and extend the duration. The two rainfall seasons typically seen in Western Nepal are likely to be more prominent under climate change.

The dry season ensemble values indicate increasing trend, however decreasing trend is also projected by some of RCMs. In addition, the magnitude and direction of change is not consistent through the years and RCMs. The average increasing trend in precipitation gives a reflection of positive impacts. This potential increase can help hydropower developers generate more energy during dry season; contribute to overcoming energy-scarcity; and provide water for dry season irrigation. In the meantime, as the demand for dry season energy is higher, it promises more revenue to the hydropower developers. However, increased rainfall may aggravate water-induced disasters such as landslides and floods (Bajracharya et al., 2018), especially downstream of the river system. This may result in land degradation and ultimately impact on lives and livelihoods of the people who are less climate resilient.

3.3.2. Projected temperature

Unlike precipitation, average annual time series of the projected temperature shows a clear increasing trend until the end of the century for both maximum and minimum temperatures (Fig. 9). Projected range of average annual maximum temperature within each future periods are 25.5–27.1 °C for NF, 25.6–27.1 °C for MF, and 25.5–29.7 °C for FF (Fig. 9), higher than the baseline value of 24.1 °C. In case of minimum temperature, the range is 12.8–14.4 °C for NF, 13.7–14.7 for MF, and 14.4–18.3 for FF. In both cases, the range widens when we move further towards future, reflecting more uncertainty towards far future.

3.3.2.1. Maximum temperature. The range of predictions for maximum temperature across the different RCM provides more consensus and certainty than that seen for precipitation. All changes for all RCMs, RCPs and futures indicate increase with both means and medians

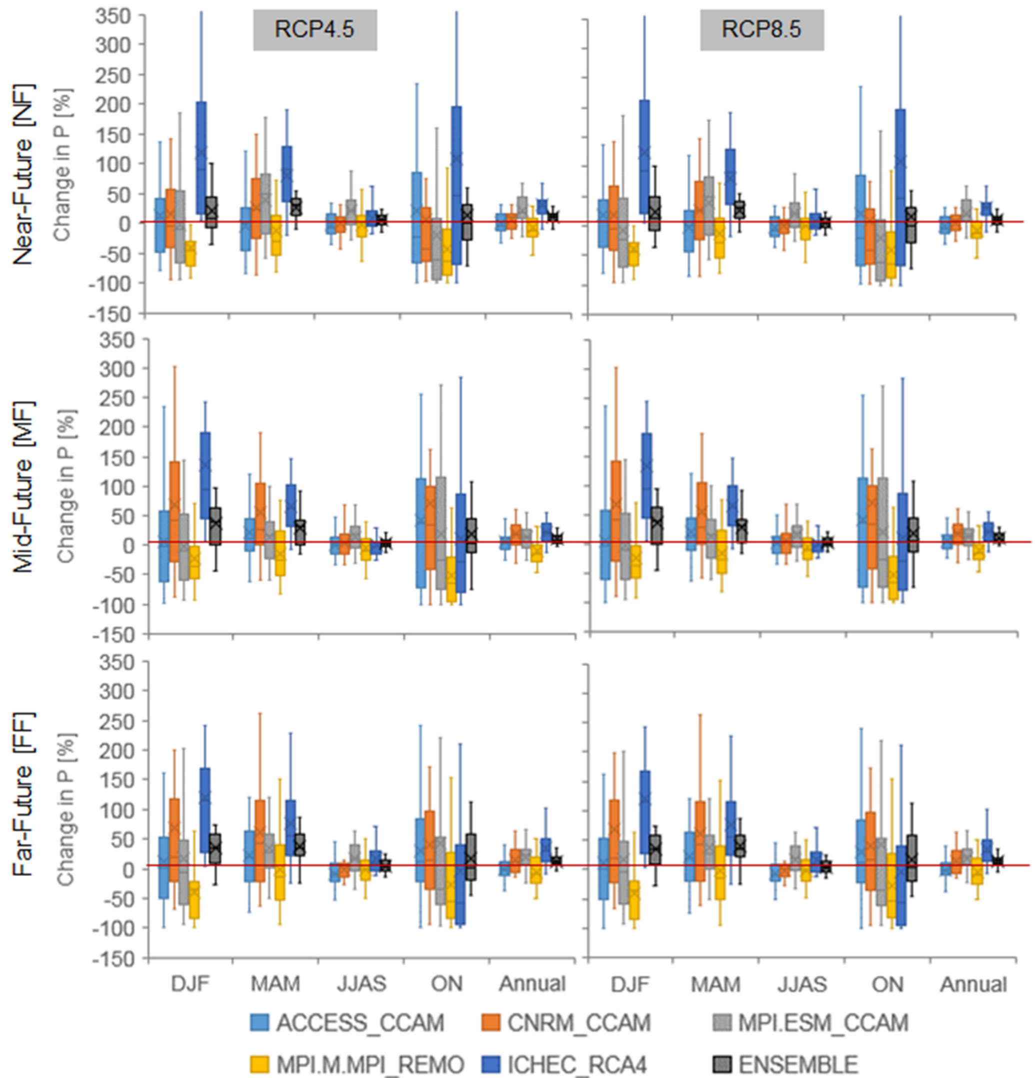


Fig. 10. Range of projected change in annual total future precipitation for different futures, RCPs and RCMs at station 103. Each box represents range in one RCM where whiskers indicate max and min values excluding the outliers, line markers indicate the median and x markers indicate the mean of change in annual total precipitation projected for each future timeframe. (Notes: DJF is December–January–February (winter season); MAM is Mach–April–May (dry season); JJAS is June–July–August–September (rainy/monsoon season); ON is October–November (post-monsoon season).)

Table 6
Projected changes in total precipitation [mm] at seasonal and annual scales at st103 station based on an ensemble of five RCMs under RCP scenarios.

Change from baseline [%]			DJF	MAM	JJAS	ON	Annual
Baseline [mm]			111.8	206.0	982.5	39.3	1340.7
RCP 4.5	NF	Mean [%]	22	26	5	15	10
		Range [%]	−36–162	−33–90	−14–24	−72–341	−10–30
	MF	Mean [%]	37	28	3	18	10
		Range [%]	−45–209	−15–92	−13–22	−74–208	−3–29
	FF	Mean [%]	35	39	5	16	13
		Range [%]	−28–134	−25–86	−14–24	−46–113	−5–34
RCP 8.5	NF	Mean [%]	22	29	6	18	11
		Range [%]	−35–75	−27–90	−11–30	−52–180	−5–27
	MF	Mean [%]	13	38	11	12	15
		Range [%]	−38–106	2–120	−12–36	−52–104	−2–35
	FF	Mean [%]	16	44	8	42	15
		Range [%]	−37–99	−7–122	−20–26	−40–197	−13–31

Notes: DJF is December–January–February (winter season); MAM is Mach–April–May (dry season); JJAS is June–July–August–September (rainy/monsoon season); ON is October–November (post-monsoon season).

lying above zero (Fig. 11). The mean and median overlaps for all cases indicating the projections over the years are spread evenly above and below the mean. It is interesting to note that despite the disparity in projected precipitation across ICHEC_RCA4 and REMO model, the maximum temperature (and minimum as well) follow the same behaviour with overlapping ranges. On the other hand, the three CCAM models are slightly dissimilar in comparison to their behaviour for precipitation.

Projected average annual maximum temperature for RCP4.5 scenarios, based on an ensemble of five RCMs, are gradually increasing compared to the baseline over three future periods by 0.9 °C (for NF), 1.4 °C (for MF) and 1.6 °C (for FF) (Table 7). In case of RCP8.5, it is projected to increase by 3.4 °C until the FF. It is increasing across all the seasons too, but the amount of increase is not consistent. Winter (DJF) temperature is projected to increase more for all the three futures and two scenarios considered, followed by dry (or pre-monsoon; MAM) season (Table 7). It reflects that warmer winters are expected in the Chamelia watershed during all the future periods considered. However, it should be noted that rate of increase is not consistent throughout the RCMs and years as shown as range in Table 7. The range of uncertainty in the

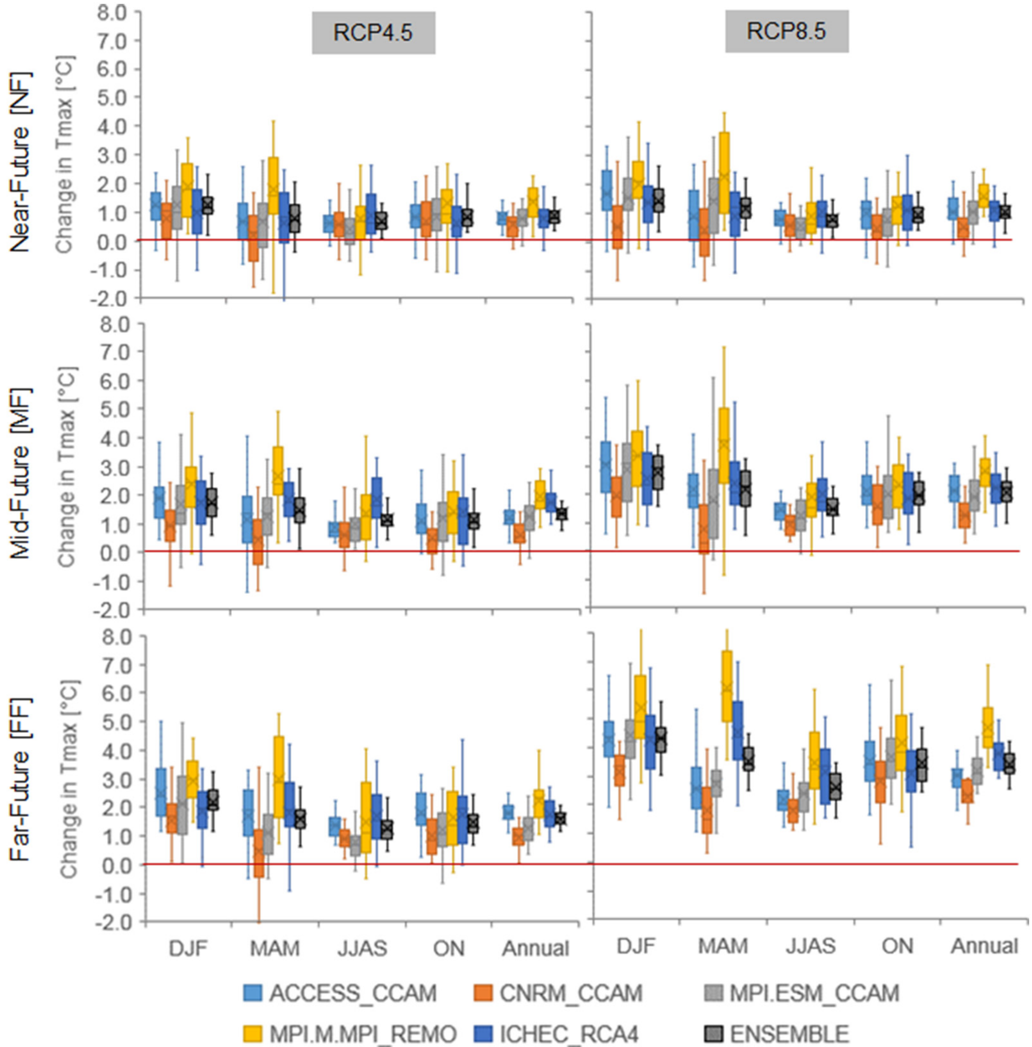


Fig. 11. Range of projected change in future maximum temperature for different scenarios and RCMs for the study watershed. Each box represents range in one RCM where whiskers indicate max and min values excluding the outliers, line markers indicate the median and x markers indicate the mean of change in annual total precipitation projected for each future timeframe.

projection is relatively high in winter (DJF) and pre-monsoon (MAM) seasons (Fig. 11).

3.3.2.2. Minimum temperature. The range of predictions for minimum temperature across the different RCMs, RCPs, and seasons provide more consensus and certainty that future minimum temperatures will rise as all model medians and majority of model projections lie above zero (Fig. 12).

The average annual minimum temperature is projected to increase from the baseline value by 0.9 °C, 1.7 °C, and 2.0 °C for NF, MF and FF, respectively, under RCP4.5 scenarios (Table 8). In case of RCP8.5 scenarios, the rate of increase is significantly higher; up to 3.9 °C increase from the baseline period for FF. The increasing trend is consistent across all the seasons and for both the scenarios; albeit the rate of increase varies with the season. A higher rate of increase is projected for summer (JJAS) and winter (DJF) seasons in both scenarios, which means warmer nights in the summer and winter. The uncertainty range in the change of projected minimum temperature varies with season; higher degree of uncertainty exists in pre- and post-monsoon seasons (Fig. 12). Unlike precipitation, the range of uncertainty in temperature increase (both minimum and maximum) is considerably less. It increases when we move from NF to FF.

Table 7
Projected future maximum temperature [°C] at Chamelia watershed based on ensemble of five RCMs under RCP scenarios.

Change from baseline [°C]			DJF	MAM	JJAS	ON	Annual
Baseline [°C]			18.0	26.9	28.5	24.1	24.8
RCP 4.5	NF	Mean [°C]	1.2	0.8	0.7	0.8	0.9
		Range [°C]	0.2–3.4	−0.4–2.1	0.1–1.3	0.3–2.0	0.4–1.7
	MF	Mean [°C]	1.7	1.5	1.1	1.1	1.4
		Range [°C]	0.6–2.7	0.1–3.0	0.5–1.9	0.2–2.2	0.8–1.8
	FF	Mean [°C]	2.2	1.6	1.3	1.5	1.6
		Range [°C]	0.8–3.3	0.6–2.7	0.5–2.3	0.7–2.5	1.1–2.0
RCP 8.5	NF	Mean [°C]	1.4	1.2	0.8	0.9	1.1
		Range [°C]	0.4–2.6	−0.3–2.2	0.2–1.5	0.4–2.2	0.3–1.7
	MF	Mean [°C]	2.8	2.2	1.5	2.0	2.1
		Range [°C]	1.6–3.7	0.6–3.2	0.6–2.3	0.7–2.8	1.0–2.9
	FF	Mean [°C]	4.3	3.5	2.6	3.4	3.4
		Range [°C]	3.0–6.1	2.5–4.5	1.5–3.4	2.4–4.7	2.6–4.2

3.4. Climate change impacts on water availability

Change in water balance components under he projected changes in future temperature and precipitation were simulated using the calibrated and validated SWAT model and analysed at annual as well as seasonal scales. The water balance components considered were:

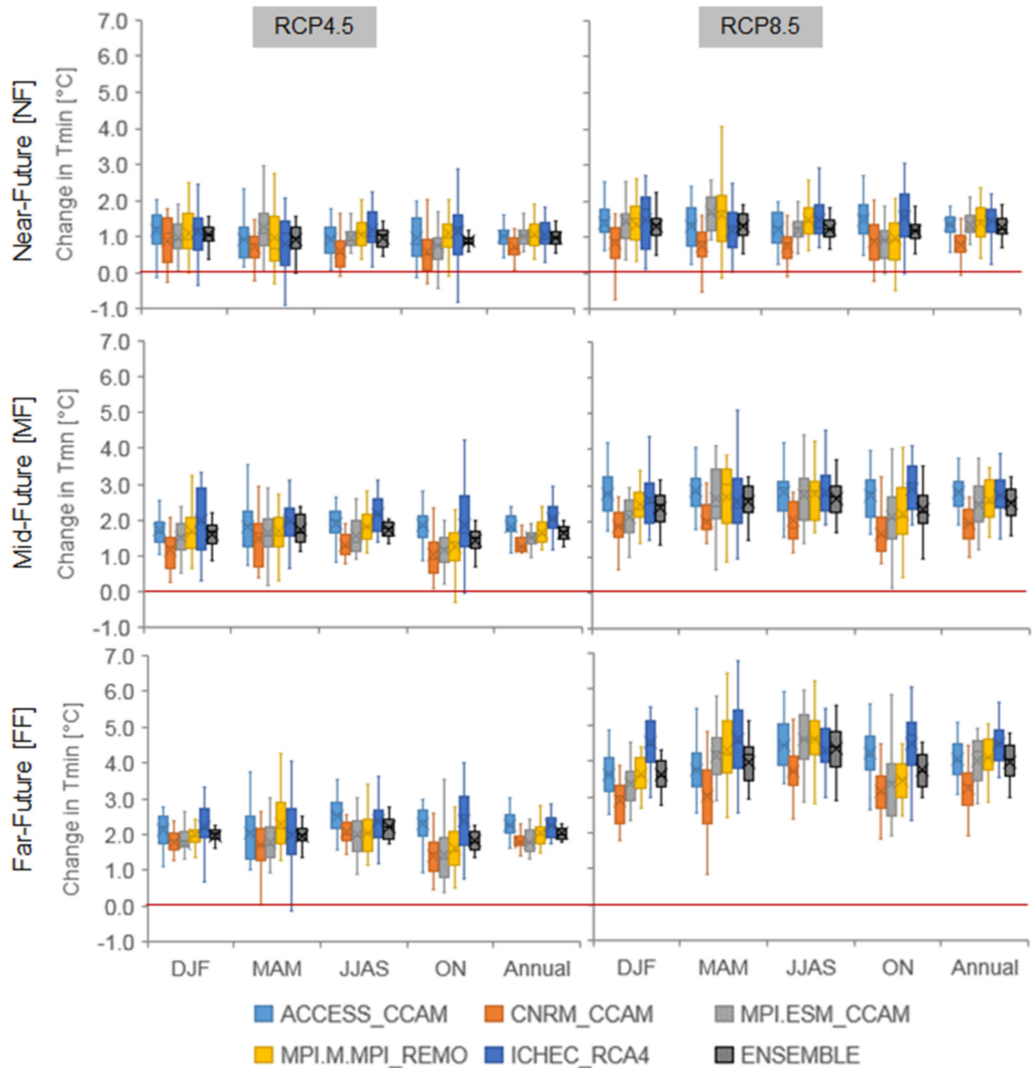


Fig. 12. Range of projected change in future minimum temperature for different scenarios and RCMs for the study watershed. Each box represents range in one RCM where whiskers indicate max and min values excluding the outliers, line markers indicate the median and x markers indicate the mean of change in annual total precipitation projected for each future timeframe.

precipitation, snowmelt, evapotranspiration, and water yield. Since observed data for all the water balance components for the basin was not available, we used the SWAT output for current hydrology as the reference baseline to estimate changes in the water balance components for

Table 8
Projected future minimum temperature [°C] at Chamelia watershed based on ensemble of five RCMs under RCP scenarios.

Change from baseline [°C]			DJF	MAM	JJAS	ON	Annual
Baseline [°C]			5.1	13.3	19.2	11.1	12.9
RCP 4.5	NF	Mean [°C]	1.1	0.9	1.0	0.9	0.9
		Range [°C]	0.4–1.6	0–1.6	0.5–1.4	0.4–1.7	0.5–1.4
	MF	Mean [°C]	1.6	1.7	1.8	1.4	1.6
		Range [°C]	0.9–2.2	1.1–2.4	1.3–2.1	0.7–2	1.2–1.9
	FF	Mean [°C]	2.0	2.0	2.2	1.8	2.0
		Range [°C]	1.1–2.3	0.8–2.7	1.7–2.8	1.4–2.3	1.7–2.3
RCP 8.5	NF	Mean [°C]	1.3	1.3	1.2	1.2	1.2
		Range [°C]	0.5–2.3	0.5–1.9	0.7–1.8	0.4–2.4	0.7–1.9
	MF	Mean [°C]	2.4	2.5	2.6	2.3	2.5
		Range [°C]	1.4–3.1	1.5–3.2	1.7–3.7	1–3.6	1.6–3.2
	FF	Mean [°C]	3.6	4.0	4.3	3.7	3.9
		Range [°C]	2.8–4.3	2.9–5.1	2.9–5.6	3–4.5	2.9–4.7

future scenarios. Climate change impacts are assessed at Qt120 (sub-basin ID: 13) located near to the outlet of the Chamelia (Fig. 1).

The projected range of streamflow change for the future periods, scenarios, and RCMs are shown in Fig. 13. The projected change in streamflow for an ensemble of five RCMs shows increasing trend for annual as well as seasonal values, for all the future periods considered, and for all the scenarios. For reasons other than MAM, individual RCMs project increase in future streamflow with means and medians lying above zero. As was seen for projected precipitation in Fig. 10, REMO projections are relatively dry while ICHEC_RCA4 projections are wetter than other RCMs. ICHEC_RCA4 also has the widest range of streamflows.

Average annual streamflow is projected to increase gradually from NF towards MF under both the scenarios (Fig. 14). For RCP4.5, the annual values are projected to increase by 8.2% in NF, 12.2% in MF, and 15.0% in FF. Such a significant increase was also reported for other watersheds in Nepal (e.g., Immerzeel et al., 2013; Bhattarai and Regmi, 2016). The projected increasing trend is consistent across all the seasons (Fig. 14). However, the increase in streamflow is greater in winter (DJF), and then for pre-monsoon (MAM), post-monsoon (ON), and then to monsoon (JJAS) seasons. Considering RCP4.5 scenarios, the projected increase in winter season (DJF) flow is 34% in NF, 40% in MF, and 42% in FF. In addition, uncertainties in the simulate flow are shown with a grey

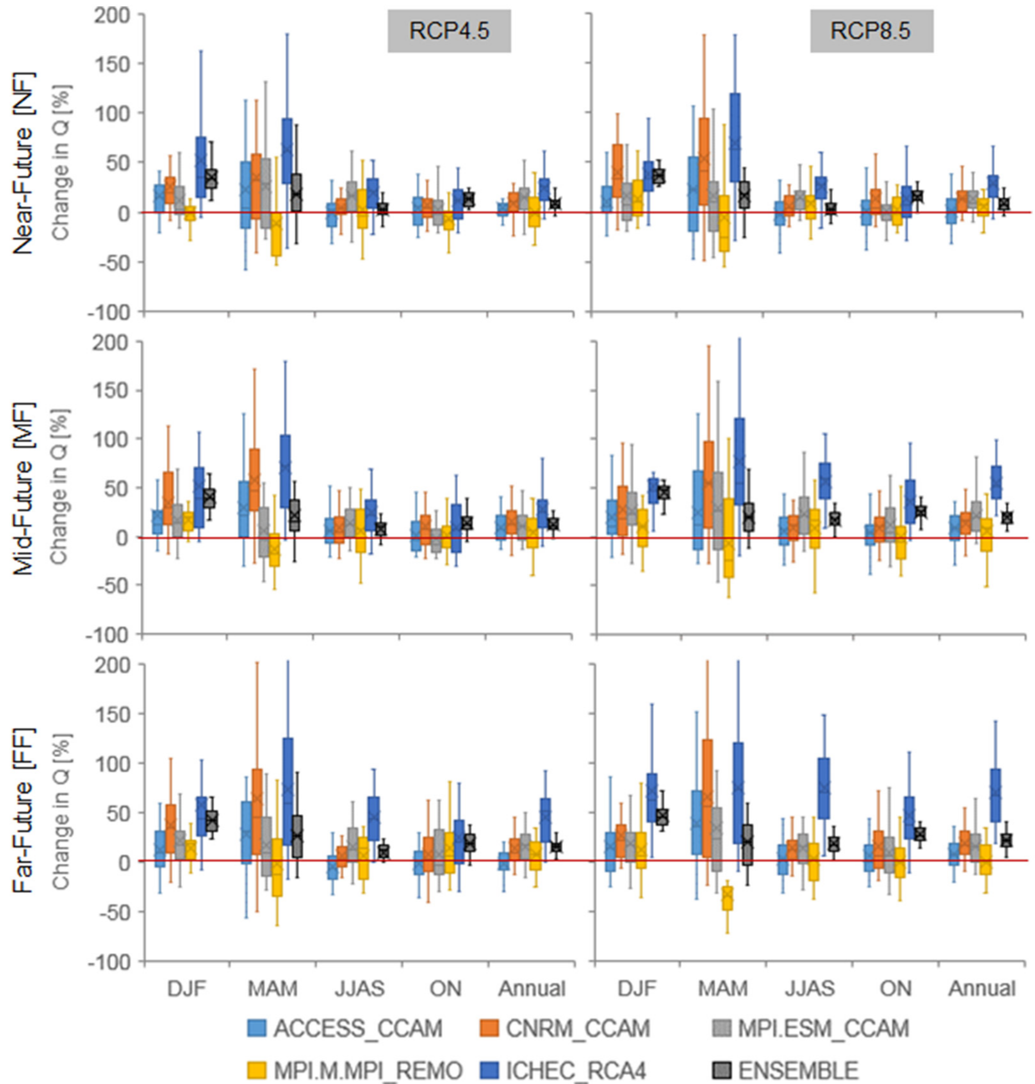


Fig. 13. Range of projected change (%) in simulated streamflow for the future periods, scenarios, and RCMs in the Chamelia watershed. Each box represents range in one RCM where whiskers indicate max and min values excluding the outliers, line markers indicate the median and x markers indicate the mean of change in annual total precipitation projected for each future timeframe.

band indicating minimum-maximum range in projections as well as average values for each period future timeframe. For long-term average flow, historical as well as projected flows for all the seasons lie within the mix-max band. The bandwidth is wider during high-flow season and gradually decreases during low flow seasons. The wider bandwidth indicating higher model prediction uncertainty may be propagated by natural variability observed in streams during the high flow periods. Similar trends can be seen in the historical and projected FDC shown in the third row of Fig. 14.

Fig. 15 further analyses the change in water balance components under future scenarios. The net water yield here refers to the net amount of water contributed by the sub-basins and HRUs to the streamflow. The increase in streamflow is mostly contributed by increases in precipitation (Fig. 15). The increase in total streamflow is less compared to the increase in precipitation because of loss of some precipitation by evapotranspiration. In addition, percolation has also increased significantly with an increasing rate towards the future (e.g., 37.1% in NF, 40.1% in MF, and 43.7% in FF under RCP4.5 scenario). On the other hand, even though the precipitation and total streamflow have increased, overland flow (SurQ) has decreased. In Annex-4 we further analysed changes in actual evapotranspiration (AET) to confirm the trend. Figures show that AET is projected to increase from near to far future across all the months/seasons and scenarios as the result of projected increase in temperature. The projected increase (w.r.t. baseline) in average annual AET for RCP8.5 scenario ranges from 15% in NF to 20% in FF; however, there is a strong seasonality in magnitude of the change. The increase in DJF season ranges from 58% (NF) to 68% (FF), whereas from 29% (NF) to 37% (FF) (Annex-4). The aforementioned results indicate that more of SURQ is projected to be lost as AET and there is a likelihood of an increase in groundwater recharge with increased precipitation, and subsequent release into streams in the form of baseflow (lateral flow and groundwater flow). The most affected water balance component in the Chamelia watershed is the percolation (with the largest percentage increase) followed by net water yield, AET, and precipitation. The increased precipitation may result increased frequency of wet soil conditions that are conducive to percolation.

4. Conclusions

SWAT model was developed to simulate hydrological responses of the Chamelia watershed. The model performance is reasonably good in terms of capability to reproduce hydrological patterns including flow duration curves and statistical properties of the observed daily

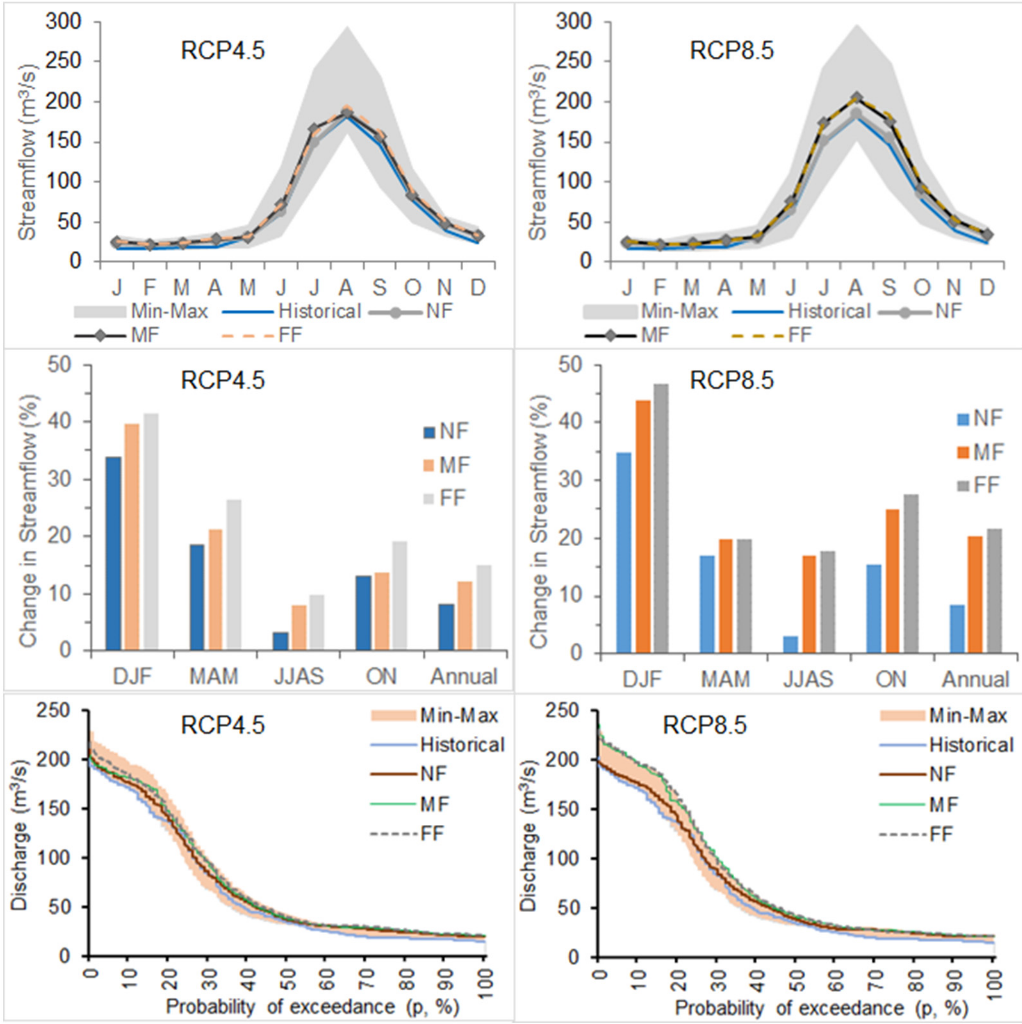


Fig. 14. Change in simulated streamflow at Q120 station under future climate represented as an ensemble of selected RCM outputs for RCP4.5 (top) and RCP8.5 (bottom) scenarios. The first, second and third rows show monthly hydrograph, change in streamflow from baseline, and flow duration curve (FDC), respectively. NF, MF and FF refer to near-, mid- and far-futures, respectively; Min-Max refer to a band of variation for the months.

and monthly time-series. Multi-site calibration approach has ensured better representation of hydrological variability within the sub-basin. The model is most reliable for Q120 along the main stem of the watershed, which is also the most important station from a hydropower development perspective.

Future climatic conditions were taken from five RCMs under two RCP scenarios and bias corrected using quantile mapping method. On an average, both annual and seasonal values of precipitation are projected to increase, with a greater percentage of increase in winter and pre-monsoon seasons. However, models project both increases

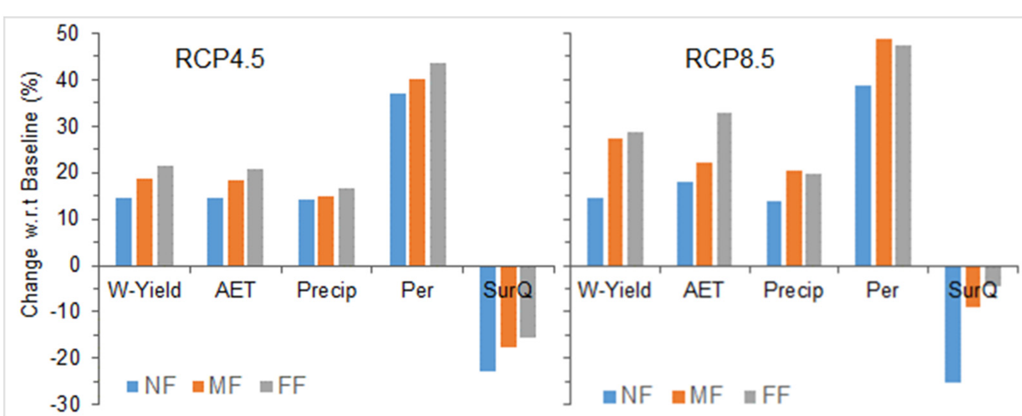


Fig. 15. Impacts of projected changes in precipitation and temperature on annual average water balance components in the Chamelia watershed for near future (NF), mid future (MF), and far future (FF) under RCP4.5 and RCP8.5 scenarios. W-Yield is water yield; AET is actual evapotranspiration; Precip is precipitation; Snow is snowmelt; Per is percolation; and SurQ is surface runoff (or overland flow).

and decreases in precipitation over the years, indicating lack of consensus about precipitation change. Both maximum and minimum temperatures are projected to increase with higher certainty than with precipitation; albeit, with varying rates. Water availability in the changed future climate is also projected to increase gradually from baseline to near-, mid-, and far-futures. An ensemble of five RCMs shows dry season (or pre-monsoon and winter) water availability is projected to increase at a higher rate than the average annual values, which would be beneficial for water resources infrastructure projects.

While the average values for future precipitation, temperature and streamflow indicate increases across all parameters for all the futures, the SWAT model and RCMs considered also project decreases in these values over time. Especially when looking at seasonal responses, precipitation does not have a generic trend across the seasons. Based on the five RCMs considered here across all futures for RCP 4.5, average annual changes in precipitation at st103 may vary between −10 and 34%; maximum temperature between 0.4 and 2.0 °C; and minimum temperature between 0.5 and 2.3 °C. A deeper look at the consensus seen across the models in each season is needed to further quantify the likelihood of values within these ranges of projected future climate and water resource availability.

Local watersheds might also have various projects of importance even if the sizes are not that large. This study indicates that local watersheds could be vulnerable to climatic risks and therefore should be considered in the planning process. Results from this study provide a benchmark for water available in the basin and discussion of water allocation and use across various water users in the basin. Especially with discussions of hydropower development, the quantification of water balance components will be a key information for understanding impacts across the water-energy-food nexus. Furthermore, as downstream watersheds have more base flow, interventions in the form of recharge or watershed protection in the upstream is likely to have positive impact in terms of enhancing dry season flows in the downstream. Therefore, water management needs to be coordinated across the basin.

Acknowledgements

This study is made possible by the generous support of the American people through the United States Agency for International Development (USAID) under Digo Jal Bikas (DJB) project. The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government. We would like to acknowledge Miss. Claire Swingle for her help in language editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.09.053.

References

Abbaspour, K.C., et al., 2007. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. J. Hydrol. 333 (2–4), 413–430.
Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Meteorological data – radiation. Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization (FAO), Rome, Italy.
Andermann, C., Longuevergne, L., Bonnet, S., Crave, A., Davy, P., Gloaguen, R., 2012. Impact of transient groundwater storage on the discharge of Himalayan rivers. Nat. Geosci. 5, 127–132.
Arnold, J.G., Srinivasan, P., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modelling and assessment. Part I. Model development. J. Am. Water Resour. Assoc. 34, 73–89.
Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., Van Griensven, A., Van Liew, M.W., Kannan, N., Jha, M.K., 2012. SWAT: model use, calibration, and validation. Trans. Am. Soc. Agric. Biol. Eng. (ASABE) 55 (4), 1491–1508.
Bajracharya, A.R., Bajracharya, S.R., Shrestha, A.B., Maharjan, S.B., 2018. Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal. Sci. Total Environ. 625, 837–848.
Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominant regions. Nature 438, 303–309.
Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.P. (Eds.), 2008. Climate Change and Water: Technical Paper of the Intergovernmental Panel on Climate Change (IPCC). IPCC Secretariat, Geneva (210 pp.).
Berg, P., Feldmann, H., Panitz, H.J., 2012. Bias correction of high resolution regional climate model data. J. Hydrol. 448–449, 80–92.
Bharati, L., Gurung, P., Jayakody, P., Smakhtin, V., Bhattarai, U., 2014. The projected impact of climate change on water availability and development in the Koshi Basin, Nepal. Mt. Res. Dev. 34, 118–130.
Bharati, L., Gurung, P., Maharjan, L., Bhattarai, U., 2016. Past and future variability in the hydrological regime of the Koshi Basin, Nepal. Hydrol. Sci. J. 61 (1), 79–93.
Bhattarai, B.C., Regmi, D., 2016. Impact of climate change on water resources in view of contribution of runoff components in stream flow: a case study from Langtang Basin, Nepal. J. Hydrol. Meteorol. 9 (1), 74–84.
Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J.G., ... Bajracharya, S., 2012. The state and fate of Himalayan glaciers. Science 336 (6079), 310–314.
Chen, J., Brissette, F.P., Chaumont, D., Braun, M., 2013. Finding appropriate bias correction methods in downscaling precipitation for hydrologic impact studies over North America. Water Resour. Res. 49, 4187–4205.
Choudhary, A., Dimri, A.P., 2017. Assessment of CORDEX-South Asia experiments for monsoonal precipitation over Himalayan region for future climate. Clim. Dyn. 1–22.
Devkota, L.P., Gyawali, D.R., 2015. Impacts of climate change on hydrological regime and water resources management of the Koshi River Basin, Nepal. J. Hydrol. Reg. Stud. 4 (Part B), 502–515.
Dijkshoorn, J.A., Huting, J.R.M., 2009. Soil and Terrain (SOTER) Database for Nepal. Report 2009/01. ISRIC – World Soil Information, Wageningen Available at. http://www.isric.org/isric/webdocs/docs/ISRIC_Report_2009_01.pdf, Accessed date: 15 December 2016 (Online Dataset).
Dixit, A., Upadhya, M., Dixit, K., Pokhrel, A., Rai, D.R., 2009. Living With Water Stress in the Hills of the Koshi Baisn, Nepal. ICIMOD, Nepal.
Fontaine, T.A., Cruickshank, T.S., Arnold, J.G., Hotchkiss, R.H., 2002. Development of a snowfall–snowmelt routine for mountainous terrain for the soil water assessment tool (SWAT). J. Hydrol. 262 (1), 209–223.
Ghimire, S., Choudhary, A., Dimri, A.P., 2015. Assessment of the performance of CORDEX-South Asia experiments for monsoonal precipitation over the Himalayan region during present climate: part I. Clim. Dyn. 2–4.
Gudmundsson, L., Bremnes, J.B., Haugen, J.E., Engen-Skaugen, T., 2012. Technical note: downscaling RCM precipitation to the station scale using statistical transformations — a comparison of methods. Hydrol. Earth Syst. Sci. 16, 3383–3390.
Gupta, H.V., Sorooshian, S., Yapo, P.O., 1999. Status of automatic calibration for hydrologic models: comparison with multilevel expert calibration. J. Hydrol. Eng. 4 (2), 135–143.
Hasan, M.A., Pradhanang, S.M., 2017. Estimation of flow regime for a spatially varied Himalayan watershed using improved multi-site calibration of the Soil and Water Assessment Tool (SWAT) model. Environ. Earth Sci. 76 (23), 787. https://doi.org/10.1007/s12665-017-7134-3.
ICIMOD, 2010. Land Cover of Nepal 2010. International Center for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal Available online at:. http://rds.icimod.org/Home/DataDetail?metadataId=9224, Accessed date: 12 January 2017.
Immerzeel, W.W., Pellicciotti, F., Bierkens, M.F.P., 2013. Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. Nat. Geosci. 6, 742–745.
IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M.M.B., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report (AR5). Cambridge Univ Press, New York.
IWMI, 2014. Water Availability and Agricultural Adaptation Options of the Koshi Basin Under Global Environmental Change. Final Report Submitted by International Water Management Institute (IWMI) to International Center for Integrated Mountain Development (ICIMOD), December 2014 (Kathmandu).
IWMI, 2017. Progress Report of Digo Jal Bikas (DJB) Project Submitted to United States Agency for International Development (USAID). International Water Management Institute (IWMI), Kathmandu, Nepal (September, 2017).
Khadka, D., Babel, M.S., Shrestha, S., Tripathi, N.K., 2014. Climate change impact on glacier and snow melt and runoff in Tamakoshi basin in the Hindu Kush Himalayan (HKH) region. J. Hydrol. 511, 49–60.
Kim, U., Kaluarachchi, J.J., 2009. Climate change impacts on water resources in the Upper Blue Nile river basin, Ethiopia. J. Am. Water Resour. Assoc. 45 (6), 1361–1378.
Knutti, R., Furrer, R., Tebaldi, C., Cermak, J., Meehl, G.A., 2010a. Challenges in combining projections from multiple climate models. J. Clim. 23, 2739–2758.
Knutti, R., Abramowitz, G., Collins, M., Eyring, V., Gleckler, P.J., Hewitson, B., Mearns, L., 2010b. Good practice guidance paper on assessing and combining multi model climate projections. IPCC Expert Meet. Assess. Comb. Multi Model Clim. Proj. (15 pp.)
Krishnan, N., Raj, C., Chaubey, I., Sudheer, K.P., 2018. Parameter estimation of SWAT and quantification of consequent confidence bands of model simulations. Environ. Earth Sci. 77 (12), 470. https://doi.org/10.1007/s12665-018-7619-8.
Kure, S., Jang, S., Ohara, N., Kavvas, M.L., Chen, Z.Q., 2013. Hydrological impact of regional climate change for the snowfed and glacierfed river basins in the Republic of Tajikistan: hydrological responses of flow to climate change. Hydrol. Process. 27 (26), 4057–4070.
Latif, M., 2011. Uncertainty in climate change projections. J. Geochem. Explor. 110 (1), 1–7.
Leta, O.T., et al., 2015. Assessment of the different sources of uncertainty in a SWAT model of the River Senne (Belgium). Environ. Model. Softw. 68, 129–146.
Li, H., Xu, C.Y., Beldring, S., Tallaksen, L.M., Jain, S.K., 2016. Water resources under climate change in Himalayan basins. Water Resour. Manag. 30 (2), 843–859.

Liu, Y.B., de Smedt, F., 2004. WetSpa Extension, a GIS-based Hydrologic Model for Flood Prediction and Watershed Management – Documentation and User Manual. Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Brussel, Belgium, pp. 1–126.
Lutz, A.F., ter Maat, H.W., Biemans, H., Shrestha, A.B., Wester, P., Immerzeel, W.W., 2016. Selecting representative climate models for climate change impact studies: an advanced envelope-based selection approach. Int. J. Climatol. 36, 3988–4005.
Manandhar, S., Pandey, V.P., Ishidaira, H., Kazama, F., 2013. Perturbation study of climate change impacts in a snow-fed river basin. Hydrol. Process. 27, 3461–3474.
McGregor, J.L., Dix, M.R., 2001. The CSIRO Conformal-Cubic Atmospheric GCM. In: Hodnett, P.F. (Ed.), IUTAM Symposium on Advances in Mathematical Modelling of Atmosphere and Ocean Dynamics. Fluid Mechanics and Its Applications vol. 61. Springer, Dordrecht.
Moriasi, D.N., Arnold, J.G., van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50 (3), 885–900.
Mukherjee, S., Hazra, A., Kumar, K., Nandi, S.K., Dhyani, P.P., 2017. Simulated projection of ISMR over Indian Himalayan region: assessment from CSIRO-CORDEX South Asia experiments. Meteorog. Atmos. Phys. 1–17.
NASA JPL, 2009. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (GDEM V2). United States National Aeronautics and Space Administration – Jet Propulsion Laboratory (NASA JPL) https://doi.org/10.5067/ASTER/ASTGTM.002 (accessed on March 27, 2013).
Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I – a discussion of principles. J. Hydrol. 10 (3), 282–290.
Neitsch, S., Arnold, J., Kiniry, J., Williams, J., 2011. Soil and Water Assessment Tool Theoretical Documentation Version 2009. Texas Water Resources Institute, Texas A&M University System, Texas.
Rahman, K., Marinanti, C., Beniston, M., Widmer, F., Abbaspour, K., Lehmann, A., 2012. Streamflow modeling in a highly managed mountainous glacier watershed using SWAT: the Upper Rhone River watershed case in Switzerland. Water Resour. Manag. 27 (2), 323–339.
Rasul, G., 2016. Managing the food, water, and energy nexus for achieving the sustainable development goals in South Asia. Environ. Dev. 18, 14–25.
Rostamian, R., Jaleh, A., Afyuni, M., Mousavi, S.F., Heidarpour, M., Jalalian, A., Abbaspour, K.C., 2008. Application of a SWAT model for estimating runoff and sediment in two mountainous basins in central Iran. Hydrol. Sci. J. 53 (5), 977–988.
Saeed, F., Suleri, A.Q., 2015. Future Heat Waves in Pakistan Under IPCCs AR5 Climate Change Scenario. Sustainable Development Policy Institute, Islamabad, Pakistan.
Saltelli, A., Ratto, M., Tarantola, S., Campolongo, F., 2006. Sensitivity analysis practices: strategies for model-based inference. Reliab. Eng. Syst. Saf. 91, 1109–1125.
Samuelsson, P., Jones, C.G., Willen, U., Ullerstig, A., Gollvik, S., Hansson, U., Jansson, C., Ejellstrom, E., Nikulin, G., Wyser, K., 2011. The Rossby Centre regional climate model RCA3: model description and performance. Tellus 63 (1), 4–23.
Sanjay, J., Krishnan, R., Shrestha, A.B., Rajbhandari, R., Ren, G.Y., 2017. Downscaled climate change projections for the Hindu Kush Himalayan region using CORDEX South Asia regional climate models. Adv. Clim. Chang. Res. 8, 185–198.
Scinocca, J.F., et al., 2015. Coordinated global and regional climate modeling. J. Clim. 29 (1), 17–35.
Shrestha, S., Htut, A.Y., 2016. Modeling the potential impacts of climate change on hydrology of the Bago River Basin, Myanmar. Int. J. River Basin Manag. 14 (3), 287–297.
Shrestha, M., Acharya, S.C., Shrestha, P.K., 2017a. Bias correction of climate models for hydrological modelling – are simple methods still useful? Meteorol. Appl. https://doi.org/10.1002/met.1655 (xx: xx-xx).
Shrestha, N.K., Du, X., Wang, J., 2017b. Assessing climate change impacts on fresh water resources of the Athabsca River Basin, Canada. Sci. Total Environ. 601–602, 425–440.
Siddiqui, S., Bharati, L., Gurung, P., Maharjan, L.D., 2012. Climate Change and Vulnerability Mapping in Watersheds in Middle and High Mountains of Nepal. International Water Management Institute (IWMI), Kathmandu, Nepal.
Srinivasan, R., 2012. Beginner SWAT - Training Manual.
Srinivasan, R., Ramanarayanan, T.S., Arnold, J.G., Bednarz, S.T., 1998. Large area hydrological modeling and assessment. Part II: model application. J. Am. Water Resour. Assoc. 34 (1), 91–101.
Teichmann, C., Eggert, B., Elizalde, A., Haensler, A., Jacob, D., Kumar, P., Moseley, C., Pfeifer, S., Rechid, D., Remedio, A., Ries, H., Petersen, J., Preuschmann, S., Raub, T., Saeed, F., Sieck, K., Weber, T., 2013. How does a regional climate model modify the projected climate change signal of the driving GCM: a study over different CORDEX regions using REMO. Atmosphere 4 (2), 214–236.
Teutschbein, C., Seibert, J., 2012. Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. J. Hydrol. 456–457, 12–29.
ul Hasson, S., 2016. Seasonality of precipitation over himalayan watersheds in CORDEX South Asia and their driving CMIP5 experiments. Atmosphere (Basel) 7, 123.
Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Clim. Chang. 109, 5–31.
Versini, P.A., Pouget, L., McEnnis, S., Custodio, E., Escaler, I., 2016. Climate change impact on water resources availability: case study of the Llobregat river basin (Spain). Hydrol. Sci. J. 61 (14), 2496–2508.
WECS, 2011. Water Resources of Nepal in the Context of Climate Change. Water and Energy Commission Secretariat (WECS), Government of Nepal, Kathmandu.
Wilby, R.L., 2010. Evaluating climate model outputs for hydrological applications. Hydrol. Sci. J. 55, 1090–1093.
Wood, A.W., Leung, L.R., Sridhar, V., Lettenmaier, D.P., 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Climate Change 62, 189–216.
World Bank, 2009. Glacier Retreat in the Nepal Himalaya: An Assessment of the Role of Glaciers in the Hydrologic Regime of the Nepal Himalaya. Prepared for the South Asia Sustainable Development (SASDN) Office, Environment and Water Resources Unit.
Zhu, T., Ringler, C., 2012. Climate change impacts on water availability and use in the Limpopo river basin. Water 4, 63–84.

Annex 2-7

Spatio-temporal distribution of water availability in Karnali-Mohana Basin, Western Nepal: Hydrological model development using multi-site calibration approach (Part-A)

Vishnu Prasad Pandey[1,*], Sanita Dhaubanjar[1], Luna Bharati[1] , Bhesh Raj Thapa[1]

[1]*International Water Management Institute (IWMI), Nepal Office, Lalitpur, Nepal*

**Corresponding Author:* *v.pandey@cgiar.org*

Abstract

Study region: Karnali-Mohana (KarMo) river basin, Western Nepal.

Study focus: This study has developed a hydrological model using multi-site calibration approach for a large basin, the Karnali-Mohana (KarMo) in Western Nepal, which has a lot of potential for water resources development and contribute to the national prosperity. It further applies the model to characterize hydrology and water resources availability across spatio-temporal scales to enhance understanding on water availability and potential uses. The newly developed hydrological model in Soil and Water Assessment Tool (SWAT) is capable of reproducing the hydrological pattern, the average flows, and the flow duration curve at the outlet of the basin and five major sub-basins.

New hydrological insights for this region: The model simulated results showed that about 34% of average annual precipitation in the KarMo basin is lost as evapotranspiration, but with a large spatio-temporal heterogeneity. The Hills and Tarai are relatively wetter than the Mountains. The average annual flow volume at the basin outlet is estimated as 46,250 million-cubic-meters (MCM). The hydrological characterization made in this study are further used for climate change impact assessment (Part-B in the same journal), environmental flows assessment and evaluating trade-offs among various water development pathways, which are published elsewhere. This model developed in this study, therefore, has potential to contribute for strategic planning and sustainable management of water resources to fuel the country's prosperity.

Keywords: *Hydrology; Karnali; Mohana; SWAT; Water Resources; Western Nepal*

---

1. Introduction

Hydrological observations at a high spatial and temporal resolution is resource-intensive. Therefore, many countries are yet to reach to that level even though the coverage is improving over the years. Even if the coverage is adequate, developing hydrological simulation models can provide reliable estimates for water yield and availability in a basin over a wide range of input watershed conditions under a variety of climatic scenarios. Spatial explicit hydrological models are particularly useful to evaluate impacts under various scenarios on water availability and distribution (Thapa et al., 2017). Furthermore, the simulation models provide an excellent platform for evaluating various options for water and environmental planning. Such information is crucial for policy/decision-makers, implementing agencies, and practitioners to quantify different types of threats to water and environmental security; design policies and programmes; and devise strategies for better allocation, utilization, and management of freshwater resources (Sunsnik, 2010; Thapa et al., 2017) as well as environmental protection for the country's prosperity. The need for such a modelling system is stimulated and sometimes even enforced by many activities required by river basin planning and management (Halwatura and Najim, 2013). For example, water balance studies in Iran are customary for allocating budgets to water resource policies and projects (Ghandhari and Alavi-Moghaddam, 2011). It is therefore imperative to develop hydrological models for the basins of interest and apply to characterize spatio-temporal distribution of hydrology and water resources.

Western Nepal is generally perceived as one of the poorest regions in the country with low literacy, limited development, high poverty, very little market access, and similar disadvantages (Pandey et al., 2018). Such perceptions reflect inadequate understanding of the untapped natural resources potential that the region has. The Karnali and Mahakali basins in the region account for 28% of total available water resources in Nepal (Pandey et al., 2010). Natural resources are also abundant and tourism potentials are also high. With steep slopes and meandering rivers, Western Nepal also offers tremendous potential for hydropower development. There are 150 identified hydropower projects of various types, including 19 storage projects, under various stages of development, with proposed installed capacity ranging from 0.5 to 6,720 megawatts (MW) (IWMI, 2018). Total estimated installed capacity of all these projects is more than 21,000 MW. Implementing all these projects will contribute to energy security and fuel economic growth for national prosperity. Mohana basin, with the catchment area of 3,730 km^2; is located in the south of the Karnali basin; originates from Nepali Churia hills; and varies in topography from 113 to 1,928 masl. The Mohana basin hosts at least 11 irrigation projects under operation with a total net command area of 26,583 hectares (ha). The net command area of the 11 projects vary from 155 ha to 15,800 ha. An endangered species of Ganges River dolphin (Platanista gangetica) were recently reported to inhabit the Mohana river. It is therefore imperative to maintain a healthy aquatic environment in order to protect an endangered species. Despite having tremendous potentials of the region, adequate development and management of water resources is yet to gain momentum for various reasons, including inadequate scientific understanding on spatio-temporal distributional of water availability.

There are several studies focusing on hydrological modelling at Nepalese watersheds (Babel et al., 2014; Bajracharya et al., 2018; Bharati et al., 2014), however only one (Dhami et al., 2018) focuses on the Karnali basin in the western Nepal, and none in the Karnali-Mohana (KarMo) basin (Fig. 1). Even the one focusing on the Karnali has used limited number of stations for model calibration, and has not characterized hydrology adequately from spatio-temporal distribution perspective. Furthermore, various hydrological models have been used over the time to reproduce hydrological patterns over a watershed. Some of them are empirical (e.g. Tank Model, Sugawara 1979), while others are lumped (e.g., HEC-HMS, Feldman, 2000), semi-distributed (e.g., SWAT, Arnold et al., 1998; Srinivasan et al., 1998), or fully distributed (e.g., BTOPMC, Takeuchi et al. 1999). However, application for a specific purpose and for a typical study area depends upon several factors. The Soil and Water Assessment Tool (SWAT) is widely used at different spatial scales to simulate hydrology, soil erosion, sedimentation, and impacts studies, among others (Aryal et al., 2018; Bajracharya et al., 2018; Bharati et al., 2016; Devkota and Gyawali, 2015; Jeong et al., 2010). The SWAT model is therefore selected in this study for hydrological simulation of the study basin.

Many studies use SWAT model with calibration at only the outlet to characterize hydrology. However, in highly heterogeneous large basins such as KarMo, with basin area of 49,892 km^2, it needs to be calibrated at multiple sites should we expect the model truly reproduce spatial heterogeneity in hydrological processes. Recent literatures (e.g., Hasan and Pradhanang, 2017; Nkiaka et al., 2018; Pandey et al., 2019) also put emphasis on multi-variable multi-site calibration approach considering the need to better represent spatial heterogeneity within the modelled watershed. This study therefore aims to develop a hydrological model in SWAT environment for the KarMo basin with multi-site calibration approach, and then apply it to characterize spatio-temporal distribution in water availability across the basin. The fully calibrated and validated hydrological model is then used for climate change impact assessment (in forthcoming concurrent paper), environmental flows assessment and evaluating trade-offs among various water development pathways (Pakhtigian et al., 2019).

2. STUDY AREA

The KarMo basin area above Nepal-India border covers 49,892 km^2, of which 6.9% falls in the Tibetan Plateau, China and the rest in Western Nepal. The Karnali river originates in Tibetan Plateau and Trans-Himalayas (TrH) at altitudes of 5,500 m to 7,726m and flows through Mountains (Mnt), Hills (Hil), and Indo-Gangetic Plain (IGP) as shown in Fig. 1 and Fig. 2. The river spans 230 km from the northern basin boundary to the *Chisapani* station (Q280) in the south (length of mainstream Karnali river). The smaller Mohana river originates in Churia hills of Nepal, descends through the Terai, and drains into Karnali river at the Nepal-India border. The watershed area of Mohana alone above the Nepal-India border is 3,730 km^2. Karnali has a dendritic stream network in most of the areas while Mohana comprises of parallel stream network characterized by flash floods in the monsoon. Major tributaries of the Karnali river are Bheri, Thuli Bheri, Seti, Mugu Karnali and Humla Karnali.

The KarMo basin has a wide spatial heterogeneity in biophysical and climatic characteristics. The topographical variation ranges from 69 – 7,726 meters above mean sea level (masl) (Fig. 1). There are nine generic land use/cover classes with dominance of forest cover (about one-third of the basin area) (Fig. 3a), and 21 soil types with dominance of Gleic Leptosol (34.2% of basin area) (Fig. 3b) in the basin. Hydro-climatic conditions also vary, as evident from data at 36 meteorological stations from Department of Hydrology and Meteorology (DHM), and six grid points from Indian Meteorological Department (IMD) (Fig. 1).

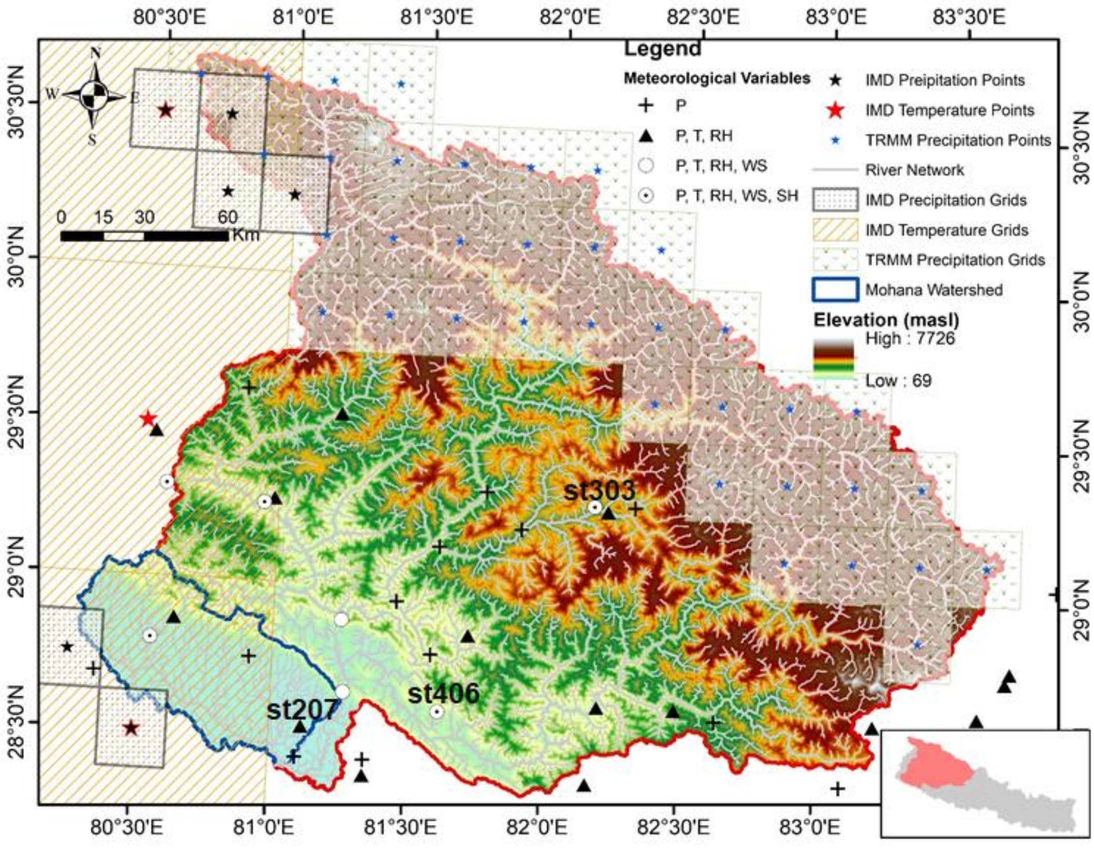


Figure 1: Study area: location, topographical variation, and meteorological stations/grids

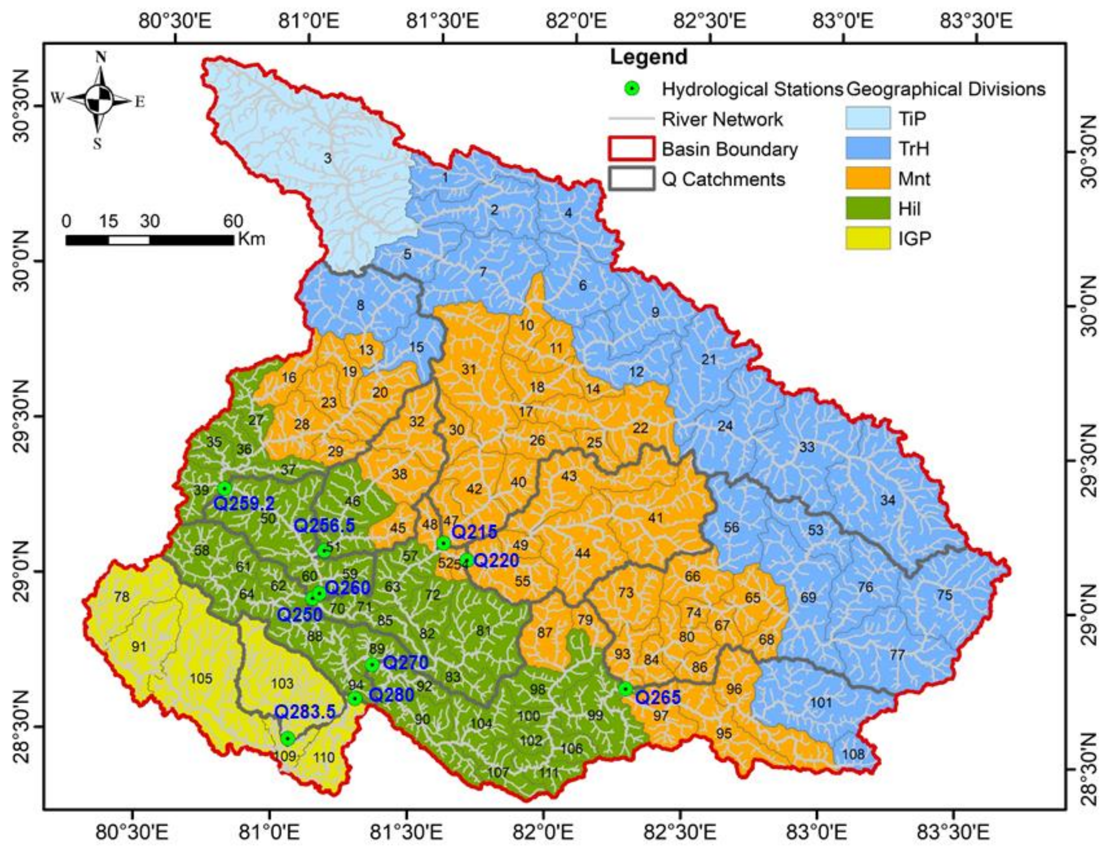


Figure 2: SWAT sub-watersheds and model calibration stations along with geographical divisions of the KarMo basin. TiP is Tibetan Plateau; TrH is Trans-Himalaya; Mnt is Mountain; Hil is Hill; IGP is Indo-Gangetic Plain; Q-catchments are catchments above gauging stations.

A database compiled by the Digo Jal Bikas project (http://djb.iwmi.org/) shows that there are 127 hydropower projects ranging from 0.5 to 1,003 megawatts (MW) at various stages of development in the KarMo basin. Similarly, 48 existing and one under-construction irrigation projects are also located within the basin. The net command area of these projects range from 100 – 98,026 ha. There are ample prospects for future water resources development activities in the basin, including tourism, and therefore, understanding spatio-temporal distribution in water availability and implications of climate change (CC) is important for the stakeholders across various water-use sectors.

3. METHODOLOGY AND DATA

Fig. 4 depicts the methodological flowchart and following sub-sections describe them in detail.

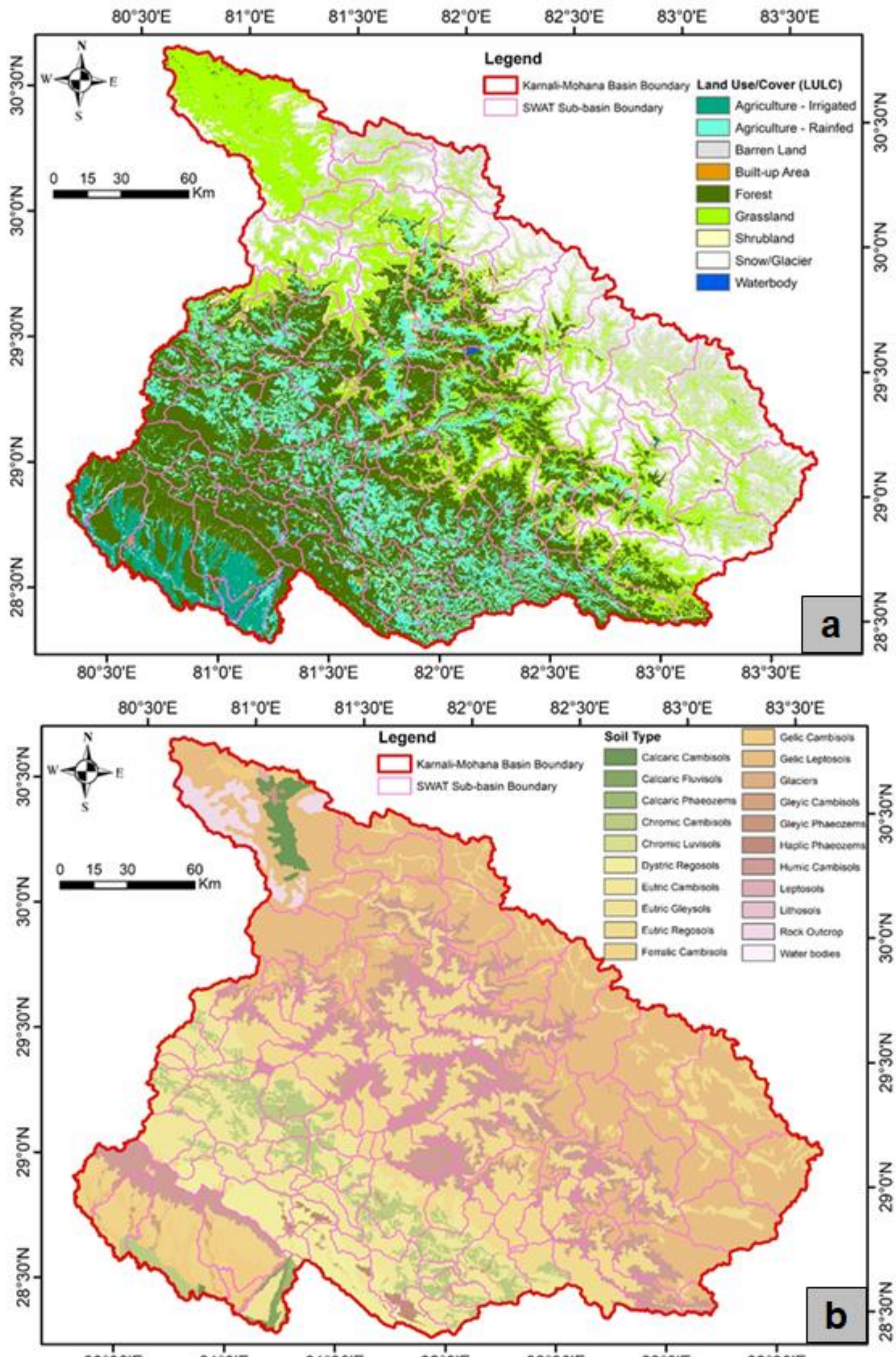


Figure 3: Land use/cover (a) and soil type (b) distribution within Karnali-Mohana basin (Source: ICIMOD (2010) and ESA (2015) for land use/cover and Dijkshoorn and Huting (2009) for soil type)

3.1 Model overview

SWAT is a process-based hydrological model capable of simulating hydrology, sediment transport, vegetation growth and management practices in complex basins with varying soils, land use/cover and management conditions (Arnold et al., 1998; Srinivasan et al., 1998). Conceptually, SWAT divides a basin into sub-basins and further into Hydrologic Response Units (HRUs). A stream channel connects the sub-basins. Each HRU represents a unique combination of a soil, land use/cover and slope type within a sub-watershed. The hydrologic cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{n} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

Where, SW_t is Final soil water content (mm); SW_0 is Initial soil water content (mm); t is Time in days; R_{day} is Amount of precipitation on day i (mm); Q_{surf} is Amount of surface runoff on day i (mm); E_a is Amount of evapotranspiration on day i (mm); w_{seep} is Amount of percolation on day i (mm); and Q_{gw} is Amount of return flow on day i (mm).

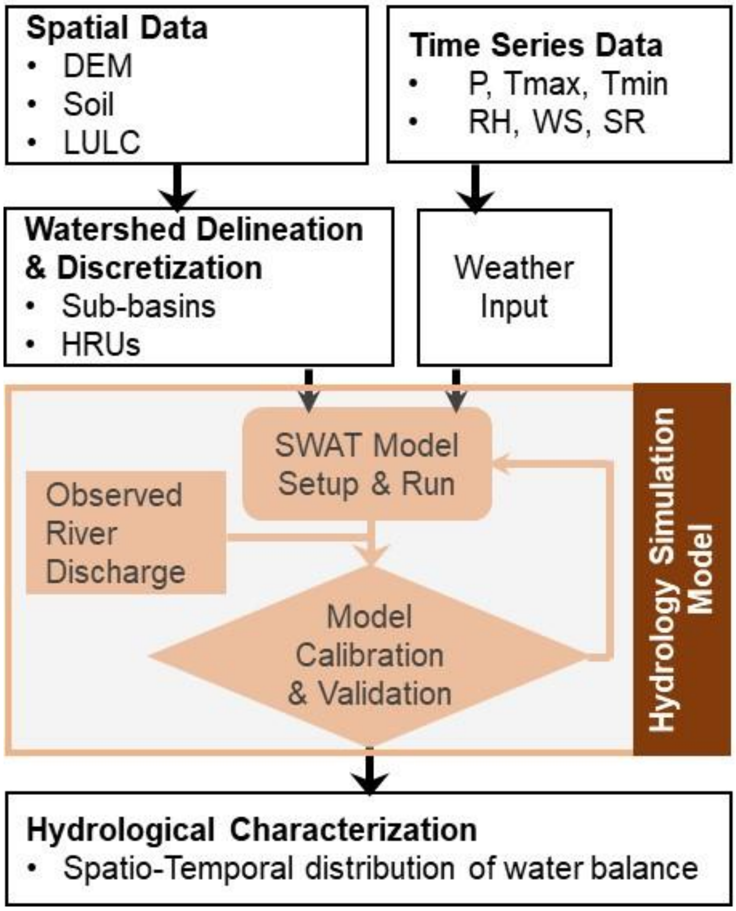


Figure 4: Methodological framework for developing and applying hydrological model for hydrological characterization of the Karnali-Mohana (KarMo) basin. DEM is Digital Elevation Model; LULC is land use/cover; HRU is hydrological response unit; P is precipitation (in mm); T is temperature (in °C); RH is relative humidity (in fraction); WS is wind speed (in m/s); and SR is solar radiation ($MJ/m^2/day$).

SWAT simulates water balance at the HRU level and then aggregates into sub-basin level. Subdivision of the basin into HRUs enables it to reflect differences in evapotranspiration for various land cover crops and soils. Runoff is predicted separately for each sub-basin and routed along the stream channel to obtain total runoff at the basin outlet. Such spatial representation increases accuracy and gives a much better physical description of the water balance. Arnold et al. (1998) and Srinivasan et al. (1998) provide descriptions of the model.

3.2 Model set-up

Spatially distributed data for topography (Fig. 1), land use/cover (Fig. 3a), and soil (Fig. 3b) were used as inputs to set-up the model. Daily time series of observed meteorological variables at various locations (Fig. 1) were taken from secondary sources as indicated in Table 1. The climatic data were then pre-processed to convert into SWAT-compatible format. Precipitation and temperature were used in the same unit as collected from DHM. In case of relative humidity, two sets of observed data per day (morning and evening) were averaged and converted into a fraction before feeding into SWAT. Daily sunshine hours were converted into solar radiation (MJ/m^2/day) using Angstrom-Prescott (AP) model (Allen et al., 1998). Daily wind speed data available in km/hr was converted into m/s before using with SWAT.

Table 1: Data type, properties and sources used in this study

Dataset [Unit]	Data Type	Data Description/ Properties	Data Source	Resolution (Time frame)
Terrain [m]	Spatial grids	Digital Elevation Model (DEM)	NASA JPL (2009)	30m x 30m grids (for 2009)
Soil [-]	Spatial vectors	Soil classification and physical properties (e.g., texture, porosity, field capacity, wilting point, saturated conductivity and soil depth)	Dijkshoorn and Huting (2009)	1:1 million map (from multiple years)
Land use/cover (LULC) [-]	Spatial grids	Landsat land use/cover classification (9 classes)	ICIMOD (2010); ESA (2015)	30m x 30m grids (for 2010)
Precipitation [mm]	Time-series and spatial grids	Daily observed precipitation	DHM; Indian Meteorological Department (IMD), and TRMM	36 DHM stations; 6 IMD stations, (1981-2013); and 36 TRMM grids (0.25° x 0.25°)
Temperature [°C]	Time-series	Daily observed minimum and maximum temperature	DHM, Nepal IMD, India	16 DHM stations and 3 IMD stations (1981-2013)
Relative humidity [-]	Time-series	Daily observed relative humidity in morning and evening	DHM, Nepal	15 stations (1981-2013)
Sunshine hours [hrs]	Time-series	Daily observed sunshine hours	DHM, Nepal	5 stations (1981-2013)
Wind speed [m/s]	Time-series	Daily observed mean wind speed	DHM, Nepal	7 stations (1981-2013)
River discharge [m^3/s]	Time-series	Daily observed streamflow	DHM, Nepal	10 stations (1981-2013)

DHM is Department of Hydrology and Meteorology, Nepal; TRMM is Tropical Rainfall Measuring Mission; NASA is National Aeronautics and space Administration (NASA); IMD is Indian Meteorological Department.

ArcSWAT2012 was used as a platform to set-up SWAT model. A threshold area of 3,000 ha was defined to generate river network. To capture spatial heterogeneity, the basin was divided into 111 sub-basins with areas ranging from 44 – 3,183 km^2 and HRU area from 100 – 1,000 km^2. Next, 2,122 HRUs were defined using land use/cover (2%), soil type (5%) and three slope classes (0 – 15%; 15-30%; and more than 30%). Ten elevation bands at an interval of 500m were defined to model snowmelt as well as orographic distribution of temperature and precipitation. Weather input was fed in the form of daily precipitation (78 stations), maximum and minimum temperatures (19 stations), relative humidity (15 stations), wind speed (7 stations) and sunshine hours (5 stations) (Annex-2; Fig. 1). SCS curve number method was used to estimate surface runoff, where daily curve number was estimated as a function of soil moisture. The Penman-Monteith method was used to estimate potential evapotranspiration (PET). Variable storage method was adopted to route channel flow. No point source discharge was defined. Eight existing irrigation projects were included as water abstraction points in the setup. Rice-Wheat-Maize cropping pattern was assigned as the representative cropping pattern in the sub-basins of Mohana.

3.3 Sensitivity analysis

Sensitivity analysis was carried out using SWAT-CUP, which combines the Latin Hypercube (LH) and one-factor-at-a-time (OAT) sampling (Van Griensven, 2005). In the OAT approach, one parameter values are changed at a time while keeping others constant. Twenty (20) model parameters (Table 2) were shortlisted for sensitivity analysis based on literature review (e.g., Bharati et al., 2014; Shrestha et al., 2016; Bajracharya et al., 2018; Dhami et al., 2019; Pandey et al., 2019) and prior experience of the modelling team. For each calibration point, sensitivity of parameters for the sub-watersheds upstream of the point is expected differ. Some parameters could be highly sensitive in some sub-watersheds, while other parameters in other sub-watersheds. Therefore, it is not possible to assign a sensitivity rank across the entire basin to the parameters.

3.4 Model calibration and validation

Multi-station and multi-variable calibration approach was adopted to better represent spatial heterogeneity in the KarMo basin. The calibration and validation was first performed at upstream stations and then gradually moved towards downstream stations. Once calibrated, sub-basins above upstream stations were locked and model parameters were not changed. The SWAT model was calibrated and validated against daily and monthly observed flows at 10 hydrological stations shown in Fig. 2 (please refer Annex-1 for details of the stations) along five major tributaries in KarMo basin. Three stations (Q215; Q250 and Q280) are in the Karnali-main river, two (Q265 and Q270) in Bheri; three (Q259.2, Q256.5 and Q260) in Seti; one (Q 220) in Tila; one (Q 283.3) in Mohana. Stations were selected to represent upstream downstream conditions in each tributary to analyse spatial variation in model performance.

The calibrated and validation periods considered are 1995-2002 and 2003-2009, respectively, for six stations (i.e., Q220, Q250, Q259.2, Q265, Q270, A280) whereas varying periods for other stations based on availability of good quality and continuous time series (Annex-2). A warm up period of three years was used to develop appropriate soil and groundwater conditions. The model was calibrated in three stages: i) Sensitivity analysis; ii) Auto-calibration; and iii) Manual calibration. After sensitivity analysis, SWAT-CUP was used for auto-calibration. The model was run for 1,000 iterations initially to narrow down the range of values for the sensitive parameters. Then auto-calibration results were further subjected to manual calibration based on knowledge of the basin.

During manual calibration, adjustments were made firstly to those parameters which were most sensitive and then moving to the less sensitive ones. Observed and simulated flows were visually compared in terms of the hydrographs (peak, time to peak, shape of the hydrograph and baseflow); scatter plots; flow duration curve; statistical parameters, and water accumulation to evaluate and improve model performance during manual calibration. Following statistical parameters were considered: mean, coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), and percent bias (PBIAS). Details of these methods are available in Nash and Sutcliffe (1970), Gupta et al. (1999), and Moriasi et al. (2007). The model performance was evaluated for both monthly and daily simulations. Due care was given to keep physically-based parameters within a reasonable range (Table 2) throughout the calibration process.

Table 2: SWAT parameters selected for multi-site model calibration of Karnali-Mohana basin

Parameter*	Definition	Unit	Process (Data file)*	Level*	Range	Initial value
ALPHA_BF	Baseflow recession constant	days	Groundwater (.gw)	HRU	0 – 1	0.048
GW_DELAY	Delay time for aquifer recharge	days	Groundwater (.gw)	HRU	0 – 500	31
GW_REVAP	Groundwater revap coefficient	-	Groundwater (.gw)	HRU	0.02 – 0.2	0.02
SHALLST	Initial depth of water in shallow aquifer	mm	Groundwater (.gw)	HRU	0 – 50000	1000
GWQMN	Threshold depth of water in shallow aquifer for groundwater return flow to occur	mm	Soil (.gw)	HRU	0 – 5000	1000
RCHRG_DP	Deep aquifer percolation fraction	-	Groundwater (.gw)	HRU	0 – 1	0.05
REVAPMN	Threshold depth of water in shallow aquifer for revap to occur	mm	Groundwater (.gw)	HRU	0 – 500	750
CANMX	Maximum canopy storage	mm	Runoff (.hru)	HRU	0 – 100	0
EPCO	Plant uptake compensation factor	-	Evaporation (.hru)	HRU	0 – 1	1
ESCO	Soil evaporation compensation factor	-	Evaporation (.hru)	HRU	0 – 1	0.95
LAT_TTIME	Lateral flow travel time	days	HRU (.hru)	HRU	0 – 180	0
SOL_AWC	Available water storage capacity of the soil layer	-	Soil (.sol)	HRU	0 – 1	Varies
SOL_K	Saturated soil conductivity	mm/hr	Soil (.sol)	HRU	0 – 2000	Varies
SOL_Z	Depth from soil surface to bottom of layer	mm	Soil (.sol)	HRU	0 – 3500	Varies
CN2	SCS runoff curve number for moisture condition II	-	Runoff (.mgt)	HRU	35 – 98	Varies
CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/hr	Channel (.rte)	Reach	0 – 500	0
CH_N2	Manning's "n" value for the main channel	-	Channel (.rte)	Reach	0 – 1	0.014

TLAPS	Temperature lapse rate	°C/km	Topographic effect (.sub)	Sub-basin	-10 – 10	-5.6
PLAPS	Precipitation lapse rate	mm/km	Topographic effect (.sub)	Sub-basin	-1000 – 1000	0
CH_N1	Manning's "n" value for the tributary channel	-	Runoff (.sub)	Sub-basin	0.01-30	0.014

For detailed explanation of the parameters, please refer to Arnold et al. (2012).

3.5 Data and sources

Both geo-spatial and time-series data reflecting biophysical, hydro-climatic and future climatic contexts are required in this study. They were collected from local and global sources as described in Table 1.

4. RESULTS AND DISCUSSION

4.1 Evaluation of SWAT model

The SWAT model is calibrated and validated at 10 hydrological stations (Fig. 2) spread across five major tributaries of the KarMo basin, namely, Karnali-main, Bheri, Seti, Tila, and Mohana. The calibrated parameter values are listed in Table 3. The number of parameters calibrated varies across the sub-basins, from 6 (in Q280) to 18 (in Q283.5), depending upon their sensitivity (Table 3). The sensitive parameters were not consistent across the sub-basins. However, baseflow recession factor (ALPHA_BF), curve number (CN2), and groundwater delay (GW_DELAY) were among the most sensitive parameters for most of the sub-basins. The level of influence of those parameters to the results, however, varied from one to another sub-basin. The model under-estimated baseflow with default SWAT parameter values. Therefore, CN2 was fine-tuned to increase infiltration and subsequent increase in groundwater contribution to the baseflow. Values of ALPHA_BF was adjusted based on visual inspection of shape of the recession limb of hydrograph. Similarly, other flow-related parameters such as soil depth (SOL_Z, available capacity of soil moisture (SOL_AWC), saturated hydraulic conductivity (SOL_K), soil evaporation compensation factor (ESCO), and lateral flow travel time (LATTIME), among others, were adjusted to match simulated and observed flows as well as reasonably approximate the water balance components. Defining elevation bands allowed for variable temperature laps rate (TLAPS) and precipitation laps rate (PLAPS) to account for spatial distribution of temperature and precipitation.

The model performance within major tributaries is discussed hereunder. At each station, a summary plot as shown in Fig. 5 was prepared to compare fit of hydrological simulation at daily and monthly scales, scattering of observed versus simulated points from the mean, model capability to reproduce flow duration curve (FDC), and model performance indicators.

4.1.1 Karnali-main stations

Three hydrological stations located in upstream, mid-stream, and downstream points of the Karnali-main are considered. At Q215 (Lalighat), upstream of Karnali-main, observed data for 1995-2004 are available so calibration and validation periods are shorter than for other stations. In Fig. 6a, it is clear that the model is not fully capturing extremes (both high and low flows). The inadequate capturing of low flows holds true for both snowmelt and non-snow melt seasons. Therefore, relatively larger size of the basin (area = 15,200 km^2) with only one hydrological station, snowmelt contribution as key source of inflow, but relatively weak snowmelt module of SWAT could be attributed as potential reasons for lower performance on capturing low-flows. Furthermore, the issue is more prominent for the years 1999-2003, whereas low flows is reproduced well for other years as evident from monthly hydrograph. It indicates that data quality can also be a potential reason for overall low performance of the model for the low flows. Similarly, for high flows too, except for few years (e.g., 1997, 1998 2000, and 2004), it is reproduced reasonably. Same reasons for low flows may hold true for low performance in high flows for selected years as well.

There is a wide-range scattering of the observed-simulation dots, indicating relatively weaker performance as well as underestimation of high flows. Nevertheless, average flow conditions are reproduced to a good extent with bias of around 16% (Fig. 6a). The NSE is 0.6 for calibration and more than 0.7 for validation period for daily simulation. The values, at over 0.8, are better for the monthly simulation.

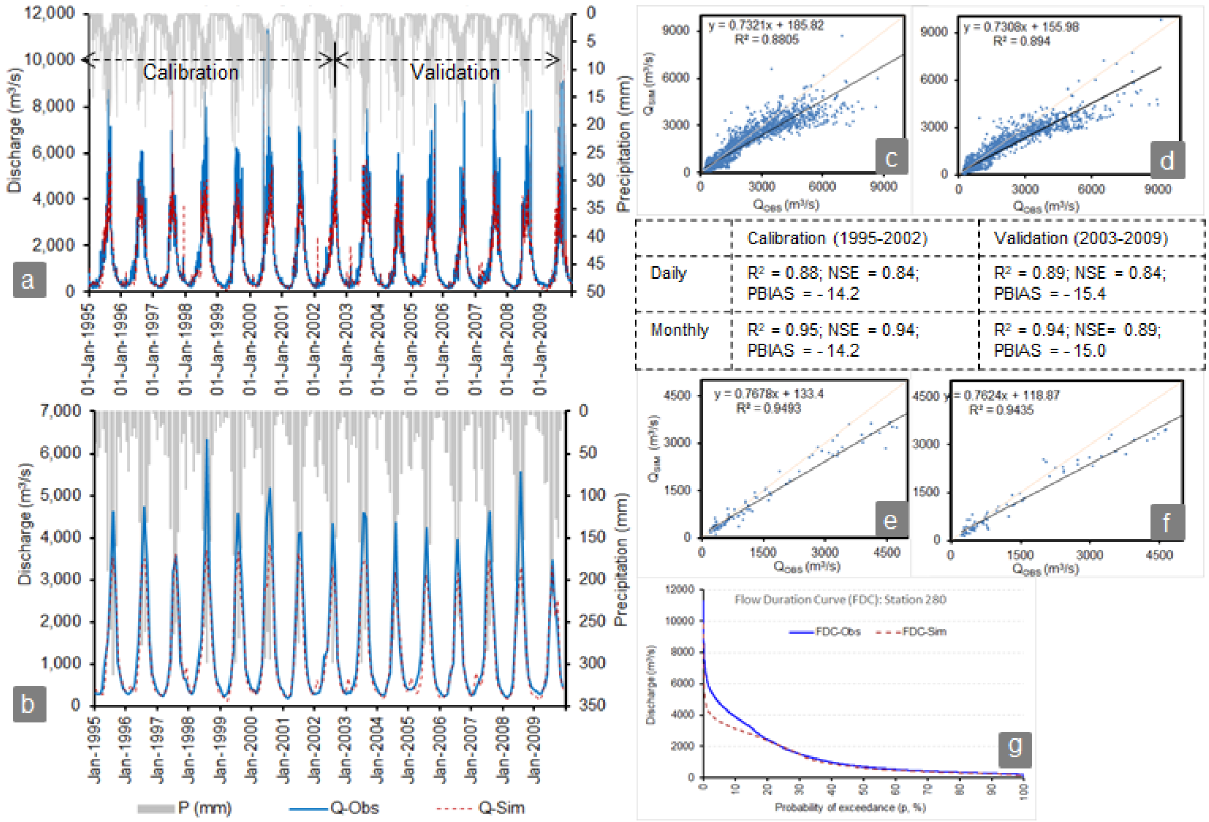


Figure 5: Model performance at Q280 (Karnali River) – a) Observed and simulated daily hydrographs; b) Observed and simulated monthly hydrographs; c & d) Scattered plots for daily flow calibration and validation; e & f) Scattered plots for monthly flow calibration and validation; and g) Flow duration curve (FDC, daily).

At the mid-stream of the Karnali-main, i.e., at Q250 (Benighat), daily observed data for the period of 1995-2009 are available. Hydrological patterns for daily and monthly flows are reasonably reproduced. R^2 for daily and monthly simulation are 0.83 and 0.91 for calibration and better for validation. NSE values are 0.75 and 0.82 for daily and monthly calibration. Scatter points lie closer to the centerline, but still reflects under-estimation for high flows. As Q250 is at downstream of Q215 in the Karnali-main, the reasons for Q215 holds true for Q250 as well. Therefore, the snowmelt as dominant source of input but relatively weaker snow module in SWAT and data quality could be attributed as potential reasons for note capturing high flows across all the years. The PBIAS for average flow simulation is around -20% for calibration and -24% for validation. Higher bias than upstream station can be expected as errors from upstream sub-basins propagate downstream.

Downstream of the Karnali-main, i.e. at Q280 (Chisapani), daily and monthly flows are simulated for the period of 1995-2009. The simulated hydrographs correspond to the precipitation pattern and reasonably reproduce hydrological regime as well as FDC (Fig. 5). The higher flows are again underestimated, most likely due to cumulative error in the upstream sub-basins. However, average flows are well reproduced with PBIAS of around 15% for both calibration and validation periods. NSE values during calibration are 0.84 for daily and 0.94 for monthly simulation and during validation are over 0.84 for both time scales. Considering all stations along the Karnali-main River, the model is better suited for application based on average flows than for evaluation of extreme events such as high and low flow periods.

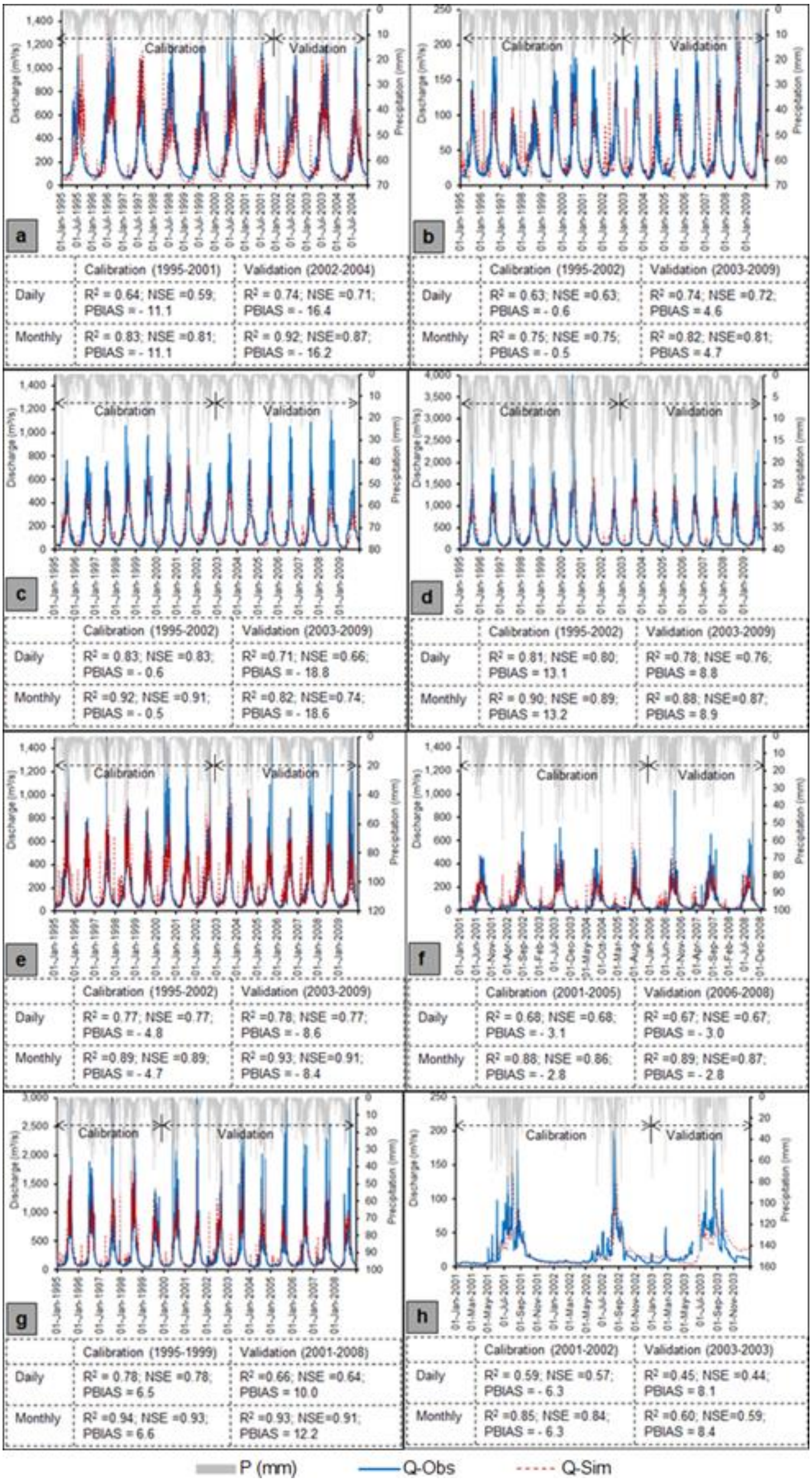


Figure 6: Simulated and daily hydrographs and performance indicators at eight hydrological stations in KarMo basin – a) Q215 (Karnali-Main), b) Q220 (Tila), c) Q265 (Thuli Bheri), d) Q270 (Bheri), e) Q259.2 (Seti Upstream), f) Q256.5 (Budhi Ganga), g) Q260 (Seti), and h) Q283.5 (Pathriya, Mohana)

4.1.2 Bheri sub-basin

Simulated hydrographs at the two stations in Bheri sub-basin, upstream at Q265 (Rimna) and downstream at Q270 (Jamu), are comparable with observed, for daily as well as monthly simulations, for the period of 1995-2009. At Q265, as shown in Fig 6c, the long-term average flow is underestimated by less than 1% for calibration and by 18.8% for validation periods. However, mostly high flows are underestimated while low flows are reasonably reproduced. The NSE for calibration and validation of daily flows are 0.83 and 0.66, respectively, with better performance for monthly simulation. The R^2 values are also over 0.8 for both calibration and validation. At Q270, as shown in Fig 6d, flow patterns, as indicated by hydrographs and FDC, as well as average flow conditions are well reproduced, with a long-term average bias of only 13% during calibration and 8.8% during validation for the daily flows. The NSE and R^2 for all cases are over 0.8 and, except daily validation period; for which, NSE and R^2 are 0.76 and 0.78, respectively. As at the stations along the Karnali-main, low and average flow are better simulated than high flows.

4.1.3 Seti sub-basin

The SWAT model in the Seti sub-basin is evaluated at three stations located in upstream at Q259.2 (Ghopa Ghat), at Q256.5 (Budhi Ganga), and downstream at Q260 (Bangna) as shown in Fig. 2. At the upstream station Q259.2, simulated hydrographs correspond well to precipitation pattern and reproduce observed daily as well as monthly flows. There is slight underestimation of long-term average flows by less than 5% during calibration and 10% during validation (Fig. 6e). The FDC is well reproduced. The NSE is 0.8 for daily and 0.9 for monthly simulations. The R^2 values are also in the same range as NSE. In case of Q256.5 (i.e., in Budhi Ganga), hydrograph patterns as well as FDC are reproduced reasonably with a slight underestimation of long-term average flows by less than 3% for daily as well as monthly simulations (Fig. 6f). The R^2 and NSE values are 0.68 for daily simulation and over 0.86 for monthly. However, there is relatively wide scattering of observed-simulated dots, thus reflecting a wider variation in simulated values. At the downstream (Q260), very close to the outlet of Seti, the simulated and observed hydrographs as well as FDCs match closely. Unlike other stations in Karnali and Seti, at Q260 simulations slightly over-estimate long-term average flows by 6.5% during calibration and around 10% during validation (Fig. 6g). The downstream HRUs generate enough runoff to compensate the flow underestimation in upstream, indicating more contribution of the downstream HRUs to the flow at the basin outlet. Land and water management practices in these downstream HRUs, therefore, can have a significant impact on water availability in the sub-basin. The evaluation at three stations suggest that the model is capable of reproducing hydrological regime and average flow conditions in the Seti.

4.1.4 Mohana sub-basin

Simulated and observed hydrographs at Q283.5 located in Pathriya, a tributary of Mohana, was made for SWAT performance in Mohana. Very limited reliable data from 2001-2003 is available at this station. Due to the seasonal flash floods in the region, hydrological stations in Mohana have been difficult to maintain and monitor for continuous long-term data as per our personal communication with DHM. As indicated by hydrograph and FDC in Fig. 6h, the flow pattern is reproduced well with long-term average flows underestimated by less than 10% for both daily and monthly simulations The NSE and R^2 for calibration are also over 0.8 for monthly simulation, even though it drops down to about 0.6 for daily flows. The scattering of simulated-observed dots is very high, which indicates, less reliability in simulated flow pattern across all the seasons even though long-term average is reproduced reasonably. However, considering potential errors in hydrological data collection in the southern rivers like Mohana, the performance can be considered as acceptable.

Table 3: Calibrated values of SWAT parameters at 10 stations in five major tributaries in the KarMo basin.

Parameter	Suggested Range	Bheri		Seti			Karnali-Main			Tila	Mohana
		Q265	Q270	Q259.2	Q256.5	Q260	Q215	Q250	Q280	Q220	Q283.5
ALPHA_BF	0 – 1	0.60	0.66	0.80	0.50	0.50	0.10	0.90	0.90	0.40	0.95
GW_DELAY	0 – 500	70	50	15	8	-	80	5	-	80	200
GW_REVAP	0.02 – 0.2	-	-	0.2	-	-	-	-	-	-	0.2
SHALLST	0 – 50000	-	-	-	-	-	-	-	-	-	500
GWQMN	0 – 5000	200	200	100	-	-	500	40	-	-	5000
RCHRG_DP	0 – 1	-	-	-	-	-	-	0.01	-	-	0.1
REVAPMN	0 – 500	-	-	50	130	261	-	-	-	-	100
CANMX	0 – 100	85	-	50	50	63	60	80	70	3	5
EPCO	0 – 1	0.1	-	-	-	-	-	-	-	-	0.1
ESCO	0 – 1	0.98	0.20	-	0.99	0.99	-	0.99	0.99	0.99	0.99
LAT_TTIME	0 – 180	80	60	60	35	40	15	100	-	70	25
SOL_AWC	0 – 1	0.4	0.4	0.4	0.3	0.5	0.5	0.4	-	0.3	-
SOL_K	0 – 2000	0.3	0.5	0.6	0.4	-	0.6	2.0	-	0.3	2.0
SOL_Z	0 – 3500	0.40	0.70	2.00	0.70	0.61	0.60	-	0.61	0.60	0.60
CN2	35 – 98	1.25	1.10	1.25	1.21	1.15	1.10	1.25	1.10	1.22	0.6
CH_K2	0 – 500	400	120	104	20	200	-	480	104	450	500
CH_N2	0 – 1	0.80	0.55	0.25	0.10	-	0.50	0.56	-	-	-
TLAPS	-10 – 10	-5.2	-	-7.1	-7.5	-7.1	-7.1	0.0	-	-2.0	-9.5
PLAPS	-1000 – 1000	-	-	200	75	-	-	500	-	-	50
CH_N1	0.01-30	-	-	-	10	-	-	-	-	-	0.6

Note: Please refer to Table 2 for the definition of parameters. Parameter values not adjusted during calibration are shown as "-". Suggested range is based on SWAT manual

4.1.5 Tila sub-basin

The model performance at Tila is evaluated at Q220 station for the simulation period of 1995-2009. The hydrograph pattern is reproduced satisfactorily with same NSE and R^2 values of 0.6 and 0.7 for daily and monthly calibrations, respectively (Fig. 6b). The long-term average flow is slightly underestimated by 0.6% during calibration. The scatter plot indicates good model fit with dots aligned along the central line. The FDC is well reproduced. Compared to other sub-basins, the calibrated SWAT model is capable of reproducing average as well as high flow conditions in the Tila.

4.2 Spatial distribution of water balance

Fig. 7 depicts sub-basin wide distribution of major water balance components (average annual P, AET and net water yield) within the KarMo basin as simulated by the model for the hydrological baseline period (1995–2009). The net water yield (NWY) refers to a combination of surface runoff, lateral flow, and groundwater flow, with deduction in transmission losses and pond abstractions (Arnold et al., 1998). The average annual P over the entire basin is 1,375 mm. Net water yield is 927 mm. The average annual AET over the entire basin is 474 mm, which is about 34% of the average annual P. It however, varies across the regions.

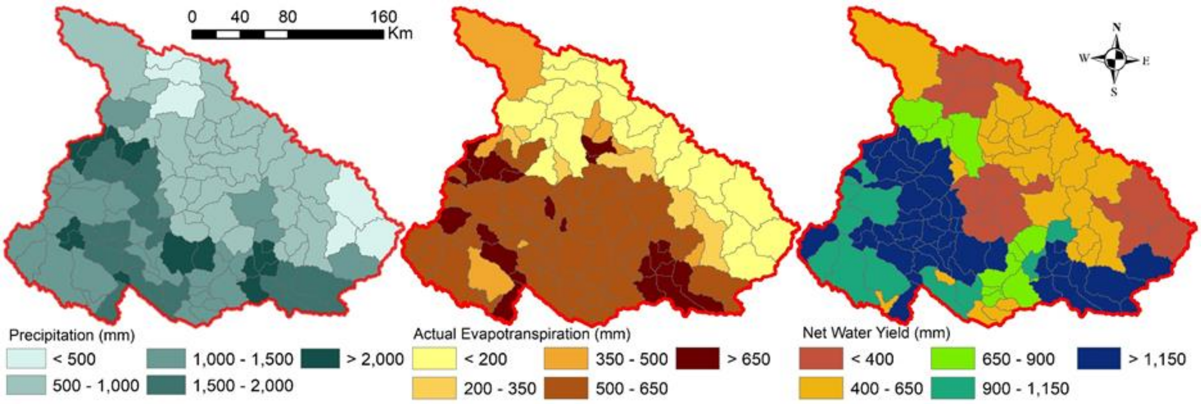


Figure 7: Spatial distribution of average annual precipitation (P), actual evapotranspiration (AET) and net water yield (NWY) across sub-basins in Karnali-Mohana basin

The water balance components vary spatially across the sub-basins, with pattern matching the geographical regions of northern Trans-Himalayas (TrH), Mountains (Mnt), Hills (Hil), and southern Tarai flatland, which is a part of Indo-Gangetic Plan (IGP). The precipitation varies from less than 500mm to above 2,000 mm across the 111 sub-basins (Fig. 7a). Fig. 8 depicts variation in the average annual precipitation, AET, and NWY in different geographical regions in the study basin. The error bars indicate the maximum-minimum range for each parameter with the specific region. The Mnt (P = 1,435 mm); Hil (P = 1,625 mm), and IGP (P = 1,566 mm) regions of the basin are relatively wetter compared to the TrH (P = 875 mm) region (Fig. 8). The values of the water balance components across the sub-basins in all the geographical regions vary widely as shown in Fig. 8.

Similarly, the average annual AET across the sub-basins varies from less than 200 mm to over 650 mm (Fig. 7b). The AET value are higher in the Hil (587 mm) and IGP (553 mm) regions, compared to other two regions (Fig. 8), owing to greater area under cultivation and proximity to the oceanfront and equator, especially in case of IGP. Furthermore, due to large forest covers and greenery in the Hil, AET is expected to be higher. The AET decreases as we move to the sub-basins from the southern plains to the northern Trans-Himalayan regions (Fig. 7b) as temperature decreases with altitude. This trend is comparable with the case of Koshi river basin in the eastern Nepal, in which too, AET increases from IGP towards the TrH region (Bharati et al., 2019). The AET in Hil, Mnt, and TrH regions are 587mm, 528 mm, and 227 mm, respectively. The AET as percentage of P in TrH, Mnt, Hil, and IGP regions are 26%, 37%, 36%, and 35%, respectively. The distribution pattern of AET also follows that of precipitation, which is the major source of moisture in the Western Nepal.

Long-term average NWY in the form of discharge at the sub-basin outlet varies across the sub-basins from 1.1 to 1,357.5 m^3/s, where sub-basin areas range from 44 to 3,183 km^2. The NWY across the KarMo sub-basins varies from less than 450 mm to above 1,150 mm (Fig. 7c). In terms of geographical regions, the long-term average NWY aggregated over the region decreases as we move upstream from Hil to TrH with values of 1,105 mm in Hil, 961 mm in Mnt, and 587 mm in TrH (Fig. 8).

In fifty (or 45%) sub-basins, NWY are more than 80% of P and in 101 (or 91%) sub-basins the NWY are more than half of P. The surface runoff has the dominant contribution in the net water yield across most of the sub-basins whereas contribution of groundwater and lateral flow varies. Two-third of the sub-basins have more than one-third contribution from surface runoff and rest from other components. In 28% of the sub-basins, contribution of surface runoff is above 50%. The groundwater contribution to the net water yield is less than one-third in 105 (or 94.6%) sub-basins and less than one-quarter in 93 (or 83.8%) sub-basins. It is to be noted that direct comparison in terms of absolute values may not provide critical insights as the sub-basin sizes vary largely from 44 to 3,183 km^2.

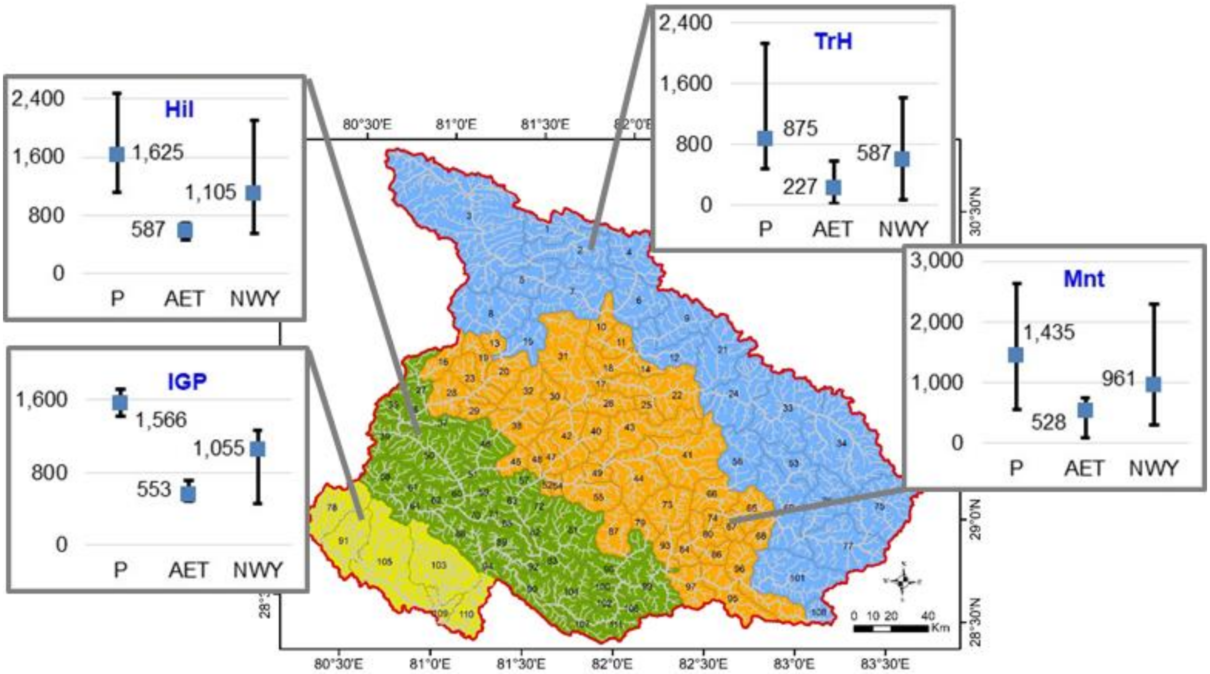


Figure 8: Spatial distribution of average annual precipitation (P), actual evapotranspiration (AET) and net water yield (NWY) across geographical regions in Karnali-Mohana basin. TiP is Tibetan Plateau; TrH is Trans-Himalaya; Mnt is Mountain; Hil is Hill; IGP is Indo-Gangetic Plain. The values displayed in the figures are means.

The sum of NWY and AET are different than P in all the regions, primarily because, NWY is not simply the difference between P and AET, but it refers to a combination of surface runoff, lateral flow, and groundwater flow, with deduction in transmission losses and pond abstractions. The net water yield does not always follow the precipitation pattern, but it gets affected by factors such as rainfall intensity, soil properties, and land use/cover characteristics. (Bharati et al., 2019). Therefore, NWY is actually higher than the difference between P and AET in the entire basin as well as some regions (e.g., Mnt, Hil, and IGP) and lower in other region (i.e., TrH), as evident in Fig. 8, due to various reasons. Such issues are evident in other studies as well, such as in the Koshi basin, Eastern Nepal (Bharati et al., 2019). In the TrH region, change in storage – the collective term including groundwater recharge, change in soil moisture storage in the vadose zone and model inaccuracies – is 7% (positive) of the precipitation (rainfall and snowmelt). Ideally, the change in storage in the entire basin as well as regions are supposed to be near to zero, for a long-term average. The positive value of change in storage may reflect that not all the precipitation ina year in the TrH region is contributing to streamflow; part of that may have been lost in the form of infiltration through steep hills covered with snows, which may re-emerge as lateral flow in the downstream in the basin, and major part of the remaining precipitation could have been stored in the TrH region itself in the form of snow accumulation. Similarly, in Mnt and Hil regions, change in storage are around 4% (negative) of the precipitation, reflecting that NWY is higher than the difference between P and AET. It is likely that the NWY in the Mnt and Hil regions gets contribution from snowmelt and lateral flow emerging from the percolation of precipitation in the TrH region. When moving further downward in the IGP, the southern plain of the basin, the change in storage is still negative but with only 2.7%. In this region, potential contributors to the excess NWY (to P-AET) could be lateral flow as well as fluctuation in groundwater table. As IGP is a part of large groundwater aquifer shared by both India and Nepal, and extends beyond the hydrological boundary, both inflow as well as outflow of groundwater from/to the basin is possible depending upon situation. Finally, average change in storage of the entire basin is 1.9% (negative). The deficit of precipitation in the basin to contribute to NWY might have been compensated from fluctuation in groundwater table, inflow of groundwater from other part of the aquifer extending beyond the KarMo basin boundary, and snowmelt contribution in the upstream of the basin. Though the model results are reasonable at the basin, major sub-basins, as well as a regional scales and useful for planning purpose, model accuracy-related and data-related limitations are certainly embedded in the simulation results. Therefore, results for the small sub-basins located far from the calibration points should be used cautiously because of possible low confidence in results due to calibration and validation of the model at limited number of stations.

4.3 Temporal distribution of water balance

The monthly average water balance for the baseline period shows a large temporal variation (Fig. 9). The precipitation (P) is taken as a sum of rainfall and snowmelt. P is taken as observed value while snowmelt, which accounts of 11% of total precipitation, is the model simulated value. Mean seasonal distribution of P in KarMo varies from 68 mm in the post-monsoon (ON) season to 1,098 mm in the monsoon (JJAS). AET is related to P, land use/cover as well as temperature. Mean seasonal distribution of AET in the basin varies from 23 mm in the winter (DJF) season to 290 mm in the monsoon season. And NYW too varies across the season from 72 mm in the winter to 654 mm in the monsoon season. The NWY does not always follow the P patterns because it is also affected by precipitation intensity, soil properties, subsurface storage and land use/cover. For example, rain falling with high intensity on bare and compacted soils will produce higher runoff than longer precipitation events on deep soils and cropped areas (Bharati et al., 2014). The results still show that the monsoon is the main hydrological driver as all the water balance components (i.e. P, AET and NWY) are highest during the monsoon.

The monsoon season (JJAS) contribution is 73%, 61%, and 71% in the average annual P, AET, and NWY, respectively at the KarMo outlet (Fig. 9), which is comparable to values obtained by Bookhagen and Burbanks (2010). As per the results from SWAT simulation, average annual flow volume at the basin outlet under the current climatic scenarios is 46,250 million-cubic-meters (MCM); 71% of which is available during JJAS. The monsoon season contribution varies across the sub-basins, from 63% at the outlet of Q220 to 68% at Q215, 71% at Q270, and 73% at Q260 (please refer Fig. 2 for the locations).

The 'Δ storage' is negative in the monsoon (JJAS) season with the absolute value of 17 mm indicating recharge to aquifer (or add to the storage) and positive in the post-monsoon until December, and then becomes negative from January onwards albeit with minimal values. The highest positive value of 91 mm in the post-monsoon (ON) season indicates groundwater contribution to streamflow, which might have appeared as a result of recharge during the monsoon season (JJAS) and discharge of that recharge water in the post-monsoon. Similarly, minimal negative values from January onwards can be explained as the result of winter precipitation.

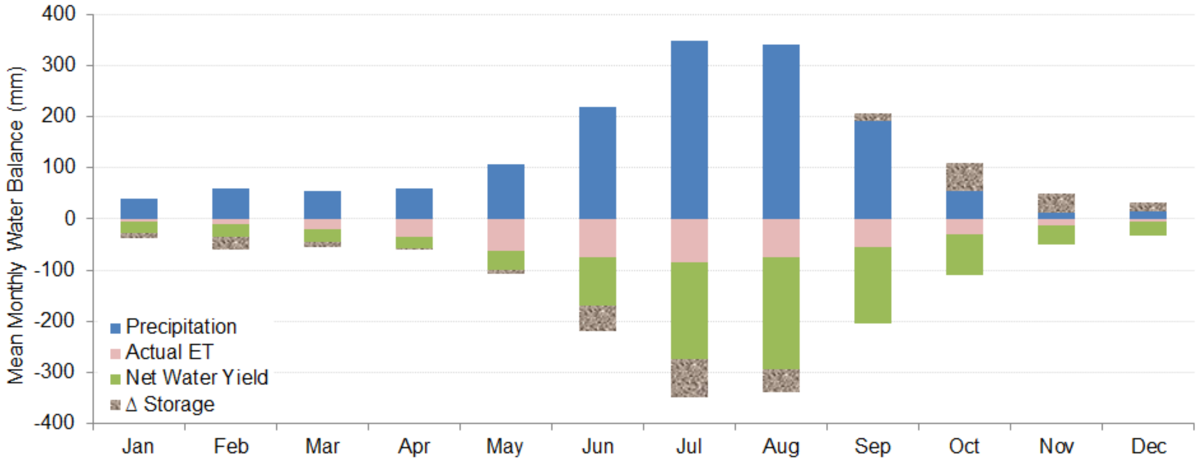


Figure 9: Mean monthly simulated (1995-2009) water balance in KarMo basin. The 'Δ storage' is a collective term including groundwater recharge, change in soil moisture storage in the vadose zone and model inaccuracies. Negative (-ve) value of 'Δ storage' indicates recharge to the aquifer and vice-versa.

5. CONCLUSIONS

This study discretized the Karnali-Mohana (KarMo) basin in Western Nepal into 111 sub-basins and developed a hydrological model in SWAT using multi-site calibration approach to characterize spatio-temporal distribution in water availability. The model was reasonably calibrated and validated using visual inspection of hydrological pattern as well as statistical indicators for average flows and biases. The annual average precipitation (P) of the KarMo basin is estimated as 1,375 mm and actual evapotranspiration (AET) is 34% (approximately) of the P, but with a large spatio-temporal heterogeneity. The P across the sub-basins vary from less than 500 mm to above 2,000 mm. The Mountain, Hill, and Tarai (a part of Indo-Gangetic Plain) regions are relatively wetter compared to the trans-Himalayan and Tibetan Plateau regions. The AET on the other hand varies from less than 200 mm to over 650 mm, which decreases as we move to the sub-basins from southern plains to the northern Trans-Himalayan regions. And average annual flow volume at the basin outlet under the baseline scenario is 46,250 million-cubic-meters (MCM), and the discharge at the sub-basin outlets vary from 1.1 to 1,357.5 m^3/s. Majority of P in most of the sub-basins flow out as river discharge (or net water yield, NWY). The surface runoff has the dominant contribution in NWY across most of the sub-basins whereas contribution of groundwater and later flow varies. In terms of seasons, P varies from 68 mm (post-monsoon) to 1,098 mm (monsoon), AET from 23 mm (winter) to 290 mm (monsoon), and NWY from 72 mm (winter) to 654 mm (monsoon). The monsoon season (JJAS) contribution is 73%, 61%, and 71% in the average annual P, AET, and NWY, respectively at the KarMo outlet.

These model results are adopted for developing national irrigation master plans, estimating environmental flows, and evaluating trade-offs among various future water development pathways. Furthermore, the model is used for climate change impact assessment (Part-B of this paper). The model results are therefore valuable for water resources planners and managers for developing location-specific strategies even within a single basin for sustainable utilization of water resources for the country's prosperity.

ACKNOWLEDGEMENTS: This study is made possible by the generous support of the American people through the United States Agency for International Development (USAID) under Digo Jal Bikas (DJB) project. The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government.

ABBREVIATIONS & ACRONYMS

AET:	Actual Evapotranspiration
BTOPMC:	Block-wise use of TOP Model with Muskingum Kung method
CC:	Climate change
DEM:	Digital Elevation Model
DHM:	Department of Hydrology and Meteorology, Government of Nepal
DJB:	Digo Jal Bikas
DJF:	December-January-February (Winter season)
FDC:	Flow Duration Curve
Hil:	Hill
HRU:	Hydrologic Response Unit
IGP:	Indo-Gangetic Plain
IMD:	Indian Meteorological Department
JJAS:	June-July-August-September (Monsoon season)
KarMo:	Karnali-Mohana basin
LH:	Latin-Hypercube
LULC:	Land use/cover
MAM:	March-April-May (Pre-monsoon season)
masl:	Meters above the mean sea level
MCM:	Million Cubic Meters
mm:	Milimeters
Mnt:	Mountain
MW:	Mega Watts
NASA:	National Aeronautics and Space Administration
NSE:	Nash-Sutcliffe Efficiency
NWY:	Net Water Yield
OAT:	One-factor-at-a-time
ON:	October-November (Post-monsoon season)
P:	Precipitation
PBIAS:	Percentage Bias
PET:	Potential Evapotranspiration
RH:	Relative Humidity
SR:	Solar Radiation
SWAT:	Soil and Water Assessment Tool
T:	Temperature
TiP:	Tibetan Plateau
TrH:	Trans-Himalayas
TRMM:	Tropical Rainfall Measuring Mission
USAID:	United States Agency for International Development
WS:	Wind Speed

REFERENCES

Allen R.G., Pereira L.S., Raes D., Smith M. (1998). Meteorological data – Radiation. In: Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56, Rome, Italy.

Arnold J.G., Moriasi D.N., Gassman P.W., Abbaspour K.C., White M.J., Srinivasan R., Santhi C., Harmel R.D., Van Griensven A., Van Liew M.W., Kannan N., Jha M.K. (2012). SWAT: model use, calibration, and validation*. Transactions of the American Society of Agricultural and Biological Engineers (ASABE)*, 55(4): 1491-1508.

Arnold J.G., Srinivasan P., Muttiah R.S., Williams J.R. (1998). Large area hydrologic modelling and assessment. Part I. Model development. Journal of American Water Resources Association, 34: 73–89.

Aryal, A., Shrestha, S., & Babel, M. S. (2018). Quantifying uncertainty sources in an ensemble of hydrological climate impact projections. *Theroitical and Applied Climatology*. https://doi.org/doi:10.1029/2011WR011533

Babel, M. S., Bhusal, S. P., Wahid, S. M., & Agarwal, A. (2014). Climate change and water resources in the Bagmati River Basin, Nepal. *Theoretical and Applied Climatology*, *115*(3–4), 639–654.

Bajracharya, A. R., Bajracharya, S. R., Shrestha, A. B., & Maharjan, S. B. (2018). Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal. *Science of the Total Environment*, *625*, 837–848.

Bharati L., Gurung P., Jayakody P., Smakhtin V., Bhattarai U. (2014). The projected impact of climate change on water availability and development in the Koshi Basin, Nepal. Mountain Research and Development, 34:118–130.

Bharati, L., Gurung, P., Maharjan, L., & Bhattarai, U. (2016). Past and future variability in the hydrological regime of the Koshi Basin, Nepal. *Hydrological Sciences Journal*, *61*(1), 79–93.

Bharati, L.; Bhattarai, U.; Khadka, A.; Gurung, P.; Neumann, L. E.; Penton, D. J.; Dhaubanjar, S.;Nepal, S. 2019. From the mountains to the plains: impact of climate change on water resources in the Koshi River Basin. Colombo, Sri Lanka: International Water Management Institute (IWMI). 49p. (IWMI Working Paper 187). doi: 10.5337/2019.205

Bookhagen B, Burbank DW (2010). Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. J Geophys Res 115, F03019. doi: 10.1029/2009JF001426

Devkota, L. P., & Gyawali, D. R. (2015). Impacts of climate change on hydrological regime and water resources management of the Koshi River Basin, Nepal. *Journal of Hydrology: Regional Studies*, *4*, 502–515.

Dhami B., Himanshu S.K., Pandey A., Gautam A.K. (2019). Evaluation of the SWAT model for water balance study of a mountainous snowfed river basin of Nepal. Environmental Earth Sciences, 77: 21.

Dijkshoorn J.A., Huting J.R.M. (2009). Soil and terrain (SOTER) database for Nepal. Report 2009/01, ISRIC – World Soil Information, Wageningen [Online Dataset]. Available at http://www.isric.org/isric/webdocs/docs/ISRIC_Report_2009_01.pdf (Accessed on 15th Dec 2016).

ESA (2015). Climate Change Initiative (CCI) - Land Cover Project: 300 m annual global land cover map from 2015 [Dataset], [online] Available from: http://maps.elie.ucl.ac.be/CCI/viewer/download.php (Accessed 31 August 2016), 2015.

Feldman A.D. (2000). Hydrologic Modeling System HEC-HMS, Technical Reference Manual. U.S. Army Corps of Engineers, Hydrologic Engineering Center, HEC, Davis, CA, USA.

Ghandhari, A., Alavi Moghaddam, S.M.R. (2011). Water balance principles: a review of five watersheds in Iran. J. Environ. Sci. Technol. 4 (5), 465–479.

Gupta H.V., Sorooshian S., Yapo P.O. (1999). Status of automatic calibration for hydrologic models: comparison with multilevel expert calibration. J. Hydrol. Eng., 4 (2): 135–143.

Halwatura D., Najim M.M.M. (2013). Application of the HEC-HMS model for runoff simulation in a tropical catchment. Environmental Modelling & Software, 46: 155-162.

Hasan, M.A., Pradhanang, S.M. (2017). Estimation of flow regime for a spatially varied Himalayan watershed using improved multi-site calibration of the Soil and Water Assessment Tool (SWAT) model. Environ. Earth Sci. 76 (23), 787.

ICIMOD (2010). Land Cover of Nepal 2010 [Dataset]. International Center for Integrated Mountain Development (ICIMOD): Kathmandu, Nepal. Available online at: http://rds.icimod.org/Home/DataDetail?metadataId=9224 [Accessed on 12thJanuary 2017).

IWMI (2018). Annual Report of Digo Jal Bikas (DJB) Project submitted to United States Agency for International Development (USAID). International Water Management Institute (IWMI): Kathmandu, Nepal. April, 2018.

Jeong, J., Kannan, N., Arnold, J., Glick, R., Gosselink, L., & Srinivasan, R. (2010). Development and Integration of Sub-hourly Rainfall-Runoff Modeling Capability Within a Watershed Model. *Water Resources Management*, *24*(15), 4505–4527.

Moriasi D.N., Arnold J.G., van Liew M.W., Bingner R.L., Harmel R.D., Veith T.L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 50 (3): 885–900.

NASA JPL (2009). Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (GDEM V2) [Dataset]. United States National Aeronautics and Space Administration – Jet Propulsion Laboratory (NASA JPL). doi:10.5067/ASTER/ASTGTM.002. (accessed on March 27, 2013)

Nash J.E., Sutcliffe J.V. (1970). River flow forecasting through conceptual models part I – a discussion of principles. J. Hydrol. 10 (3), 282–290.

Nkiaka E., Nawaz N.R., Lovett J.C. (2018). Effect of single and multi-site calibration techniques on hydrological l model performance, parameter estimation and predictive uncertainty: a case study in the Logone catchment, Lake Chad basin. Stoch. Environ. Res. Risk Assess., 32: 1665-1682.

Pakhtigian E.L., Jeuland M., Dhaubnjar S., Pandey V.P. (2019). Balancing intersectoral demand in basin-scale planning: The case of Nepal's western river basins. Water Resources Economics. In Press. https://doi.org/10.1016/j.wre.2019.100152

Pandey V.P., Babel M.S., Shrestha S., Kazama F. (2010). Vulnerability of freshwater resources in large and medium Nepalese river basins to environmental change. Water Science and Technology, 61(6): 1525-1534.

Pandey V.P., Dhaubanjar S., Bharati L., Thapa B.R. (2018) Climate Change and Water Availability in Western Nepal. In: Proceedings of National Seminar on Nature for Water. 28 Mar 2018. Nepal Academy of Science and Technology (NAST), Mahendranagar, Nepal. pp 8-19.

Pandey V.P., Dhaubanjar S., Bharati L., Thapa B.R. (2019). Hydrological response of Chamelia watershed in Mahakali Basin to climate change. Science of The Total Environment, 650 (Part 1): 365-383.

Shrestha S., Shrestha M., Babel M.S. (2016). Modeling the potential impacts of climate change on hydrology and water resources in the Indrawati River Basin, Nepal. Environmental Earth Sciences, 75 (4): 1-13

Srinivasan R., Ramanarayanan T.S., Arnold J.G., Bednarz S.T. (1998). Large area hydrological modeling and assessment. Part II: Model application Journal of American Water Resources Association, 34(1): 91-101

Sugawara M. (1979). Automatic calibration of the tank model. Hydrological Sciences Journal, 24 (3): 375-388.

Sunsnik J. (2010). Literature Review and comparative analysis of existing methodologies for water balance, European Commission Seventh Framework (EUFP7) Project.

Takeuchi K, Ao T Q, Ishidaira H (1999). For hydroenvironmental simulation of a large ungauged basin: introduction of block-wise use of TOPMODEL and Muskingum-Cunge method. Hydrological Science Journal, 44(4): 633–646.

Thapa B.R., Ishidaira H., Pandey V.P., Shakya N.M. (2017). A multi-model approach for analysing water balance dynamics in Kathmandu Valley, Nepal. Journal of Hydrology: Regional Studies, 9: 149: 162.

Van Griensven A. (2005). Sensitivity, auto-calibration, uncertainty and model evaluation in SWAT 2005. Unpublished report, 25

Annex 1: Description of hydrological stations used in this study

Index	Lat. (N)	Lon. E)	Elevation (masl)	S. Name	River	Drainage (km^2)	Calibration Period	Validation Period
215	29.159	81.591	590	Lalighat	Humla Karnali	15,200	1995 – 2001	2002 - 2004
220	29.107	81.680	1,935	Nagma	Tila	1,870	1995 – 2002	2003 - 2009
250	28.961	81.119	320	Benighat	Karnali	21,240	1995 – 2002	2003 - 2009
256.5	29.163	81.216	506	Chitra	Budhi Ganga	1,576	2001 – 2005	2006 – 2008
259.2	29.300	80.775	750	Ghopa Ghat	West Seti	4,420	1995 – 2002	2003 - 2009
260	28.978	81.144	328	Bangna	Seti	7,460	1995 – 1999	2001 - 2008
265	28.713	82.283	550	Rimna	Thulo Bheri	6,720	1995 – 2002	2003 - 2009
270	28.756	81.350	246	Jamu	Bheri	12,290	1995 – 2002	2003 - 2009
280	28.644	81.292	191	Chisapani	Karnali	42,890	1995 – 2002	2003 - 2009
283.5	28.504	81.054	284	Chhachharawa	Pathariya	983	2001 – 2002	2003 - 2003

Annex 2: Description of meteorological stations used in this study

Index	S. Name	Lat. (N)	Lon. (E)	Elevation (masl)	Variables	Data Availability (From - To)				
						P	T (Max, Min)	RH	WS	SH
103	Patan (West)	29.467	80.533	1,266	P, T, RH	1956-2015	1981-2015	1981-2015		
104	Dadeldhura	29.300	80.583	1,848	P, T, RH, WS, SH	1956-2015	1978-2015	1978-2015	2000-2009	1991-2009
106	Belapur Shantipur	28.683	80.350	159	P	1971-2014				
201	Pipalkot	29.617	80.867	1,456	P	1956-2015				
202	Chainpur (West)	29.550	81.217	1,304	P, T, RH	1956-2013	1980-2013	1980-2013		
203	Silagadhi, Doti	29.267	80.983	1,360	P, T, RH	1956-2015	1987-2015	1987-2015		
206	Asara Ghat	28.950	81.450	650	P	1963-2014				
207	Tikapur	28.533	81.117	140	P, T, RH	1976-2014	1976-2014	1976-2014		
208	Sandepani	28.750	80.917	195	P	1962-2009				

209	Dhangadhi Airport	28.800	80.550	187	P, T, RH, WS, SH	1956-2015	1975-2015	1976-2015	2000-2015	1993-2012
215	Godavari (West)	28.867	80.633	288	P, T, RH	1975-2014	1975-2014	1976-2014		
218	Dipayal, Doti	29.252	80.946	617	P, T, RH, WS, SH	1982-2015	1982-2015	1982-2015	2000-2015	1999-2012
302	Thirpu	29.317	81.767	1,006	P	1957-2015				
303	Jumla	29.283	82.167	2,300	P, T, RH, WS, SH	1957-2015	1970-2015	1977-2015	2000-2014	1991-2014
304	Guthi Chaur	29.283	82.317	3,080	P	1976-2015				
305	Sheri Ghat	29.133	81.600	1,210	P	1966-2015				
308	Nagma	29.200	81.900	1,905	P	1971-2015				
310	Dipal Gaon	29.267	82.217	2,310	P, T, RH	1974-2015	1985-2014	1987-2014		
401	Pusma Camp	28.883	81.250	950	P, T, RH, WS	1963-2015	1965-2015	1976-2015	2000-2008	
402	Dailekh	28.850	81.717	1,402	P, T, RH	1957-2015	1957-2015	1976-2015		
405	Chisapani	28.650	81.267	225	P, T, RH, WS	1963-2014	1965-2013	1976-2013	2000-2007	
406	Surkhet	28.600	81.617	720	P, T, RH, WS, SH	1957-2015	1973-2015	1976-2015	2000-2014	1991-2013
410	Balebudha	28.783	81.583	610	P	1965-2015				
411	Rajapur	28.433	81.100	129	P	1977-2015				
415	Bargadaha	28.433	81.350	200	P	1967-2015				
417	Rani Jaruwa Nursery	28.383	81.350	200	P, T, RH	1976-2015	1976-2015	1976-2015		
501	Rukumkot	28.600	82.633	1,560	P	1957-2015				
511	Salyan Bazar	28.383	82.167	1,457	P, T, RH	1960-2015	1957-2015	1976-2015		
513	Chaur Jhari Tar	28.633	82.200	910	P, T, RH	1975-2015	1979-2015	1987-2015		
514	Musikot, Rukumkot	28.633	82.483	2,100	P, T, RH	1973-2015	1981-2015	1981-2015		
601	Jomson	28.783	83.717	2,744	P, T, RH	1957-2015	1957-2015	1981-2015		
604	Thakmarpha	28.750	83.700	2,566	P, T, RH	1967-2015	1969-2014	1976-2014		
607	Lele	28.633	83.600	2,384	P, T, RH	1969-2015	1998-2015	1998-2015		
610	Ghami	29.050	83.883	3,465	P	1973-2013				

615	Bobang	28.400	83.100	2,273	P	1978-2015				
616	Gujra Khani	28.600	83.217	2,530	P, T, RH	1979-2015	1999-2014	1999-2014		

***Notes**: masl is "meters above mean sea level"; Index is "Station Identification Number of Department of Hydrology and Meteorology, Nepal"; Lat. Is "Latitude"; Lon. Is "Longitude"; S. is "Station"; Q is "River Discharge"; P is "Precipitation"; T is "Temperature"; RH is "Relative Humidity"; All mean five variables (i.e., P, T, RH, sunshine hours, and wind speed).*

Spatio-temporal distribution of water availability in Karnali-Mohana Basin, Western Nepal: Climate change impact assessment (Part-B)

Vishnu Prasad Pandey[1,*], Sanita Dhaubanjar[1], Luna Bharati[1] , Bhesh Raj Thapa[1]

[1]*International Water Management Institute (IWMI), Nepal Office, Lalitpur, Nepal*

**Corresponding Author: v.pandey@cgiar.org*

Abstract

Study region: Karnali-Mohana river basin, Western Nepal.

Study focus: This study aims to project future climate and assess impacts of climate change (CC) on water availability in the Karnali-Mohana (KarMo) basin. Bias-corrected future climate was projected based on ensembles of multiple models selected from a set of 19 regional circulation models (RCMs). The impacts on water availability were then assessed by forcing a well calibrated and validated hydrological model with projected future precipitation (P) and temperature (T) for various climatic scenarios.

New hydrological insights for this region: Results showed that future T is projected to increase spatio-temporally with higher rate for the mountain stations in the winter season; whereas future P has no distinct spatio-temporal trend but increase in dry season precipitation for future periods. The projected changes in P, T and evapotranspiration are expected to alter average annual flow at the outlets of the KarMo and its sub-basins, albeit with varying rate. The simulated results showed higher impacts in water availabilty at higher altitudes, thus indicating higher vulnerability of northern mountainous region to CC than the southern flatlands. Being the first ever study of such nature in the study area, these results will be useful for planning and development of climate-resilient water development projects in the region.

Keywords: *Climate Change; Karnali; Mohana; Water Resources; Western Nepal*

1. Introduction

Climate change (CC) is projected to impact availability and quality of water in future (IPCC, 2014). Climate change alters the timing and intensity of rainfall, temperature, and runoff; challenges coping capacities of existing infrastructures; and brings higher risk of drought and floods, which ultimately affects the hydrological cycle, locally and globally (Kundzewicz et al., 2009; Zhu and Ringler, 2012). The impacts will be further aggravated by demographic, economic, environmental, social, and technological activities (UN-WWAP, 2015). Understanding the extent and significance of CC-induced alterations in the hydrological cycle and subsequent water availability is of a great interest to environment and water resources managers globally (Bates et al., 2008; Honti et al., 2014). Several studies are being carried out at global, local and regional scales to understand water availability under CC (Abbaspour et al., 2009; Aryal et al., 2018; Bharati et al., 2016; Devkota and Gyawali, 2015; Pandey et al., 2019a; Shrestha et al., 2016; Trang et al., 2017). However, many local basins such as Karnali-Mohana (KarMo) in Western Nepal (Fig. 1) still lack such studies.

The KarMo basin in the region covers the area of 49,892 km^2 above Nepal-India border, of which 6.9% falls in the Tibetan Plateau, China and the rest in Western Nepal, as elaborated in Pandey et al. (2020) (Part-A of this paper). The watershed area of Mohana alone is 3,730 km^2. The Karnali river originates in the Trans-Himalayas (TrH) and flows through Mountains (Mnt), Hills (Hil), and Indo-Gangetic Plain (IGP) (Annex-1). The KarMo basin offers large fertile lands for agriculture. In addition, steep slopes, with topographical variations from 69 to 7,726 meters above mean sea level (masl), and meandering rivers further offer tremendous potential for hydropower development. Water resources development activities in the KarMo basin are expected to accelerate in future given the country’s focus on harnessing water as resource and the potential the KarMo basin has for that. Alterations in streamflow and hydrology induced by CC may affect availability of water for irrigation and hydropower production and then impacts food production, energy generation, and provincial and national economies. Therefore, understanding implications of projected change in climate on spatio-temporal distribution in water availability provides a useful knowledgebase for the policy/decision-makers to quantify different types of water security threats; design policies and programmes; and devise strategies for better allocation, utilization, and management of freshwater resources for the country's prosperity.

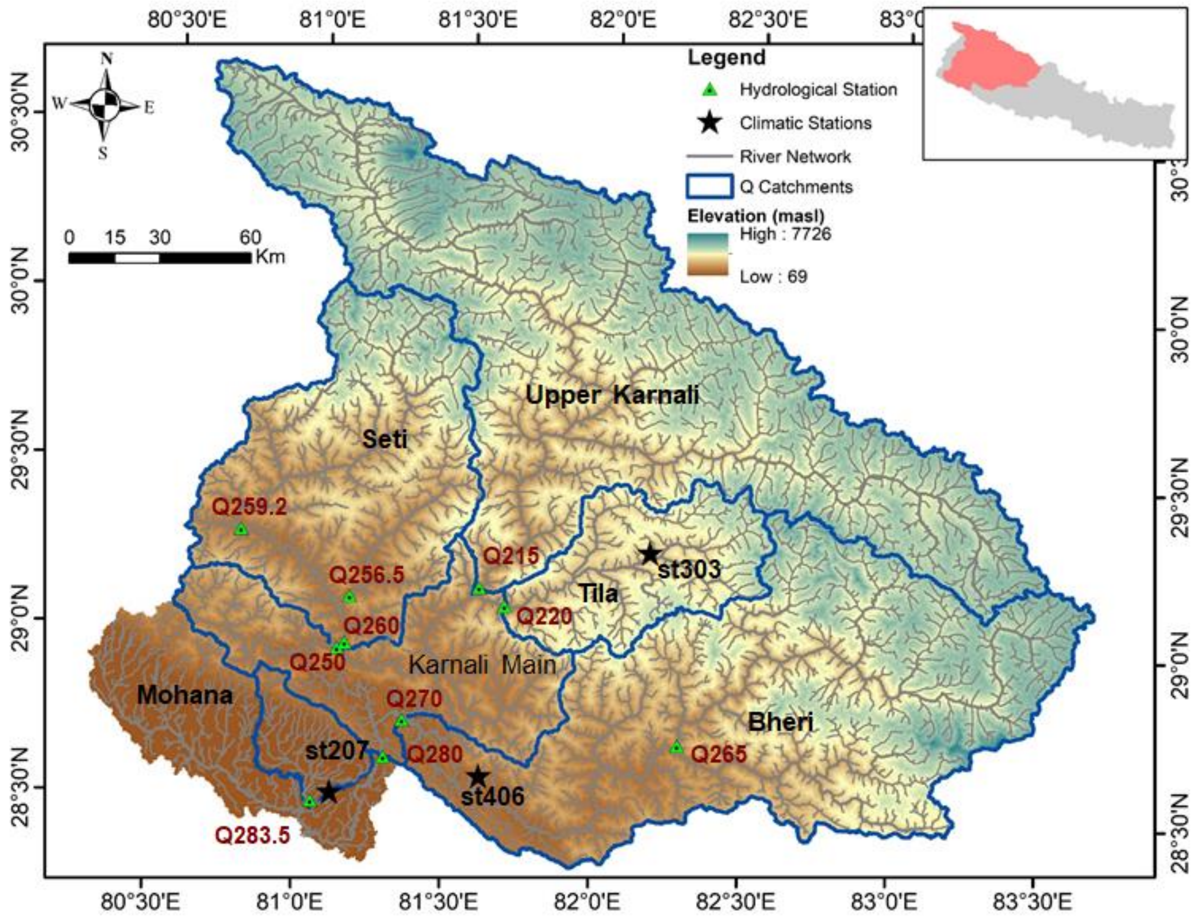


Figure 1: Location, topographic details, and hydrological stations of the Karnali-Mohana (KarMo) basin. Q-catchments are catchments above the gauging stations.

There are several studies focusing on hydrological modelling and CC impacts assessments at both local and watershed scales in Nepal (Bajracharya et al., 2018; Bharati et al., 2014; Dhami et al., 2018; Pandey et al., 2019); however none are focused in the KarMo basin. The Western Nepal is mostly susceptible to drought, flood, and climate shocks with increasing magnitude and frequency in the recent years (WECS, 2011). In addition, increase in extreme precipitation events in western mountains are observed in recent decades (Talchabhadel et al., 2018), which could impact aversely to the hydrological cycle and water availability, and then hydropower and agriculture sectors, among others.

A typical CC impact study exploring the hydrological perspective requires time series of projected meteorological variables (at minimum, precipitation and temperature) representing future climate and a well calibrated and validated hydrological model. Future climate projections can be obtained from global circulation models (GCMs) and regional circulation models (RCMs). For local-scale basins such as KarMo, projections from RCMs are considered better than that from GCMs. However, RCM projections are not free of biases due to coarse spatial resolution, and therefore need bias-correction before using for local scale CC impact assessments (Maraun, 2014; Teutschbein and Seibert, 2010). Statistical techniques such as empirical quantile mapping (QM) (Maraun, 2014) are used for correcting the biases (Berg et al., 2012; Shrestha et al., 2017; Pandey et al., 2019a). Additionally, to reduce uncertainties in the projections, bias-corrected RCM outputs are combined into ensembles representing various climate models as described in Dhaubanjar et al. (2018). Ensemble time series are fed to hydrological model for CC impact assessment (Aryal et al., 2018; Tuetschbein and Seibert, 2012).

Climate change impacts on hydrology and water resources availability are generally assessed by forcing a well calibrated and validated hydrological model with bias-corrected RCM outputs under different future scenarios (Bastola et al., 2011). A well calibrated and validated hydrological model in Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) is already developed for the KarMo basin by Pandey et al. (2020). This study therefore uses that model to assess CC impacts on spatio-temporal distribution in water availability in the basin under current and future conditions for the most recent representative concentration pathways (RCP) scenarios from multiple RCMs. During the process, it also characterizes future climate in the study basin using multi-RCM approach.

2. Methodology and Data

This study adopts a model-based approach to assess impacts of projected future climate on spatio-temporal distribution of water availability in the KarMo basin. Fig. 2 depicts a flowchart of adopted methodology and following sub-sections describes them in detail. Future climate were projected using multiple RCMs. Current and future water availabilities were assessed using a hydrological model developed in SWAT.

2.1 Hydrological model

We used the SWAT (Arnold et al., 1998) hydrological model developed by Pandey et al. (2020) (Part-A of this paper) by discretizing the KarMo basin into 111 sub-basins and 2,122 Hydrologic Response Units (HRUs). The model was calibrated and validated at 10 hydrological stations along five tributaries of the KarMo (Fig. 1).

2.2 Future climate projection

Nineteen RCMs available in COordinated Regional Downscaling EXperiment for South Asia (CORDEX-SA) platform were evaluated as discussed in Dhaubanjar et al. (2019). The study first compared the annual projections for the northern Mountains, mid Hills and southern Terai regions in Western Nepal from the 19 RCMs using the Australian Climate Futures Framework (Clarke et al., 2011; Whetton et al., 2012). For each region, projected changes in annual temperature and precipitation were classified into qualitative categories of changes to generate a *climate future matrix*. Three future periods were investigated: near-future (NF; 2021-2045), mid-future (MF; 2046-2070), and far-future (FF; 2071-2095). Considering two RCPs (RCP 4.5 and 8.5) and three future periods, six climate future matrices were developed representing six climate scenarios in each region. From the 18 matrices (6 scenarios x 3 regions = 18 matrices), the RCMs that represent the consensus case (i.e., the matrix category that majority of the RCMs project) were identified and selected.

The future climate data at the meteorological stations were then bias-corrected using quantile mapping (QM) method (Gudmundsson et al., 2012; Teutchbein and Seibert, 2012), implemented in R using a qmap package (Gudmundsson et al., 2012). QM corrects quantiles of RCM data to match with that of observed ones by creating suitable transfer functions. The bias corrected times series from the selected RCMs for each station were averaged to create a multi-model averaged ensemble for each climate scenario. The projected future CC and associated impacts were analysed based on those ensembles.

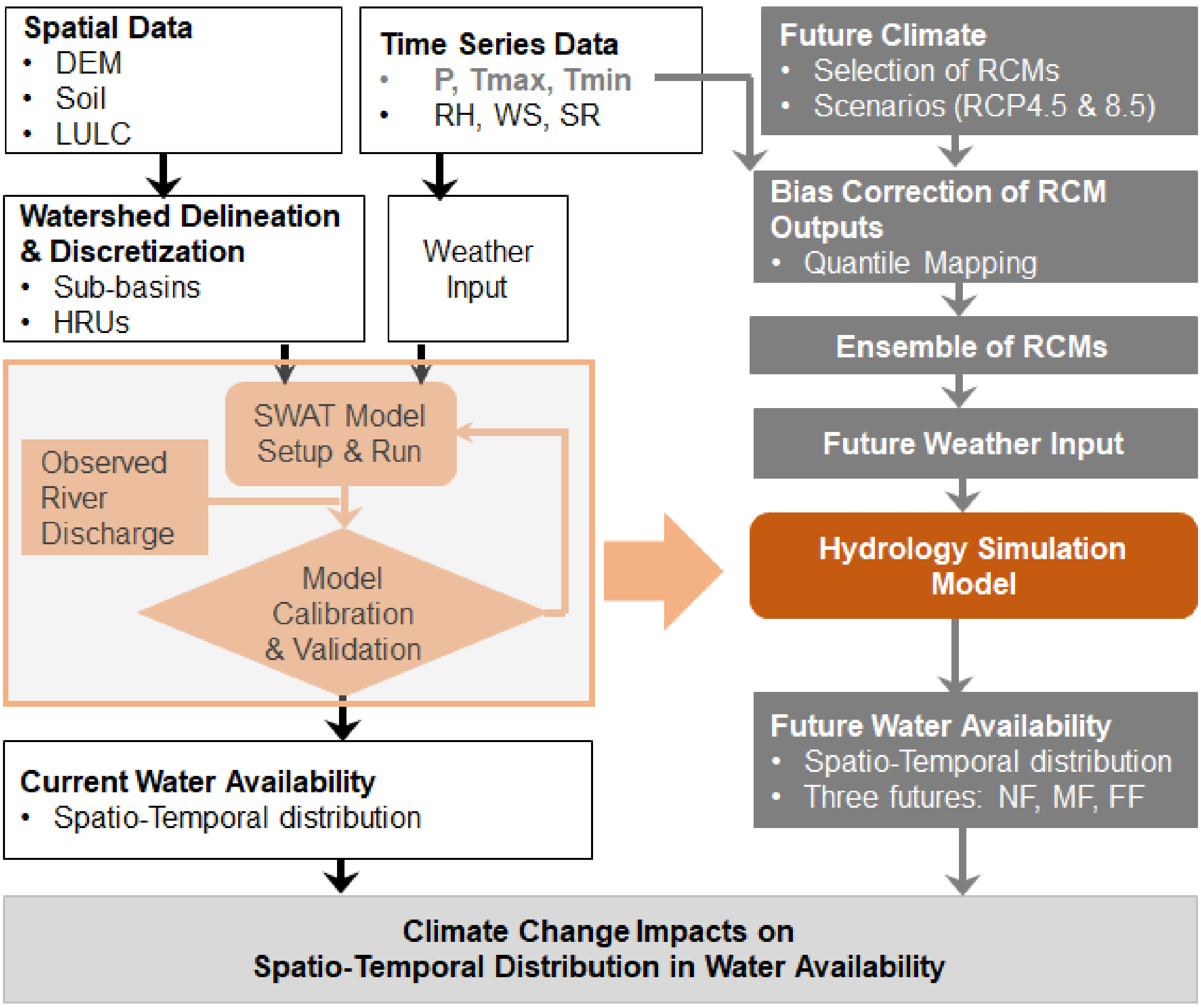


Figure 2: Methodological framework for assessing climate change impacts on water availability in the Karnali-Mohana (KarMo) basin using a SWAT model. NF, MF, and FF refer to Near-, Mid-, and Far-Futures, respectively; DEM is Digital Elevation Model, LULC is land use/cover; HRU is hydrological response unit.

2.3 Climate change impacts assessment

Bias-corrected precipitation and temperature ensemble projections for six climate scenarios (2 RCPs and three future periods) at the meteorological stations were fed into the calibrated and validated SWAT model developed by Pandey et al. (2020). The simulated streamflows were then characterized in terms of average annual and seasonal values for the three future periods. The deviation of streamflow (annual and seasonal) with respect to baseline (1980-2005) were considered as impact of projected CC on water availability. Similarly, impact of CC in other water balance components such as precipitation and actual evapotranspiration were also assessed as deviation of future values with respect to baseline, using similar approach as used for streamflows. The spatial distribution of change in key water balance components compared to baseline in each sub-basin were explored through spatial maps.

2.4 Data and sources

The data used in hydrological modelling are reported in Pandey et al. (2019b). Daily precipitation data at 36 stations, temperature data at 16 stations, relative humidity data at 15 stations, sunshine hours data at 5 stations, and wind speed data at 7 stations were collected from the Department of Hydrology and Meteorology (DHM), the Government of Nepal. Future time series of precipitation (mm) and temperature (°C) data projected by 19 RCMs were extracted from spatial grids of 0.44° x 0.44° (1981 – 2100) as detailed in Dhaubanjar et a. (2019).

3. Projected Future Climate

Given the large size of the KarMo, one certainly expects spatial heterogeneity in the projected future climate. To reflect that, future climate at three representative stations spread across the three physiological regions are analysed. The stations are st303 (region = Mountain; elevation = 2,300 masl; sub-basin = Tila); st406 (region = Hill; elevation= 720 masl; sub-basin = Thuli Bheri); and st207 (region = Terai in IGB; elevation= 140 masl; sub-basin = Mohana). The station locations are shown in Fig. 1. All changes are reported with respective to average of 1980-2005, as the climatic baseline. The spatio-temporal distribution in the projected precipitation and temperature across the three stations are provided in Fig. 3 and Fig. 4, respectively and their ranges are tabulated in Annex-2 and Annex-3.

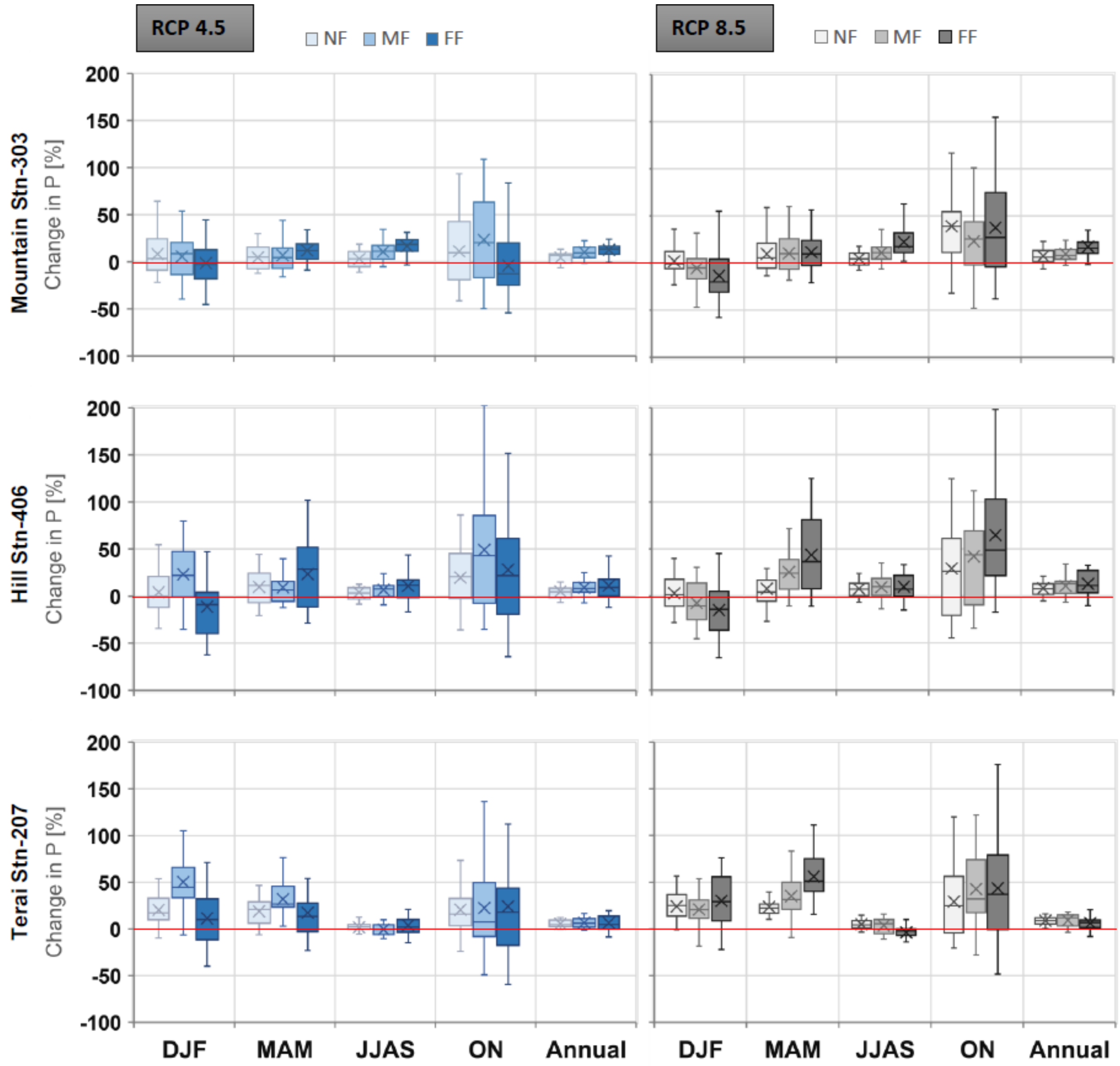


Figure 3: Spatio-temporal distribution in projected change in precipitation. NF, MF and FF refer to Near-, Mid-, and Far-Futures, respectively. Each box represents range in each season, whiskers indicate max and min values excluding the outliers, '-' marker indicate median, and 'x' marker indicate mean; DJF, MAM, JJAS and ON refer to winter, pre-monsoon, rainy; and post-monsoon seasons, respectively.

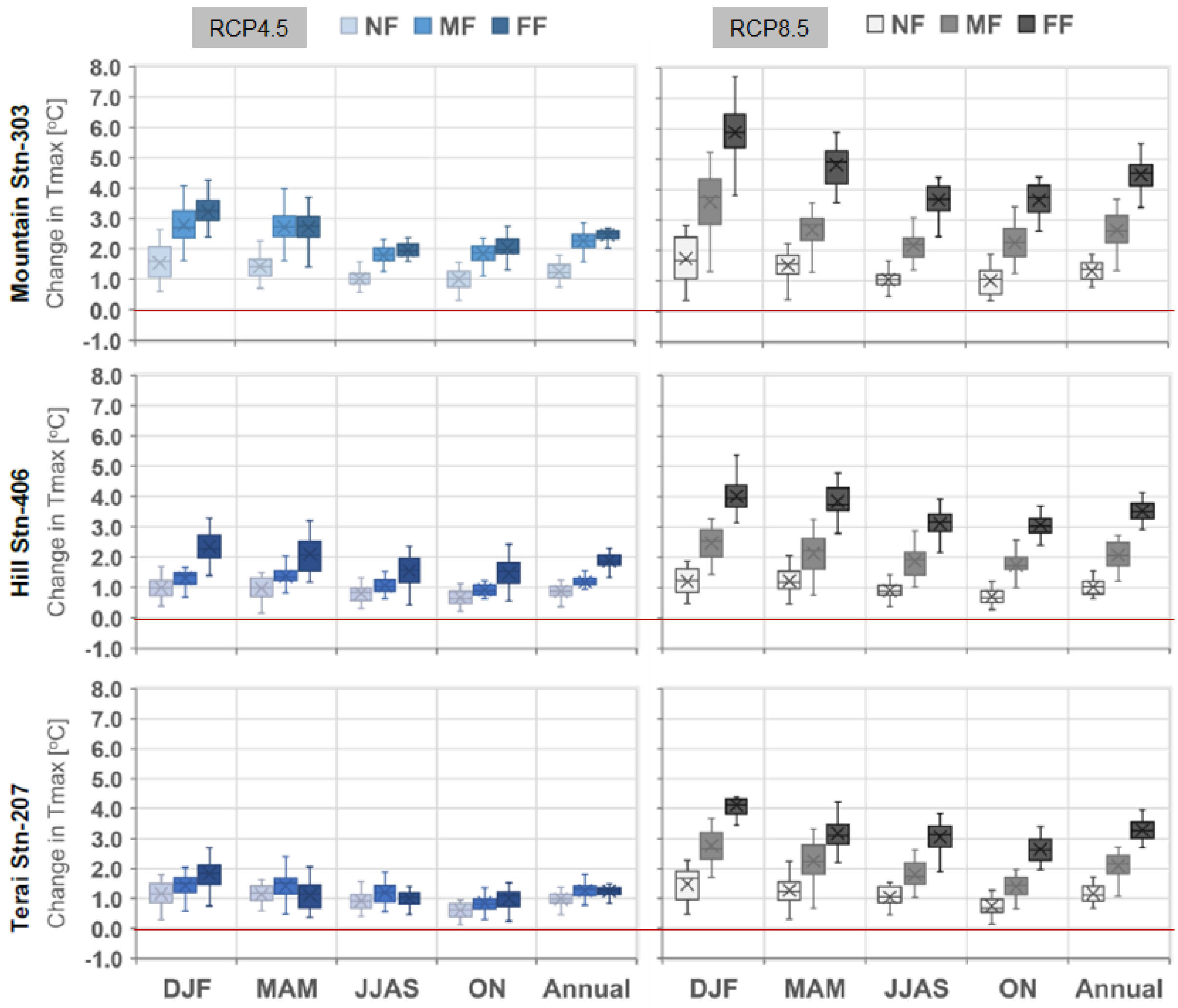


Figure 4: Spatio-temporal distribution in projected change in maximum temperature. NF, MF and FF refer to Near-, Mid-, and Far-Futures, respectively. Each box represents range in each season, whiskers indicate max and min values excluding the outliers, '-' marker indicate median, and 'x' marker indicate mean

At a ***mountain*** station-303, average annual precipitation (P) for RCP4.5 (RCP8.5) scenarios are projected to increase by 4% (7%), 10% (10%) and 13% (17%) in NF, MF, and FF, respectively; however, with variation in rate of change across the seasons (Fig. 3). The rate of change in P varies across the seasons with the highest amount of increase as well as range of projection for ON season for all the future periods and climate scenarios considered, thus, indicating wetter future. In terms of temperature, average annual maximum temperature (Tmax) for RCP4.5 (RCP8.5) scenarios are projected to increase by 1.3°C (1.3°C) in NF, 2.3°C (2.7°C) in MF, and 2.5°C (4.5°C) in FF (Fig. 4). A higher increase is projected for DJF and MAM seasons, which in DJF is 1.6°C (1.7°C) in NF, 2.8°C (3.6°C) in MF and 3.2°C (5.9°C) in FF under RCP4.5 (RCP8.5) scenarios (Fig. 4). The average annual minimum temperature (Tmin) under RCP4.5 (RCP8.5) scenarios as reported in Dhaubanjar et al. (2019), on the other hand, is projected to increase by 1.0°C (1.1°C) in NF, 1.7°C (2.3°C) in MF, and 1.8°C (3.9°C) in FF albeit with higher increase in MAM and ON seasons.

At a ***hill*** station-406, average annual P under RCP4.5 (RCP8.5) scenarios are projected to increase by 5% (8%), 9% (11%), and 11% (13%) in NF, MF, and FF, respectively, with projection ranges as shown in Fig. 3. With higher increase projected for MAM and ON seasons, there exists seasonality in amount and ranges of change in P. In terms of temperature, average annual Tmax under RCP4.5 is projected to increase by 0.9°C, 1.2°C, and 1.9°C in NF, MF, and FF, respectively (Fig. 4). For both the scenarios (RCP4.5 and 8.5), higher increase in Tmax is projected for DJF and MAM seasons, reflecting warmer winters in future. The average annual Tmin, as discussed in Dhaubanjar et al. (2019), is also projected to increase by 1.8°C, 2.7°C, and 3.9°C during NF, MF, and FF, respectively, under RCP4.5 with changes varying across the seasons.

In case of a ***Tarai*** station-207, the P for RCP4.5 (RCP8.5) scenarios are projected to increase by 5% (9%) in NF, 7% (9%) in MF and 6% (6%) in FF (Fig. 3). There is no distinct trend towards the future. In terms of seasons, P is projected to increase in all the seasons, however, with more increase for ON and MAM than others seasons for both the scenarios and all the future considered. Average annual Tmax for RCP4.5 (RCP8.5) scenarios are projected to increase by 1.0°C (1.2°C) in NF, 1.3°C (2.1°C) in MF, and 1.2°C (3.3°C) in FF (Fig. 4). All the seasons project increase in Tmax, however, higher amount of increase is projected for DJF and MAM seasons. In case of Tmin, annual averages under RCP4.5 (RCP8.5) scenarios are projected to increase by 1.2°C (1.5°C) in NF, 1.7°C (2.8°C) in MF, and 1.8°C (4.4°C) in FF. The MAM and ON seasons are projected to have higher increase in Tmin compared to other seasons as well as annual averages.

Across the three stations, the projection ranges for annual as well as seasonal changes in precipitation and maximum temperature are increasing in general – though not consistent for all the stations, seasons, and scenarios – when we move farther into the future years. It indicates increase in uncertainty in the projection when moved farther in the future. The annual projections for temperature and precipitation seen here are comparable to the ranges reported in Lutz et al. (2016), Sanjay et al. (2017) and Choudhary and Dimri (2018) for the greater Hindu Kush Himalayas. However, seasonal ranges not reported explicitly in most of the studies vary, especially for precipitation. Local orographic effects affect seasonal changes in climate more than annual averages. Variation across the Mountain, Hill and Tarai in Fig. 3 and Fig. 4 are likely due to heterogeneity in local conditions and microclimates. Furthermore, given the larger size of the basin, global warming phenomenon might also have contributed to change sin both precipitation and temperature in the entire basin.

4. Climate Change Impacts on Water Availability

Projected future temperature and rainfall time series based on an ensemble of the selected RCMs for six consensus scenarios were used as input to the calibrated and validated SWAT model to simulate the CC impacts on future water balance components. Changes in water balance components over the sub-basins as well as months/season were analyzed to understand spatio-temporal distribution of the changes under projected future climates. Since observed data of different water balance components are not available for the basin, output from the SWAT model was used as the baseline to compare with future scenarios.

The sub-basin wide distribution in the change of water balance components, namely, precipitation (P), actual evapotranspiration (AET), and net water yield, for two RCPs (4.5 and 8.5) and three future periods (NF, MF, and FF) are shown in the Figs. 5-6. As seen in the plots for station-406 (Figs. 3-4), average annual P is projected to increase gradually from NF to FF. The rate of projected change, however, varies widely across the sub-basins extending beyond +/- 25% (Fig. 5). Change in P as well as temperature (T) has altered AET from baseline value by varying rates across the sub-basins as shown in Fig. 6. The sub-basin wide AET varies from less than -15% to above 50% under the six future scenarios considered. The change in AET is more pronounced at the sub-basins in higher and middle elevations than at the lower elevations, potentially due to higher rate of increase in T in these regions. Similar results are reported for the Koshi basin in Nepal as well (Bharati et al., 2014).

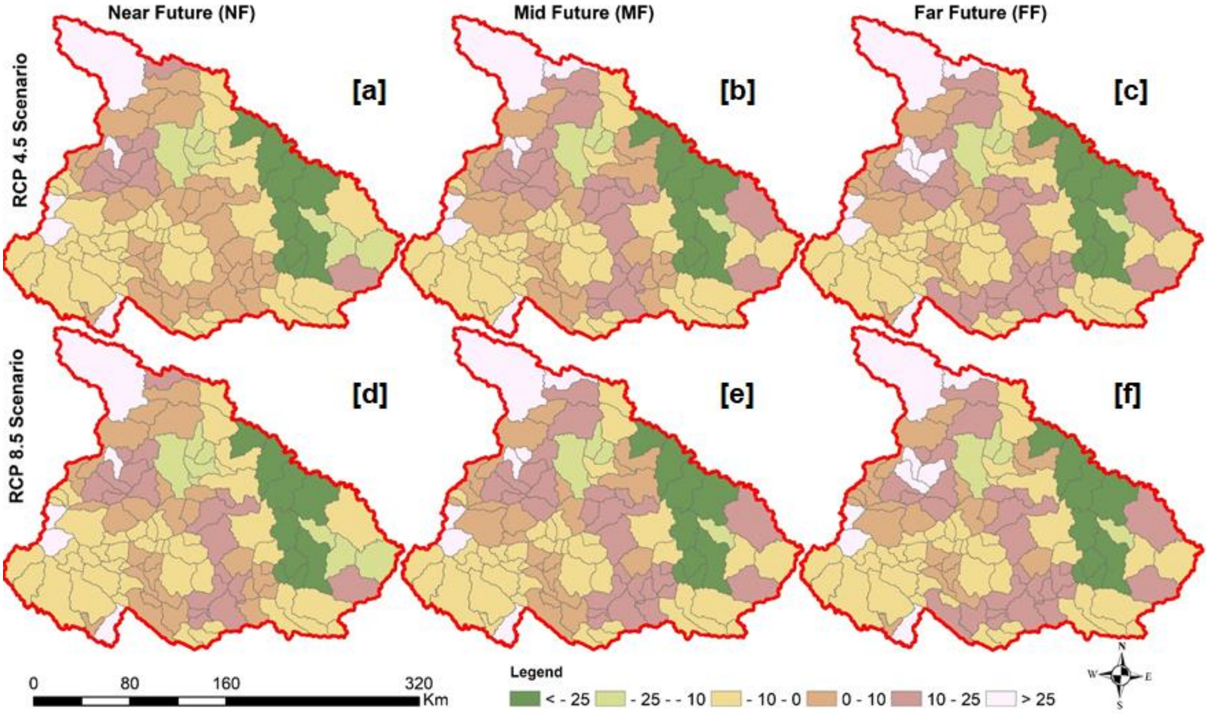


Figure 5: Change (%) in average annual precipitation with respect to the baseline

The percentages of sub-basins that show increase and decrease in P, AET, and Q are reported in Table 1. For example, the percentages of sub-basins that show increase (decrease) in P by more than 10% under RCP4.5 are 10% (15%) in NF, 26% (12%) in MF, and 32% (12%) in FF, under bot the RCP scenarios (Table 1). Similarly, the percentages of the sub-basins that show increase(decrease) in AET by more than 10% under the RCP4.5 scenarios are 51% (3%) in NF, 51% (3%) in MF, and 51% (4%) in FF. Similar results for RCP8.5 are reported in Table 1.

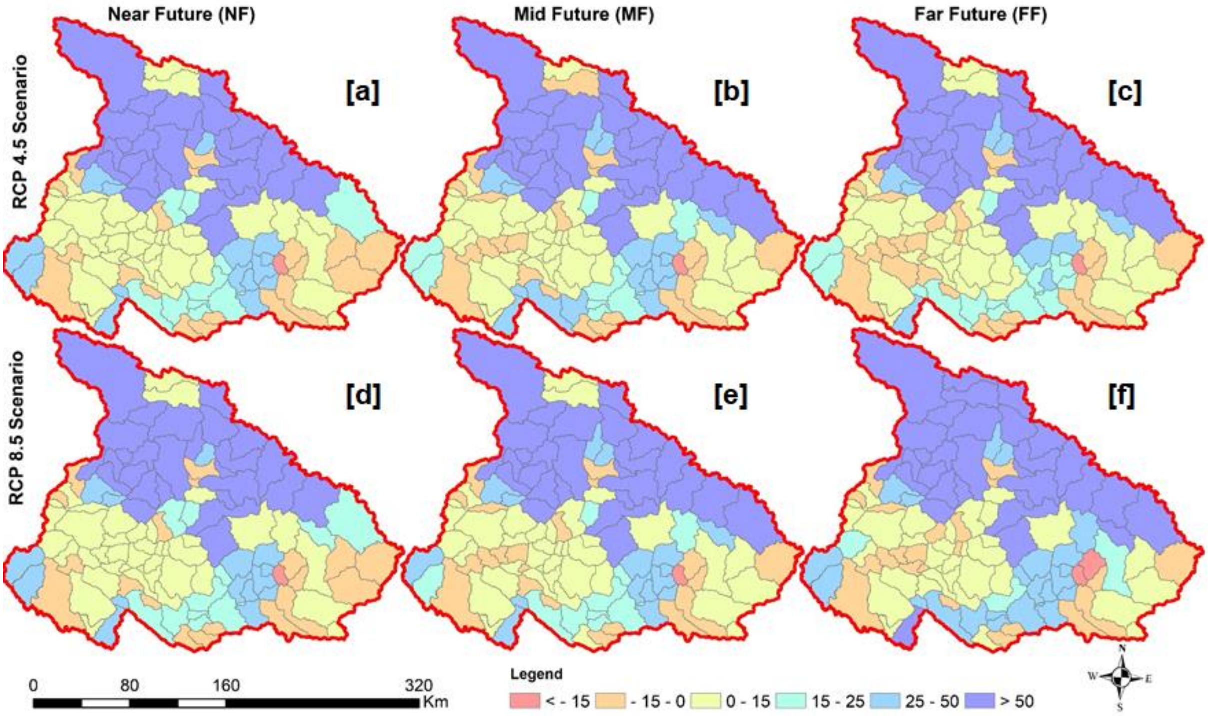


Figure 6: Change (%) in average annual actual evapotranspiration with respect to the baseline

As a result of changes in P and AET, average annual flow at outlets of the KarMo sub-basins are projected to alter as shown in Fig. 7. In comparison to temperature and precipitation, other input variables such as radiation, relative humidity, and wind speed have a less significant effect on water yield (Stonefelt et al., 2000). The Fig. 7 shows variation in projected changes in average annual flows under RCP4.5 and 8.5 scenarios for the three future periods considered (i.e., NF, MF, and FF). The spatial variation in the change in average annual flow also follows similar pattern as future P, however, the variations across the sub-basins fluctuate a lot. The impacts in the sub-basins at higher altitudes are relatively higher perhaps due to melting of snow/glaciers as a result in change in T. This indicates that high mountain regions are more vulnerable to CC than the flatlands in the lower part of the basin. For example, under RCP4.5 scenarios, the regional average net water yield in NF for IGP, Hil, Mnt, Mnt and TrH are projected to change by 8.3%, -0.2%, -2.8% and -5.6%, respectively.

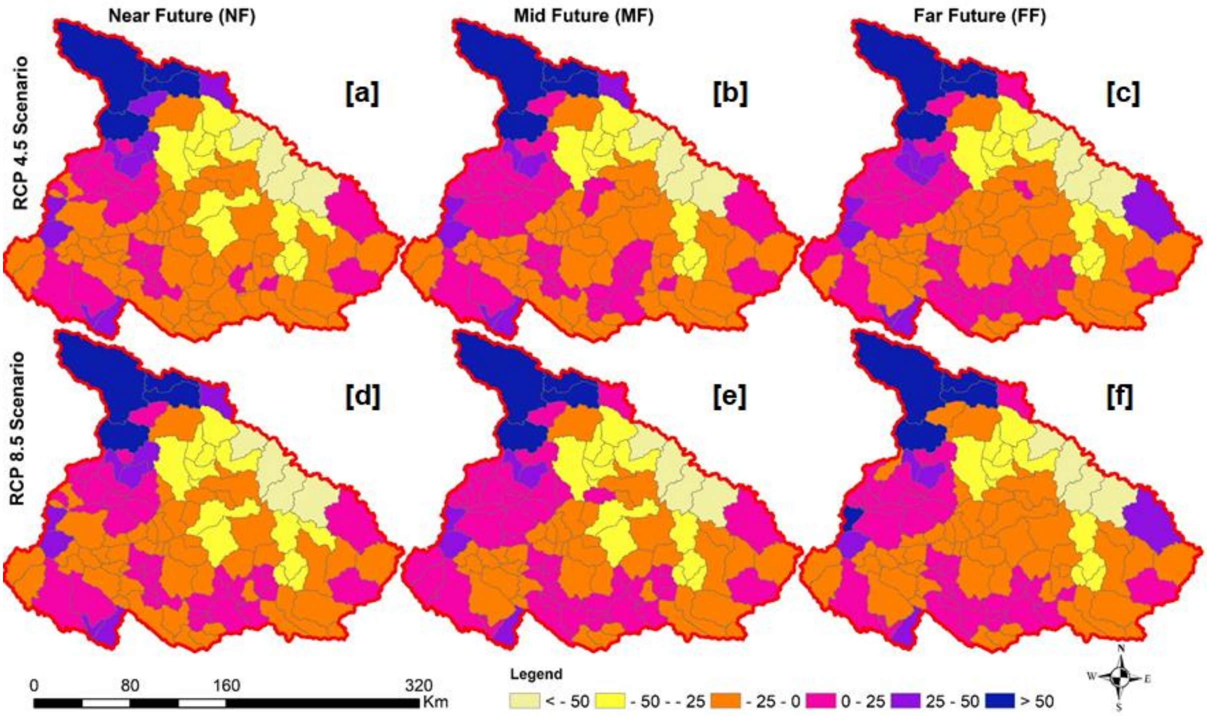


Figure 7: Change (%) in average annual flows with respect to the baseline.

Table 1: Percentage (%) of the sub-basins experiencing various levels of changes under two future scenarios and three futures considered

Description	RCP4.5			RCP8.5		
	NF	MF	FF	NF	MF	FF
Increase in P by > 1%	44	50	43	44	50	43
Increase in P by > 10%	10	26	32	19	31	32
Decrease in P by > 1%	49	46	47	49	44	47
Decrease in P by > 10%	15	12	12	15	12	12
Increase in AET by > 1%	74	74	71	73	72	72
Increase in AET by > 10%	51	51	51	51	53	53
Decrease in AET by > 1%	17	15	18	17	12	17
Decrease in AET by > 10%	3	3	4	3	3	4
Increase in Q by > 1%	31	39	42	39	44	36

Increase in Q by > 10%	14	18	23	19	21	20
Decrease in Q by > 1%	61	55	50	56	51	56
Decrease in Q by > 10%	28	23	23	27	22	34

The range of alteration of projected average annual flow as well as variation across the months at the outlets of Karnali-main and its key tributaries are tabulated in Table 2, the changes with respect to baseline are shown in Fig. 8, and discussed hereunder.

Bheri river basin: The Bheri river basin above the Q270 hydrological station has a catchment area of 12,290 km^2. The average annual flow volume at Q270 for the baseline period is estimated at 11,383 MCM, which under RCP4.5 scenarios are projected to decrease in NF by -5.4% and then increase in MF by 3%. Under RCP8.5 scenarios, it is projected to decrease by -2.5% and -1.3% for NF and MF, respectively. However, intra-annual variations of the projected changes vary across the scenarios and future periods considered. Projected changes under both the scenarios vary from -30.5% (May) to 11.7% (January) in NF, -28.5% (May) to 26.2% (January) in MF, and -28.5% (May) to 13.4% (January) in FF. While moving towards farter in the future, the flow volume in the Bheri river is projected to decrease during pre-monsoon and monsoon seasons but increase in post-monsoon and winter seasons (January, November and December). The decrease during pre-monsoon and monsoon seasons are linked both to overall decrease in precipitation (though there are mixed trends, both increase and decrease, for different sub-basins of Bheri) (Fig. 5) and increase in AET as we move farther in the future, as evident from Fig. 6. However, projected increase in river flows during post-monsoon and winter seasons are likely due to contribution from the melting of snows and ice that are covering the headwaters of the Bheri river basin (please refer Pandey et al. (2020), Part-A of this Paper, for the land use/cover map). At least a quarter of the watershed area of Thuli Bheri (above Q265, please refer Fig. 1 for location) is covered with permanent snow and ice. Furthermore, percolation of monsoon season precipitation to aquifers and appearing that into the river in the form of baseflow could also have contributed to increase in the river flows in the post-monsoon and winter seasons.

Seti river basin: The Seti river basin above Q260 hydrological station covers an area of 7,460 km^2. The average annual flow volume at Q260 for the baseline period is estimated at 8,944 MCM, which under RCP4.5 scenarios is projected to increase from 13.9% in NF to 16.1% in FF. In case of RCP8.5 scenarios, it is projected to increase from 14.5% in NF to 16.0% in MF. The rate of increase, however, is not consistent across the months, scenarios, and future periods considered. The projected changes in monthly flow volumes under both the scenarios vary from 4.5% (July) to 57.3% (January) in NF, 1.3% (September) to 82.4% (April) in MF, and 1.5% (June) to 46.0 % (January) in FF. The flow volumes in the Seti river is projected to increase across all the months, albeit with varying rates; higher increase in winter, pre-monsoon and post-monsoon seasons and lower during the monsoon season. The increase in flow volume in the Seti river outlet is likely due to increase in precipitation in the basin (Fig. 5) and varying rates across the seasons are due to varying amount of precipitation and actual evapotranspiration. Therefore, future water infrastructure projects such as hydropower and irrigation have potential to get benefited from more water availability during dry seasons.

Table 2: Projected change [%] in river flow at the outlets of key tributaries of Karnali river

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Q270 [Bheri Outlet]	Baseline (m^3/s)	110.4	97.5	92.8	106.1	146.8	279.4	804.9	1209.1	769.8	370.0	198.3	146.5	361.0
	RCP4.5-NF	10.0	-6.1	-10.7	-19.1	-30.0	-26.3	-9.6	-4.1	0.4	-0.8	5.4	4.5	-5.4
	RCP4.5-MF	26.2	0.3	-6.2	-4.5	-11.0	1.5	1.2	0.4	1.3	4.8	18.4	16.9	3.0
	RCP4.5-FF	13.4	-5.6	-11.2	-16.9	-28.5	-12.5	-3.1	2.2	3.0	0.5	8.8	7.4	-0.7
	RCP8.5-NF	11.7	-3.9	-9.6	-18.4	-30.5	-25.7	-5.0	-0.3	3.3	1.2	7.9	6.7	-2.5
	RCP8.5-MF	13.5	-4.1	-10.0	-17.2	-28.5	-21.5	-4.2	0.0	4.8	2.6	9.8	7.6	-1.3
	RCP8.5-FF	11.3	-8.1	-16.4	-19.3	-28.5	-18.9	-3.6	-2.4	2.5	-0.7	6.0	5.6	-3.1
Q260 [Seti Outlet]	Baseline (m^3/s)	79.3	76.6	77.7	89.6	122.4	260.9	724.5	871.5	634.8	249.4	121.1	95.4	283.6
	RCP4.5-NF	57.3	28.9	32.5	40.5	28.2	7.9	4.5	12.0	4.8	18.2	29.2	35.6	13.9
	RCP4.5-MF	42.9	19.4	32.4	82.4	33.0	19.9	8.1	10.0	1.3	7.2	7.1	28.0	13.8
	RCP4.5-FF	46.0	16.7	27.2	29.8	20.5	5.7	10.8	18.1	9.6	22.2	29.8	30.3	16.1
	RCP8.5-NF	53.9	29.5	32.3	40.1	27.7	6.3	5.1	12.1	6.8	21.1	31.7	36.3	14.5
	RCP8.5-MF	41.4	20.6	29.5	33.2	22.3	8.9	9.3	17.7	7.5	23.7	30.1	30.6	16.0
	RCP8.5-FF	39.5	11.2	19.6	15.1	7.8	1.5	9.1	17.1	9.8	20.7	24.3	24.7	13.2
Q215 [Upper Karnal]	Baseline (m^3/s)	83.5	74.7	80.0	124.9	284.6	445.5	662.9	750.8	460.4	221.1	133.4	100.0	285.2
	RCP4.5-NF	20.5	12.8	21.6	43.6	-16.3	-31.2	-7.0	-8.3	-9.4	-3.0	-2.8	9.9	-7.3
	RCP4.5-MF	37.0	15.1	48.8	72.0	-6.0	-24.5	2.3	2.4	-7.7	0.4	9.5	58.2	2.3
	RCP4.5-FF	27.7	14.8	34.3	45.0	-12.1	-23.7	0.4	0.0	-10.3	0.6	8.9	47.0	-1.0
	RCP8.5-NF	19.9	13.7	23.6	40.8	-16.6	-30.2	-6.7	-8.2	-9.5	-2.7	-2.4	10.1	-7.2
	RCP8.5-MF	27.9	17.6	41.1	48.3	-12.3	-26.8	1.8	1.6	-9.2	-2.2	6.3	59.1	-0.3
	RCP8.5-FF	26.5	17.4	51.2	27.2	-22.9	-33.8	-3.7	-3.2	-13.8	-4.3	3.7	45.7	-5.8
Q220 [Tila	Baseline (m^3/s)	18.0	15.2	14.7	18.5	27.1	40.9	85.7	126.0	98.2	60.1	32.1	23.0	46.6
	RCP4.5-NF	-12.9	-22.9	-25.5	-25.0	-25.8	-35.1	-14.9	-17.9	-19.2	-28.1	-24.3	-24.8	-21.6

	RCP4.5-MF	24.2	6.3	30.8	33.6	21.0	-5.9	7.2	-13.3	-13.5	-3.4	-2.2	-14.8	-1.2
	RCP4.5-FF	-7.7	-24.8	-19.8	-22.1	-20.9	-32.1	-0.7	-5.6	-12.2	-20.7	-15.0	-18.1	-13.4
	RCP8.5-NF	-11.2	-20.2	-24.0	-20.1	-22.6	-34.3	-11.7	-16.6	-18.0	-25.5	-20.7	-22.5	-19.5
	RCP8.5-MF	-12.2	-21.6	-20.6	-20.7	-22.3	-31.5	-3.9	-14.0	-15.7	-24.5	-20.9	-21.0	-17.2
	RCP8.5-FF	-7.3	-26.2	-25.2	-26.5	-20.1	-29.6	2.9	-8.1	-11.4	-18.2	-14.4	-16.9	-13.2
Q280 [Karnali-main]	Baseline (m^3/s)	350.7	301.8	301.3	428.0	791.6	1462.8	3253.3	4551.5	2960.1	1391.4	705.4	474.0	1414.3
	RCP4.5-NF	25.2	7.8	10.0	18.3	-1.9	-12.9	-0.8	-0.1	1.5	-2.7	7.1	10.3	0.6
	RCP4.5-MF	36.1	7.8	21.5	47.3	10.8	-0.3	6.7	3.3	1.4	-1.3	13.3	19.8	6.4
	RCP4.5-FF	28.7	2.9	12.0	17.7	-2.0	-9.2	5.2	5.4	3.4	-0.1	12.2	13.5	4.2
	RCP8.5-NF	25.0	8.8	10.9	18.1	-2.2	-12.7	1.2	1.4	3.3	-1.0	9.2	11.7	1.9
	RCP8.5-MF	27.0	5.0	14.5	19.7	-1.2	-10.6	4.7	5.0	3.9	-0.1	11.5	15.2	4.2
	RCP8.5-FF	26.1	0.7	11.4	8.6	-8.6	-14.9	3.5	2.5	2.8	-1.5	8.8	11.0	1.6

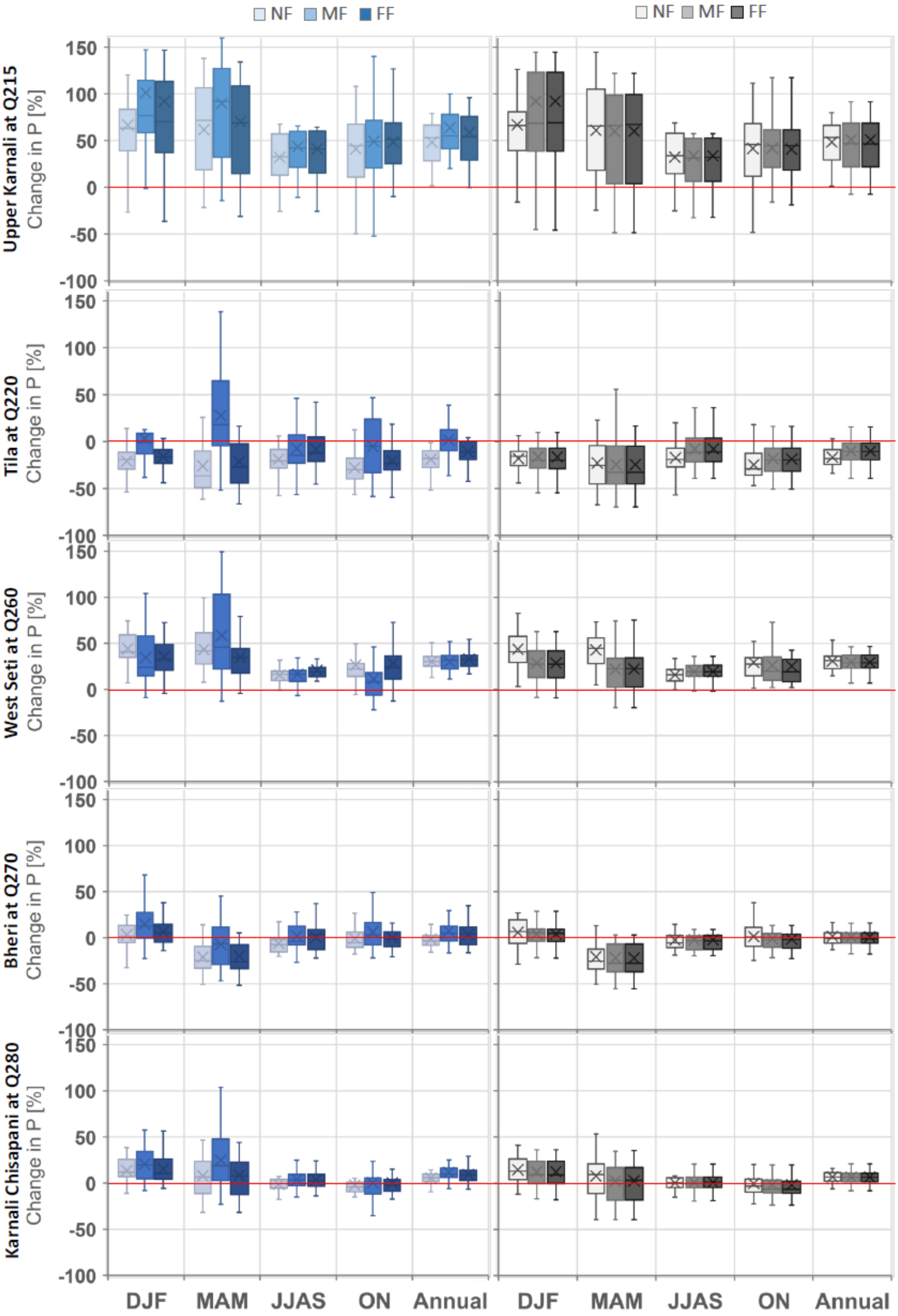


Figure 8: Temporal distribution in projected change in river discharge at outlets of the Karnali-main and its major tributaries. NF, MF and FF refer to Near-, Mid-, and Far-Futures, respectively. Each box represents range in each season, whiskers indicate max and min values excluding the outliers, '-' marker indicate median, and 'x' marker indicate mean

Upper Karnali river basin: The Upper Karnali river basin in this study refers to the area above Q215 hydrological station. It covers an area of 15,200 km^2. The average annual flow volume at Q215 is estimated at 8,993 MCM, which is projected to change by -7.3% in NF and 2.3% in MF. Under the RCP8.5 scenarios, the projected changes are -7.2% in NF and -5.8 in FF. The projected changes are not uniform throughout the months, which vary from -31.2% (June) to 43.6% (April) in NF, -26.8% (June) to 72% (April) in MF, and -33.8% (June) to 51.2% (March) in FF. The flow volumes are projected to decrease during monsoon season (JJAS) and increase during winter and pre-monsoon season; albeit with varying rates. Both decrease in precipitation and increase in AET are projected for the sub-basins in the Upper Karnali river basin (Fig. 5 and Fig. 6) thus resulting in decrease in flows during monsoon season. However, given the large area of the Upper Karnali river basin covered with permanent snow and ice, melting of snow and ice contributes to increase in river flows during pre-monsoon and winter seasons.

Tila river basin: The Tila river basin here refers to the area above Q220 hydrological station. It covers an area of 1,870 km^2. The average annual flow volume at Q220 is estimated at 1,470 MCM, which under RCP4.5 scenarios is projected to change by -21.6% in NF and -13.4% in FF. Under the RCP8.5 scenarios, it is projected to alter by -19.5% in NF, -17.2% in MF, and -13.2% in FF. The intra-annual variations across the months are -35.1% (June) to -11.2% (January) in NF, -31.5% (June) to 33.6% (April) in MF, and -32.1% (June) to 2.9% (July) in FF. Except in March and April in MF under RCP4.5, projections for all other scenarios and futures show decrease in flow volume across all the months/seasons, it is because sub-basins of Tila also shows projected decrease in precipitation (Fig. 5) and increase in actual evapotranspiration (Fig. 6).

Karnali-main river basin: The Karnali-main river basin here refers to the area above Q280 hydrological station. It covers an area of 42,890 km^2. The average annual flow volume near to the outlet of Karnali-main (before joining Mohana) [at Q280 station] for the baseline period is estimated at 44,602 MCM, which in NF and MF are projected to increase by only 0.6% and 6.4% under RCP4.5 and 9% and 4.2% under RCP8.5 scenarios, respectively. The projections, however, varies across the months for different scenarios and future periods. For example, projected changes under both the scenarios in NF vary from -12.9% (June) to 25.2% (January). When moving towards mid-future, it varies from -10.6% (June) to 47.3% (April); and in far-future it ranges from -14.9% (June) to 28.7% (January). Future flow volume is projected to decrease in June and increase winter and later stage of the monsoon season even though the average annual is projected to increase. As the KarMo is the snow-fed river basins, increase in river flows from the later stage of the monsoon to winter are potentially the contributions from melting of snow and ice.

5. Conclusions

This study applied a well calibrated and validated SWAT hydrological model to assess impacts of climate change on spatio-temporal distribution of water availability in the Karnali-Mohana (KarMo) basin located in Western Nepal. Future climate was projected based on an ensemble of selected RCMs for six consensus cases from a set of 19. The temperature (T) is projected to have an increasing trend across all regions and seasons, with highest amount of increase for the mountain stations in the winter season. The amount of increase in the projections vary across the seasons, however, no strong skewness suggests annual values can represent a seasonal change in the region. Projection in the minimum temperature also follows similar spatio-temporal trends across the stations. In case of projected precipitation, it does not have a distinct spatio-temporal trend at the seasonal or annual scale. The highest variability in total P is seen for the post-monsoon season (ON), especially for the mountains and hills, indicating wetter dry seasons for future. With both maximum T and P increasing on an average in the winter seasons, glacier and snow-melt may be expected to increase.

The impacts of projected change in climate to spatio-temporal distribution of water availability was assessed by perturbing the climatic inputs to the calibrated/validated SWAT model with projected future time-series of P and T. As a result of changes in P, T and AET, average annual flow at outlets of the KarMo sub-basins are projected to alter, however, in general, following similar patterns as P. The impacts in the sub-basins at higher altitudes are relatively higher, indicating higher vulnerability to CC of the high mountain regions of the basin than the flat lands in Tarai. For example, in NF under RCP4.5 scenarios, the annual flow volume at the outlet of Tila is projected to change by -21.6%, at upper Karnali by -7.2%, Seti by +13.9%, Bheri by -5.4%, and Karnali-main by 0.6%. It clearly reflects the spatial-heterogeneity in the impacts of projected CC on an annual scale. In addition, projected alterations also vary across the seasons. Taking the case of RCP4.5 and NF again, it alters from -35.1% (June) to -11.2% (January) in Tila, -31.2% (June) to 43.6% (April) in upper Karnali, 4.5% (July) to 57.3% (January) in Seti, -30.5% (May) to 11.7% (January) in Bheri, and -12.9% (June) to 25.2% (January) in Karnali-Main.

These findings from this study are valuable information for water resources planners and managers for developing location-specific strategies even within a single basin for sustainable utilization of water resources for the country's prosperity.

Acknowledgements: This study is made possible by the generous support of the American people through the United States Agency for International Development (USAID) under Digo Jal Bikas (DJB) projected. The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government

References

Abbaspour, K. C., Faramarzi, M., Ghasemi, S. S., & Yang, H. (2009). Assessing the impact of climate change on water resources in Iran. *Water Resources Research*, *45*(10), 1–16.

Arnold J.G., Srinivasan P., Muttiah R.S., Williams J.R. (1998). Large area hydrologic modelling and assessment. Part I. Model development. Journal of American Water Resources Association, 34: 73–89.

Aryal, A., Shrestha, S., & Babel, M. S. (2018). Quantifying uncertainty sources in an ensemble of hydrological climate impact projections. *Theroitical and Applied Climatology*. https://doi.org/doi:10.1029/2011WR011533

Babel, M. S., Bhusal, S. P., Wahid, S. M., & Agarwal, A. (2014). Climate change and water resources in the Bagmati River Basin, Nepal. *Theoretical and Applied Climatology*, *115*(3–4), 639–654.

Bajracharya, A. R., Bajracharya, S. R., Shrestha, A. B., & Maharjan, S. B. (2018). Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal. *Science of the Total Environment*, *625*, 837–848.

Bastola, S., Murphy, C., & Sweeney, J. (2011). The role of hydrological modelling uncertainties in climate change impact assessments of Irish river catchments. *Advances in Water Resources*, *34*(5), 562–576. https://doi.org/10.1016/j.advwatres.2011.01.008

Bates, B. C., Kundzewicz, Z. W., Wu, S., & Palutikof, J. P. (2008). *Climate Change and Water*. *Climate change and water*. https://doi.org/10.1016/j.jmb.2010.08.039

Berg P., Feldmann H., Panitz H.J. (2012). Bias correction of high resolution regional climate model data. J. Hydrol., 448-449: 80–92.

Bharati L., Gurung P., Jayakody P., Smakhtin V., Bhattarai U. (2014). The projected impact of climate change on water availability and development in the Koshi Basin, Nepal. Mountain Research and Development, 34:118–130.

Bharati, L., Gurung, P., Maharjan, L., & Bhattarai, U. (2016). Past and future variability in the hydrological regime of the Koshi Basin, Nepal. *Hydrological Sciences Journal*, *61*(1), 79–93.

Choudhary A., Dimri A.P. (2018). Assessment of CORDEX-South Asia experiments for monsoonal precipitation over the Himalayan region for future climate. Climate Dynamics, 50(7-8): 3009-3030.

Clarke J.M., Whetton P.H., Hennessy K.J. (2011). Providing Application-specific Climate Projections Datasets: CSIRO's Climate Futures Framework. MODSIM2011, 19th Int. Congr. Model. Simul. 2683–2687. doi:10.13140/2.1.1915.2649

Devkota, L. P., & Gyawali, D. R. (2015). Impacts of climate change on hydrological regime and water resources management of the Koshi River Basin, Nepal. *Journal of Hydrology: Regional Studies*, *4*, 502–515. https://doi.org/10.1016/j.ejrh.2015.06.023

Dhami B., Himanshu S.K., Pandey A., Gautam A.K. (2019). Evaluation of the SWAT model for water balance study of a mountainous snowfed river basin of Nepal. *Environmental Earth Sciences*, 77: 21.

Dhaubanjar S., Pandey V.P., Bharati L (2019). Climate Futures for Western Nepal based on Regional Climate Models in the CORDEX-SA. *International Journal of Climatology*. https://doi.org/10.1002/joc.6327

Gudmundsson, L., Bremnes, J. B., Haugen, J. E., & Engen-Skaugen, T. (2012). Technical Note: Downscaling RCM precipitation to the station scale using statistical transformations – A comparison of methods. *Hydrology and Earth System Sciences*, *16*(9), 3383–3390.

Honti, M., Scheidegger, A., & Stamm, C. (2014). Importance of hydrological uncertainty assessment methods in climate change impact studies. *Hydrology and Earth System Sciences Discussions*, *11*(1), 501–553. https://doi.org/10.5194/hessd-11-501-2014

IPCC. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. *Core Writing Team, R.K. Pachauri and L.A. Meyer*. https://doi.org/10.1017/CBO9781107415324.004

Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Jimenez, B., Oki, T., … Shiklomanov, I. (2009). The implications of projected climate change for freshwater resources and their management resources and their management. *Hydrological Sciences Journal*, *6667*(January), 2–10.

Lutz A.F., ter Maat H.W., Biemans H., et al. (2016). Selecting representative climate models for climate change impact studies: an advanced envelope-based selection approach. Int J Climatol 36:3988–4005. doi: 10.1002/joc.4608

Maraun, D. (2014). Bias Correction, Quantile Mapping, and Downscaling: Revisiting the Inflation Issue. *Journal of Climate*, *26*(2013), 2013–2014.

Pandey V.P., Dhaubanjar S., Bharati L., Thapa B.R. (2018) Climate Change and Water Availability in Western Nepal. In: Proceedings of National Seminar on Nature for Water. 28 Mar 2018. Nepal Academy of Science and Technology (NAST), Mahendranagar, Nepal. pp 8-19.

Pandey V.P., Dhaubanjar S., Bharati L., Thapa B.R. (2019). Hydrological response of Chamelia watershed in Mahakali Basin to climate change. *Science of The Total Environment*, 650 (Part 1): 365-383.

Pandey V.P., Dhaubanjar S., Bharati L., Thapa B.R. (2020). Spato-temporal distribution of water availability in Karnali-Mohana Basin, Western Nepal: Hydrological model development using multi-site calibration approach (Part-A). *Journal of Hydrology – Regional Studies*, Submitted.

Sanjay J., Krishnan R., Shrestha A.B., et al. (2017). Downscaled climate change projections for the Hindu Kush Himalayan region using CORDEX South Asia regional climate models. Adv Clim Chang Res 8:185–198.

Shrestha M., Acharya S.C., Shrestha P.K. (2017). Bias correction of climate models for hydrological modelling – are simple methods still useful? Meteorological Applications, 24(3): 531-539.

Shrestha, S., Shrestha, M., & Babel, M. S. (2016). Modelling the potential impacts of climate change on hydrology and water resources in the Indrawati River Basin, Nepal. *Environmental Earth Sciences*, *75*(4), 1–13. https://doi.org/10.1007/s12665-015-5150-8

Stonefelt, M.D., Fontaine T.A., Hotchkiss R.H. (2000). Impacts of climate change on water yield in the upper Wind River basin. J. Am. Water Resour. Assoc. 36 (2), 321–336.

Talchabhadel, R., Karki, R., Thapa, B. R., & Maharjan, M. (2018). Spatio-temporal variability of Extreme precipitation in nepal. *International Journal of Climatology*.

Teutschbein C., Seibert J. (2012). Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. J. Hydrol, 456-457: 12–29.

Teutschbein, C., & Seibert, J. (2010). Regional Climate Models for Hydrological Impact Studies at the Catchment Scale: A Review of Recent Modeling Strategies: Regional climate models for hydrological impact studies. *Geography Compass*, *7*, 834–860.

Trang, N. T. T., Shrestha, S., Shrestha, M., Datta, A., & Kawasaki, A. (2017). Evaluating the impacts of climate and land-use change on the hydrology and nutrient yield in a

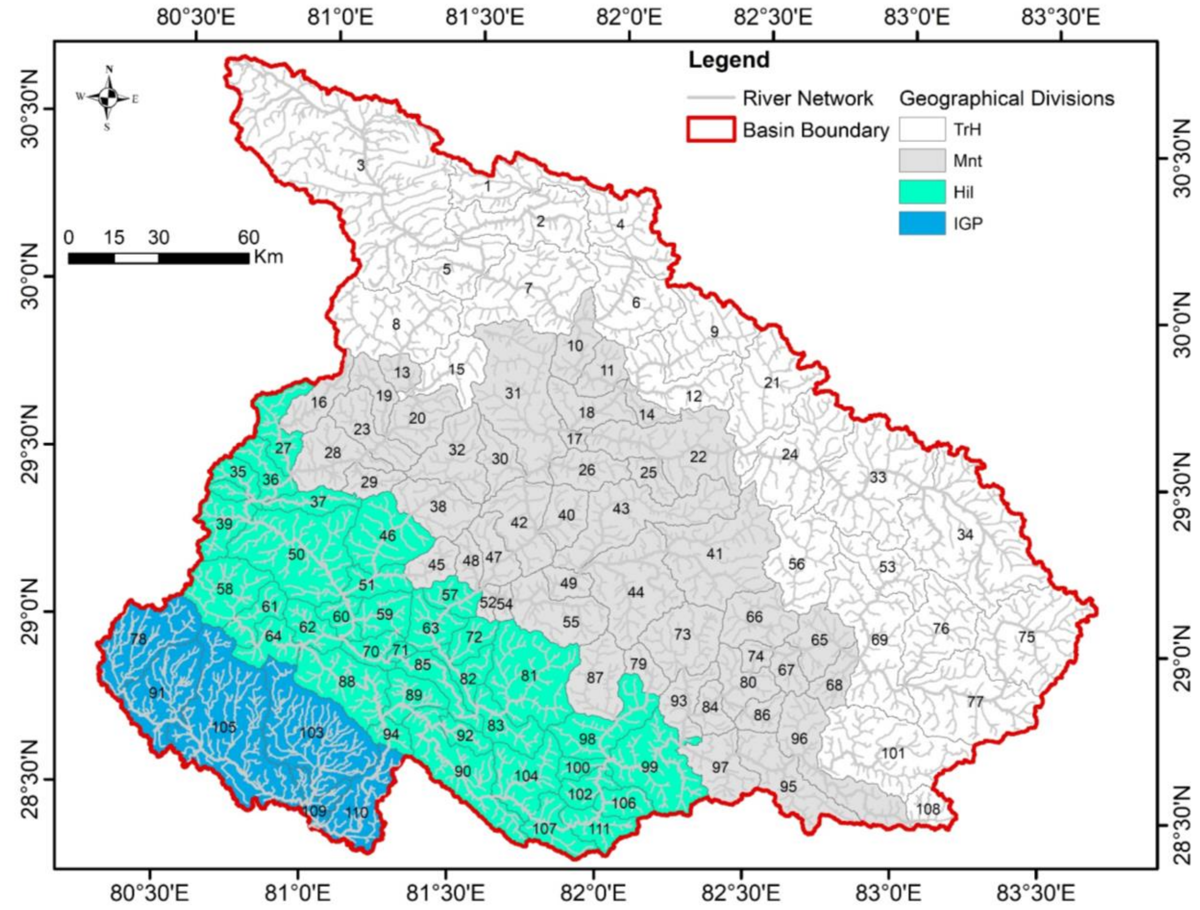
UN-WWAP (2015). World Water Development Report 2015: Water for a Sustainable World. The United Nations World Water Assessment Program (UN-WWAP). Paris: UNESCO.

WECS (2011). Water Resources of Nepal in the Context of Climate Change.Water and Energy Commission Secretariat (WECS), Government of Nepal, Kathmandu.

Whetton P., Hennessy K., Clarke J., McInnes K., Kent D. (2012). Use of Representative Climate Futures in impact and adaptation assessment. Clim. Change 115, 433–442.

Zhu, T., Ringler, C. (2012). Climate change impacts on water availability and use in the Limpopo river basin. Water 4, 63–84.

Annex-1: Geographical regions and sub-basins (small polygons with numbers) considered in SWAT model development. TrH is Trans-Himalaya; Mnt is Mountain; Hil is Hill; IGP is Indo-Gangetic Plain.



Annex-2: Projected changes in future precipitation in the Karnali-Mohana basin.

Change from baseline				DJF	MAM	JJAS	ON	Annual
Baseline [mm]				89	162	559	45	855
Station - 303	RCP 4.5	NF	Mean [%]	8	5	3	11	4
			Range [%]	*-22 - 64*	*-12 - 30*	*-11 - 19*	*-42 - 94*	*-6 - 13*
		MF	Mean [%]	6	7	11	23	10
			Range [%]	*-40 - 54*	*-16 - 44*	*-5 - 35*	*-50 - 109*	*-2 - 22*
		FF	Mean [%]	-2	12	17	-4	13
			Range [%]	*-45 - 61*	*-9 - 46*	*-7 - 31*	*-54 - 84*	*-1 - 24*
	RCP 8.5	NF	Mean [%]	2	10	5	39	7
			Range [%]	*-35 - 36*	*-14 - 59*	*-8 - 32*	*-32 - 161*	*-6 - 23*
		MF	Mean [%]	-5	10	11	23	10
			Range [%]	*-47 - 32*	*-18 - 60*	*-6 - 36*	*-48 - 101*	*-2 - 24*
		FF	Mean [%]	-13	12	22	38	17
			Range [%]	*-58 - 55*	*-21 - 56*	*2 - 63*	*-38 - 155*	*-2 - 45*

Baseline [mm]				99.4	142.8	1409.9	52.8	1705
Station - 406	RCP 4.5	NF	Mean [%]	4	10	4	20	5
			Range [%]	*-34.3 - 54.7*	*-20.7 - 44.4*	*-8.5 - 42.5*	*-35.9 - 86.1*	*-6.6 - 38.7*
		MF	Mean [%]	23	9	7	49	9
			Range [%]	*-35.3 - 79.7*	*-12.2 - 57.1*	*-9.2 - 23.6*	*-35.4 - 202.4*	*-7.2 - 25*
		FF	Mean [%]	-11	24	11	28	11
			Range [%]	*-62.5 - 86.8*	*-28.4 - 101.9*	*-16.8 - 54.7*	*-64.3 - 151.4*	*-11.9 - 45.5*
	RCP 8.5	NF	Mean [%]	3	8	8	29	8
			Range [%]	*-57 - 39.9*	*-26.9 - 57.3*	*-6.6 - 23.9*	*-44.7 - 124.4*	*-5.4 - 20.9*
		MF	Mean [%]	-8	25	9	42	11
			Range [%]	*-45.4 - 30.3*	*-10.5 - 71.9*	*-13.7 - 35.3*	*-34.3 - 187.4*	*-6.5 - 34*
		FF	Mean [%]	-15	44	10	65	13
			Range [%]	*-65.3 - 45*	*-10.8 - 124.7*	*-14.9 - 33.3*	*-17.2 - 198.1*	*-10.2 - 32.5*
Baseline [mm]				129	257	1825	59	2271
Station - 207	RCP 4.5	NF	Mean [%]	20	19	2	21	5
			Range [%]	*-10 - 54*	*-6 - 47*	*-6 - 13*	*-24 - 87*	*-1 - 12*
		MF	Mean [%]	50	32	-1	22	7
			Range [%]	*-7 - 128*	*3 - 76*	*-11 - 10*	*-49 - 156*	*-2 - 16*
		FF	Mean [%]	11	17	4	24	6
			Range [%]	*-40 - 71*	*-23 - 91*	*-15 - 21*	*-60 - 166*	*-9 - 19*
	RCP 8.5	NF	Mean [%]	24	24	5	29	9
			Range [%]	*-30 - 57*	*-6 - 55*	*-3 - 14*	*-21 - 120*	*0 - 16*
		MF	Mean [%]	21	35	3	43	9
			Range [%]	*-19 - 54*	*-9 - 83*	*-11 - 16*	*-28 - 122*	*-4 - 18*
		FF	Mean [%]	30	56	-4	44	6
			Range [%]	*-22 - 76*	*15 - 111*	*-25 - 10*	*-48 - 176*	*-8 - 20*

Annex-3: Projected changes in future maximum temperature in the Karnali-Mohana basin.

Change from baseline				**DJF**	**MAM**	**JJAS**	**ON**	**Annual**
Baseline [ºC]				14.5	21.1	24.8	20.1	20.5
Station - 303	RCP 4.5	NF	Mean [ºC]	1.6	1.4	1.0	1.0	1.3
			Range [ºC]	*0.6 - 2.6*	*0.7 - 2.5*	*0.6 - 1.6*	*0.3 - 1.6*	*0.8 - 1.8*
		MF	Mean [ºC]	2.8	2.7	1.8	1.8	2.3
			Range [ºC]	*1.6 - 4.1*	*1.6 - 4*	*1.3 - 2.3*	*1.1 - 2.4*	*1.6 - 2.9*

		FF	Mean [ºC]	3.2	2.7	2.0	2.0	2.5
		FF	*Range [ºC]*	*1.6 - 4.3*	*1.4 - 3.7*	*1.6 - 2.4*	*1.3 - 2.7*	*2 - 3.1*
	RCP 8.5	NF	Mean [ºC]	1.7	1.5	1.0	1.0	1.3
	RCP 8.5	NF	*Range [ºC]*	*0.4 - 2.8*	*0.4 - 2.2*	*0.5 - 1.7*	*0.4 - 1.9*	*0.8 - 1.9*
	RCP 8.5	MF	Mean [ºC]	3.6	2.7	2.2	2.3	2.7
	RCP 8.5	MF	*Range [ºC]*	*1.3 - 5.2*	*0.8 - 4.2*	*1.4 - 3.1*	*1.3 - 3.4*	*1.4 - 3.7*
	RCP 8.5	FF	Mean [ºC]	5.9	4.8	3.7	3.7	4.5
	RCP 8.5	FF	*Range [ºC]*	*3.8 - 7.7*	*3.6 - 5.9*	*2.5 - 4.4*	*2.6 - 4.4*	*3.4 - 5.5*
Baseline [ºC]				20.9	31.3	30.9	26.6	27.8
Station - 406	RCP 4.5	NF	Mean [ºC]	1.0	1.0	0.8	0.7	0.9
Station - 406	RCP 4.5	NF	*Range [ºC]*	*0.4 - 1.7*	*0.2 - 1.5*	*0.3 - 1.3*	*0.2 - 1.1*	*0.4 - 1.2*
Station - 406	RCP 4.5	MF	Mean [ºC]	1.3	1.4	1.1	0.9	1.2
Station - 406	RCP 4.5	MF	*Range [ºC]*	*0.5 - 1.7*	*0.5 - 2*	*0.6 - 1.5*	*0.6 - 1.6*	*0.7 - 1.6*
Station - 406	RCP 4.5	FF	Mean [ºC]	2.3	2.1	1.5	1.5	1.9
Station - 406	RCP 4.5	FF	*Range [ºC]*	*1.4 - 3.3*	*1.2 - 3.2*	*0.4 - 2.4*	*0.6 - 2.4*	*1.3 - 2.3*
Station - 406	RCP 8.5	NF	Mean [ºC]	1.2	1.2	0.9	0.7	1.0
Station - 406	RCP 8.5	NF	*Range [ºC]*	*0.5 - 1.9*	*0.5 - 2.1*	*0.4 - 1.4*	*0.3 - 1.2*	*0.6 - 1.6*
Station - 406	RCP 8.5	MF	Mean [ºC]	2.5	2.1	1.9	1.7	2.1
Station - 406	RCP 8.5	MF	*Range [ºC]*	*1.4 - 3.3*	*0.8 - 3.3*	*1 - 2.9*	*0.9 - 2.6*	*1.2 - 2.7*
Station - 406	RCP 8.5	FF	Mean [ºC]	4.0	3.8	3.1	3.1	3.5
Station - 406	RCP 8.5	FF	*Range [ºC]*	*3.1 - 5.4*	*2.8 - 4.8*	*2.2 - 3.9*	*2.4 - 4.1*	*2.9 - 4.1*
Baseline [ºC]				22.6	34.4	33.2	29.2	30.2
Station - 207	RCP 4.5	NF	Mean [ºC]	1.2	1.1	0.9	0.6	1.0
Station - 207	RCP 4.5	NF	*Range [ºC]*	*0.3 - 1.8*	*0 - 1.6*	*0.4 - 1.6*	*0.1 - 1*	*0.5 - 1.4*
Station - 207	RCP 4.5	MF	Mean [ºC]	1.4	1.4	1.2	0.8	1.3
Station - 207	RCP 4.5	MF	*Range [ºC]*	*0.6 - 2*	*0.5 - 2.4*	*0.6 - 1.9*	*0.3 - 1.8*	*0.8 - 1.8*
Station - 207	RCP 4.5	FF	Mean [ºC]	1.8	1.1	1.0	1.0	1.2
Station - 207	RCP 4.5	FF	*Range [ºC]*	*0.8 - 2.7*	*0.4 - 2.1*	*0.5 - 1.9*	*0.2 - 1.5*	*0.8 - 1.5*
Station - 207	RCP 8.5	NF	Mean [ºC]	1.5	1.3	1.0	0.7	1.2
Station - 207	RCP 8.5	NF	*Range [ºC]*	*0.5 - 2.3*	*0.3 - 2.3*	*0.5 - 1.5*	*0.1 - 1.3*	*0.7 - 1.7*
Station - 207	RCP 8.5	MF	Mean [ºC]	2.8	2.2	1.8	1.4	2.1
Station - 207	RCP 8.5	MF	*Range [ºC]*	*1.7 - 3.7*	*0.7 - 3.3*	*1 - 2.6*	*0.7 - 2*	*1.1 - 2.7*
Station - 207	RCP 8.5	FF	Mean [ºC]	4.1	3.2	3.0	2.6	3.3
Station - 207	RCP 8.5	FF	*Range [ºC]*	*3.1 - 5.4*	*2.2 - 4.2*	*1.9 - 3.8*	*2 - 3.4*	*2.7 - 4*

Annex 2-8

Received: 4 December 2018 | Revised: 11 July 2019 | Accepted: 19 September 2019

DOI: 10.1002/joc.6327

RESEARCH ARTICLE

International Journal of Climatology RMetS

Climate futures for Western Nepal based on regional climate models in the CORDEX-SA

Sanita Dhaubanjar | Vishnu Prasad Pandey | Luna Bharati

International Water Management Institute (IWMI), Kathmandu, Nepal

Correspondence
Sanita Dhaubanjar, International Water Management Institute (IWMI), Kathmandu, Nepal.
Email: sdhauban@gmail.com

Funding information
Asian Development Bank; Nordic Development Fund; Climate Investment Fund; United States Agency for International Development

Abstract

With the objective to provide a basis for regional climate models (RCMs) selection and ensemble generation for climate impact assessments, we perform the first ever analysis of climate projections for Western Nepal from 19 RCMs in the Coordinated Regional Downscaling Experiment for South Asia (CORDEX-SA). Using the climate futures (CF) framework, projected changes in annual total precipitation and average minimum/maximum temperature from the RCMs are classified into 18 CF matrices for two representative concentration pathways (RCPs: 4.5/8.5), three future time frames (2021–2045/2046–2070/2071–2095), three geographic regions (mountains/hills/plains) and three representative CF (low-risk/consensus/high-risk). Ten plausible CF scenario ensembles were identified to assess future water availability in Karnali basin, the headwaters of the Ganges. Comparison of projections for the three regions with literature shows that spatial disaggregation possible using RCMs is important, as local values are often higher with higher variability than values for South Asia. Characterization of future climate using raw and bias-corrected data shows that RCM projections vary most between mountain and Tarai plains with increasing divergence for higher future and RCPs. Warmer temperatures, prolonged monsoon and sporadic rain events even in drier months are likely across all regions. Highest fluctuations in precipitation are projected for the hills and plains while highest changes in temperature are projected for the mountains. Trends in change in annual average discharge for the scenarios vary across the basin with both precipitation and temperature change influencing the hydrological cycle. CF matrices provide an accessible and simplified basis to systematically generate application-specific plausible climate scenario ensembles from all available RCMs for a rigorous impact assessment.

KEYWORDS

climate model selection, climate projection, CORDEX South Asia, future water resources, Karnali, regional climate model, Western Nepal

1 | INTRODUCTION

Regional climate models (RCMs) are arguably better suited for climate change impact assessments in the heterogeneous and steep terrains of Nepal than global climate models (GCMs; Kundzewicz and Stakhiv, 2010; Flato *et al.*, 2013). The Intergovernmental Panel on Climate Change (IPCC) recognizes that similar to GCMs, RCMs have inherent limitations and are a work in progress (Stocker *et al*., 2013; Rummukainen *et al*., 2015). Nonetheless, the IPCC reports with *high confidence* that RCMs "add value to the simulation of spatial climate detail in regions with highly variable topography and for mesoscale phenomena such as orographic effect, convection etc." (Pg 815 in Flato *et al*., 2013). Though Coordinated Regional Downscaling Experiment for South Asia (CORDEX-SA) represents the state-of-the-arts in RCMs for South Asia (Giorgi and Gutowski, 2016), evaluation and application of CORDEX-SA over Nepal, specifically at the basin scale, is still lacking. We present the first study to use 19 CORDEX-SA RCMs to generate climate futures (CF) ensembles for water resources assessment in Western Nepal, namely the Karnali basin, with the underlying objective to provide a basis for RCM selection to generate application-specific ensemble projections to suit the specific goals of a climate impact assessment.

Given the abundance of water, steep mountains in the north, rich forests in the mid hills and fertile plains in the south, many plans for developing large hydropower, irrigation and inter-basin water transfer projects exist in Western Nepal (IWMI, 2018a). Nearly 43% of the country's untapped hydropower potential comes from Karnali (Sharma and Awal, 2013). Alongside, Bheri-Babai inter-basin water transfer and the Rani-Jamara Kuleriya irrigation projects are envisioned for mechanization of agriculture. The Digo Jal Bikas (DJB) project is analysing the trade-offs offered by these water resource development visions for Western Nepal to identify pathways and policies that balance sustainable growth, social justice and resilient ecosystems (IWMI, 2018b). Assessment of climate impacts on water resources is indispensable for such long-term planning given that Western Nepal is considered one of the most vulnerable regions within Nepal to climate change (Siddiqui et al., 2012). Western Nepal is also important for the larger Hindu-Kush Himalayas (HKH) as it is the headwaters of the trans-boundary Ganges river basin. Changes in water availability in Western Nepal will affect flow available downstream in India.

Limited studies address the changing climate in Western Nepal (Shrestha *et al*., 2015; Khatiwada *et al*., 2016) and its impact on water resources (Shiwakoti, 2017; Pandey *et al*., 2019). Fewer studies use RCM ensembles (Karmacharya *et al*., 2007; Devkota *et al*., 2015; Pandey *et al*., 2019). Evaluations of CORDEX-SA RCM performance over the greater South Asian sub-continent and the HKH show that biases exist but RCM performances are promising. Ghimire *et al*. (2015) considering 11 CORDEX-SA RCMs, Sanjay *et al*. (2017a) considering 10 RCMs, Sanjay *et al*. (2017b) considering five RCMs and Mukherjee *et al*. (2017) considering five RCMs show that most RCMs capture spatiotemporal pattern of South Asian precipitation, though skill in reproducing absolute observed values is variable. Nengker *et al*. (2017) and Choudhary and Dimri (2018) considering five different RCMs find similar trends for temperature. Generally, the ensemble outperforms individual RCMs in hindcasting (Ghimire *et al*., 2015; Nengker *et al*., 2017). However, studies highlight that biases in individual CORDEX-SA RCMs vary spatially (geographically and attitudinally) and temporally for both temperature and precipitation for both past (Ghimire *et al*., 2015; Nengker *et al*., 2017) and future climate (Choudhary and Dimri, 2018). Evaluation and correction of spatiotemporal biases is imperative for impact assessment studies, especially those focusing on hydrological application at finer scales, (Wilby, 2010). Quantile-mapping has emerged as promising for correcting RCM and GCM biases in Nepal (Lutz *et al*., 2016; Pandey *et al*., 2019) and abroad (Teutschbein and Seibert, 2012; Themeßl *et al*., 2012; Lafon *et al*., 2013).

Known CORDEX-SA biases also highlight the need for spatial disaggregation in RCM evaluation and application. Furthermore, aggregation to regional scales as done by aforementioned studies may lead to cancellation of spatial variation, especially for climate extremes. Lutz *et al*. (2016) suggest evaluation at scale finer than the South Asian basins done in their study to prevent dilution of local climate signals. Spatial disaggregation is particularly important for Nepal, because it lies in the central part of the HKH characterized by a complex climate regime dependent on the Indian summer monsoon and the winter westerly disturbances (Bookhagen and Burbank, 2010; Palazzi *et al*., 2013). Sanjay *et al*. (2017a, 2017b) find that past performance of CORDEX-SA RCMs is divergent for central HKH. Microclimates occur due to the steep elevations and heterogeneous landscapes in close proximity to the ocean. The past and future trends for precipitation (b; Karmacharya *et al*., 2007; Mcsweeney *et al*., 2010a) and streamflow (Gautam and Acharya, 2012) vary across the east–west and north–south of Nepal.

Large multi-model ensembles are necessary to provide robust characterization of known RCM biases and incorporation of projection uncertainties into climate impact assessments (Wilby, 2010; Sanjay *et al*., 2017b). But past assessments in Nepal are largely based on GCMs (Immerzeel *et al*., 2012; Bharati *et al*., 2014; Shrestha *et al*., 2014; Mishra *et al*., 2018), using at most five models with limited justification for model selection. Such practices consider few deterministic future projections and ignore uncertainties and their dependence on the model selection criteria itself. While the climate modelling community increasingly promotes the use of multi-model ensembles and probabilistic projections for impact assessments (Knutti *et al*., 2010; Stocker *et al*., 2013), real-life application of such datasets is seldom done by practitioners (Clarke *et al*., 2011; Whetton *et al*., 2012) and hydrologists (Wilby, 2010). Additional burden is levied by having four representative concentration pathways (RCPs) defined as global future scenarios considering anthropogenic changes (van Vuuren *et al*., 2011). Handling multi-model and multi-scenario probabilistic datasets require time, computation resources and technical skills in RCM/GCM data processing and bias correction. Given large uncertainties in observation datasets and models themselves, it is challenging for practitioners in the global south to justify spending their limited resources on the tedious task of generating robust climate projections.

RCM selection methods can help narrow down the ever-increasing pool of models (Whetton *et al*., 2012; Weaver *et al*., 2013; Lutz *et al*., 2016). Aforementioned RCM evaluation studies in South Asia use different models and ensembles and assess different variables–providing limited basis for cross-comparisons. Lutz *et al*. (2016) combine the envelope approach and the past performance approach to identify four representative models out of 94/69 GCMs for RCP 4.5/8.5 for impact assessment in major basins in the HKH. McSweeney *et al*. (2012) reverse the sequence to select GCMs for Vietnam. While Lutz *et al*. (2016) and McSweeney *et al*., (2012)'s approaches are thorough, considering both range of available projections and model skills, their replication to RCMs and finer spatial scale would require significant work. For instance, Bajracharya *et al*. (2018) skip re-application of the method and directly use the four models chosen by Lutz *et al*. (2016) for the entire Indus, Ganges and Brahmaputra basins for their future water resources assessment in Kaligandaki, a small sub-basin of the Ganges. Few existing web-based tools like the KNMI Climate Explorer (https://climexp.knmi.nl/plot atlas form.py) and the World Bank Climate Change Knowledge Portal (CCKP-http://sdwebx.worldbank.org/climateportal/) focus only on comparison of GCMs. CCKP, targeted towards practitioners, is well designed and user-friendly but provides limited help allowing for comparison of only one parameter from two datasets. KNMI suiting technical audience is promising but has a steep learning curve requiring substantial online data processing. Both provide limited support for sub-national analyses.

The Australian Representative Climate Future framework (CSIRO and BOM, 2015, 2018), is a simpler model selection tool catering to the needs of practitioners with limited knowledge and resources, typical in the global south. It allows scientists to provide a snapshot of model projections and associated uncertainties to decision-makers by classifying all projections in a visual matrix (Clarke *et al*., 2011; Whetton *et al*., 2012). Users can then select relevant climate models by focusing on climate risks important to their impact assessment, considering the entire range of projections. As Whetton *et al*. (2012) highlight, the strength of CF framework lies in its scalability and flexibility for generating application-specific climate projections. The framework can be applied across disciplines and spatiotemporal scales, comprising multiple climate parameters, and be updated as new models emerge.

A robust climate impact assessment can only be conducted with robust projections generated through analysis of multiple climate models. The spatial detail captured by RCMs provides a stronger basis than GCMs to generate climate projections at finer scales suitable for local studies in heterogeneous terrains such as in the HKH. But the application of RCMs and the use of multi-model ensembles have been limited, especially in smaller basins in the global south that are often hotspots vulnerable to climate change. To this end, we explore three key matters for the first time for Western Nepal—the usefulness of CF matrices to generate application-specific ensemble climate projections tailored to the needs of a climate impact assessment; the performance of RCMs compared to historical observations at stations in three geographic areas; and the need for spatial disaggregation in climate impact assessment studies. We provide a simple basis for RCM selection and ensemble generation in the form of the first ever CF matrices for Western Nepal. Considering the case of Karnali water resources assessment for long-term water resources planning, we customize the Australian framework to generate spatially disaggregated annual CF matrices synthesizing precipitation and temperature projections extracted from 19 CORDEX-SA RCMs applied to this region for the first time. Using the CF matrices for mountain, hill and Terai regions, we generate climate future ensembles by selectively combining the 19 RCMs, characterize future climate change at annual and seasonal scale and assess the future annual water availability in Karnali for long-term water resource development. In due process, we evaluate and correct RCM biases against station data for Nepal. The spatial disaggregation and station-based bias correction are particularly significant, as past studies have not evaluated climate change at such fine scales. The strength and limitations of the RCM-based annual CF matrices as a decision support tool to generate application-specific climate projections is explored.

2 | MATERIALS AND METHODS

2.1 | Study area

Western Nepal (Figure 1), comprising of the Karnali basin and parts of the Mahakali basin, is one of the most remote and naturally pristine regions of Nepal. The south-to-north elevation ranges from 142 m to 8,143 m (Jarvis *et al*., 2008). With 21 dominant soil types in Karnali and over 18 in

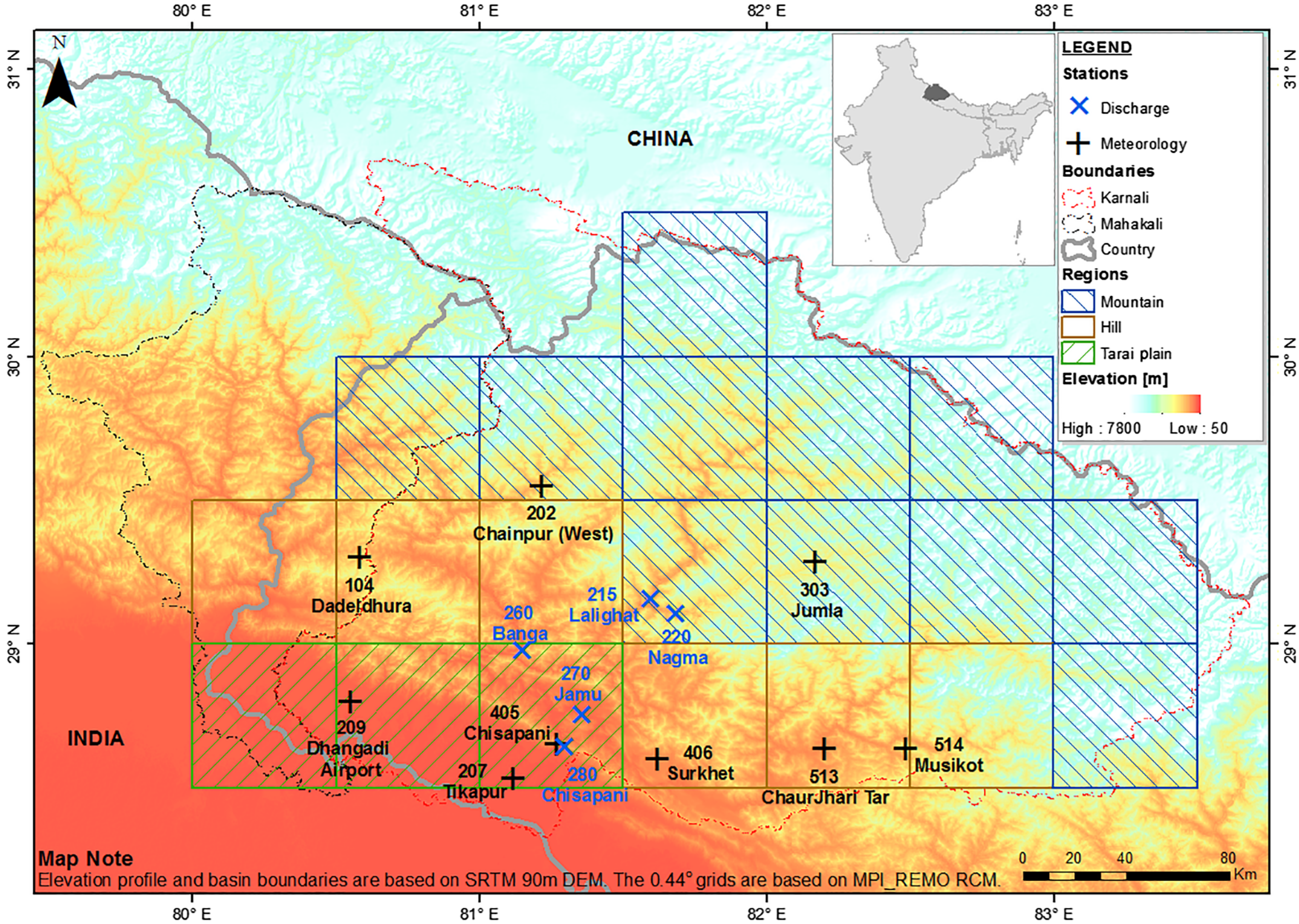


FIGURE 1 Elevation profile and geographic regions of Western Nepal overlaid with the REMO2009 RCM grids whose centres lie within the boundaries of Western Nepal and nine meteorological stations inputs and five discharge stations used for climate change impact assessment study in Karnali [Colour figure can be viewed at wileyonlinelibrary.com]

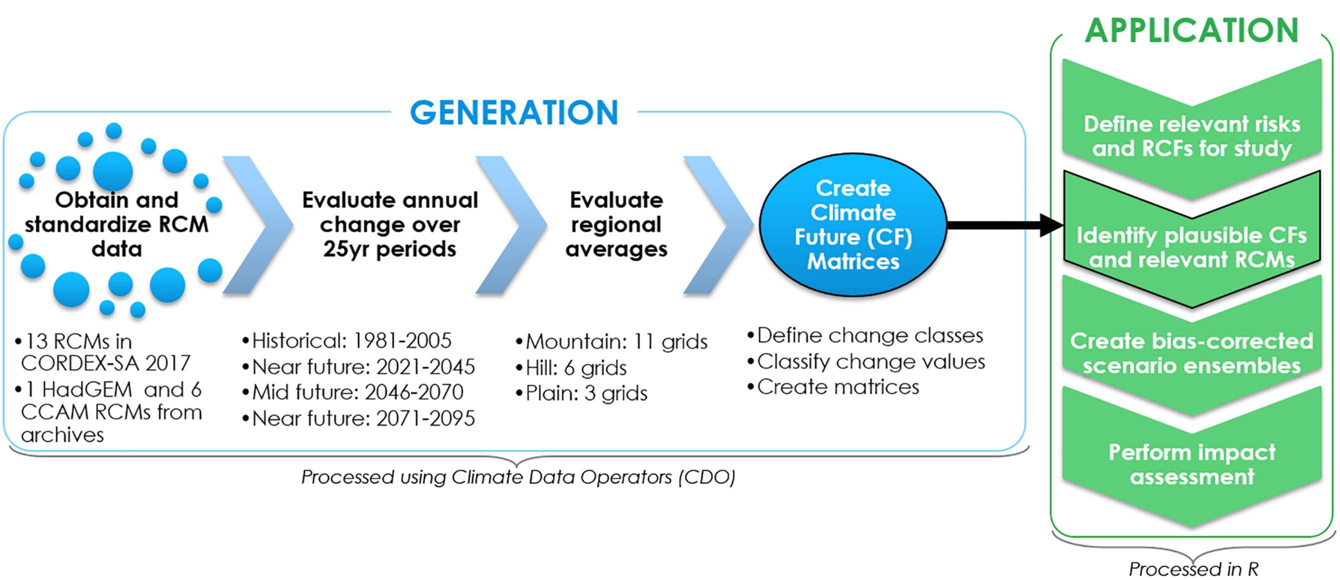


FIGURE 2 Methodology for generation and application of climate futures matrices using the Australian framework (Clarke *et al.*, 2011) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Description of the 19 CORDEX-SA RCMs in this study. All RCMs have 0.44° spatial resolution. Hits indicate number of times the model was selected for the final climate scenarios

	Short name [GCM_RCM]	Driving GCM	CORDEX-SA RCM description	RCM modelling Centre	Timeframe	Coordinate system	Hits
1.	ACCESS_CCAM	ACCESS1.0	CSIRO-CCAM-1391 M: Conformal cubical atmospheric model (McGregor and Dix, 2001)	Commonwealth scientific and industrial research organization (CSIRO), marine and atmospheric research, Melbourne, Australia	Hist: 1970–2005 RCP4.5/8.5:2006–2099	Regular	15
2.	CNRM_CCAM	CNRM-CM5			Hist: 1970–2005 RCP4.5/8.5:2006–2099	Regular	10
3.	GFDL_CCAM	GFDL-CM3			Hist: 1970–2005 RCP4.5:2006–2070 RCP8.5:2006–2099	Regular	6
4.	MPI_CCAM	MPI-ESM-LR			Hist: 1970–2005 RCP4.5/8.5:2006–2099	Regular	17
5.	NorESM_CCAM	NorESM-M			Hist: 1970–2005 RCP4.5:2006–2099 RCP8.5: None	Regular	7
6.	HadGEM_RA	HadGEM2-AO	HadGEM3-RA: HadGEM3 regional atmospheric model (Moufouma-Okia and Jones, 2014)	Met Office Hadley Centre (MOHC), UK	Hist: 1970–2005 RCP4.5/8.5:2006–2,100	Curvilinear rotated_Latitude _longitude	10
7.	CNRM_RCA4	CNRM-CM5	SMHI-RCA4: Rossby Centre regional atmospheric model version 4 (Samuelsson *et al.*, 2011)	Rossby Centre, Swedish Meteorological and Hydrological Institute (SMHI), Sweden	Hist: 1951–2005 RCP: 2006–2,100	Rotated pole	13
8.	ICHEC_RCA4	ICHEC-EC-EARTH			Hist: 1970–2005 RCP: 2006–2,100	Rotated_latitude _Longitude	13
9.	IPSLMR_RCA4	IPSL-CM5A-MR			Hist: 1951–2005 RCP: 2006–2,100	Rotated_pole	2
10.	MIROC5_RCA4	MIROC-MIROC5			Hist: 1951–2005 RCP: 2006–2,100	Rotated_pole	9
11.	MPI_RCA4	MPI-ESM-LR			Hist: 1951–2005 RCP: 2006–2,100	Rotated_pole	10
12.	NOAA_RCA4	NOAA-GFDL -GFDL-ESM2M			Hist: 1951–2005 RCP: 2006–2,100	Rotated_pole	14
13.	MPI_REMO	MPI-ESM-LR	MPI-CSC-REMO2009: MPI regional model 2009 (Teichmann *et al.*, 2013)	Climate service Centre (CSC), Germany	Hist: 1970–2005 RCP: 2006–2,100	Regular	8
14.	CanESM2_RegCM4	CCCma-CanESM2	IITM-RegCM4:	Centre for Climate Change Research	Hist: 1951–2005 RCP4.5/8.5:2006–2099	Rotated_mercator	13

(Continues)

TABLE 1 (Continued)

	Short name [GCM_RCM]	Driving GCM	CORDEX-SA RCM description	RCM modelling Centre	Timeframe	Coordinate system	Hits
15.	CNRM_RegCM4	CNRM-CM5	The Abdus Salam International Centre for Theoretical Physics Regional Climatic Model version 4 (Giorgi *et al.*, 2012)	(CCCR), Indian Institute of Tropical Meteorology (IITM), India	Hist: 1951–2005 RCP4.5:2006–2099 RCP8.5:2006–2085	Rotated_mercator	9
16.	CSIRO_RegCM4	CSIRO-Mk3.6			Hist: 1951–2005 RCP4.5/8.5:2006–2099	Rotated_mercator	9
17.	IPSLLR_RegCM4	IPSL-CM5A-LR			Hist: 1951–2005 RCP4.5/8.5:2006–2099	Rotated_mercator	7
18.	MPIMR_RegCM4	MPI-ESM-MR			Hist: 1951–2005 RCP4.5/8.5:2006–2099	Rotated_mercator	8
19.	NOAA_RegCM4	NOAA-GFDL-GFDL-ESM2M			Hist: 1970–2005 RCP: 2006–2099	Curvilinear rotated_mercator	13

Mahakali, there is spatial heterogeneity in biophysical characteristics and biodiversity. The variation is grouped into three geographic regions by the national Department of Survey: mountain, hill and Tarai plains. Karnali, the largest basin in Nepal, drains an area of 49,889 km^2, 35% of which is covered by forests (ICIMOD, 2012). Mahakali is a transboundary river with 32% (~5,628 km^2) of the basin in Nepal, of which 47% are forests. Agriculture (rainfed and irrigated) covers 15% of Karnali and 28% of the Mahakali within Nepal. Between 1980 and 2015, the discharge at Karnali's most downstream station Chisapani (#280) averaged 43 billion m^3/year. Nearly 1,361 glaciers cover 1,740 km^2 and 907 glacial lakes cover 37.7 km^2 (Ives *et al.*, 2010).

2.2 | Generation of climate futures matrices

Figure 2 shows the workflow adapted from Clarke *et al.* (2011). Using Climate Data Operators (Mueller and Schulzweida 2011), RCMs were standardized; regional spatiotemporal averages evaluated; and projected changes classified into annual CF matrices.

2.2.1 | Standardize RCM projections

The 19 RCMs, described in Table 1, are referenced throughout the manuscript with indicated short names, combining names of driving GCM and downscaling RCM. Thirteen RCMs available in the CORDEX-SA, as of December 2017, were downloaded from: https://esg-dn1.nsc.liu.se/search/esgf-liu/. Additionally, one HadGEM_RA and five CSIRO-CCAM RCMs (greyed in Table 1) dated 2014 downloaded from CORDEX-SA in the past were also considered as newer versions were not available in CORDEX-SA at the time of our study. These latter six RCMs, considered in many studies in South Asia (Mcgregor et al., 2013; Thevakaran et al., 2015; Mukherjee *et al.*, 2017), are included to have a comprehensive set of RCMs suitable for Nepal. Only RCPs 4.5 and 8.5, representing the global scenarios for medium and high levels of greenhouse gas emissions (van Vuuren *et al.*, 2011), were available for all 19 RCMs. Hence RCPs 2.6 and 6.0 could not be considered here.

Daily precipitation and near-surface air temperature (min/max) files from all RCMs were visually inspected. Based on overlap between various RCM grids, meteorological stations and geographic regions, the MPI_REMO grids were chosen. All RCMs were re-mapped to MPI_REMO using nearest neighbour method and cropped to the same extent. Units were converted to mm for precipitation and °C for temperature.

2.2.2 | Evaluate annual changes over 25-year periods

Long-term average annual total precipitation (pr) and min/-max temperatures (*t*min/*t*max) were evaluated at each grid for four 25-year timeframes (one historical baseline and three futures) listed in Table 2. The number of RCMs available for each RCP and timeframe varies between 17 and 19. The Δpr, Δ*t*max and Δ*t*min at each grid is evaluated as:

$$\Delta pr_{RCM,t,RCP}=\frac{pr_{RCM,historical}-pr_{RCM,t,RCP}}{pr_{RCM,historical}}\times 100$$

$$\Delta t\max_{RCM,t,RCP}=t\max_{RCM,historical}-t\max_{RCM,t,RCP}$$

$$\Delta t\min_{RCM,t,RCP}=t\min_{RCM,historical}-t\min_{RCM,t,RCP}$$

2.2.3 | Evaluate regional averages

Figure 1 shows the 0.44° MPI_REMO grids classified into the northern mountains, the mid-hills and the southern Tarai plains. Table 3 summarizes the coverage for each region. Based on these region definitions, Δpr/Δ*t*max/Δ*t*min across relevant grids were spatially averaged.

2.2.4 | Create CF matrices

The regional Δpr and Δ*t*max/Δ*t*min are categorized into qualitative classes in Table 4 to create six matrices. These classes were defined subjectively, considering the ranges for Australia, the natural climate variability in Western Nepal and local demarcations of climate risks. As suggested by Clarke *et al*. (2011), the classes were defined independent of current models, to accommodate addition of future model additions. The Δpr classes form the rows and Δ*t*max/min form columns of the CF matrix with 35 cells. Each cell is called a *climate future*, representing a combination of Δpr and Δ*t*max/min classes. According to Δpr/Δ*t*max/Δ*t*min obtained, RCMs are assigned to CF cells.

TABLE 2 Time frames considered and number of RCMs available for the two RCP4.5/8.5

Timeframe	Years	# of RCMs in RCP 4.5	# of RCMs in RCP 8.5
Historical	1981–2005	19	19
Near future (NF)	2021–2045	19	18
Mid future (MF)	2046–2070	19	18
Far future (FF)	2071–2095	18	17

TABLE 3 Coverage of the 0.44° grids for mountain, hill and terai plains region

Region	# of grids	Area (km2)	Average elevation (m)
Mountain	11	29,690.9	3,929.9
Hill	6	16,304.2	1,785.8
Plain	3	8,187.7	421.8

2.3 | Application of CF matrices to Karnali

The four-step process for application of the generated CF matrices (Clarke *et al*., 2011) is described in the following. Developed annual CF matrices is applied to identify RCMs that are relevant to the climate risks being addressed by a given study, prepare bias-corrected daily time series data from these and generate ensemble projections for a climate scenario at a station location.

2.3.1 | Define relevant risks and representative climate futures (RCFs)

Climate risks should be identified subjectively in consultation with stakeholders from a practical perspective considering the application at hand. Considering long-term water infrastructure development in this study, stakeholder interaction workshop revealed low-risk future as one where relatively more water is available compared to historical averages, allowing for higher storage in reservoirs and subsequent distribution, but not significantly more water so as to increase the risk of floods and landslides. Conversely, high-risk scenario was defined as one where there is decline in average water availability. Based on the two risk scenarios defined from stakeholder perspective, we defined corresponding representative future climates (RCFs). Hotter and drier climates will create the high-risk scenario. Wetter and warmer conditions will increase precipitation create the low risk scenario. Three RCF have thus been defined considering the two risks, and a maximum consensus as:

- Low-risk: (Δ*t*max: Slightly Warmer *OR* Warmer) + (Δpr: Wetter *OR* Much Wetter)
- Consensus: CF with maximum number of models in the matrix
- High-risk: (Δ*t*max: Hotter *OR* Much Hotter) + (Δpr: Much Drier *OR* Significantly Drier)

2.3.2 | Identify plausible RCFs and relevant RCMs

For each region, there are 18 climate scenarios considering three RCFs, three future timeframes and two RCPs. For each scenario, the RCFs cells in the relevant CF matrix are inspected. If no RCMs are available in the RCF cell, the climate scenario is ignored as implausible. For plausible RCFs,

TABLE 4 Qualitative classifications of projected changes in precipitation and temperature for Western Nepal

Δ Precipitation classes		Δ Temperature classes	
Description	**Range**	**Description**	**Range**
Significantly Drier	Δpr < −25%	Colder	Δt < 0°C
Much Drier	−25% ≤ Δpr < −15%	Slightly Warmer	0 ≤ Δt < 0.5 °C
Drier	−15% ≤ Δpr < −10%	Warmer	0.5 °C ≤ Δt < 2.0 °C
Little change	−10% ≤ Δpr < 10%	Hotter	2.0°C ≤ Δt < 3.5°C
Wetter	10% ≤ Δpr < 15%	Much Hotter	Δt ≥ 3.5°C
Much Wetter	15% ≤ Δpr < 25%		
Significantly wetter	Δpr ≥25%		

the relevant RCMs are selected to generate daily projections at desired locations.

2.3.3 | Create bias-corrected scenario ensembles

Nine meteorological stations spread throughout Western Nepal (Figure 1), with relatively good quality data were selected for climate characterization. The stations were classified as mountain, hill and Tarai based on their location. For each plausible climate scenario, the relevant RCMs identified for the corresponding region in previous step were gathered. Daily time series was extracted at the station latitude-longitude from these RCMs. Observed station data were compared with RCM simulation data for the historical timeframe (1981–2005) to establish linear functions for bias correcting RCM historical and future projections using empirical quantile-mapping (Gudmundsson *et al*., 2012; Teutschbein and Seibert, 2012). Bias-corrected RCM time-series were then combined as equally weighted multi-model means to generate a single ensemble projection for each climate scenario. See Supporting Information S2 for station details (latitude, longitude, elevation) and the number of RCMs selected to generate scenarios ensembles.

Satellite-based daily climate data was explored to supplement the data from scarcely spread stations for bias correction. However, satellite data were not used because they are poor at capturing topographic dependencies of rainfall (Ghaju and Alfredsen, 2012; Krakauer *et al*., 2013; Peña-Arancibia *et al*., 2013; Bajracharya *et al*., 2015), require application of correction methods specific to the product and location of application (Müller and Thompson, 2013; Thiemig *et al*., 2013), and higher quality products are only available after the 1990s.

The performance of bias correction was evaluated using: the Nash–Sutcliffe Efficiency coefficient (NSE), the percentage bias (PBIAS) and the coefficient of determination (R^2) at seasonal (winter: DJF, pre-monsoon: MAM, monsoon: JJAS), post-monsoon-ON) and annual scales. NSE and R^2 values close to 1 and PBIAS close to 0 indicate good performance, that is, simulated values are statistically close to the observed.

2.3.4 | Perform impact assessment

A hydrological model of Karnali developed by Pandey *et al*. (2018) in Soil and Water Assessment Tool (SWAT; Arnold *et al*., 2012), was used to evaluate changes in average annual discharge (ΔQ) at five discharge stations (Figure 1) in the basin. The model discretized into 111 sub-basins to capture the spatial heterogeneity was forced with the bias-corrected ensemble projections at the nine stations for all plausible climate scenarios.

3 | RESULTS AND DISCUSSION

3.1 | Spatiotemporal variation in simulated future for Western Nepal

Table 5 reports the ranges for change in long-term average annual total precipitation (Δpr) and maximum/minimum temperature (Δ*t*max/min) extracted from the 19 RCMs for Western Nepal. Alongside, Table 5 also presents changes reported by five different climate change studies for the HKH region considering large GCM and RCM ensembles. This study finds that Δ*t*min and Δ*t*max for Western Nepal for RCP 4.5 range 0.6–5.0°C and 0.6–4.0°C, respectively; while for RCP 8.5, Δ*t*min and Δ*t*max range 0.7–9.7°C and 0.6–8.1°C, respectively. The five studies in literature report the annual mean temperature (Δ*t*mean) values over South Asia and the HKH around 0.2–4.5°C and 0.3–7.2°C for RCP 4.5 and 8.5, respectively. These South Asian Δ*t*mean ranges are comparable to the Δ*t*max/tmin for Western Nepal but underestimate Δ*t*max. Similarly, for entire Western Nepal, annual Δpr ranges from −19.2 to 48.3% for RCP 4.5 and −26.1 to 70.7% for RCP 8.5. In contrast, annual Δpr ranges for South Asia are narrower at −5.7 to 27% and −8.5 to 45% for RCP 4.5 and 8.5 scenarios based on the 42 GCMs

TABLE 5 Comparison of ranges in current study with five studies focusing on South Asia. Current study ranges are min and max of the 19 CORDEX-SA RCMs for the mountain, hill and terai plain across the three futures. For literature, min–max or quantiles are reported from sources specified in the last column

	This study				Literature values				
		Mountain	Hill	Plain		Range	Spatial scale	# of models	Source
RCP 4.5	Δpr (%)	[−12.5–33.8]	[−14.5–42.6]	[−19.2–48.3]	Δpr (%)	Annual: [−3–27] ONDJFM: [−18–28] AMJJAS: [−7–37]	South Asia	42 GCMs	1
						Annual: [−5.7–19.4]	Indus, Ganges, Brahmaputra	94 GCMs	2
						JJAS: [0–25] DJF: [−12–8]	Central HKH	10 GCMs	3
						JJAS: [−2–22] DJF: [−17–18]	Central HKH	13 RCMs	3
						JJAS: [−30–30]	HKH	10 RCMs	5
	Δ*t*max [°C]	[0.7–4.0]	[0.6–3.4]	[0.7–3.4]	Δ*t*mean [°C]	Annual: [0.2–3.5] DJF: [0.1–3.7] JJA: [0.3–3.3]	South Asia	42 GCMs	1
						Annual: [1.7–3.6]	Indus, Ganges, Brahmaputra	94 GCMs	2
	Δ*t*min [°C]	[0.6–5.0]	[0.6–3.6]	[0.7–3.5]		JJAS: [1.75–3.2] DJF: [1.5–4.5]	Central HKH	10 GCMs	3
						JJAS: [1.2–2.7] DJF: [1.5–4]	Central HKH	13 RCMs	3
						Annual: [1.0–4.5]	South Asia	5 RCMs	4
RCP 8.5	Δpr (%)	[−17.4–30.8]	[−19.0–48.6]	[−26.1–70.7]	Δpr (%)	Annual: [−7–45] ONDJFM: [−17–42] AMJJAS: [−9–57]	South Asia	39 GCMs	1
						Annual: [−8.5–37.4]	Indus, Ganges, Brahmaputra	69 GCMs	2
						JJAS: [0–35] DJF: [−20–6]	Central HKH	10 GCMs	3
						JJAS: [2–41] DJF: [−30–5]	Central HKH	13 RCMs	3
						JJAS: [−30–30]	Entire HKH	10 RCMs	5
	Δ*t*max (°C)	[1.0–8.1]	[0.7–6.0]	[0.6–5.9]	Δ*t*mean (°C)	Annual: [0.4–6.0] DJF: [0.3–7.1] JJA: [0.3–5.6]	South Asia	39 GCMs	1
						Annual: [3.6–6.5]	Indus, Ganges, Brahmaputra	69 GCMs	2
	Δ*t*min (°C)	[1.1–9.7]	[0.7–6.1]	[0.8–5.7]		JJAS: [2.2–5.5] DJF: [2.6–6.6]	Central HKH	10 GCMs	3
						JJAS: [1.5–4.9] DJF: [2.5–7.2]	Central HKH	13 RCMs	3

Note: 1. For [2016–2095] relative to [1986–2005], reported min–max in Tables 14.1 and 14.SM.1c in (Christensen *et al*., 2013).
2. For [2071–2,100] relative to [1971–2000], reported ranges in section 4.1.1 in (Lutz *et al*., 2016).
3. For [2036–2095] relative to [1976–2005], whiskers in box plot of Figure 9 in (Sanjay *et al*., 2017a).
4. For [2031–2,100] relative to [1976–2005], min–max of annual time series in Figure 7 in (Sanjay *et al*., 2017b).
5. For [2020–2099] relative to [1970–2005], ranges in colour maps in Figures 3 and 4 in (Choudhary and Dimri, 2018).

considered by Christensen *et al*. (2013) and 94 GCMs by Lutz *et al*. (2016). Values for Western Nepal are closer to seasonal precipitation changes reported by Sanjay *et al*. (2017a) and Choudhary and Dimri (2018) based on 10 RCMs. Naturally, our RCM-based ranges are closer to the literature ranges for RCM ensembles than GCMs. The comparison with literature highlights the dilution of climate signal in spatiotemporal aggregation. Local changes can differ from regional and continental changes, especially for precipitation. RCMs should be considered in local studies to resolve finer microclimates within Nepal.

Figure 3 presents the regional changes projected by the 19 RCMs under the two RCPs. The scatter plots show mountain in blue, hill in orange and plains in green; symbols indicate the three future time frames (near: x, mid: + and far: o). RCP 8.5 plot shows higher spatiotemporal spread than RCP 4.5. Scattered points for plains and hills are close to each other while those for the mountain are dispersed. The regions show greater variability in projections as well as diverge progressively from near to far future. Generally, the scattering is wider along the y-axis (Δpr) rather than x-axis (Δ*t*max/min) indicating greater uncertainty in precipitation.

Regional Δ*t*min and Δ*t*max are always positive but the values differ in magnitude and skewness across the regions. In the mountain, Δ*t*min and Δ*t*max points are higher and spread wider along the vertical axis compared to hills and plains, with Δ*t*min varying by 0.6–5.0°C and Δ*t*max by 0.7–4.0°C for RCP 4.5; for RCP 8.5 Δ*t*min ranges at 1.1–9.7°C and Δ*t*max 1.0–8.1°C. For the plains, the ranges are smaller with Δ*t*min ranging around 0.7–3.5/0.8–5.7°C and Δ*t*max 0.7–3.4/0.6–5.9°C for RCP 4.5/8.5. Also, for all regions, Δ*t*min is generally higher than Δ*t*max for both RCPs. With minimum temperature projected to rise faster than maximum, future temperature ranges may thus be narrower with higher absolute values than in the past.

Similar consistency in magnitude and direction is not found for annual Δpr over time or space. Δpr has wider spread for plain and hill than the mountain with values

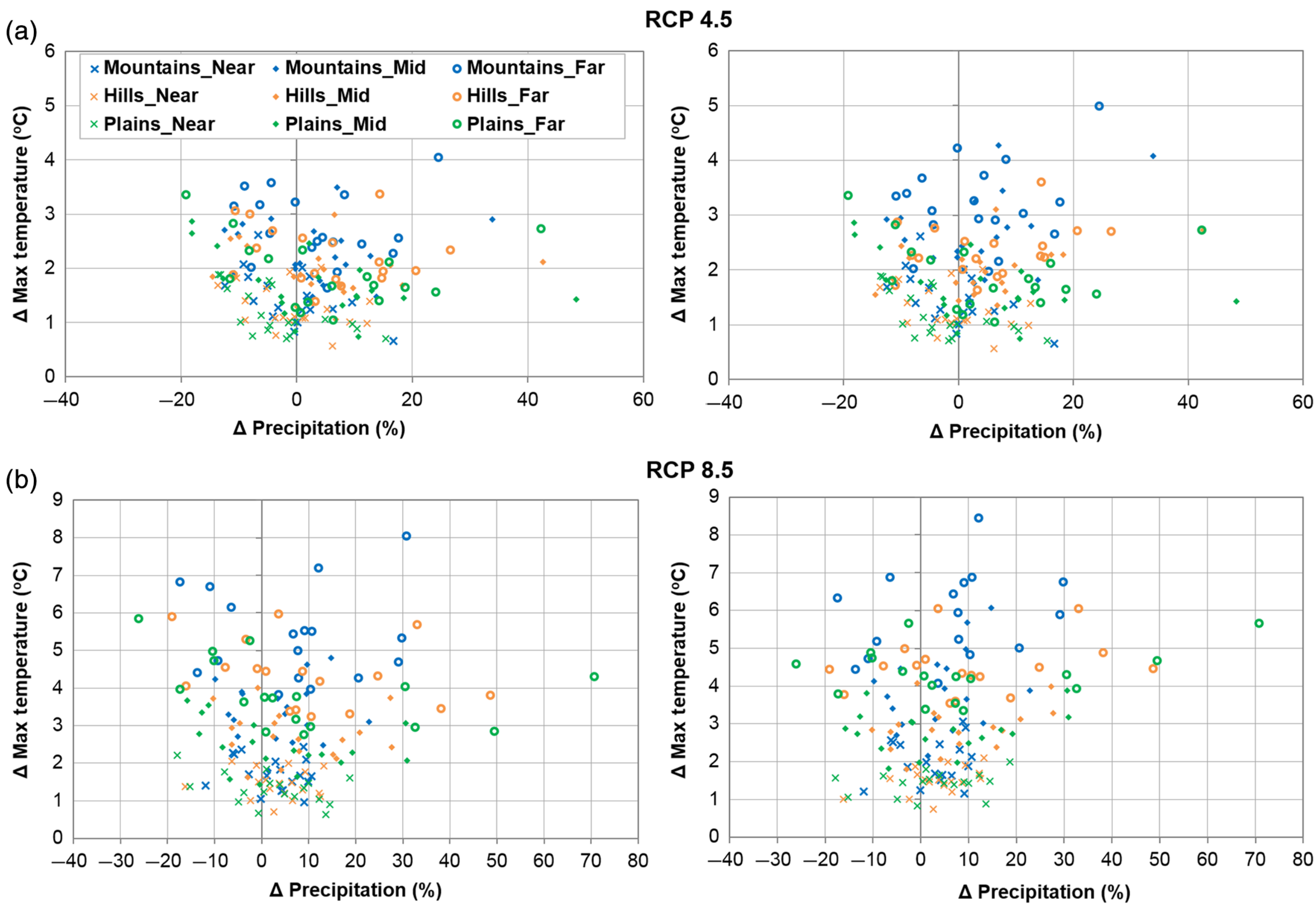


FIGURE 3 Changes in long term 25-year average annual means from historical (1981–2005) to near (2021–2045), mid (2046–2070) and far (2071–2095) future timeframes in RCP 4.5 (top) and RCP 8.5 (bottom) scenarios. Figures on the left show percentage change in long-term average annual total precipitation versus maximum temperature, whereas on the right shows the changes in precipitation versus minimum temperature. Symbol colours distinguish the regions: blue-mountain, orange-hills and green-Tarai plains. Symbol shapes distinguish the timeframes: cross-near, dot-mid and circle-far futures. Refer to web version of the figure for color references [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 6 Correlation between Δpr, Δ*t*max and Δ*t*min across the three regions for all three timeframes and two RCPs. The colour codes are described in text

For all timeframes for RCP 4.5 and 8.5		Mountain			Hill			Plain		
		Δpr	Δ*t*max	Δ*t*min	Δpr	Δ*t*max	Δ*t*min	Δpr	Δ*t*max	Δ*t*min
Mountain	Δpr	1.00	0.15	0.33	0.80	0.05	0.28	0.75	−0.11	0.22
	Δ*t*max		1.00	0.96	0.24	0.98	0.97	0.25	0.92	0.96
	Δ*t*min			1.00	0.35	0.93	0.97	0.31	0.84	0.95
Hill	Δpr				1.00	0.10	0.33	0.88	−0.06	0.27
	Δ*t*max					1.00	0.95	0.10	0.97	0.96
	Δ*t*min						1.00	0.31	0.89	0.99
Plain	Δpr							1.00	−0.06	0.26
	Δ*t*max								1.00	0.92
	Δ*t*min									1.00

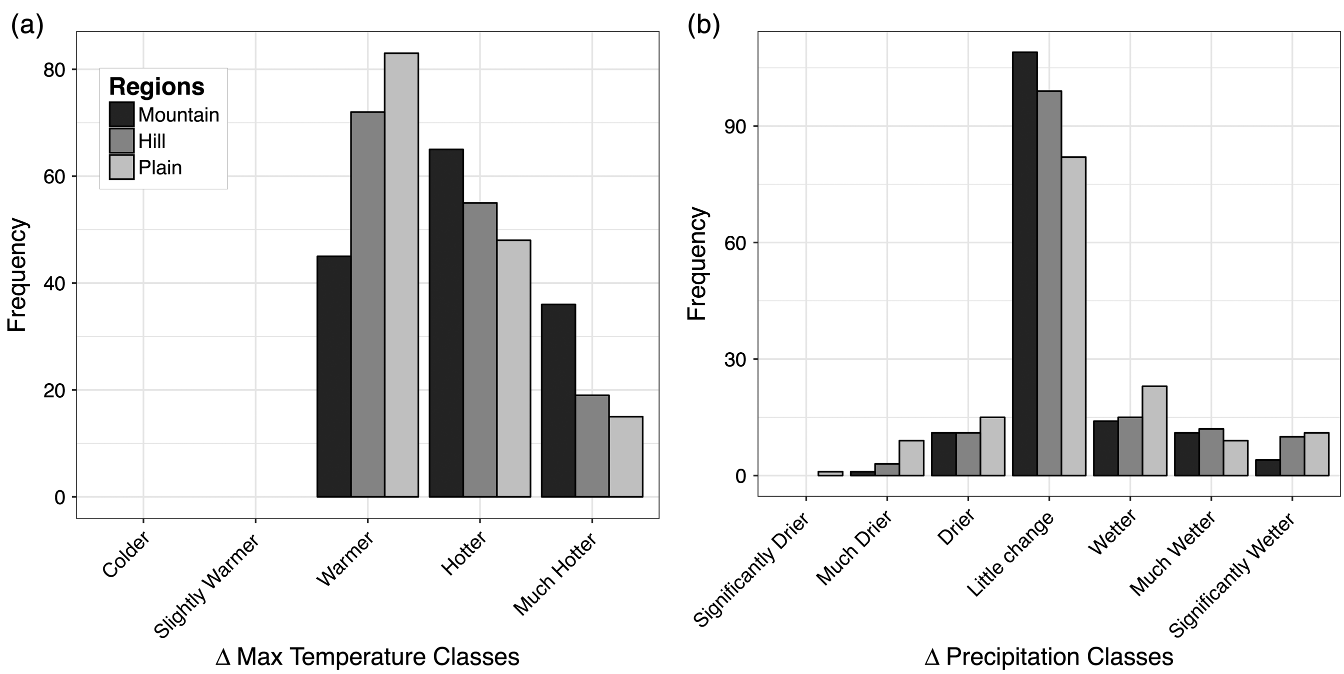


FIGURE 4 Number of models projecting values in each Δ*t*max (left) and Δpr (right) classes defined in Table 4 for the three regions considering model projections under both RCPs for all future timeframes

scattered horizontally. For the plains, Δpr ranges from −19.2 to 48.3% for RCP 4.5 and −26.1 to 70.7% for RCP 8.5, suggesting that the future precipitation is projected to be most erratic in the southern plains. The range for the mountain is narrower at −12.5 to 33.8% for RCP 4.5 and −17.4.1 to 30.8% for RCP 8.5. For hills, the range is similar to the plains for RCP 4.5 from 14.5 to 42.6%. But for RCP 8.5, the Δpr for hills ranges from −19 to 48.6% similar to mountains.

Correlation coefficients (R) listed in Table 6 show strong spatial correlations between the regions. Within each region, there is strong correlation between Δ*t*max and Δ*t*min (highlighted in red with $R = .92–.96$) and Δpr is not correlated to Δ*t*max/min ($R < .33$). Highlighted in blue, the Δpr across plain and hill show higher correlation of $R = .88$ compared to R = .80/.75 between mountain and hill/plain. In future studies, spatial disaggregation between plain and hill may be redundant. Spatial correlations for Δ*t*min (in green) and for Δ*t*max (in orange) are all high ($R > .92$).

3.2 | Climate futures matrices for Western Nepal

Given the high correlation between Δ*t*max and Δ*t*min, only Δ*t*max is considered for setting up the CF matrices. The number of models that fall in each of the Δpr and Δ*t*max

(a)

Plain_RCP8.5_Far	Δ Max temperature				
Δ Total precipitation / CF with RCM names	Colder	Slightly Warmer	Warmer	Hotter	Much Hotter
Significantly Drier					MPI_REMO2009
Much Drier					MPIMR_RegCM4
Drier					MPI_RCA4 CSIRO_RegCM4
Little change				CNRM_CCAM NOAA_RegCM4 CNRM_RCA4	ACCESS_CCAM MPI_CCAM GFDL_CCAM NOAA_RCA4 ICHEC_RCA4
Wetter				CanESM2_RegCM4	
Much Wetter					
Significantly Wetter				MIROC5_RCA4 IPSLLR_RegCM4	HadGEM3-RA IPSLMR_RCA4

(b)

Plain_RCP8.5_Far	Δ Max temperature				
Δ Total precipitation / CF with number of RCMs	Colder	Slightly Warmer	Warmer	Hotter	Much Hotter
Significantly Drier	0	0	0	0	1
Much Drier	0	0	0	0	1
Drier	0	0	0	0	2
Little change	0	0	0	3	5
Wetter	0	0	0	1	0
Much Wetter	0	0	0	0	0
Significantly Wetter	0	0	0	2	2

FIGURE 5 Simple Climate Future Matrix visuals for Tarai plain under the RCP 8.5 far future (2070–2095). (a) Presents name of RCMs in each CF while (b) presents number of models. Orange and Green boxes highlight the representative climate futures for low and high risk cases respectively. See Table 2 for RCM description [Colour figure can be viewed at wileyonlinelibrary.com]

classes are shown in Figure 4. Consistent with global trends, none of the models assessed here for RCP 4.5 and 8.5 project decrease in temperature and very few project dry conditions. For the mountains, model consensus is highest for "Hotter" future while for hills and plains "Warmer" future dominates. Precipitation changes across all three regions predominately fall under the ±10% "Little change" category. The number of models projecting "Little change" is more than three times that of other Δpr classes. Redefining Δpr classes to separate smaller model projections may be considered, keeping in mind that classes should accommodate future RCM additions.

The 18 CF matrices are visualized in three formats provided in Supporting Information S1. Figure 5 present two formats of the matrix for the Tarai plains under RCP 8.5_Far future. Figure 5a shows number of RCMs under each CF while Figure 5b lists the RCM names. Figures 6 and 7 show enhancements where the matrices are shown as classified scatter plots. Colour code indicates model consensus, that is, percentage of the models under each CF cell. Such layering of information helps users visualize the full range of projections and understand where each individual RCMs lie. For a simplified assessment looking at impacts under generic CF, Figure 5 may be sufficient. For a study interested in climate extremes and understanding projection uncertainties, Figures 6 and 7 will be valuable.

Figures 6 and 7 present CF matrices under RCP4.5_Near and RCP8.5_Far scenarios for plain and mountain, respectively. In both regions, the 19 RCMs concentrate around the "Warmer" + "Little Change" cell in RCP 4.5_Near and spread out further for RCP 8.5_Far. Even projection based on the same RCM but driven by different GCMs move in different direction. For example, see points for MPI_RCA4, MIROC5_RCA4 and IPSLMR_RCA4 that belong to the RCA4 RCM family. For both mountain and plain, MPI_RCA4 projections move towards the upper right – "Drier" + "Hotter" corner, while that for MIROC5_RCA4 and IPSLMR_RCA4 move towards the lower right – "Wetter" + "Hotter" corner. The trends for individual RCMs are also not generalizable across the three regions. In Figure 6a,b for the plains, HadGEM_RA projects "Significantly Wetter" conditions but in Figure 7b for the mountains, HadGEM_RA projects "Drier" conditions. This suggests that GCM behaviours dominate RCMs outputs, also noted by Sanjay et al. (2017a).

The matrix-based visualization allows for easy tracking of changes in Δpr and Δ*t*max over the different scenarios for individual RCMs as well as their ensemble behaviour. Such relative progression of RCMs for the across RCPs and futures is shown in the animations in Supporting Information S1. The GIFs show the movement of RCM points for the plains towards higher precipitation changes (both positive and negative) for higher RCPs and futures. For the mountains, the RCM points move more along the temperature axis, where by all RCMs fall under the "Much Hotter" category for RCP 8.5_Far (Figure 7b).

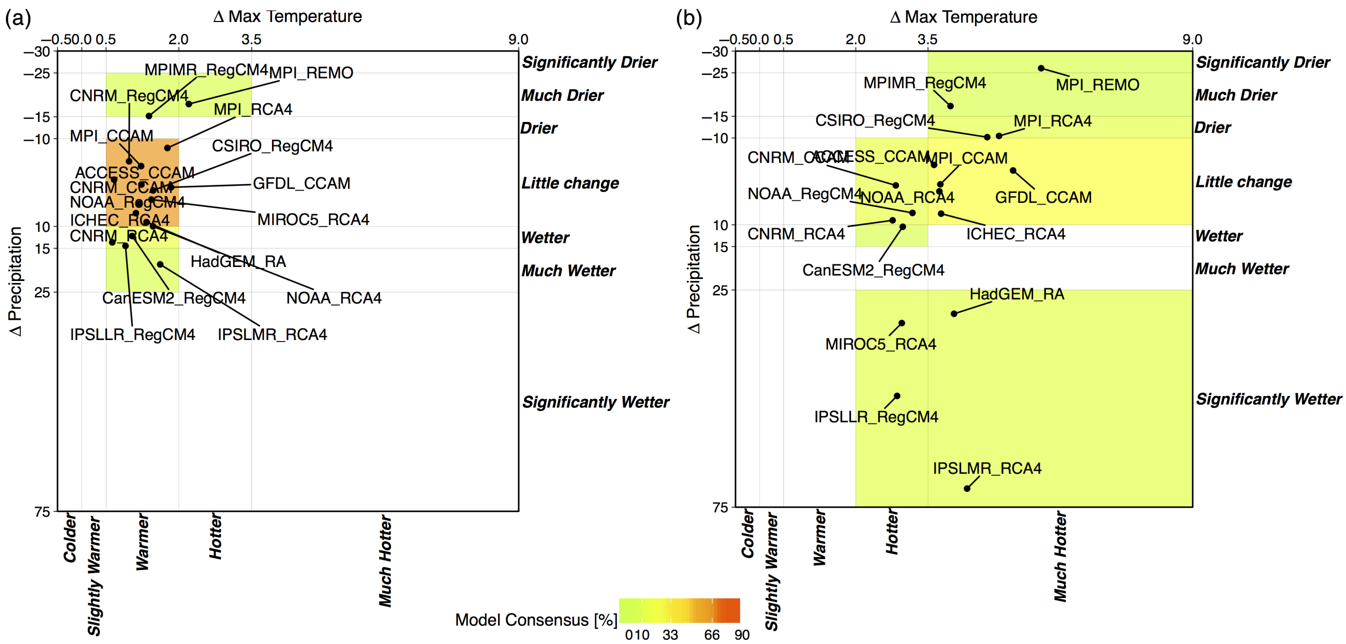


FIGURE 6 Advanced Climate Future Matrix visuals for Tarai plain under (a) RCP 4.5 near future (2021–2045) and (b) RCP 8.5 far future (2070–2095) on the right. See Table 2 for RCM description [Colour figure can be viewed at wileyonlinelibrary.com]

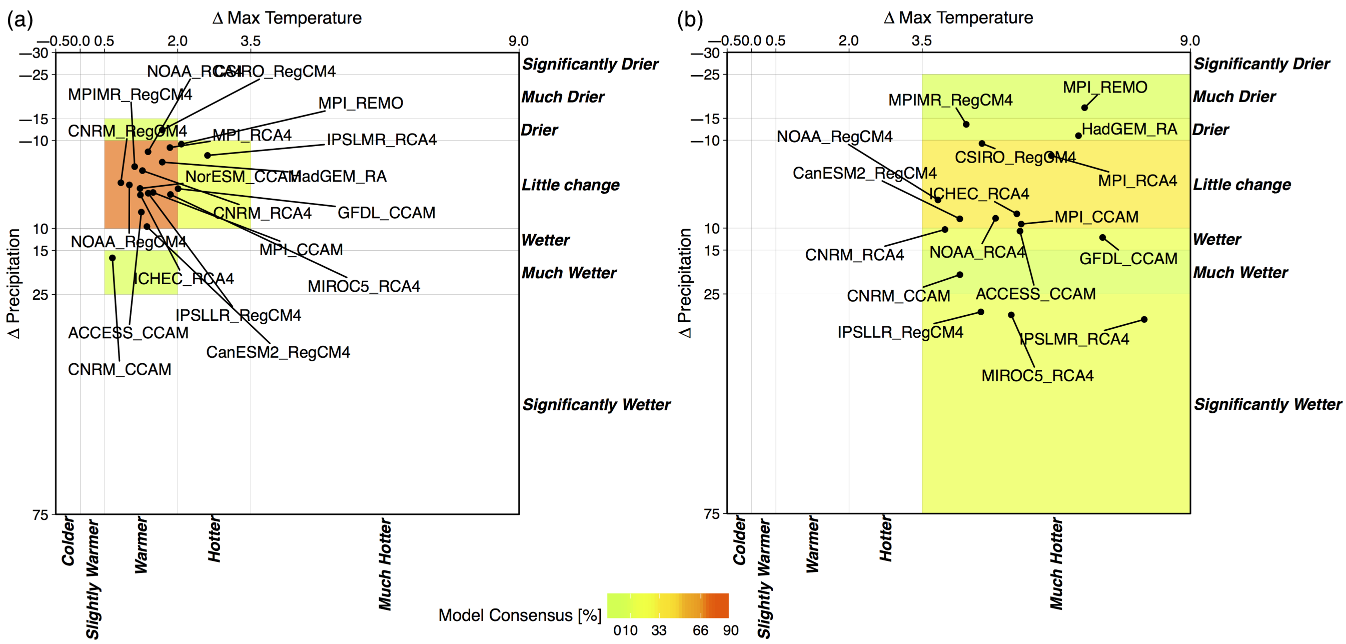


FIGURE 7 Advanced Climate Future Matrix visuals for MOUNTAIN under (a) RCP 4.5 near future (2021–2045) and (b) RCP 8.5 far future (2070–2095) on the right. See Table 2 for RCM description [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Application of CF matrices to Karnali

3.3.1 | Selected climate scenarios and relevant RCMs

Table 7 summarize the RCFs and the corresponding RCMs identified from the 18 CF matrices considering long-term water resources management. "Little change" + "Warmer" OR "Hotter" CFs are the dominant RCFs with maximum model consensus across all regions and climate scenarios. The number of models in consensus RCF decreases from 14 RCMs for RCP4.5_Near_Consensus scenario in all three regions to as low as five RCMs for the RCP8.5_Far_Consensus scenarios in hill and plain. Figure 8 shows the RCMs selected across the 18 climate scenarios for each

TABLE 7 Representative climate futures for mountain, hill and terai plain under RCP 4.5 and 8.5 for all three future time frames for application in the Karnali basin water resources assessment study

Case		Near future		Mid future		Far future	
Mountain		Future	# Models	Future	# Models	Future	# Models
RCP 4.5	Low risk	Much Wetter and Warmer	1	Wetter and Warmer	1	Wetter and Warmer	No model
	Consensus	Little change in rain and Warmer	14	Little change in rain and Hotter	9	Little change in rain and Hotter	9
	High risk	Much Drier and Hotter	No model	Much Drier and Hotter	No model	Much Drier and Hotter	No model
RCP 8.5	Low risk	Wetter and Warmer	1	Wetter and Warmer	No model	Wetter and Warmer	No model
	Consensus	Little change in rain and Warmer	10	Little change in rain and Hotter	8	Little change in rain and Much Hotter	7
	High risk	Much Drier and Hotter	No model	Much Drier and Hotter	No model	Much Drier and Much Hotter	1
Hill							
RCP 4.5	Low risk	Wetter and Warmer	2	Much Wetter and Warmer	1	Wetter and Warmer	2
	Consensus	Little change in rain and Warmer	14	Little change in rain and Warmer	10	Little change in rain and Hotter	5
	High risk	Much Drier and Hotter	No model	Much Drier and Hotter	No model	Much Drier and Hotter	No model
RCP 8.5	Low risk	Wetter and Warmer	3	Wetter and Warmer	No model	Wetter and Warmer	No model
	Consensus	Little change in rain and Warmer	12	Little change in rain and Hotter	8	Little change in rain and Much Hotter	6
	High risk	Much Drier and Hotter	No model	Much Drier and Hotter	No model	Much Drier and Much Hotter	2
Plain							
RCP 4.5	Low risk	Wetter and Warmer	1	Wetter and Warmer	5	Wetter and Warmer	3
	Consensus	Little change in rain and Warmer	14	Little change in rain and Warmer	7	Little change in rain and Warmer	5
	High risk	Much Drier and Hotter	No model	Much Drier and Hotter	2	Much Drier and Hotter	1
RCP 8.5	Low risk	Wetter and Warmer	3	Wetter and Warmer	No model	Wetter and Warmer	No model
	Consensus	Little change in rain and Warmer	12	Little change in rain and Hotter	6	Little change in rain and Much Hotter	5
	High risk	Much Drier and Hotter	1	Much Drier and Much Hotter	1	Significantly Drier and Much Hotter	1

region. For cases RCP4.5_Near_Consensus and RCP8.5 _Near_Consensus, nearly all models are selected for all three regions as there is relatively small spread in model values. The MPI_CCAM model is chosen most often across the three regions. IPSLMR_RCA4 is the least chosen – used only once for hills, once for Tarai but never used for mountain. The hits in Table 1 show that, all models are chosen an average of 10 times suggesting that no model is overarching.

Only 10 out of the 18 climate scenarios have representative RCMs available for all three regions. Three scenarios: RCP4.5_Near_High-Risk, RCP8.5_Near_Low-Risk and RCP8.5_Mid_Low-Risk do not have representative RCMs for all regions. Four high-risk scenarios: RCP4.5_Mid_High-Risk, RCP4.5_Far_High-Risk, RCP8.5_Near_High-Risk and RCP8.5_Mid _High-Risk, are only available for the plain. RCP4.5_Far_Low-Risk scenario is not available in the mountains. This suggests that high-risk scenarios are more likely for the plains than in the mountain. However, low-risk scenarios are unlikely across all regions under RCP 8.5. RCP 8.5 is a globally defined scenario representing a case where climate policies are not enforced to limit emissions, leading to high greenhouse gas concentration (Riahi and Grubler, 2007; van Vuuren *et al.*, 2011). If climate mitigation efforts are not implemented as assumed by the RCP 8.5 scenario, high-risk futures are virtually certain beyond 2045. Conversely, if stringent climate policies are enforced to lower emissions, as represented by RCP 2.6 not considered in this study, changes in temperature and precipitation are

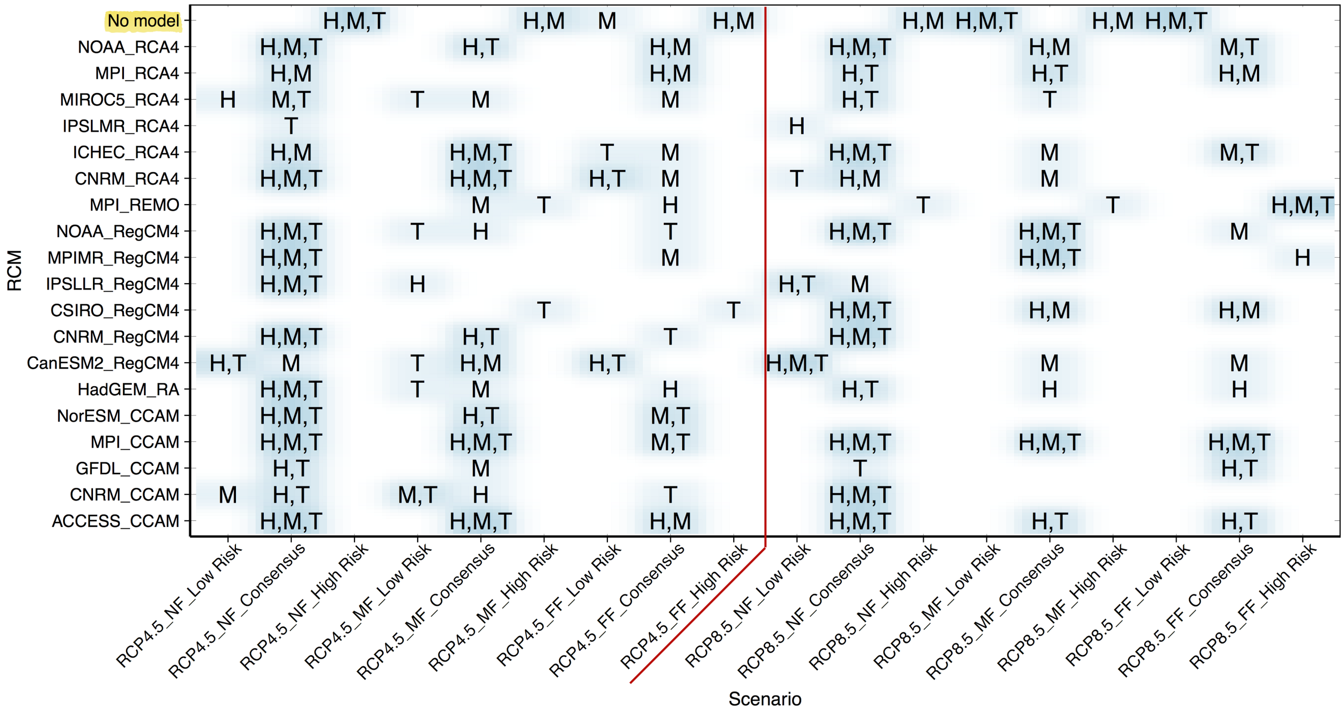


FIGURE 8 RCMs selected for the 18 different climate scenarios for the three regions (M-mountain, H-hill and T-Tarai plain) based on the climate futures matrices in Supporting Information A. See Table 2 for description of the RCMs [Colour figure can be viewed at wileyonlinelibrary.com]

likely to be lower than that presented here for RCP 4.5 and 8.5.

Figure 9 visualizes the role of CF matrices in generating the climate scenarios for Karnali by comparing the ranges in Δpr and Δ*t*max for all available RCMs to that of the ensembles representing the 18 scenarios. The bars show the ensemble means with mean values listed at the top, while the error bars show the ranges across the RCMs. The ranges are narrower for the scenarios than for "all RCMs" as the scenarios selectively group models that agree in projections. The low and high-risk scenarios have even narrower ranges because they comprise of fewer RCMs. Especially for Δpr, it is clear that each climate scenario only samples a portion of the full range of available projections. While Δpr values for all RCMs across all regions and scenarios range from −26.1 to 70.7%, the ensemble means for the scenarios are between −2.8 and 8.9%. The low-risk scenario ensembles across all regions and scenarios have mean Δpr values between 10.5 and 18.2%, consensus between −9.7 and 10.0% and high risk between −26.1 and −16.0%. Similarly, for Δtmax, when considering specifically the far future, Δ*t*max across all regions ranges between 0.9 and 5.9°C for all RCM, 0.6 and 0.2°C for low-risk, 0.6 and6.1°C for consensus and 4.1 and 6.8°C for high-risk cases.

Using an ensemble with all RCMs would in essence only simulate climate scenario with small changes in precipitation as seen for the consensus RCF because climate signals from different RCMs cancel out. Application of CF matrix as an RCM selection criterion prior to ensemble generation allows practitioners to create ensembles that match the climate risk of their interest lending well to a scenario-based impact analysis. The dilution of climate signals when creating ensembles is not as much an issue for Δ*t*max. Nonetheless, analysis that considers RCM selection consciously can provide more robust climate inputs in comparison to random use of RCMs without characterizing the nature of the projections.

3.3.2 | Bias correction of scenario ensembles

Bias-corrected multi-model ensembles were prepared at nine meteorological stations in shown in Figure 1 for the 10 climate scenarios. Stations 202 and 303 lie in the mountain; 104, 406, 513 and 514 in the hill; and 140, 187 and 225 in the plain. Figure 10 presents historical long-term average seasonal total precipitation and maximum temperature based on observed data (black bar), the raw scenario ensembles (dashed lines) and bias-corrected ensembles (coloured bars). The deviation of the raw RCM ensembles from the historical observed values indicate a spatial trend in bias. Consistent with literature listed in Table 5, the raw ensembles show wet biases for mountain stations, both wet and dry biases for hill stations and dry biases for the lower elevation plain stations. Stations 104 (1848 m) and 514 (2,100 m) classified as hilly

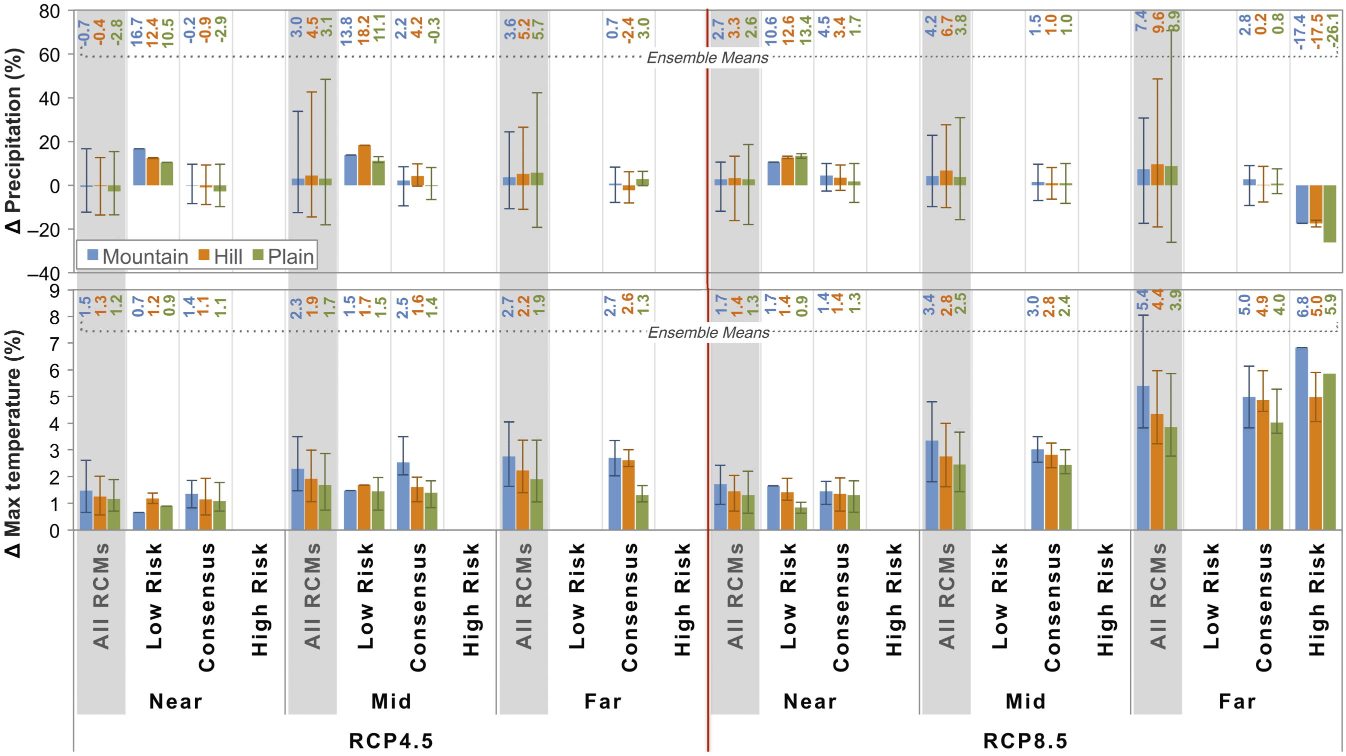


FIGURE 9 Region-wise means (bars) and ranges (error bars) in long-term annual average Δpr and Δ*t*max for all available RCMs (greyed) and representative RCM ensembles for the 18 different climate scenarios combining 2 RCPs (4.5 and 8.5), 3 futures (near, mid, far) and three RCFs (low risk, consensus, high risk). Numbers at the top of graph indicate mean value for each scenario ensemble [Colour figure can be viewed at wileyonlinelibrary.com]

station due to their latitude-longitude lie in relatively high elevations. It is interesting to note that station 104 in particular shows biases expected for the mountain region. Ghimire *et al.* (2015) also find that, RCM precipitation bias varies from −20 to 20% between 0 and6,000 m. Precipitation biases also shows a seasonal trend. In the mountain and hill, there is a wet bias across all seasons for the majority of the scenarios. However, in the plain, there is a dry bias in the monsoon (JJAS) and wet bias in winter (DJF). The least bias is seen for the pre-monsoon (MAM).

In Figure 10b for long-term average seasonal maximum temperature, the raw historical ensemble values lie below the historical observed bar in black across all stations showing systematic cold bias across all seasons and scenarios. Higher biases are seen for the mountain stations than the hill and plain stations. The bias is worst at mountain station 202, with biases as high as −29.5°C in the monsoon (JJAS), while performance is best at hill station 104. The observed cold bias is consistent with Nengker *et al.* (2017)'s findings of seasonal biases of −7°C on average and as high as −14°C for the western HKH. However, these RCM temperature biases are higher compared to GCM biases of −6.0 to 2.5°C reported by Lutz *et al*. (2016) for the entire HKH.

Quantile-mapping performs well, especially for temperature due to the systematic nature of biases. The seasonal performance statistics (NSE, R2 and PBIAS) for raw and bias-corrected RCM ensembles are reported in Supporting Information S3. For precipitation, the NSE for the raw RCM ensembles for the mountain stations are significantly worse (−5.04 to 0.60) than those for the stations in the hill (−0.01 to 0.90) and plain (0.16 to 0.92). Quantile-mapping increases the NSE across all precipitation ensembles to an acceptable range of 0.76 to 0.96 and PBIAS values from (102.8 to 193.4%) to (0.01 to 0.05%). The NSE for maximum temperature is improved from −33.8 to 0.85 for raw ensembles to 0.85 to 0.96 for bias-corrected ensembles, while the PBIAS is improved from 95% to 0% across all stations and scenarios. Meanwhile, the good R2 values for raw historical RCM ensembles for maximum temperature ranging from 0.75 to 0.95 highlight the systematic nature of the temperature bias.

3.3.3 | Future climate projection for Karnali

The solid lines in Figure 10 show seasonal averages for bias-corrected future RCM ensembles for each of the nine meteorological stations. Table 8 lists the range in seasonal and annual averages seen across each region. Future temperatures are higher than historical values across all seasons and stations with highest warming seen in the mountain stations 202 and 303. There is no discernible trend in precipitation.

Figure 11 further explores the seasonal future climate projections presenting the range of projected changes with

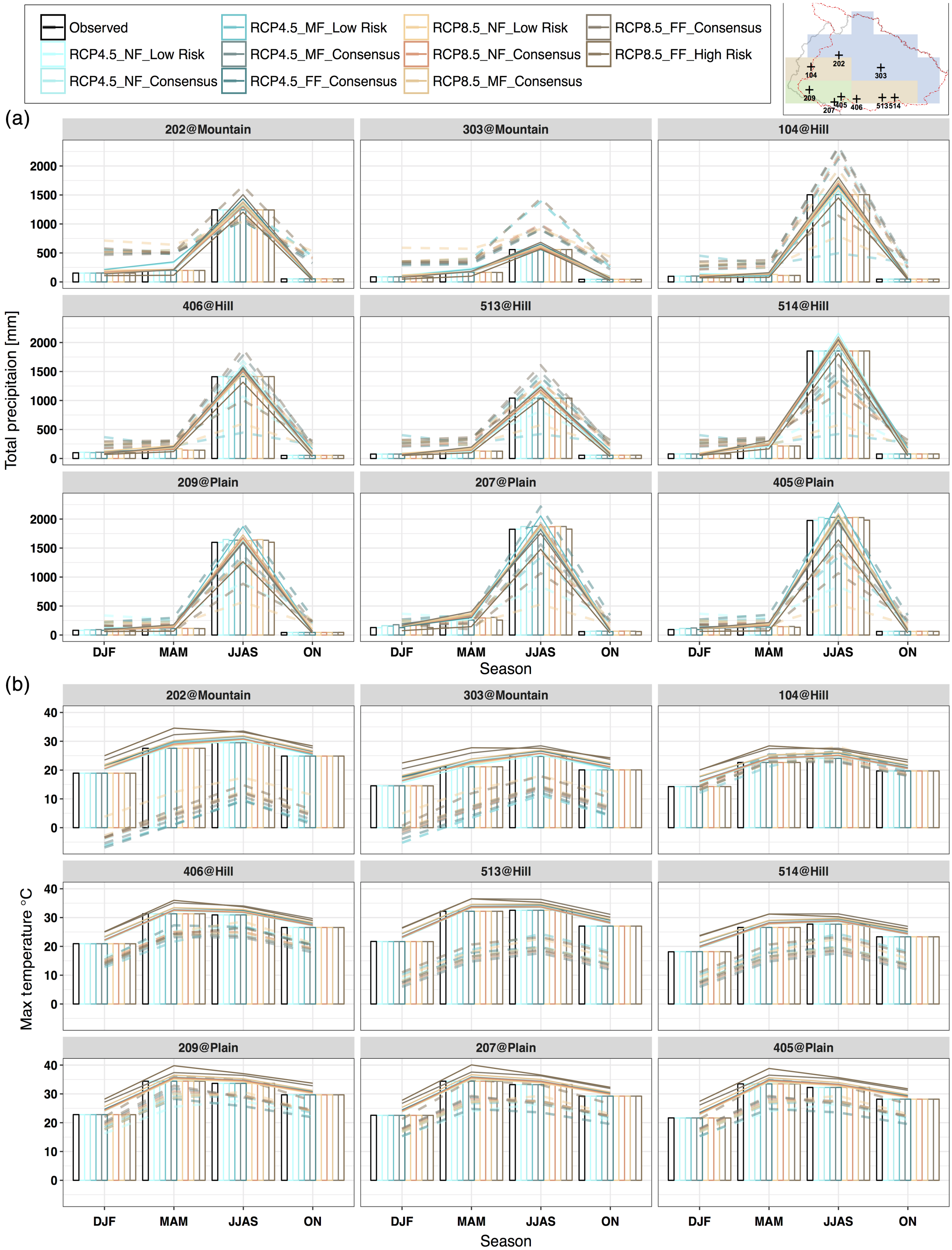


FIGURE 10 Comparison of long-term seasonal averages for (a) total precipitation and (b) maximum temperature in historical and future time frame across the nine meteorological stations. Observed historical station data and bias corrected historical RCM ensembles are shown as bar plots. Raw historical RCM ensembles are shown in dashed lines and bias corrected future RCM ensembles are in solid lines. Colours differentiate the observed (in black), five RCP 4.5 scenarios (in shades of blue) and five RCP 8.5 scenarios (in shades of brown). Refer to web version of the figure for color references. Inset in top right corner shows station locations in Karnali [Colour figure can be viewed at wileyonlinelibrary.com]

respect to the bias-corrected historical values. Δ*t*max is more similar across hills and plains than Δpr. Average Δpr has a wide range in all three regions. However, in Figure 11a the median Δpr across all seasons, scenarios and stations lie close to zero, with whiskers extending in both positive and negative directions. The medians for low-risk scenarios are generally skewed above zero while the single high-risk scenario is negatively skewed. Winter (DJF), pre-monsoon (MAM) and post-monsoon (ON) precipitation projections fluctuate more than monsoon (JJAS), suggested by the higher mean Δpr values and whiskers extending beyond 100% for these seasons. Highest changes are seen in post-monsoon (ON), with averages Δpr as high as 196% projected for the hill and as low as −51.6% in the mountain. While absolute changes in post-monsoon, winter and pre-monsoon precipitation do not appear significant compared to the monsoon in Figure 10a, the high range in percentage changes and low medians in Figure 11a suggest a shift in rainfall pattern. The mean, median and overall distribution of Δpr suggest prolonged monsoon and frequent sporadic rain events even in drier months.

In Figure 11b, Δ*t*max has a clear spatiotemporal trend with higher values and spread seen in the mountain stations, for higher futures and RCPs. All means and medians lie above zero providing strong indication of temperature rise all year-round. Only for the pre-monsoon (MAM) and for mountain stations, some whiskers extend below zero. Average Δ*t*max across all regions is highest for the mountains at 8°C in the winter (DJF) and lowest at 0.4°C in the monsoon (JJAS). The average annual Δ*t*max, ranging 0.5–5.3°C across the mountains and 0.8–4.5°C across the hills and plains are well representative of seasonal changes.

Figure 12 summarizes the changes in average annual Δpr (green) and Δ*t*max (brown/yellow), with red line in each bar chart distinguishing the RCP 4.5 and RCP 8.5 scenarios. Trends in annual Δpr and Δ*t*max across the various scenarios are similar for the stations in the same region. The average annual Δpr ranges from −14.1 to 16.7%, for mountain, −10.3 to 20.7% for hill and −23.8 to 16.4% for plain. Average annual Δpr is negative only for the last bar in each chart for RCP8.5_Far_HighRisk, the only valid high-risk scenario representing dry conditions. Across all regions average seasonal Δpr values (−51.6 to 196.8%) are much higher and variable than annual values (−23.8 to 20.7%). Increasing trends in average annual Δ*t*max across the climate scenarios and stations are similar. Average annual Δ*t*max ranging around 0.5–5.3°C is highest for the mountain, with higher values for RCP 8.5 than RCP 4.5 farther in the future. These spatial variations are consistent with prior observation based on raw RCM data that Δpr appears more prominent in the Tarai while Δ*t*max is more prominent in the mountains.

Presented projections at the nine stations reiterate the spatiotemporal variation in climate even over short distances in heterogeneous terrains. Stations 202 and 303 lie about 120 km apart in the mountains but show difference in seasonal change for both precipitation (Figure 11a) and temperature (Figure 11b). Pattern in station 104 in the hill is similar to that of the mountain stations at similar elevations; though station 514 at higher elevation follows patterns in other hill stations. Scientific advances leading to increase in reliability and resolution of satellite-based climate data and RCMs will be key to ensure future climate assessments can better capture these variations induced by complex topography and microclimates across the over 50,000 km^2 span of Western Nepal.

3.3.4 | Impact assessment study

Figure 12 presents the SWAT simulated percentage changes in average annual discharge ΔQ (blue) at five discharge stations under the 10 climate scenarios. The stations show varying level of sensitivity to change in precipitation and temperature. Specifically, station 215 in the mountain region shows higher increases with ΔQ varying from 48.2 to 63.8% while downstream station like 280 show minimal changes ranging from 01.6 to 11.6%. Maximum decline in discharge is seen in station 220 at −19.1% for the RCP

TABLE 8 Range in seasonal and annual average Δpr and Δ*t*max values across meteorological stations in the three regions. Stations considered within each region are presented in brackets

	DJF	MAM	JJAS	ON	Annual
Mean Δpr (%)					
Mountain (202, 303)	−45.7 to 43.2%	−41.8 to 73.8%	−3.1 to 22.3%	−51.6 to 104%	−14.1 to 16.7%
Hill (104, 406, 513, 514)	−32.5 to 47.7%	−29.7 to 54.5%	−6.9 to 22.9%	−45.7 to 196.8%	−10.3 to 20.7%
Plain (209, 207, 405)	−41.1 to 62.5%	−46.8 to 54.3%	−21 to 14.8%	−46.5 to 123.4%	−23.8 to 16.4%
Mean Δ*t*max (°C)					
Mountain (202, 303)	1.1 to 8.0°C	0.5 to 7.0°C	0.4 to 4.1°C	0.1 to 4.2°C	0.5 to 5.3°C
Hill (104, 406, 513, 514)	0.9 to 5.8°C	1.0 to 5.8°C	0.7 to 3.8°C	0.6 to 4.1°C	0.8 to 4.5°C
Plain (209, 207, 405)	1.1 to 5.8°C	0.6 to 5.7°C	0.6 to 3.4°C	0.5 to 4.0°C	0.8 to 4.5°C

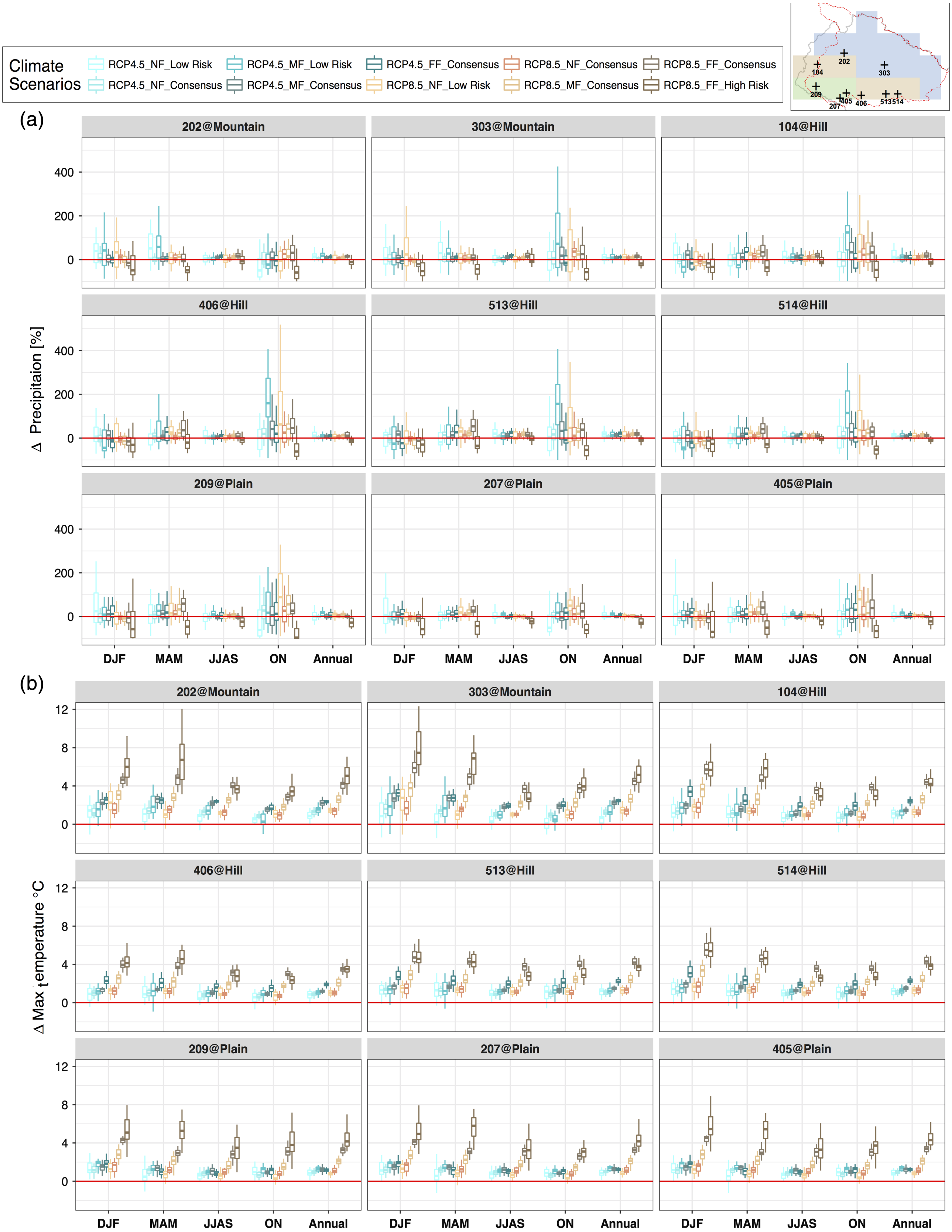


FIGURE 11 Projected changes in of long-term seasonal averages for (a) total precipitation in (%) and (b) maximum temperature in (°C) for the 10 climate scenarios at nine meteorological stations. Change evaluated with respect to historical RCM ensemble corresponding to each climate scenario. See Figure 10 for legend mapping colours to different climate scenarios. Edges of the box plot indicates interquartile range (IQR), interior line indicates median and whiskers indicate lower of ±1.5*IQR or max/min data values. Colours differentiate the five RCP 4.5 scenarios (in shades of blue) and five RCP 8.5 scenarios (in shades of brown). Refer to web version of the figure for color references [Colour figure can be viewed at wileyonlinelibrary.com]

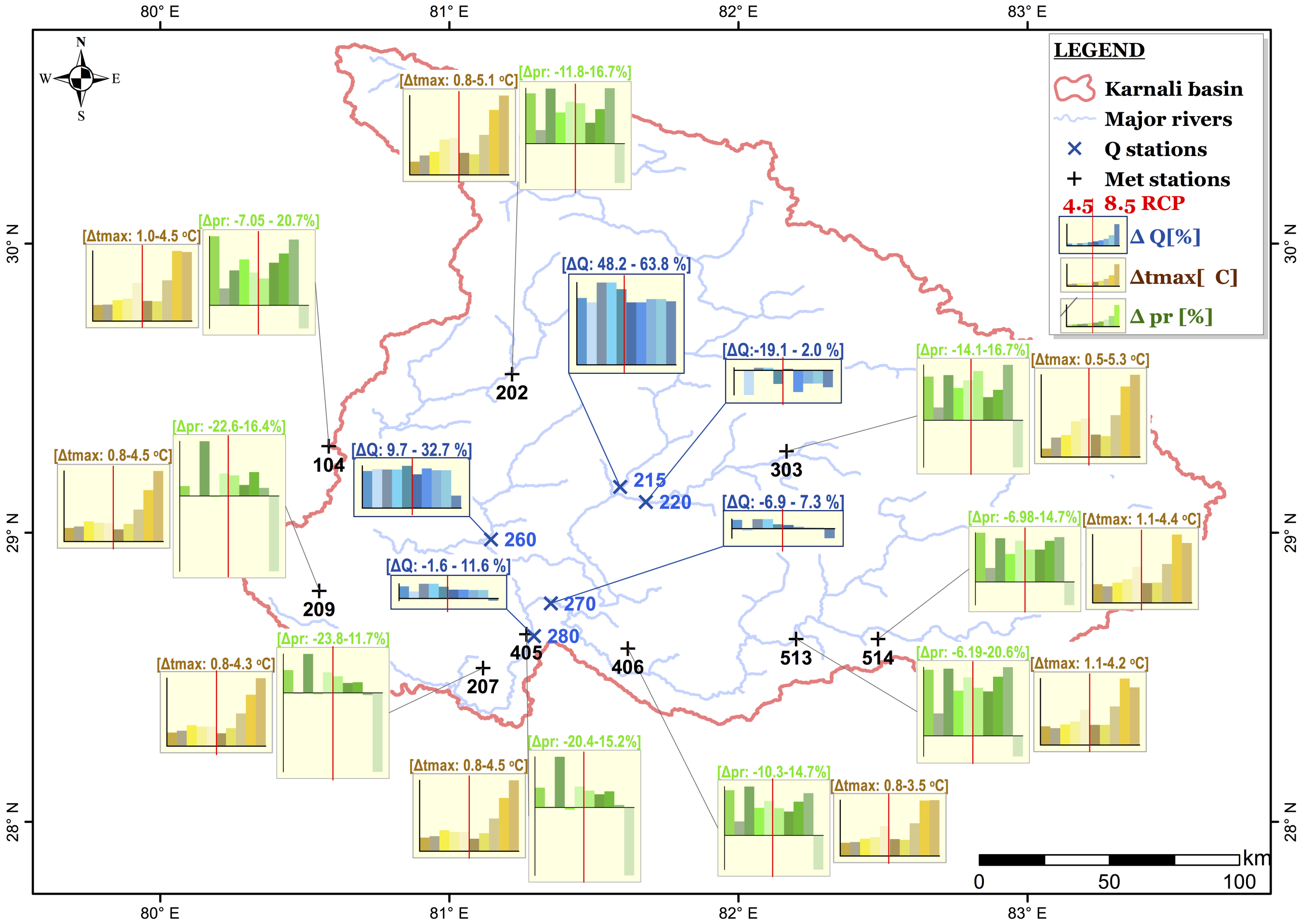


FIGURE 12 Green and brown bar charts show changes in average annual total precipitation (Δpr) and maximum temperature (Δ*t*max) respectively based on bias-corrected multi-RCM ensembles generated for ten climate scenarios at the nine meteorological stations. Blue bar charts show change in annual average discharge (ΔQ) at five discharge stations simulated by the SWAT model for the ten climate scenarios. Value range in each bar chart and unit is indicated above the chart. Order of climate scenarios in bar charts from left to right is: RCP4.5_NF_Low Risk, RCP4.5_NF_Consensus, RCP4.5_MF_Low Risk, RCP4.5_MF_Consensus, RCP4.5_FF_Consensus, RCP8.5_NF_Low Risk, RCP8.5_NF_Consensus, RCP8.5_MF_Consensus, RCP8.5_FF_Consensus, RCP8.5_FF_High Risk [Colour figure can be viewed at wileyonlinelibrary.com]

4.5_NF_Consensus scenario. Stations 220, 270 and 280 appear more resilient to climate change than others at an annual scale. Such difference in response of Q stations to Δpr may relate to location of station along the river. Rising temperatures across the region will increase evapotranspiration, which may explain low ΔQ values in downstream stations given high Δ*t*max for RCP 8.5 scenarios. In RCP8.5_FF_HighRisk, the decline in precipitation across all meteorological stations, simulated decline in discharge only in stations 220, 270 and 280, suggesting that they are rainfed. The increasing and decreasing trends seen at station 220 and 270 across the different scenarios requires further exploration of the water balance components and upstream-downstream linkages. Such rigorous analysis of sub-annual changes and uncertainties in water balance components is presented in Pandey *et al.* (2018).

3.4 | Uncertainty in the CF framework

The IPCC reports "*low confidence* in projections of many aspects of climate phenomena that influence regional climate change" due to the coarse model resolution and limited scientific understanding of aerosol and cloud processes that are key drivers of climate change (Pg. 115 in Stocker *et al.*, 2013). As seen in Figure 10, the bias in precipitation is more complex than temperature bias, potentially due to the complexities of the governing orographic processes of cloud formation. Bias from limitations in existing RCM and GCMs are hard to resolve only by statistical methods (Flato *et al.*, 2013; Sanjay *et al.*, 2017a). Such model uncertainties become more important at regional and sub-regional scale considered here. Multi-model and multi-scenario analysis using the CF framework is one alternative to consider both model and scenario uncertainties in climate impact assessments (Knutti *et al*., 2010; Stocker *et al*., 2013).

The CF framework inherently assumes spread in model projections as the only measure of uncertainty and consensus between models as the measure of confidence in the representative climate future. As such, the CF matrix does not provide a measure of total uncertainty. The framework is also sensitive to the models included in the initial ensemble; also, included models may not be independent of each other (Knutti *et al*., 2010). This may exacerbate known biases in CORDEX-SA RCM families and limitations in application of RCMs to finer scales.

The use of raw projections for generating the CF matrices is also contentious. The extent to which past performance of RCMs should be given importance in gauging confidence in future projections is a debate that extends beyond this paper (Wilby, 2010; Flato *et al*., 2013; Whetton *et al*., 2016). Lutz *et al*. (2016) also highlight this difficulty and suggest reordering the steps in their model selection approach to suit user preference. However, the similarity in projection trends in Figure 3 (raw RCMs) and in Figure 11 (bias-corrected RCMs) provides some validation that RCM selection using the raw projection-based CF matrix is reasonable. Nonetheless, raw RCM data should only be used as a first step in grouping RCMs into ensembles. Investigation of past performance and bias correction of selected RCMs to remove models with significantly poor performance is necessary. Further investigation of biases, including impact of CF matrix on biases propagation will be addressed in forthcoming papers.

The spatial scale of application is also debatable. While finer scale is desirable here, working with only a few grids may introduce physical inconsistencies, and inflate RCM uncertainties as explored by Madsen *et al*. (2017). For the case of Western Nepal, the mountain covers majority of the basin while only three grids form the Tarai plains. Combining the hill and plain for future iteration may be desirable. The suitability of using the mountain, hill and plain regions defined by the national Department of Survey as climatic zones also needs to be analysed as projections and biases vary stronger with elevation. In addition, projections discussed here for climate change in Western Nepal may not be generalizable for other parts of the country.

The CF matrices developed here uses annual scale projections. The seasonal analysis of bias-corrected projections plausibly show that the seasonal precipitation signals are not be well reflected by annual averages. Table 5 comparing annual changes reported in literature for the HKH with values obtained for Western Nepal, shows that the spatio-temporal averages can be misleading as decreasing and increasing rainfall signals cancel out providing low values for annual changes. For impact assessments sensitive to climate seasonality, such as flood prediction, extreme analysis etc., CF matrices based on sub-annual changes will be better. Further analysis of seasonal climate change and its impact on different sectors is being conducted and will be presented in the next paper.

3.5 | Climate futures as decision support tools

Though various uncertainties limit the credibility of RCMs, especially at local scales, these represent the best efforts we have. Additionally, changes in the future due to non-physical and anthropogenic activities are hard to capture. The CF framework can be a valuable decision support tool bridging the gap between credibility and usability of climate projection. Many practitioners still prefer traditional single projection measures such as means and median (Whetton *et al*., 2016). Simpler products, like the Climate Futures for Western Nepal presented here, can deliver climate projections and uncertainties in forms that resonate with users, while not requiring them to process large RCM datasets on their own (Whetton *et al*., 2016). The framework provides a middle ground whereby users can still think in terms of single projections while scientists provide some measure of uncertainty visualized in the form of model spread. Better visualization showing how climate change will vary over time under various RCPs is another way to push decision-makers towards measures that minimize such changes. Figures 3, 5–7 visualize essentially the same data with additional layers of information to make decision-makers aware of their model selection process. Additional screening of model can also be done after the CF matrices if desirable (Clarke *et al*., 2011). User-friendly tools like the CF matrices can be a basis for improvement and uptake of RCMs for conducting a robust assessment of climate impacts.

4 | CONCLUSIONS

Using projections of 19 different CORDEX-SA RCMs to develop 18 CF matrices and 10 plausible CF scenarios for long-term water resources planning, this study provides the first comprehensive RCM selection framework for Western Nepal for generating region and application-specific climate projections. We characterize the spatiotemporal variability in future climate across three regions (mountain, hill and plains) of the Karnali basin and evaluate RCM performance for the same. The 10 plausible climate scenarios identified from the 18 CF matrices suggest that high-risk scenarios, with drier and warmer climates, are more likely to occur in the Tarai plains than in the mountain.

For Western Nepal, RCM projections capture spatial variation. The magnitudes of change in climate across the three regions vary, with higher correlation between changes in hills and plains. Under RCP 4.5 and 8.5, the hill and plain show greater variability in both magnitude and direction of change in rainfall. Increases in temperature are projected across all three regions, with higher Δ*t*min/max for mountains than hills and Tarai. Projected precipitation shows increasing variability in both directions (wet and dry) further into the future. Comparison of raw projections with that for the greater HKH from literature indicates that values for Western Nepal are generally higher with wider ranges even at annual scale. Spatial disaggregation is thus necessary to identify sub-basin scale change in climate, especially precipitation, for areas like Western Nepal that show high degree of spatial heterogeneity and prevalence of microclimates. Use of coarser national or regional scale averages may underestimate local changes, which are better resolved in RCMs.

Assessment of biases across the nine meteorological stations in Karnali show that precipitation bias varies with elevation, location and season, while temperature bias varies with spatial location. RCM projections consistently show wet bias in the winter across all regions. In the monsoon, there is wet bias in the mountain stations and dry bias in the plain stations. While RCM performances need improvement, it is shown that quantile-mapping performs well for bias correction across all RCMs. The location-sensitive RCM biases highlight the need for location-specific bias correction in heterogeneous terrains. Stations data may thus be more important for bias correction of projections from RCMs than GCMs.

Across Karnali stations, the bias-corrected Δpr project highest values and spread for the post-monsoon season (JJAS), especially in the hills, indicating a potential shift in rainfall pattern with prolonged monsoon and sporadic intense rain events likely even in drier months. Average seasonal Δpr values (−51.6 to 196.8%) are much higher and variable than annual values (−23.8 to 20.7%). The average annual Δ*t*max, ranging around 0.5–5.3°C across the mountains and 0.8 to 4.5°C across the hills and plains are well representative of seasonal changes. Based on raw and bias-corrected RCM projections for RCP 4.5 and 8.5, it can be concluded that farther in the future, the hills and plains will see most fluctuation in precipitation while the mountains will see highest increases in temperature. Spatial variation in temperature is projected to be narrower, but absolute values for minimum and maximum temperature may increase. The lack of definite direction in precipitation change will be key challenge in management of climate risks.

Evaluation of future water availability in Karnali under the 10 plausible CFs showed that changes in average annual discharge at five discharge stations are not consistent with changes in annual precipitation and temperature. Discharge stations 215, 260 and 280 simulate increasing average annual ΔQ across all scenarios while stations 220 and 270 simulate variable average annual ΔQ ranging from −19.1 to 7.3%. Downstream discharge stations appear more climates resilient with limited changes in ΔQ. Further analysis of water balance components at sub-annual and seasonal scale and its implication is provided in concurrent paper.

A thorough understanding of the spatiotemporal variation in future climate is essential to build climate-resilient ecosystems. It is demonstrated that the CF framework provides a systematic basis to create multi-modal climate scenario ensembles for a robust scenario-based impact assessment by consciously sampling a subsection of all available projections that capture the most relevant climate risks. More importantly, the use of the CF framework for RCM selection can bring about the realization that climate projections should not be considered deterministic. Ideally, the CF will also motivate practitioners to delve deeper, performing additional analysis of uncertainty and biases in projections for a more manageable number of datasets that are directly relevant to their application. As many governments in the global south push for large infrastructure projects and rapid urbanization plans for development similar to the case of Western Nepal, the CF framework can support robust climate change impact assessments to identify climate-resilient development pathways. While an annual scale CF framework is deemed sufficient for long-term water resources management considered in this study, an impact assessment sensitive to seasonal changes should replicate the method to develop monthly or seasonal CF matrices to better capture the seasonal risks and uncertainties.

ACKNOWLEDGEMENTS

This research is supported by: (i) the Sustainable, just and productive water resources development in Western Nepal (DJB) project under the generous support of the American people through the United States Agency for International Development (USAID); and (ii) GRANT: 0358-NEP-Building Climate Resilience of Watersheds in Mountain Eco-regions (BCRWME)—Package 2: Watershed Hydrology Impact Monitoring Research project, between IWMI and the Department of Soil Conservation and Watershed Management, supported by the Asian Development Bank, Nordic Development Fund and Climate Investment Fund. The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government. We acknowledge the World Climate Research Programme's Working Group on Regional Climate, and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5. We also thank the climate modelling groups (listed in Table 1) for producing and making available their model output. We also acknowledge the Earth System Grid Federation infrastructure an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling and other partners in the Global Organization for Earth System Science Portals (GO-ESSP). Lastly, we thank the two anonymous reviews for their comments that helped improve and tighten up the manuscript to its final form.

ORCID

Sanita Dhaubanjar https://orcid.org/0000-0003-2974-0427
Vishnu Prasad Pandey https://orcid.org/0000-0001-5258-7446
Luna Bharati https://orcid.org/0000-0002-6218-3282

REFERENCES

Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., Haney, E.B., and Neitsch, S.L. (2012) *Soil & Water Assessment Tool: Introductory Manual*. College Station, Texas: Texas A&M, AgriLife Research.

Bajracharya, A.R., Bajracharya, S.R., Shrestha, A.B. and Maharjan, S. B. (2018) Climate change impact assessment on the hydrological regime of the Kaligandaki Basin, Nepal. *Science of the Total Environmen*, 625, 837–848. https://doi.org/10.1016/j.scitotenv.2017.12.332.

Bajracharya, S.R., Palash, W., Shrestha, M.S., et al. (2015) Systematic evaluation of satellite-based rainfall products over the Brahmaputra basin for hydrological applications. *Advances in Meteorology*, 2015, 1–17. https://doi.org/10.1155/2015/398687.

Bharati, L., Gurung, P., Jayakody, P., et al. (2014) The projected impact of climate change on water availability and development in the Koshi. *Mountain Research and Development*, 34, 118–130.

Bookhagen, B. and Burbank, D.W. (2010) Toward a complete Himalayan hydrological budget: spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *Journal of Geophysical Research - Earth Surface*, 115, 1–25. https://doi.org/10.1029/2009JF001426.

Choudhary, A. and Dimri, A.P. (2018) Assessment of CORDEX-South Asia experiments for monsoonal precipitation over Himalayan region for future climate. *Climate Dynamics*, 50, 3009–3030. https://doi.org/10.1007/s00382-017-3789-4.

Christensen, J.H., Kumar, K.K., Aldrian, E., et al. (2013) Climate phenomena and their relevance for future regional climate change. In: Stocker, T.F., Qin, D., Plattner, G.-K., et al. (Eds.) *Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY: Cambridge University Press, pp. 1217–1308.

Clarke, J.M., Whetton, P.H. and Hennessy, K.J. (2011) Providing application-specific climate projections datasets: CSIRO's climate futures framework. In: *MODSIM2011, 19th International Congress on Modelling and Simulation*. Canberra, Australia: Modelling and Simulation Society of Australia and New Zealand Inc (MSSANZ), pp. 2683–2687. http://www.mssanz.org.au/modsim2011/F5/clarke.pdf.

CSIRO and Bureau of Meteorology, (BOM)(2018) *Module 4: Climate Futures Framework*. Available at: https://www.climatechangeinaustralia.gov.au/en/climate-campus/online-training/climate-futures-framework/ [Accessed 14th May, 2018.

CSIRO and BOM (2015) *Climate Change in Australia: Technical Report*. Australia: CSIRO and Bureau of Meteorology.

Devkota, L.P., Gyawali, R. and Gyawali, D.R. (2015) Impacts of climate change on hydrological regime and water resources management of the Koshi River basin, Nepal. *Journal of Hydrology: Regional Studies*, 4, 502–515. https://doi.org/10.1016/j.ejrh.2015.06.023.

Flato, G., Marotzke, J., Abiodun, B., et al. (2013) Evaluation of climate models. In: Stocker, T.F., Qin, D., Plattner, G.-K., et al. (Eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge United Kingdom and New York, NY: Cambridge University Press, pp. 741–866.

Gautam, M.R. and Acharya, K. (2012) Streamflow trends in Nepal. *Hydrological Sciences Journal*, 57, 344–357. https://doi.org/10.1080/02626667.2011.637042.

Ghaju, S. and Alfredsen, K. (2012) Evaluation of satellite based precipitations and their applicability for rainfall runoff modelling in Narayani Basin of Nepal. *Journal of Hydrology and Meteorology*, 8, 22. https://doi.org/10.3126/jhm.v8i1.15569.

Ghimire, S., Choudhary, A. and Dimri, A.P. (2015) Assessment of the performance of CORDEX-South Asia experiments for monsoonal precipitation over the Himalayan region during present climate: part I. *Climate Dynamics*, 50, 2–4. https://doi.org/10.1007/s00382-015-2747-2.

Giorgi, F., Coppola, E., Solmon, F., et al. (2012) RegCM4: model description and preliminary tests over multiple CORDEX domains. *Climate Research*, 52, 7–29. https://doi.org/10.3354/cr01018.

Giorgi, F. and Gutowski, W.J. (2016) Coordinated experiments for projections of regional climate change. *Current Climate Change Reports*, 2, 202–210. https://doi.org/10.1007/s40641-016-0046-6.

Gudmundsson, L., Bremnes, J.B., Haugen, J.E. and Engen-Skaugen, T. (2012) Technical note: downscaling RCM precipitation to the station scale using statistical transformations – a comparison of methods. *Hydrology and Earth System Sciences*, 16, 3383–3390. https://doi.org/10.5194/hess-16-3383-2012.

ICIMOD (2012). *Land Cover of Nepal 2010 [Dataset]*. International Center for Integrated Mountain Development (ICIMOD). Available at: http://rds.icimod.org/Home/DataDetail?metadataId=9224 [Accessed 1st January 2015].

Immerzeel, W.W., van Beek, L.P.H., Konz, M., et al. (2012) Hydrological response to climate change in a glacierized catchment in the Himalayas. *Climatic Change*, 110, 721–736. https://doi.org/10.1007/s10584-011-0143-4.

Ives, J.D., Shrestha, R.B., and Mool, P.K. (2010) *Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment*. Kathmandu: International Centre for Integrated Mountain Development.

IWMI. (2018a) *Hydropower and Irrigation Projects in Western Nepal*. Digo Jal Bikas: International Water Management Institute (IWMI).

IWMI (2018b). *Sustainable, Just and Productive Water Resources Development in Western Nepal (Digo Jal Bikas)*. Available at: http://djb.iwmi.org/ [Accessed 15th May 2018].

Jarvis, A., Reuter, H.I., Nelson, A., and Guevara, E. (2008) Hole-Filled Seamless SRTM Data V4. Available at: http://srtm.csi.cgiar.org [Accessed 20th August 2015].

Karmacharya, J., Shrestha, A., Rajbhandari, R. and Shrestha, M.L. (2007) *Climate Change Scenarios for Nepal Based on Regional Climate Model RegCM3*. Kathmandu: Department of Hydrology and Meteorology, pp. 1–35.

Khatiwada, K., Panthi, J., Shrestha, M. and Nepal, S. (2016) Hydro-climatic variability in the Karnali River basin of Nepal Himalaya. *Climate*, 4, 17. https://doi.org/10.3390/cli4020017.

Knutti, R., Abramowitz, G., Collins, M., Eyring, V., Gleckler, P.J., Hewitson,B., and Mearns, L. (2010) Good practice guidance paper on assessing and combining multi model climate projections. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., and Midgley, P.M. (Eds.) *Expert Meeting on Assessing and Combining Multi Model Climate Projections*. Bern, Switzerland: IPCC Working Group I Technical Support Unit, University of Bern, p. 15.

Krakauer, N.Y., Pradhanang, S.M., Lakhankar, T. and Jha, A.K. (2013) Evaluating satellite products for precipitation estimation in mountain regions: a case study for Nepal. *Remote Sensing*, 5, 4107–4123. https://doi.org/10.3390/rs5084107.

Kundzewicz, Z.W. and Stakhiv, E.Z. (2010) Are climate models “ready for prime time” in water resources management applications, or is more research needed? *Hydrological Sciences Journal*, 55, 1085–1089. https://doi.org/10.1080/02626667.2010.513211.

Lafon, T., Dadson, S., Buys, G. and Prudhomme, C. (2013) Bias correction of daily precipitation simulated by a regional climate model: a comparison of methods. *International Journal of Climatology*, 33, 1367–1381. https://doi.org/10.1002/joc.3518.

Lutz, A.F., ter Maat, H.W., Biemans, H., et al. (2016) Selecting representative climate models for climate change impact studies: an advanced envelope-based selection approach. *International Journal of Climatology*, 36, 3988–4005. https://doi.org/10.1002/joc.4608.

Mcgregor, J., Veldore V., Thatcher M., Hoffmann P., Katzfey J., Nguyen K. (2013) CCAM simulations for CORDEX South Asia. In: CORDEX Workshop. 28 August 2013. Kathmandu, Nepal: CSIRO Marine and Atmospheric Research.

Madsen, M.S., Langen, P.L., Boberg, F. and Christensen, J.H. (2017) Inflated uncertainty in multimodel-based regional climate projections. *Geophysical Research Letters*, 44, 11,606–11,613. https://doi.org/10.1002/2017GL075627.

McGregor, J.L. and Dix, M.R. (2001) The csiro conformal-cubic atmospheric GCM. *Fluid Mech its Appl*, 61, 197–202. https://doi.org/10.1007/978-94-010-0792-4_25.

Mcsweeney, C., New, M., and Lizcano, G. (2010a). *UNDP Climate Change Country Profiles: Nepal*. New York, NY: United Nations Development Programme. Available at: http://country-profiles.geog.ox.ac.uk [Accessed 13th May 2018].

McSweeney, C., New, M., Lizcano, G. and Lu, X. (2010b) The UNDP climate change country profiles improving the accessibility of observed and projected climate information for studies of climate change in developing countries. *Bulletin of the American Meteorological Society*, 91, 157–166. https://doi.org/10.1175/2009BAMS2826.1.

McSweeney, C.F., Jones, R.G. and Booth, B.B.B. (2012) Selecting ensemble members to provide regional climate change information. *Journal of Climate*, 25, 7100–7121. https://doi.org/10.1175/JCLI-D-11-00526.1.

Mishra, Y., Nakamura, T., Babel, M.S., et al. (2018) Impact of climate change on water resources of the Bheri River basin, Nepal. *Water*, 10, 220. https://doi.org/10.3390/w10020220.

Moufouma-Okia, W. and Jones, R. (2014) Resolution dependence in simulating the African hydroclimate with the HadGEM3-RA regional climate model. *Climate Dynamics*, 44, 609–632. https://doi.org/10.1007/s00382-014-2322-2.

Mukherjee, S., Hazra, A., Kumar, K., Nandi, S.K. and Dhyani, P.P. (2017) Simulated projection of ISMR over Indian Himalayan region: assessment from CSIRO-CORDEX South Asia experiments. *Meteorology and Atmospheric Physics*, 131, 1–17. https://doi.org/10.1007/s00703-017-0547-4.

Müller, M.F. and Thompson, S.E. (2013) Bias adjustment of satellite rainfall data through stochastic modeling: methods development and application to Nepal. *Advances in Water Resources*, 60, 121–134. https://doi.org/10.1016/j.advwatres.2013.08.004.

Nengker, T., Choudhary, A. and Dimri, A.P. (2017) Assessment of the performance of CORDEX-SA experiments in simulating seasonal mean temperature over the Himalayan region for the present climate: part I. *Climate Dynamics*, 0, 1–31. https://doi.org/10.1007/s00382-017-3597-x.

Palazzi, E., von Hardenberg, J. and Provenzale, A. (2013) Precipitation in the Hindu-Kush Karakoram Himalaya: observations and future scenarios. *Journal of Geophysical Research – Atmospheres*, 118, 85–100. https://doi.org/10.1029/2012JD018697.

Pandey VP, Dhaubanjar S, Bharati L, Thapa BR (2018) *Climate Change Impacts on Spatio-Temporal Distribution of Water Availability in Karnali-Mohana Basin*. Manuscript Under Submission.

Pandey, V.P., Dhaubanjar, S., Bharati, L. and Thapa, B.R. (2019) Hydrological response of Chamelia watershed in Mahakali Basin to climate change. *Science of the Total Environment*, 650, 365–383. https://doi.org/10.1016/J.SCITOTENV.2018.09.053.

Peña-Arancibia, J.L., van Dijk, A.I.J.M., Renzullo, L.J. and Mulligan, M. (2013) Evaluation of precipitation estimation accuracy in reanalyses, satellite products, and an ensemble method for regions in Australia and south and East Asia. *Journal of Hydrometeorology*, 14, 1323–1333. https://doi.org/10.1175/JHM-D-12-0132.1.

Riahi, K., Grübler, A., and Nakicenovic, N. (2007) *Scenarios of Long-Term Socio-Economic and Environmental Development under Climate Stabilization*. Technol Forecast Soc Change, 74, 887–935. https://doi.org/10.1016/j.techfore.2006.05.026

Rummukainen, M., Rockel, B., Bärring, L., et al. (2015) Twenty-first-century challenges in regional climate modeling. In: *Bulletin of the American Meteorological Society*. Boston, MA: American Meteorological Society, pp. 135–138.

Samuelsson, P., Jones, C.G., Willén, U., et al. (2011) The Rossby Centre regional climate model RCA3: model description and performance. *Tellus: Series A, Dynamic Meteorology and Oceanography*, 63, 4–23. https://doi.org/10.1111/j.1600-0870.2010.00478.x.

Sanjay, J., Krishnan, R., Shrestha, A.B., et al. (2017a) Downscaled climate change projections for the Hindu Kush Himalayan region using CORDEX South Asia regional climate models. *Advances in Climate Change Research*, 8, 185–198. https://doi.org/10.1016/j.accre.2017.08.003.

Sanjay, J., Ramarao, M.V.S., Mujumdar, M. and Krishnan, R. (2017b, 2017) Regional climate change scenarios. In: Rajeevan, M.N. and Nayak, S. (Eds.) *Observed Climate Variability and Change over* *the Indian Region*. Singapore: Springer G. Springer Science+Business Media, pp. 285–305.

Sharma, R.H. and Awal, R. (2013) Hydropower development in Nepal. *Renewable and Sustainable Energy Reviews*, 21, 684–693. https://doi.org/10.1016/j.rser.2013.01.013.

Shiwakoti, S. (2017) *Hydrological Modeling and Climate Change Impact Assessment Using HBV Light Model: A Case Study of Karnali River Basin*. In: XVI World Water Congress, Cancun, Mexico. Paris, France: International Water Resources Association (IWRA), pp 1–19. Page

Shrestha, H., Bhattarai, U., Dulal, K.N., Adhikari, S., Marahatta, S., and Devkota, L.P. (2015) Impact of climate change on precipitation in the Karnali basin. In: Shrestha, D., Regmi, S.K., Kayastha, R.B. (Eds.) *National Symposium on Hydrology and Meteorology. Nepal, Kathmandu*, p A-7.

Shrestha, S., Khatiwada, M., Babel, M.S. and Parajuli, K. (2014) Impact of climate change on river flow and hydropower production in Kulekhani hydropower project of Nepal. *Environmental Processes*, 1, 231–250. https://doi.org/10.1007/s40710-014-0020-z.

Siddiqui, S., Bharati, L., Pant, M., Gurung, P., Rakhal, B. and Maharjan, D.L. (2012) *Climate Change and Vulnerability Mapping in Watersheds in Middle and High Mountains of Nepal*. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Stocker, T.F., Qin, D., Plattner, G.K., Alexander,L.V., Allen, S.K., Bindoff, N.L., Bréon,F.M., Church, J.A., Cubasch, U., Emori, S., Forster, P., Friedlingstein, P., Gillett,N., Gregory, J.M., Hartmann, D.L., Jansen, E., Kirtman, B., Knutti, R., KrishnaKumar, K., Lemke, P., Marotzke, J., Masson-Delmotte, V., Meehl, G.A., Mokhov, I.I.,Piao, S., Ramaswamy, V., Randall, D., Rhein, M., Rojas, M., Sabine, C., Shindell,D., Talley, L.D., Vaughan D.G., and Xie, S.P. (2013) Technical summary. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (Eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press*, pp. 33–115.

Thevakaran, A., McGregor, J. L., Katzfey, J., Hoffmann, P., Suppiah, R., & Sonnadara, D. U. J. (2015) An assessment of CSIRO Conformal Cubic Atmospheric Model simulations over Sri Lanka. *Climate Dynamics*, 46(5–6), 1861–1875. https://doi.org/10.1007/s00382-015-2680-4.

Teichmann, C., Eggert, B., Elizalde, A., et al. (2013) How does a regional climate model modify the projected climate change signal of the driving GCM: a study over different CORDEX regions using REMO. *Atmosphere (Basel)*, 4, 214–236. https://doi.org/10.3390/atmos4020214.

Teutschbein, C. and Seibert, J. (2012) Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods. *Journal of Hydrology*, 457, 12–29. https://doi.org/10.1016/j.jhydrol.2012.05.052.

Themeßl, M.J., Gobiet, A. and Heinrich, G. (2012) Empirical-statistical downscaling and error correction of regional climate models and its impact on the climate change signal. *Climatic Change*, 112, 449–468. https://doi.org/10.1007/s10584-011-0224-4.

Thiemig, V., Rojas, R., Zambrano-Bigiarini, M. and De Roo, A. (2013) Hydrological evaluation of satellite-based rainfall estimates over the Volta and Baro-Akobo Basin. *Journal of Hydrology*, 499, 324–338. https://doi.org/10.1016/j.jhydrol.2013.07.012.

van Vuuren, D.P., Edmonds, J., Kainuma, M., et al. (2011) The representative concentration pathways: an overview. *Climatic Change*, 109, 5–31. https://doi.org/10.1007/s10584-011-0148-z.

Weaver, C.P., Lempert, R.J., Brown, C., et al. (2013) Improving the contribution of climate model information to decision making: the value and demands of robust decision frameworks. *Wiley Interdisciplinary Reviews: Climate Change*, 4, 39–60. https://doi.org/10.1002/wcc.202.

Whetton, P., Hennessy, K., Clarke, J., et al. (2012) Use of representative climate futures in impact and adaptation assessment. *Climatic Change*, 115, 433–442. https://doi.org/10.1007/s10584-012-0471-z.

Whetton, P.H., Grose, M.R. and Hennessy, K.J. (2016) A short history of the future: Australian climate projections 1987–2015. *Clim. Serv.*, 2–3, 1–14.

Wilby, R.L. (2010) Evaluating climate model outputs for hydrological applications. *Hydrological Sciences Journal*, 55, 1090–1093. https://doi.org/10.1080/02626667.2010.513212.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Dhaubanjar S, Prasad Pandey V, Bharati L. Climate futures for Western Nepal based on regional climate models in the CORDEX-SA. *Int J Climatol*. 2019;1–25. https://doi.org/10.1002/joc.6327

Annex 3-1

Geoforum 96 (2018) 70–76

Contents lists available at ScienceDirect

Geoforum

journal homepage: www.elsevier.com/locate/geoforum

The politics of river basin planning and state transformation processes in Nepal

Diana Suhardiman[a,*], Ram C. Bastakoti[b], Emma Karki[b], Luna Bharati[c]

[a] International Water Management Institute, Southeast Asia Regional Office, P.O. Box 4199, Vientiane, Lao Democratic People's Republic
[b] International Water Management Institute, Nepal
[c] International Water Management Institute, Germany

ARTICLE INFO

Keywords:
Power struggles
Bureaucratic territory
Water resources planning
Sectoral egoism
Federalism
Nepal

ABSTRACT

Since the late 1990s, river basin planning has become a central idea in water resources management and a mainstream approach supported by international donors through their water programs globally. This article presents river basin planning as a function of power and contested arena of power struggles, where state actors create, sustain, and reproduce their bureaucratic power through the overall shaping of (imagined) bureaucratic territory. It argues that river basin planning is not an antidote to current 'dysfunction' in water resources management, rooted in overlapping jurisdictions, fragmented decision making, and bureaucratic competitions between various government agencies. On the contrary, it illustrates how river basin planning becomes a new 'territorial frontier', created and depicted by different government agencies as their envisioned operational boundary and as a means to sustain and increase their bureaucratic power and sectoral decision-making authority, amidst ongoing processes of federalism in Nepal.

1. Introduction

With the introduction of Integrated Water Resources Management (IWRM) concept globally (Biswas, 2008; Chikozho, 2008; Dombrowsky, 2008; McDonnell, 2008), water resources management policies in both developed and developing countries have been geared towards river basin approaches, while positioning the basin as the envisioned scale for integrated water resources planning, development, and management (Merrey, 2008; Molle, 2008). Supported both discursively and financially by major international donors such as the World Bank (WB) and the Asian Development Bank (ADB) as well as international organizations such as the Global Water Partnership, river basin approaches have become the dominant flagship and mainstream approach of global water programs (Butterworth et al., 2010; UNEP, 2012; UN-Water, 2008; van der Zaag, 2005). In Nepal, the idea of river basin planning was first initiated by Canadian International Development Agency (CIDA) (Suhardiman et al., 2015) and later also supported by other international donors including the ADB, United States Agency for International Development (USAID), and Department of Foreign Affairs and Trade (DFAT) of the Government of Australia.

This article looks at river basin planning processes in Nepal and how they are shaped and reshaped by state actors' sectoral development interests and strategies, while placing it within the wider trend to rescale environmental governance (Cohen, 2012; Cohen and Bakker, 2014; Harris and Alatout, 2010; McCarthy, 2005; Reed and Bruyneel, 2010). Cohen and Bakker (2014: 129) argue that this trend is driven by "*the desirability of 'depoliticizing decision making through alignment with ecological (rather than jurisdictional or geopolitical) boundaries*". Scholars have discussed this move towards 'watershed' approaches and its challenges in terms of accountability, public participation, and integration (Cohen, 2012; Cohen and Davidson, 2011). They have also brought to light how the current conceptualization of river basin planning views and positions river basin boundaries as natural boundaries, impenetrable by power relationships and power struggles (Allan, 2003; Blomquist and Schlager, 2005; Gyawali et al., 2006; Venot et al., 2011; Wester et al., 2003). Referring to these neglects of power structures and processes, scholars have urged the need to recognize that water resources management decisions are made based on political choices and contestation (Cohen and Bakker, 2014; Warner et al., 2008; Wester et al., 2003).

Building on this literature, we argue that while the idea of river basin planning and management fits with the need for better coordination and integration in water resources management (e.g. irrigation, hydropower, water supply infrastructure for domestic use, navigation, among others), rescaling the governance unit, in this case to basin level, would not automatically resolve the fundamental political

* Corresponding author.
E-mail addresses: d.suhardiman@cgiar.org (D. Suhardiman), r.bastakoti@cgiar.org (R.C. Bastakoti), e.karki@cgiar.org (E. Karki), l.bharati@cgiar.org (L. Bharati).

https://doi.org/10.1016/j.geoforum.2018.07.019
Received 3 May 2017; Received in revised form 4 December 2017; Accepted 25 July 2018
0016-7185/

questions. As stated by Blomquist and Schlager (2005, p. 102): "*The watershed does not resolve fundamental political questions about where the boundaries should be drawn, how participation should be structured, and how and to whom decision makers within a watershed are accountable.*" Drawing institutional boundaries is indeed a political act: "*Boundaries that define the reach of management activities determine who and what matters*" (p. 105).

River basin planning processes are shaped by power structures and relationships, manifested in bureaucratic competition between sectoral ministries, as well as overlapping operational boundaries between government agencies working across the different administrative levels (e.g. national, provincial, local). Linking river basin planning with state transformation processes in Nepal, this article shows that basin planning is not an antidote to current 'dysfunction' in water resources management, rooted in overlapping jurisdictions, fragmented decision making, and bureaucratic competition between the different segments of governments. On the contrary, it illustrates how river basin planning becomes a new 'territorial frontier', created and depicted by various government agencies as their envisioned operational boundary, amidst ongoing processes of federalism. Most importantly, it shows how government ministries' preference for basin planning approaches is rooted in their interest to preserve and increase their bureaucratic power and sectoral decision-making authority, through the framing of basin scale as the scale where the country's water resources should be governed, vis-à-vis ongoing processes of federalism to transfer decision making authority to provincial and local government bodies.

Building on Molle's (2009b) analysis on how the concept of river basin has been used by particular social groups or organizations to strengthen the legitimacy of their agendas, this article positions river basin planning as a function of power, contested territorial boundary, and arena of power struggles (Molle, 2009a; Warner et al., 2008), where state actors create, sustain, and reproduce their bureaucratic power through the overall shaping of (imagined) bureaucratic territory. As stated by Molle (2009a: 484): "*Beyond its relevance as a geographical unit for water resources development and management purposes, the river basin is also a political and ideological construct, with its discursive representations and justifications*". Here, river basin planning processes become an arena where government ministries compete for influence, jurisdiction and responsibility. Consequently, the basin becomes the newly envisioned, albeit overlapping, bureaucratic territory.

Based on a review of policy documents and legal frameworks, as well as series of in-depth semi-structured interviews conducted with respectively 12 government officials from various government agencies at the national level, 3 international donor representatives, and 5 civil society organizations, we highlight the central positioning of river basin planning approaches in different government ministries' policies and legal frameworks in Nepal. Next to these national level interviews conducted in Kathmandu, we carried out 11 semi-structured interviews with officials from the different government and non-government agencies at various administrative levels (provincial, district and municipality) within the boundary of Karnali and Mahakali basin as our study area. Through these interviews, we gather information on how the different actors perceive current challenges in water resources management and how they view river basin planning approaches as part of their strategies to cope with these challenges. Both series of interviews took place from December 2016 to March 2017. Interviews were transcribed word-for-word. Each transcription was coded using predefined nodes, including nodes defined by the first author before the fieldwork, and new nodes for information that emerged during the interviews. The coding process was done manually and designed in line with NVIVO 10 tool.

2. River basin as new territorial frontier for sectoral egoism

Scholars have highlighted the political characteristics of scale, and how it can be used to shape and reshape power structure and power relationship (Delaney and Leitner, 1997; McCarthy, 2005). Marston's (2000) conception of the politics of scale shows that scale is neither natural nor given, but is constantly shaped and reshaped as a result of contestation and power struggles by various actors. Or as stated by Newstead et al (2003: 486): Scale is usually defined as "*the temporary fixing of the territorial scope of particular modalities of power*". Similarly, Molle (2009a) shows how the choice to focus on specific scale (e.g. basin level) resembles not only the interests of those in power, but also the process of inclusion and exclusion. Cohen and Bakker's (2014: 131) define scales as "*fluid rather than fixed, constructed rather than pre-given, and political in both construction and function*". Scale has also been understood as an important dimension of the political opportunity structure available for political agents and social groups to resist (Staeheli, 1994).

This is in line with Harvey's modern adaptation of space, which reinforces 'spatiality' as not just a representation of human rationality but also as a tool for asserting particular rationalities (Hubbarb and Kitchin, 2011: 237). Like scale, space is therefore, "not absolute, …[but something that] depends on the circumstances" (Harvey, 2004: 3). Or, as stated by Lefebvre (2009: 186): "*These circumstances involve subject positions, or actors, who permeate and support the spatial constructs that designate social interactions*". Policy actors conceive of space in terms of their socio-economic, cultural and political positions within that space. Shome (2003: 40) asserts that space is neither a "metaphor" nor "backdrop" for these subjects but a flexible construction that emerges from human interactions, while simultaneously molding these interactions into a kind of spatialized reality.

Drawing upon the concept of the politics of scale and spatialized reality, this article presents river basin as (imagined) bureaucratic territory, shaped and reshaped by national government ministries' sectoral development interests, strategies, and changing perceptions of power. It illustrates how river basin planning as a concept has evolved from a holistic approach to integrate and coordinate sectoral ministries' development plans and activities in water resources management (e.g. irrigation, industry, drinking water, environmental conservation), to become a new territorial frontier, bureaucratic means and arena of power struggles.

The article contributes to the current discourse on river basin planning and rescaling governance in two ways. First, it shows how river basin planning could serve as a new territorial frontier for sectoral egoism, amidst the ongoing process of federalism and despite the conceptual contradictions. Many have brought to light sectoral egoism, resembled in bureaucratic competition between the different government agencies as one of the key drivers behind the current 'dysfunction' in water resources management. Centering on how international donors have promoted the idea of river basin planning, by conflating river basins with IWRM (Cohen and Davidson, 2011), basin planning has been presented as the antidote to address such 'dysfunction'. Our Nepal case study shows, however, how bureaucratic competition and sectoral fragmentation prevail within the very context of river basin planning processes, thus proving not only the ineffectiveness of such antidote, but also how it has become a means to extend sectoral egoism, following the country's political move to federalism. Unlike before where sectoral ministries view river basin planning as potential threats to their sectoral decision-making authority and bureaucratic power that comes with it (Suhardiman et al., 2015), river basin planning has now become an integral part of sectoral ministries' strategies to sustain, reproduce, and justify their role in water resources management vis-à-vis provincial and local level governments' to be defined roles and responsibilities.

Second, it reveals how river basin planning processes are more closely linked with conflicts than integration. Following the country's move to federalism, different sectoral ministries sustain and expand their bureaucratic operational boundary and respective sectoral decision-making authority, while relying on the centrality of river basin planning approaches. Here, the prevailing sectoral egoism results in national government agencies' sectoral development interest driving the overall process of transfer of decision-making authority to federal/ provincial and local governing bodies. As such process renders the latter to either resist or being co-opted by the national government ministries' sectoral development interest, we argue that it also makes the overall transition process to federalism more prone to conflict. Consequently, national government agencies' strategies to position river basin planning as their means to sustain bureaucratic power might result not only in horizontal power struggles between agencies working at national level, but also vertical power struggles involving provincial government and local governing bodies, as the latter emerge as key actors in the country's overall development following federalism.

3. Background

Nepal's decade long civil conflict between Maoist insurgents and state forces ended in November 2006 with a Comprehensive Peace Agreement that opened the most democratically contested chapter in a process of state restructuring (Shneiderman and Tillin, 2015; Stepan, 1999). Consensus on federalism is hard to achieve as political actors hold not only different but also conflicting ideas about what federalism should entail (e.g. by ethnicity, and/or by means of political recognition) and what it should achieve (Lawoti, 2012; Lecours, 2013; Middleton and Shneiderman, 2008; Paudel, 2016). Nonetheless, political parties agreed that the federal system would be comprised of three levels of administrative governments at respectively central, provincial, and local.

In line with the ongoing processes to move to the federal system, the government held election for local government bodies in three stages during May to September 2017. Through this election, four categories of local governing bodies are being formed, including 6 metropolises, 11 sub-metropolises, 276 municipal councils and 460 village councils. These local governing bodies are part of district, and formed primarily based on population size and annual revenue. For example, each metropolis has minimum population of 280 thousand and annual revenue of at least 100 million Nepalese Rupees. Each sub-metropolis has minimum population of 150 thousand and annual revenue of at least 400 million Nepalese Rupees. Further, each municipal council has minimum population of 20 thousand and annual revenue of at least 4 million Nepalese Rupees. Each of them has similar function within their territory with the district acting as a coordination unit. The elected local bodies would serve for 5 years.

Nepal follows a two-tier local government system based on the Local Self Governance Act (LSGA) of 1999. Nonetheless, the last elected representatives left office in 2002 when their terms expired. While past attempts to hold election for local government bodies were thwarted due to political unrest, this resulted in the government representatives under the Ministry of Federal Affairs and Local Development (MoFALD) to take over instead. The lack of accountability and accessibility of these local institutions have hampered planned developmental activities, including controversies related to corruption and misappropriation of funds (Asia Foundation, 2012). After an 18-year hiatus, the recent local election plays an important role to provide power to the people under the existing government structure.

For water resources management in particular, at the time of writing, ten different ministries are responsible for dealing with water-related issues in Nepal (see Table 1). In general, these ministries manage their activities through line agency offices at provincial and district level. Some of the ministries include (semi) autonomous agencies, in addition to the dedicated departments. For example, Water and Energy Commission Secretariat (WECS) and Nepal Electricity Authority (NEA) are parts of Ministry of Energy (MoE) but they work as independent agency.

The idea of river basin planning originated from the development of the Karnali and Mahakali river basin master plans in 1993, supported by Japan International Cooperation Agency (JICA) and continued to gain traction since then. Partially driven by the global push and the agenda of major international donors to promote IWRM, the Government of Nepal formulated its Water Resource Strategy (2002) and National Water Plan (2005), which both endorse river basin planning approaches for the country's water resources management. In 2005, WECS[1] developed a draft act, outlining the institutional frameworks need to be established for integrated river basin management. In 2010, WECS also prepared the Koshi River Basin Management Plan together with World Wildlife Fund. In practice, however, sectoral ministries resisted the idea of river basin planning, as they viewed the latter as potential threat to their sectoral decision-making authority (Suhardiman et al., 2015). This resistance is most apparent from the way the draft act was never approved, because of MoE's objection. Similarly, the river basin management plan was drafted mainly involving international organizations, hardly taking into account sectoral ministries' development plans. In the next section, we discuss how this resistance towards basin planning approaches evolves over time, following Nepal's political move to federalism.

4. The shaping of power struggles

This section illustrates and discusses the central positioning of river basin planning approaches in shaping the country's water resources management following processes of federalism. Viewing river basin planning as an arena of power struggles, we look at WECS' recent initiative to formulate Water Resources Policy, vis-à-vis different sectoral ministries' strategies to sustain their bureaucratic power and sectoral decision-making authority. We look at how these strategies transformed the overall notion of river basin planning as a new territorial frontier, with basin as the newly envisioned, albeit overlapping, bureaucratic territories. Ongoing state transformation processes in Nepal manifested in highly complex and dynamic institutional landscape in water resources management. This is revealed not only in the different roles of national, provincial and local government, but also how different sectoral ministries and national government agencies define their strategic maneuver, based on how they perceive the changing power relationship and its potential implications for water resources management. This complexity and dynamism is most apparent in both WECS' and the sectoral ministries' proposal to establish basin offices, resulting in stacked institutional set up in river basin planning and management.

4.1. WECS' strategy to formulate Water Resources Policy

Recently, WECS formulated the draft Water Resources Policy to guide the country's water resources management amidst the ongoing processes of federalism. In the time of writing, WECS has received comments from relevant government agencies, donors and international organizations following its national consultation, as well as from local stakeholders attending the basin-level consultation meetings. The first national consultation was conducted in Kathmandu in December 2016, and was followed by a series of consultation meetings in three selected basins: (1) 22nd of February in Pokhara; (2) 2nd of March in Nepalgunj; and (3) 6th of March in Biratnagar. Following these series of consultation processes, the draft policy is now under revision. According to our key informant at WECS, ongoing discussions centered on the need to restructure the existing water institutions, to make it more aligned with federalism structure as implied in the new constitution.

WECS' move to draft the Water Resources Policy is in line with the Government of Nepal's proposal to form the Ministry of Water

[1] WECS is the permanent secretariat of the Water and Energy Commission (WEC), which was established by then His Majesty's Government of Nepal in 1975 with the objective of developing the water and energy resources in an integrated and accelerated manner (ADB, 2004).

Table 1
Government ministries responsible for water-related issues.

Ministry	Area of responsibility
Ministry of Energy (MoE)	Electricity generation and overall power sector development
Ministry of Irrigation (MoI)	Irrigation development
Ministry of Water Supply (MoWS)	Drinking water supply and water sanitation provision
Ministry of Agriculture and Cooperatives (MoAC)	Crop production and agricultural development
Ministry of Forest and Soil Conservation (MoFSC)	Forest management and soil conservation
Ministry of Urban Development (MoUD)	Water related to urban development
Ministry of Science, Technology and Environment (MoSTE)	Innovation and scientific research
Ministry of Population and Environment (MoPE)	Environmental conservation, pollution prevention and control
Ministry of Physical Infrastructure and Transport (MoPIT)	Development of physical infrastructure to link rural areas
Ministry of Federal Affairs and Local Development (MoFALD)	Development of local infrastructure in the rural areas

Resources and Energy (MoWRE),[2] as an overarching institutional set up where MoI, MoE, WECS would be located. This proposal is derived from the government's decision to have only 16 ministries at the central level, as stated in the new Constitution. The proposal would benefit WECS in several ways. First, it would increase its bureaucratic profile, as a government agency working under a powerful ministry (MoWRE), while keeping both MoI and MoE and itself at the same bureaucratic level. Second, it would secure its access to development fund from government revenue that fall under MoWRE. Still related to the second point, as part of MoWRE, WECS would be justified to request for permanent staffing, which is currently lacking.

In anticipation to the above proposal and according to the draft Water Resources Policy, WECS is to have 3 basin offices, to be located in respectively Eastern (with the basin office covering Koshi to Bagmati), Central (up to Panjang), and Western (from Rapti to Mahakali) region of Nepal. As mentioned by WECS Joint Secretary: "*This decision to establish basin offices was made because we need an institution that keeps the overview of basin planning at central level, following the ongoing processes of federalism. This is needed not only from basin planning perspective, but also to prevent potential conflicts between provinces.*" (interview with WECS Joint Secretary, February 2017). The framing of river basin as the scale where the central government should keep an overview of water resources management and prevent potential conflicts between provinces is key for justifying WECS' proposal to establish basin offices to expand the scope and degree of its organizational activities, and thus increase its bureaucratic power. Here, basin planning is presented as a means to insert WECS' importance in water resources management, amidst the ongoing processes of federalism. With its three basin offices, WECS would be equipped with staff to support its role and responsibility. It would no longer have to depend on sectoral ministries' willingness to support its work through their respective provincial and district offices. Moreover, WECS would be in charge of all licensing related to water use. For instance, when provincial and local governments issued a license to use groundwater, this needs to be initially approved by WECS basin office. Nonetheless, it is unclear as to whether the proposed three basin offices would have to report to WECS alone, or also to MoI and MoE, following the Nepal government's proposal to put these three government ministries under MoWRE.

According to the draft Water Resources Policy, provincial government would play an important role in connecting the federal and local government, with the latter having more decision making power under federalism.[3] At institutional level, provincial offices will be formed. These offices would incorporate 8–9 ministerial representatives at provincial level, including those from the water sector. Each provincial office will have different organizational structure, depending on the prominence of water resources development activities at specific provinces. For example, if a hydropower dam is going to be built in a specific province, the provincial office should include the Department of Electricity Development under MoE. In other provinces without hydropower facility, on the other hand, such representation might not be needed.

The ongoing formulation processes of Water Resources Policy give a pretext and provide an entry point for WECS to take part and to a certain extent lead the discussion on institutional change and bureaucratic restructuring in the water sector, amidst ongoing processes of federalism. It provides WECS with the opportunity to insert its position in river basin planning, while urging the latter's importance for the country's water resources management. Most importantly, WECS' proposal to have three basin offices formed and established following processes of federalism brings to light how it uses river basin planning as a means to increase and extend its bureaucratic power, from the central to the local, through the basin. Here, river basin planning becomes an integral part of WECS' strategy to justify its bureaucratic existence and increase its bureaucratic importance. In the next subsection we discuss sectoral ministries' strategies to protect their sectoral development interest, while inserting the latter as part of river basin planning processes.

4.2. Sectoral development perspectives driving river basin planning processes

In line with WECS' initiative to draft the Water Resources Policy and its proposal to form and establish basin offices, sectoral ministries have also endorsed the need for river basin planning approaches for the country's water resources management following federalism. This is most apparent from the way they put basin perspective central in their respective policies and legal frameworks. The Groundwater Resources Development Board (GWRDB) under the Ministry of Irrigation (MoI) adopted river basin planning approaches in its Groundwater Act formulation processes, emphasizing the need to link groundwater and surface water management at basin level throughout the country. At the time of writing, Department of Water Induced and Disaster Prevention (DWIDP) under MoI and Department of Soil Conservation and Watershed Management (DSCWM) under the Ministry of Forestry and Soil Conservation (MoFSC) were formulating respectively Watershed Policy and River Law. Both legal frameworks emphasize the importance of river basin planning approaches in the context of watershed and river management.

While river basin planning approaches have become sectoral ministries' common strategy to sustain their bureaucratic power, as implied in the above policies and legal frameworks, they are neither inclined to link their envisioned roles nor seeing the need to fine tune their overlapping bureaucratic territories in the basin planning processes. On the

[2] Following the government restructuring in 2017, MoE and MoI were merged into the Ministry of Energy Water Resources and Irrigation (MoEWRI) in 2018.

[3] Currently, the government still discusses as to how they should transfer central government's decision-making power to local government. As said by the WECS Joint Secretary: *"As it stands now, there are more than 3000 VDCs in Nepal. This is too many in terms of coordination. Ideally, they would have 300–400 local governing units, but the number will probably be increased to 750 units due to political parties' request"* (interview with WECS Joint Secretary, February 2017).

contrary, bureaucratic power struggles are most apparent from the prevailing sectoral egoisms shaping and reshaping different government agencies' views on river basin planning processes. Different sectoral ministries competed with each other, while arguing that their respective roles in water resources management are more important than others'. As expressed by WECS official: "*WECS' role is to manage the overall water use in the basin, as water use forms the core element in river basin planning*" (interview with WECS official, February 2017). This view is counter argued by DSCWM official, who expressed that: "*WECS' role is to manage the overall water use, while DSCWM's role is to manage the whole watershed, from its source of water (upstream) to its different uses*" (interview with DSCWM official, February 2017). This illustrates how DSCWM perceives its role as more holistic and thus more important than WECS', given its emphasis on the whole watershed. Similarly, DWIDP's idea to formulate the River Law is based on the need to insert its role as the government ministry in charge for managing the river, vis-à-vis WECS' and other sectoral ministries' role in water resources management. As mentioned by DWIDP official: "*MoI is in charge for irrigation, while MoE is in charge for hydropower development. But who is managing the river? Currently DWIDP is already doing this, so this needs to be clarified and formally recognized by others*" (interview with DWIDP official, February 2017).

Centering on their respective sectoral development interests and perspectives, sectoral ministries envisioned river basin planning merely as a means to sustain and increase their bureaucratic power amidst processes of federalism. Here, basin scale is used merely as a means to extend and insert respective government agency's role in water resources management, without linking these with the overall notion of integration and coordination in river basin planning processes. On the contrary, while sectoral ministries formulated policies and legal frameworks that incorporate the need for river basin planning approaches, these served mainly as their legal back up to formally justify their leading roles in basin planning processes, without any intention to fine tune these roles with each other.

Bureaucratic power struggles occurred not only at inter-ministerial level, but also between departments under the different government ministries. This is most apparent from the GWRDB's strategy to formulate Groundwater Resources Act as a legal means to justify their bureaucratic existence amidst federalism. If approved, the Act would give the Board the authority to regulate groundwater development and use at national level. It would also take over the authority of Kathmandu Valley Water Supply and Management Board (KVWSMB) under the Ministry of Water Supply and Sanitation (MoWSS). As it stands now, KVWSMB is in charge for groundwater management, including permit and licensing for Kathmandu area, especially in relation to the ongoing Melamchi drinking water project. Following the passing of the groundwater Act, KVWSMB would retain its authority until the Melamchi project is completed. After the project completion, GWRDB will take over the authority. As expressed by GWRDB official: "KVWSMB *was not happy about this as they also have an Act that legally supports their mandate. However, as this Act concerns mainly* KVWSMB *role in one specific area, and not nationally, the Act will automatically loose meaning when the new Act is promulgated*" (interview with GWRDB official, February 2017).

Sectoral ministries formulated policies and legal frameworks to legally back up their envisioned roles in water resources management, while also presenting it as a means to compete and remove potential bureaucratic opponents. Referring mainly to the to be promulgated Groundwater Act, GWRDB justified its plan to take over KVWSMB's role and responsibility in groundwater use for drinking water in Melamchi project. We argue that the real issue at stake here is not about how GWRDB could fulfill its role and responsibility, but rather, how they could gain more power and authority in relation to other government agencies. As to whether or not this authority would be meaningful in terms of water resources management, it is much less important. For example, GWRDB officials we interviewed did not see the transition period as a matter of concern, even when this could potentially result in disruption of drinking water supply, when the take over did not happen smoothly. On the contrary, as long as GWRDB could expand its power by recruiting more staff, they would support the transition, rather than acknowledging and recognizing the role of KVWSMB in delivering the existing services in drinking water provision. Similarly, referring to the draft Watershed Policy, DSCWM used the idea of watershed management as its means to insert its role in water resources management, while also emphasizing its higher importance compare to MoI's and MoE's roles in respectively irrigation and hydropower development. For example, rather than trying to link the idea of watershed management with existing irrigation and hydropower development plans, DSCWM official we interviewed would rather present watershed management as key measure for forest protection. Similarly, envisioning the basin offices to function under MoFSC, the same official presented forest management as the core issue for watershed management.

River basin planning approaches serve merely as sectoral ministries' bureaucratic means to sustain their bureaucratic importance through the preservation of their sectoral development roles and perspectives. Here, basins serve merely as a new bureaucratic territory, both substantially and contextually. Substantially, river basin becomes the conceptual embodiment of prevailing sectoral egoism. Contextually, it becomes a mere reflection of how different government agencies envisioned their new, albeit overlapping, bureaucratic territories. In the next sub-section, we discuss how the envisioning of these new bureaucratic territories results in stacked institutional set up, albeit imaginary, in river basin planning and management.

4.3. Common strategy with stacked institutional set up

River basin planning becomes national government agencies' common strategy to impose their roles in water resources management vis-à-vis provincial and local-level government bodies. At policy level, this is most evident in the way various government agencies' policies and legal frameworks highlight the need to use basin perspective as the overarching operational boundary and new bureaucratic territory to govern water resources. At institutional level, this imposition is most apparent from the way the different government agencies propose the formation, establishment, and/or sustenance of their respective, albeit overlapping, basin offices throughout the country.

WECS, DWIDP and GWRDB (both under MoI), and DSCWM under MoFSC all proposed to have basin offices as the organizational unit to manage the country's water resources. In line with the draft Water Resources Policy, WECS proposed to have three basin offices in respectively Eastern, Central, and Western region of Nepal. [4] Similarly, DSCWM planned to establish four basin offices in respectively Gandaki, Mahakali, Karnali, and Koshi basin. Moreover, GWRDB would focus on four basin offices located in Bagmati, Gandaki, Karnali, and Koshi basin. See also Fig. 1 for the location of major river basins in Nepal.

While WECS proposed to form and establish these basin offices from scratch, DSCWM would rely on their 61 district offices for the establishment of the basin offices. As for GWRDB, it would continue working in its four basin offices, while also reducing its staff coverage from its initial nine basins operation. This reduction in operational coverage is based on how GWRDB positioned provincial government as the responsible agency in charge for water resources management following federalism, on the one hand, and how it perceived the importance of centralized groundwater management, on the other hand. As expressed by GWRDB official: "*Following federalism, provincial governments would be responsible for water resources management within their provincial*

[4] According to our key informant from WECS, the exact location of basin offices will only be defined following the completion of ongoing federal and provincial elections, or upon the finalization of provincial headquarters location.

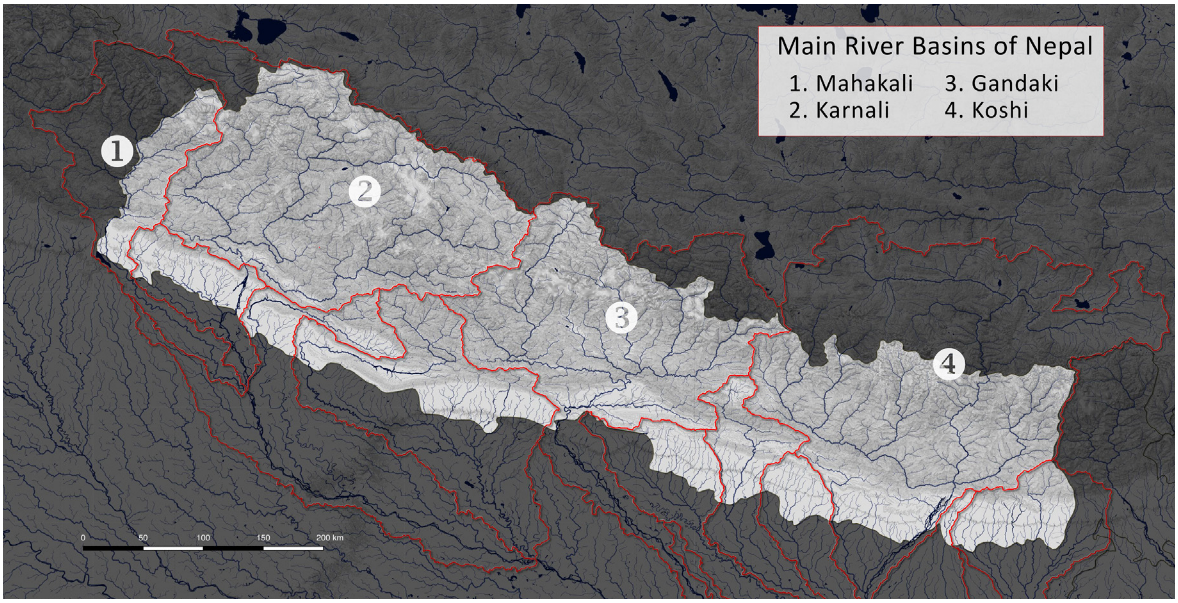


Fig. 1. Location of major river basins in Nepal.

boundary. At the same time, we need to keep the four basin offices, because centralized groundwater management is eminent for the country's water resources management" (interview with GWRDB official, February 2017). In addition, the National Planning Commission (NPC) also envisioned the establishment of basin offices as part of its apex body for water resources planning.

While basin offices have been presented as the overarching bureaucratic territory, it is unclear as to how WECS and the different sectoral ministries would coordinate their role in their respective, overlapping and stacked basin offices throughout the country. For instance, while DSCWM could in principle incorporate its district offices into the four basin offices, the question remains as to how this will be linked to other sectoral ministries' district offices and their plans to form basin offices as well. Moreover, as WECS and sectoral ministries are envisioning the same idea of basin planning approaches through basin offices, the question remains as to whose basin offices would prevail.

While different proposals on the future institutional set up following federalism will be discussed at the parliament level, following the recommendation from the Council of Ministers, the question remains as to how they will take forward WECS' and sectoral ministries' proposal to adopt river basin planning approaches, while also trying to address the problem of stacked institutional set up. The issue of stacked institutional set up and how it is originated from sectoral ministries' strategies to sustain and increase their sectoral bureaucratic importance reveals both policy and institutional complexities in basin planning processes. Obviously, it is not only about drawing the institutional boundaries between various government agencies and their respective basin offices, and thus as to where these basin offices would be located and to whom they would have to report to with regard to their overall functioning. Most importantly, it is also about to whom these basin offices would be accountable to and whether the latter would also have any say in drawing the actual boundaries.

5. Discussions and conclusion

This article highlights the political characteristics of river basin planning processes. It contests the central positioning of river basin planning approaches as an antidote to current dysfunction in water resources managements, resembled by fragmented decision making and bureaucratic competition between different government agencies operating at various administrative levels. Most importantly, it illustrates that river basin planning are no match to sectoral egoisms, as revealed from how it has been transformed from a holistic approach in water resources management, to become a new territorial frontier for the prevailing bureaucratic competitions.

Linking river basin planning with state transformation processes in Nepal, it illustrates how the first becomes a new territorial frontier, where national government agencies insert their envisioned roles and positions, while persistently pushing for their respective sectoral development interests and perspectives. Here, river basin planning becomes a means for national government agencies to sustain and increase their bureaucratic power and importance, amidst ongoing processes of institutional change and bureaucratic restructuring following federalism. Through the presentation of river basin as a scale where water resources management should be referred to, national government ministries drive the ongoing processes of federalism in the water sector, thus partially sidelining provincial and local government bodies' emerging importance and roles.

Viewing river basin planning as an arena of power struggles, the article reveals how such planning processes are more closely linked with conflicts than integration. The way different government agencies have adopted basin perspectives as their means to sustain and gain bureaucratic power amidst processes of federalism highlights constant power struggles in basin planning processes, taking place at both policy and institutional level. At policy level, this is manifested in the overlapping, conflicting policies and legal frameworks, formulated in parallel with each other, for the purpose of supporting the different government ministries' leadership roles and responsibility in river basin planning. At institutional level, it results in overlapping, stacked institutional set up for river basin planning and management. While WECS' and the different sectoral ministries' envisioning of their respective basin offices reveals their common strategy to sustain their bureaucratic power, overlapping operational boundaries between their respective basin offices brings to light prevalent bureaucratic competition as one of key institutional challenges in managing the country's water resources. We argue that while bureaucratic competition is a common phenomenon in water resources management, in the context of federalism, it might also make the overall transition processes, from central government to provincial and local level government bodies, more prone to conflict.

From a policy perspective, this article highlights the importance of

WECS consultation processes of the draft Water Resources Policy as potential platform where state actors could share and discuss their overall views on how river basin planning should be done through cross-sectoral collaboration, involving not only national level government agencies, but also incorporating development needs and aspirations of provincial and local government bodies. While WECS designed the consultation process merely as a means to gather other government agencies' and local bodies' inputs on the draft Water Resources Policy, linking this process with the outcome of local election is pertinent. Put differently, if the policy is to have any actual significance, it needs to also incorporate provincial and local government bodies' views and perceptions on water resources management across scales.

We argue that incorporating these views and perceptions could serve as the first step in the right direction, to fine tune national, provincial, local development perspectives on water resources management. Moreover, it could also serve as a starting point to develop institutional mechanism to prevent potential conflict concerning actual water use, following actual transfer of decision-making authority in water resources management, from the central ministries to provincial and local bodies. In the aftermath of the local election, local government bodies would gain decision-making authority on water resources management, among others. Hence, when they view the policy as lacking actual significance in water resources management at local level, they would contest it. Also, bearing in mind that the new governance structure once the federal structure is activated could be entirely different, a series of consultation processes involving the newly elected local governments in selected sites would be required.

While politics and power relationship will continue to shape and reshape the overall process of power struggles with regard to river basin planning, it is pertinent that the actual outcome of the envisioned basin planning processes will be significantly derived from informed and accountable decision-making processes, involving key stakeholders across scales.

Acknowledgement

The study was made possible by the generous support of the American people through the United States Agency for International Development (USAID). The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government.

References

Allan, J.A., 2003. IWRM/IWRAM: A New Sanctioned Discourse? SOAS Occasional Paper No. 50. SOAS, London.
Biswas, A., 2008. Integrated water resources management: is it working? Int. J. Water Resour. Dev. 24, 5–22.
Blomquist, W., Schlager, E., 2005. Political pitfalls of integrated watershed management. Soc. Nat. Resour. 18, 101–117.
Butterworth, J., Warner, J., Moriarty, P., Smits, S., Batchelor, C., 2010. Finding practical approaches to integrated water resources management. Water Altern. 3, 68–81.
Chikozho, C., 2008. Globalizing integrated water resources management: a complicated option in Southern Africa. Water Resour. Manage. 22, 1241–1257.
Cohen, A., 2012. Rescaling environmental governance: watersheds as boundary objects at the intersection of science, neoliberalism, and participation. Environ. Plan. A 44, 2207–2224.
Cohen, A., Bakker, K., 2014. The eco-scalar fix: rescaling environmental governance and the politics of ecological boundaries in Alberta, Canada. Environ. Plan. D: Soc. Space 32, 128–146.
Cohen, A., Davidson, S., 2011. The watershed approach: challenges, antecedents and the transition from technical tool to governance unit. Water Altern. 4 (1), 1–14.
Delaney, D., Leitner, H., 1997. The political construction of scale. Polit. Geogr. 16 (2), 93–97.
Dombrowsky, I., 2008. Integration in the management of international waters: economic perspectives on a global policy discourse. Glob. Gov. 14, 455–477.
Gyawali, D., Allan, J.A., Antunes, P., Dudeen, B.A., Laureano, P., Fernandez, C.L., Pahl-Wostl, C., 2006. EU-INCO Water Research from FP4 to FP6 (1994–2006): A Critical Review. Office for Official Publications of the European Communities, Luxembourg.
Harris, L., Alatout, S., 2010. Negotiating hydro-scales, forging states: comparison of the Upper Tigris/Euphrates and Jordan river basins. Polit. Geogr. 29, 148–156.
Harvey, D., 2004. Space as a Keyword. Paper for Marx and Philosophy Conferences, 29 May 2004. Institute of Education, London, pp. 1–16.
Hubbarb, P., Kitchin, R., 2011. Thinkers on Space and Place. Sage, UK.
Lawoti, M., 2012. Ethnic politics and the building of an inclusive state. In: von Einsiedel, S., Malone, D., Pradhan, S. (Eds.), Nepal in Transition: From People's War to Fragile Peace. Cambridge University Press, Cambridge, pp. 129–152.
Lecours, A., 2013. The question of federalism in Nepal. J. Federalism 44, 609–632.
Lefebvre, H., 2009. State, Space, World: Selected Essays. University of Minnesota Press, Minneapolis.
Marston, S.A., 2000. The social construction of scale. Prog. Hum. Geogr. 24 (2), 219–242.
McCarthy, J., 2005. Scale, sovereignty and strategy in environmental governance. Antipode 37 (4), 731–753.
McDonnell, R.A., 2008. Challenges for integrated water resources management: how do we provide the knowledge to support truly integrated thinking? Int. J. Water Resour. Dev. 24, 131–143.
Merrey, D., 2008. Is normative integrated water resources management implementable? Charting a practical course with lessons from Southern Africa. Phys. Chem. Earth. 33, 899–905.
Middleton, T., Shneiderman, S., 2008. Reservations, federalism and the politics of recognition in Nepal. Econ. Polit. Weekly 39–45.
Molle, F., 2009a. Water, politics and river basin governance: repoliticizing approaches to river basin management. Water Int. 34 (1), 62–70.
Molle, F., 2009b. River basin planning and management: the social life of a concept. Geoforum 40, 484–494.
Molle, F., 2008. Nirvana concepts, narratives and policy models: insights from the water sector. Water Altern. 1, 131–156.
Newstead, C., Reid, C., Sparke, M., 2003. The cultural geography of scale. In: Andersen, K., Domosh, M., Pile, S., Thrift, N. (Eds.), Handbook of Cultural Geography. Sage, London, pp. 485–497.
Paudel, D., 2016. Ethnic identity politics in Nepal: liberation from, or restoration of, elite interest? Asian Ethnic. 1–18.
Reed, M., Bruyneel, S., 2010. Rescaling environmental governance, rethinking the state: a three dimensional review. Prog. Hum. Geogr. 34 (5), 646–653.
Shneiderman, S., Tillin, L., 2015. Restructuring states, restructuring ethnicity: looking across disciplinary boundaries at federal futures in India and Nepal. Modern Asian Stud. 49, 1–39.
Shome, R., 2003. Space matters: the power and practice of space. Commun. Theory 13 (1), 39–56.
Staeheli, L.A., 1994. Empowering political struggle: spaces and scales of resistance. Polit. Geogr. 13 (5), 387–391.
Stepan, A., 1999. Federalism and democracy: beyond the US model. J. Democr. 10 (4), 19–34.
Suhardiman, D., Clement, F., Bharati, L., 2015. Integrated water resources management in Nepal: key stakeholders' perceptions and lessons learned. Int. J. Water Resour. Dev. 31 (2), 284–300.
The Asia Foundation, 2012. A Guide to Government in Nepal: Structures, Functions and Practices. The Asia Foundation, Kathmandu, Nepal.
UNEP, 2012. The UN-Water Status Report on the Application of Integrated Approaches to Water Resources Management. UNEP, Nairobi.
UN-Water, 2008. Status Report on IWRM and Water Efficiency Plans for CSD 16. UN-Water, Geneva.
Van der Zaag, P., 2005. Integrated water resources management: relevant concept or irrelevant buzzword? A capacity building and research agenda for Southern Africa. Phys. Chem. Earth. 30, 867–871.
Venot, J.P., Bharati, L., Giordano, M., Molle, F., 2011. Beyond water, beyond boundaries: spaces of water management in the Krishna river basin, South India. Geogr. J. 177 (Part2), 160–170.
Warner, J., Wester, P., Bolding, A., 2008. Going with the flow: river basins as the natural units for water management? Water Policy 10 (2), 121–138.
Wester, P., Merrey, D.J., de Lange, M., 2003. Boundaries of consent: stakeholder representation in river basin management in Mexico and South Africa. World Dev. 31, 797–812.

Annex 3-2

Putting Power and Politics Central in Nepal's Water Governance

Diana Suhardiman[1], Emma Karki[2], Ram Bastakoti[2]

[1] International Water Management Institute, Southeast Asia Regional Office, Vientiane, Lao PDR

[2] International Water Management Institute, Kathmandu, Nepal

Abstract
Power relations and the politics shaping and reshaping these relations are key in determining spaces of influence in water governance. Nonetheless, current discourse on water governance tends to de-center these political aspects, while presenting water governance decision-making processes merely as a neutral, technical and a-political exercise. Taking Nepal as a case study, this paper puts power and politics central in water governance debates. It brings to light how water resources management is closely linked with state transformation processes, manifested in the country's political move towards federalism. In particular, it looks at: 1) political fragmentation characterizing development planning processes in the country; 2) how this works in tandem with the prevailing sectoral egoism in water resources management; and 3) its implications for river basin planning approaches.

Keywords*: federalism; institutional analysis; Nepal; power relations; water resources management.*

1. Introduction

Over the past decades, Nepal has undergone a rapid period of political reform as it has transitioned from a government led by a monarchy towards a democratically elected federal government. Driven by the political move towards federalism, to place greater decision-making authority to local governing bodies, this period has been characterized by power struggles between major political parties, government agencies, civil society organizations, and local communities competing for decision making across scales. This paper links water governance with state transformation processes in Nepal. It brings to light how power relations centered on the politician-bureaucrat relationship shape the country's water resources management. In particular, it looks at: 1) political fragmentation characterizing development planning processes in the country; 2) how this works in tandem with the prevailing sectoral egoism in water resources management; and 3) its implications for river basin planning approaches.

Scholars have discussed current weaknesses in river basin planning approaches, centering on its neglect of political structure and processes (Allan, 2003; Blomquist and Schlager, 2005; Gyawali et al. 2006; Wester et al. 2003). They have shown how such neglect manifests in the presentation of river basin planning as a prescriptive policy concept (Lautze et al. 2011; Biswas, 2004; Varis et al. 2008), while highlighting the need to recognize that water resources management decisions are made based on political choices and contestation (Cohen and Bakker, 2014; Warner et al. 2008; Wester et al. 2003). Public administration scholars have also discussed politician-bureaucrat relationships and their positioning as power holders in their respective political and bureaucratic domains (Mosse, 2004; Quarles van Ufford, 1988; Niskanen, 1971). They have shown how bureaucratic decisions are linked to political decisions, thus implying that water resources development and management decisions cannot be discussed in isolation from the wider political constellation.

Building on these works, the paper contributes to the current discourse on river basin planning and state transformation processes in two ways. First, it brings to light the close linkages between sectoral egoism and political fragmentation, and how the two can work in tandem through politician-bureaucrat relationship. It shows how the prevailing sectoral egoisms, rooted in bureaucratic competition between different government ministries is politically sustained and reproduced. It illustrates politician-bureaucrat relations shaping and reshaping state transformation processes, and how competing development agendas, rooted in political parties' interest to gain and sustain their power within the government, drive the country's water governance, resulting in fragmented development planning. Linking water governance with state transformation processes, the paper highlights the need to put power and politics central in our understanding of water governance structures, processes and outcomes.

Second, it argues that amidst the move towards federalism, the current fragmented development planning processes could also serve as entry points for civil society groups and the wider society to convey their voice and exert their influence. While ongoing federalism would manifest in internal power struggles between government bodies across scales, it would also provide opportunities for local community to put pressure to local governing bodies to be more accountable. The paper presents power struggles as spaces to influence. Putting political space central in water governance analysis, it discusses how federalism could create, sustain and reproduce such space, *"for whom, and with what social justice outcomes"* (Gaventa, 2009:31). Here, we define political space as a space where plurality, conflict, and power can be visible and contestable as such. Or, as stated by Dikec (2005: 172): *"space becomes political in that it becomes the polemical place where a wrong can be addressed and equality can be demonstrated"*.

To understand how politicians and bureaucrats navigate their ways through their interactions and how these manifested in the country's fragmented development planning processes, we conducted in-depth semi-structured interviews with 16 government officials from various government ministries, 7 political party representatives, 3 international donor representatives, and 5 civil society organizations. Throughout these interviews, taken from March 2017 to May 2018, we also gathered information on how the different actors perceive current challenges in water resources development and management and how these challenges are linked to ongoing state transformation processes and the prevailing political fragmentation. Interviews were transcribed word-for-word. Each transcription was coded using predefined nodes, including nodes defined by the first author before the fieldwork, and new nodes for information that emerged during the interviews. The coding process was done manually and designed in line with the requirement of NVIVO tool.

In the following sections, we discuss Nepal's political move towards federalism and its implications for the country's water resource management, before highlighting the need to put power and politics central in water governance analysis in section 3. Following that we illustrate and discuss how political fragmentation and bureaucratic competition between central government ministries result in fragmented planning and disjointed development activities, while unpacking politician-bureaucrat relations in section 4. Finally, we reflect on the implications of state transformation processes for river basin planning approaches, while connecting the latter with the notion of political representation and social justice, thus positioning local governing bodies as local community's first point of contact to convey their needs and hold the government accountable.

2. Nepal's Political Move Towards Federalism and its Implications for Water Resource Management

Nepal's decade long civil conflict between Maoist militants and state forces ended in November 2006 with a Comprehensive Peace Agreement that opened the most democratically contested chapter in a process of state restructuring (Shneiderman and Tillin, 2015; Stepan, 1999). Consensus on federalism is hard to achieve as political actors hold not only different but also conflicting ideas about what federalism should entail (e.g. by ethnicity, and/or by means of political recognition) and what it should achieve (Lawoti, 2012; Lecours, 2013; Middleton and Shneiderman, 2008; Paudel, 2016). Nonetheless, political parties agreed that the federal system would be comprised of three levels of administrative governments at respectively central, provincial, and local.

Prior to the move to federalism, Nepal followed a two-tier local government system based on the Local Self Governance Act (LSGA) of 1999. Nonetheless, the last elected representatives left office in 2002 when their terms expired. While past attempts to hold election for local government bodies were thwarted due to political unrest, this resulted in the government representatives under the Ministry of Federal Affairs and Local Development (MoFALD) to take over instead. The lack of accountability and accessibility of these local institutions in the absence of elected representatives have hampered planned developmental activities, including controversies related to corruption and misappropriation of funds (Asia Foundation, 2012).

In line with the ongoing processes to move to the federal system, the government held election for local government bodies in three stages during May to September

2017. Through this election, four categories of local governing bodies are being formed, including 6 metropolises, 11 sub-metropolises, 276 municipalities and 460 rural municipalities. These local governing bodies are part of district and formed primarily based on population size and annual revenue. For example, each metropolis has minimum population of 280 thousand and annual revenue of at least 100 million Nepalese Rupees. Each sub-metropolis has minimum population of 150 thousand and annual revenue of at least 400 million Nepalese Rupees. Further, each municipality has minimum population of 20 thousand and annual revenue of at least 4 million Nepalese Rupees. Each of them has similar function within their territory with the district acting as a coordination unit. The elected local bodies would serve for 5 years. After an 18-year hiatus, the recent local election plays an important role to provide power to the people under the existing government structure.

As part of the Federal structure all three levels of the government are responsible for formulating and implementing policies and plans following seven-steps of planning process including budget development and management. This means that local level government will also be responsible for collecting taxes and revenues. The provincial government steps in when matters concern more than one local unit. State government as a whole still maintains power to develop plans of national interest. In terms of natural resource management all three levels of government have powers but the central government remains in charge of large-scale projects which include irrigation and hydropower projects. As the restructuring process is ongoing and given the unfamiliarity and unclear consensus on how federalism should take place, there is bound to be power struggles between government bodies throughout the three level administrative units as well as within the unit themselves. While such struggles would probably center on issue such as revenue collection, this will also indirectly affect the way water resources development and management is currently being done, as this would have implications for tax and revenue collection as well (e.g. royalty fee for hydropower development).

For water resources development and management in particular, at the time of writing, nine different ministries are responsible for dealing with water-related issues in Nepal (see Table 1). In 2018, the Government of Nepal (GoN) merged the Ministry of Irrigation (MoI) and Ministry of Energy (MoE) into the Ministry of Energy, Water Resources and Irrigation (MoEWRI). This merge was not new, as initially both ministries were located under the MoEWRI, before the latter was split into respectively MoI and MoE in 2009 (Bhandari and Lama, 2016). Prior to the formation of local governing bodies in recent election, these ministries manage their activities through line agency offices at provincial and district level. Some of the ministries include (semi) autonomous agencies, in addition to the dedicated departments. For example, Water and Energy Commission Secretariat (WECS) and Nepal Electricity Authority (NEA) are parts of Ministry of Energy (MoE) but they work as independent agencies. Following the recent elections, discussions are focused on how to create better administrative linkages between central ministries and local governing bodies, while ensuring transfer of responsibility and decision-making power from the first to the latter. These include the idea to transfer central government ministries staff to provincial and local level, to support local governing bodies.

Table 1: Government ministries responsible for water-related issues

Ministry	Area of responsibility
Ministry of Energy, Water Resource and Irrigation (MoEWRI)	Water resources management including irrigation and hydropower development.
Ministry of Water Supply (MoWS)	Drinking water supply and water sanitation provision
Ministry of Agricultural and Livestock Development (MoALD)	Crop production and agricultural development
Ministry of Urban Development (MoUD)	Water related to urban development
Ministry of Education, Science and Technology (MoEST)	Education, innovation and scientific research
Ministry of Forest and Environment (MoFE)	Forest management, environmental conservation, pollution prevention and control
Ministry of Physical Infrastructure and Transportation (MoPIT)	Development of physical infrastructure to link rural areas
Ministry of Federal Affairs and General Administration (MoFAGA)	Development of local infrastructure in the rural areas
Ministry of Land Management, Cooperatives, and Poverty Alleviation (MoLMCPA)	Develop land use plans for efficient and sustainable management of available land resources

Water resources development and management in Nepal cannot be discussed and analyzed in isolation from the ongoing process of state transformation and the political move towards federalism. Politically, federalism will shift political decision from central government to local governing bodies. Administratively, it will shift bureaucratic decision from central government ministries to local governing bodies. Both will have implications on how the country's water resources can be managed.

In the past decades, the government has directed the country's water resources management towards river basin planning approaches (Merrey, 2008; Molle, 2008), derived from the principles of integrated water resources management (Biswas, 2008; Chikozho, 2008; Dombrowsky, 2008; McDonnell, 2008), as means to address the problem of persistent lack of cross-sectoral coordination. The idea of integrated water resources management was incorporated into its Water Resources Strategy (2002) and National Water Plan (2005), but was never implemented, partly due to prevailing sectoral egoisms (Suhardiman et al. 2015). Following federalism, the question remains as to whether river basin planning could still be referred as key principles in the country's water resources management, and if so, how river basin planning can be done with greater participation from local governing bodies. At present, the government and major political parties have agreed on the three-tier government at respectively central, provincial and local level. Nonetheless, current discussions on the division of tasks and responsibilities between the different administrative level, and how they should coordinate with each other are still ongoing.

In the next section, we highlight the need to put power and politics central in water governance analysis.

3. Centering Power and Politics in Water Governance

Water governance scholars have brought to light the importance of politics, power structure and power relationships in shaping water resources management, primarily in the context of irrigation system (Wittfogel, 1967; Wade, 1982; Mollinga and Bolding, 2004; Molle et al. 2009) and hydropower development (Molle et al. 2009; Katus et al. 2015)[1]. This paper broadens the scope of water governance analysis to include the important role played by politicians in shaping and reshaping water governance decision. While various scholars have discussed the role of politicians in shaping water governance decision-making processes and outcomes, there is very few analyses that unpack such role in relation to water resources management. For example, Wade's analysis of institutionalized corruption in irrigation system management in India shows the close linkage between bureaucratic and political decisions on actual management of state funds. Nonetheless, the study does not elaborate on the politician-bureaucrat relationships and how the latter shape and reshape water management decisions.

Political science studies look at politician-bureaucrat relations through two distinct analytical lenses. The first lens looks specifically at the political forces (i.e. Parliament, Senate, Judicial system) (Weingast and Moran, 1983; Waterman and Meier, 1998; Miller, 2005) governing and influencing bureaucratic functioning (Furlong, 1998). It positions politicians as the power holders and emphasizes the role of political authorities in shaping the bureaucracy (Moe, 2002), bringing to light the bureaucracy many 'masters'. The second lens highlights the role of government bureaucracy as an agent with its own interests and identity (Niskanen, 1971; Quarles van Ufford, 1988). It discusses the notion of bureaucratic autonomy or the political power of the agent in policy making, and how such power can be gained by ensuring the agent's access to important resources. This lens focuses on the analysis of agencies expertise and mission (Rourke, 1984) and how they use these as a source of power vis-à-vis the power of politicians to control the bureaucracy. As stated by Olsen (2008: 17): *"The bureaucracy is an institution with a raison d'etre of its own, organizational and normative principles with intrinsic value, and some degree of autonomy and legitimate non-adaptation to leaders' orders and environmental demands".* Quarles van Ufford (1988), Moe (1989) and Mosse (2004) also discuss

[1] See also Suhardiman et al. (2017) on the importance of understanding power relations and politics shaping and reshaping water governance and collective action across scales.

this notion of 'bureaucratic identity', emphasizing the importance of understanding the government bureaucracy's main interests, and basic mechanisms in shaping its strategy to gain, sustain, and reproduce power (Espeland, 2000).

Building on these works, the paper unpacks politician-bureaucrat relations, shaping and reshaping water resources development and management direction in Nepal. It brings to light politicians' and bureaucrats' various strategies to presume power. It illustrates how politicians could push government bureaucracy to follow certain political decisions through the central positioning of the Prime Minister as their political agent. Similarly, it shows how bureaucrats could to a certain extent resist political domination, while relying on their technical expertise. We argue that this is possible bearing in mind that water resources management has been areas of public administration in which bureaucrats or technocrats have a relatively large say in determining development decisions.

In our analysis, we build on Lukes' (2005) three dimensions of power. In particular, we look at: 1) how actors and institutions define and exercise their influence over others through various means such as financial, technical, socio-political resources (instrumental power); 2) the role of socio-economic and political context within which decisions and actions are embedded (structural power); and 3) actors' ability to shape social norms, values, and identities in favor of their interests (ideational power). We look at how politicians and bureaucrats shape and reshape these different dimensions of power (e.g. access to power, the types and sources of power that they possess), and how they strategically use the obtained power to produce authority, gain control and achieve their respective political and bureaucratic interests, amidst the country's political fragmentation. How does political fragmentation drive the country's development planning processes and with regard to water resources management in particular? What are politicians' and bureaucrats' various strategies to navigate through this political fragmentation? And what are the implications for the country's water resources development and management? These are the primary questions explored here.

4. Political Fragmentation Characterizing Development Planning in Nepal

In this section we illustrate how the country's development planning processes are driven by political parties' competing development agendas, how politicians and bureaucrats navigate through these internal power struggles within the government, and how it manifests in disjointed project development activities.

4.1. Development planning driven by political competition

After the political transition that brought the new Maoist government into power in 2008, the country's political landscape is characterized by continuous power struggles between the 5 major political parties. These parties are: Nepal Congress, Communist Party of Nepal Unified Marxist-Leninist (CPN-UML), Maoist, Rastriya

Prajatanta Party (RPP), and Rashtriya Janata Party Nepal (RJPN[2]). These power struggles are most apparent from the high frequency of change in the country's political leadership. For example, in 10 years since the Maoist government took power, Nepal has had nine different Prime Ministers, each serving for less than 2 years on average. Changes in political leadership, due to political fragmentation has over ruled the need for holistic planning in the country's overall development in general, and water resources management in particular. Driven mainly by major political parties' competing development agendas, the country's overall development is politically divided and sectorally fragmented.

Politically, the country's overall development is shaped and reshaped by major political parties' competing development agendas. For example, while National Congress would bring to light the need for large infrastructure development such as hydropower dams as key means to promote the country's economic growth, other political parties (such as CPN-UML) would oppose the idea, while referring to the populist notion and how the dam would impact local community instead. Internal power struggles driven by competing development agendas are most apparent from how development of large infrastructure projects (e.g. various hydropower dam projects such as Arun 3, Upper Karnali, among others) often got delayed due to changes in government's policies and/or strong opposition from other major political parties. For example, while the government (at that time led by the Nepal Congress) had signed the Memorandum of Understanding with the hydropower company to build the Upper Karnali hydropower project back in 2008, the project was continuously delayed due to major political parties' opposition to it (e.g. CPN-UML). At time of writing, CPN-UML, now the ruling party within the government, has agreed to proceed with the dam development. Nonetheless, recent attacks on the company's office in Surkhet district indicate certain degree of political fragmentation, even within the different communist parties. Similarly, Arun 3 hydropower dam was to be constructed back in 1990s, but was delayed significantly, and was inaugurated only in 2018.

Institutionally, political fragmentation is translated into the central government bureaucracy through the establishment of inner circle of power, centered on the Prime Minister's (PM) role as the highest decision-making authority within the government bureaucracy, and his strong political affiliation with the ruling political party. The establishment of this inner circle of power is most apparent from how the PM appointed the members of the National Planning Commission (NPC), deriving mainly from his closest political alliances. In turn, the political relationship between the PM and NPC members transforms the latter's role from a potential think tank responsible for formulating comprehensive and systematic development plans, into merely a group of political advisors loyal to the PM and the ruling political party, not necessarily equipped with relevant knowledge to direct the country's overall development. Here, the NPC organizational functioning is driven mainly by the need

[2] The eight Madheshi parties put their differences aside and came together to establish the Rashtriya Janata Party Nepal for the elections in 2017.

to deliver political leverage to the ruling political party, through the sustenance and extension of the PM's political power.

The central positioning of NPC as the PM's inner circle of power is most apparent from how NPC membership changes every time a PM is changed. For example, when the new PM from the Communist Party of Nepal (CPN-UML) came in power, he would restructure the NPC membership composition, ensuring his political alliances are included, while removing potential political opposition with allegiance to the previous PM from the Nepal Congress. As said by one of civil society representative: *"Not a single PM wanted to maintain the previous NPC members simply because they cannot trust these members. They are not part of his political alliance. And to stay in power, the PM has to be able to rely on his political alliances"* (interview with civil society organization, February 2017). Consequently, the new NPC would prepare a new development plan rather than continuing with the existing plan formulated by the previous NPC members. Viewing the previous NPC as its political competitor, the new NPC thought that continuing with the existing plan and implementing it successfully would only give credit to the previous PM and his political party.

The PM's inner circle of power also includes the central government ministers. As the latter are politically appointed positions, major political parties can appoint their representatives and cadres for the positions, in accordance with the number of seats the parties have in the parliament. At present, the Communist Party of Nepal (CPN-UNL) holds minister positions in most of the ministries including Ministry of Home Affairs (MoHA), Ministry of Finance (MoFin), Ministry of Defence (MoD), among others. In general, the ruling party appoints its ministers based on the budget the central government allots each ministry. Depending on the relationship with other parties in the coalition government, the PM may choose to appoint a minister from another party to a ministry with a large budget to strengthen political ties. As a minister's bureaucratic leadership is rooted in his/her political affiliation with the major political parties, s/he would shape the leadership in line with the political party's political agenda and interests. S/he is loyal to the political party who had appointed him/her the position, rather than accountable to his/her ministerial staff. Consequently, development plans and activities are defined and implemented as means to advance the political party's political and development agenda regardless of how the plans and activities coincide with people's development needs and whether or not the government has the technical capacity to implement the plans. Thus, each appointed new minister would prepare new sectoral work plan and priorities rather than taking up the existing plan formulated by his/her predecessors. As expressed by one of our interview respondents: "*When a new minister came into office, s/he would start with a new development initiative to show his/her party's political leverage. S/he would never continue with existing development activities belong to his/her predecessor, as this might work against the interest of the political party s/he is affiliated to. Thus, every time a new minister comes, existing plan will be replaced by a new plan, not necessarily linked with the first, resulting in inconsistent and disjointed development"* (interview with international donor agencies, February 2017).

The way the PM would choose its ministers and NPC members based on political connection significantly sidelines the importance of technical expertise and administrative experience in the country's overall development plans. The combination of the need to deliver political leverage and the lack of technical expertise result in inconsistent and ad-hoc development plan based on short-term political interest, while lacking the long-term strategic development visions. This reflects the current systemic failure in the country's development planning, most evident in NPC's inability to come up with a solid, comprehensive development plan for the country. Initially Nepal has 5-year development plan. Later, this was reduced into 3-year plan, due to political situation in the country in general and following the government's decision to go for federalism in particular. In theory, NPC should develop a national development plan that incorporates all sectoral ministries' development plans and activities. In practice, however, when PM changes almost every year, NPC membership and minister appointment change too, leaving the newly appointed members and ministers very little time to formulate and implement their development plans and programs. Technically, NPC plays a key role in formulating national development plans such as periodic plan and annual program in coordination with the Ministry of Finance. Nonetheless, when it comes to actual influence the NPC is unable to exert power due to a lack of resources and authority to implement these plans. Thus, apart from some development projects funded and implemented with support from INGO and international donors, the overall role of NPC in the execution of development plans remains limited.

From the perspective of planning and program implementation, it is nearly impossible for NPC members and ministers to develop a long-term development plan. This is not only because the defined plan has to be in line with the major political parties' development agendas since it is common for NPC members to be politically appointed, but also due to the fact that in most cases such plan could not be materialized and completed given frequent power change at the level of PM, ministers and NPC members. As expressed by one of our interview respondents: *"Nepal's development planning processes resemble policy inconsistency and lack of continuity. The first minister came and planted the seed of his/her development program, but had to go almost as soon as s/he arrived. The second minister arrived and instead of continuing with the program, s/he wanted to know where such program came from, which party supported it, thus further delaying the program implementation if not halting it altogether, before s/he had to go too. When the third minister came, s/he would have his/her own idea and instead of implementing the earlier program, s/he would develop a new one. So, the cycle of developing a new program after one another, but without having ample opportunities to implement these programs continues"* (interview with civil society representative, February 2017). When the notion of planning in the country's development is reduced into the need to provide political leverage for the political parties through its political leaders (in this case the PM and politically assigned ministers) ruling in very short duration (less than one or two year), this results in scattered, inconsistent and sometimes conflicting national development planning. Put differently, as the overall rationale of planning is driven by the need to ensure political stability through alliance formation and consolidation, development then took place on ad-hoc basis, based on ever changing political agenda and interests, thus overlooking the long-term perspective of development planning altogether.

In the next sub-section, we discuss how political fragmentation provides stronger rooting for the preservation and reproduction of sectoral egoisms among central government ministries.

4.2. Political fragmentation preserving the practice of sectoral egoisms

Sectoral egoism, rooted in bureaucratic rivalries between government agencies responsible for water resources management is a prevalent feature in developing countries worldwide (Suhardiman et al. 2012; Suhardiman et al. 2015). In Nepal, these bureaucratic rivalries are most apparent from the relationship between Ministry of Energy, Water Resources and Irrigation (MoEWRI) and Investment Board of Nepal (IBN). Established under the Maoist government in 2011 to attract foreign direct investment, IBN is formally responsible for hydropower dams with electricity generating capacity larger than 500MW, while MoEWRI/Department of Electricity Development (DoED) is responsible for hydropower dams with electricity generating capacity smaller than 500MW. In practice, however, both conduct their tasks without any coordination with each other. This lack of coordination is most apparent in several planned hydropower projects in the Arun river basin. Upstream of the river, there is Kimathanka Arun hydropower project with electricity generation capacity of 450MW, produced mainly for domestic use and is under the responsibility of MoEWRI. Downstream of this dam, there is another planned dam: Upper Arun, with 335MW electricity generating capacity and Ikhuwa Khola with a capacity of 30MW. This dam is under the responsibility of Nepal Electricity Authority (NEA) and will produce electricity for domestic use. Further downstream there is Lower Arun 3 dam, with planned power generation capacity of 900MW, though the purview will come under IBN, due to its electricity generating capacity exceeding 500MW. Despite these dams' location, cascading each other, there is hardly any fine-tuning or coordination between the different agencies responsible for the dam development. This lack of coordination resulted in conflict situation surrounding the amount of available water to generate electricity as well as with regard to the design of the dam (e.g. dam height in relation to water level). Similarly, ineffective and ad hoc dam construction will also result in ineffective development of transmission line and grid system. [3]

---

[3] Bureaucratic rivalries between MoEWRI and IBN are also evident in the way licensing issue has plagued the country's hydropower development. In charge to give licenses to develop hydropower projects to private companies, MoEWRI screws up the possibility to develop systematic hydropower development plan to better position hydropower development for the country's development, when it simply grants such license based mainly on first come first serve mechanisms. As it stands now, private developer can build hydropower dam almost everywhere in any river, without having to link this dam with other planned/operating dams. The licensing issue highlights how MoEWRI can easily

We argue that ongoing political fragmentation in Nepal contributes to preserve and reproduce sectoral bureaucratic rivalries. While bureaucratic competition is rooted in the different sectoral ministries' interest to secure access to development budget and increase their bureaucratic power, we argue that the political fragmentation and the way development plans and activities have been driven primarily by political parties' competing development agendas has provided stronger rooting for preserving the practice of sectoral egoisms. The current systemic failure in Nepal's development planning processes as resembled in the government's inability to come up with a strategic national plan indirectly enables sector ministries to proceed with their respective sectoral development agenda, without having to coordinate with other ministries, or risking the agenda being questioned or contested. This systemic failure in the country's development planning also allows political parties in power to capitalize on their access to top leadership within the government, as means to serve their parties' interests and access to development fund.

The absence of strategic development plan is created, sustained, and reproduced by political parties' interests to use it as a means to advance their political interest and gains. It reveals the rules of the game commonly agreed by major political parties, to distribute their share based on where they position their ministers within the government bureaucracy. As each minister is representing the political party that has assigned him/her, sectoral development planning is driven by each political party's agenda and interest to gain popular votes and political basis, while relying on government's development budget for that. For example, party A can gain access to government's development budget through its minister position in MoEWRI, while party B is doing this through MoAD. As stated by a political party representative we interviewed: *"Major political parties often have competing development agendas. However, in practice they will focus their efforts on how to divide the government's development budget among themselves, through their respective access to different sectoral ministries. Hence, no need to fight with each other if everyone gets the piece of the cake"* (interview with political party representative, May 2018).

The ruling political party lacks any incentive to support other political parties' sectoral development program, fearing the latter might distort or stood in the way of its own development priorities. Similarly, from the perspective of political parties in opposition, they also lack political incentive to support NPC's work to develop the national plan, as this will give credit to the ruling political party. Not to mention the potential of such plan in distorting their own individual 'plan' centered on their leadership in various government ministries. Hence, from the major political parties' perspective, sustaining the prevailing sectoral egoism, centered in bureaucratic competition between different sectoral ministries seem to be the most

---

challenge and distort IBN's role in dealing with large hydropower projects, especially when they (have already) given the license for smaller projects in the surrounding or in the same localities.

logical way forward to achieve their respective development agendas and political leverage.

The current systemic failure in the country's development planning processes is also linked with the practice of institutionalized corruption, especially surrounding lucrative project deals, as the latter is often used as a source of political leverage (Suhardiman and Mollinga, 2017). As stated by civil society representative: *"Despite the current political fragmentation, institutionalized corruption prevails, linking government ministries with their respective political parties. This practice of cronyism within the government agencies centers on NPC members' decision-making power to approve development projects proposed by sectoral ministries. In return, these members receive a certain percentage of fund, which they then again used to channel to their respective political parties, as part of their political leverage"* (interview with civil society representative, February 2017).

The practice of institutionalized corruption within the government bureaucracy is most apparent from the way the Ministry of Finance (MoFin) reviews sectoral ministries' development budget. In general, sectoral ministries would propose their development budget to MoFin. MoFin would then decide on the budget ceiling, which is around the same with the allocated budget of the previous year plus approximately 10% increase[4]. In practice, however, MoFin could allocate lower and higher development budget to relevant sectoral ministries, depending on their political relationship. Sectoral ministry could propose a considerable budget increase to MoFin and get it if they belong to the same political alliances (e.g. when both ministers are appointed by the same political parties). As said by official from MoFSC: *"When I joined the ministry in 2016, I managed to increase the budget allocation considerably, up to 20 percent. While I have presented the overall development plan to justify the increase, my ability to secure this budget increase is also linked with my political connection with MoFin minister"* (interview with official from MoFSC, February 2017).

This highlights how government's decision is driven primarily by political parties' interest to gain and increase their political power, regardless of the proposed programs' relevance and whether or not it fits local population's development needs and aspirations. Political parties' interests dominated and steered administrative government decisions. Political connections define what is possible and how things should be done through what channels. When money from institutionalized corruption comes from lucrative development project funds is fed back into the system through political parties' domination in ongoing policy discussion, this highlights not only massive policy-disconnect between national and local, but also reveals how policy discussion at national level has been captured by elites' interest.

[4] This rule of 10% additional budget increment serves not only as procedural rule to favor gradual increase in fund allocation, it also ensures the sustenance of existing power structure within the government bureaucracy.

The government's and political parties' approach to center their efforts on their political networks and alliances, and inner circle of power has distanced themselves from the reality on the ground and what the people really want and need.

In the next sub-section, we unpack how political fragmentation and the central positioning of ministers as political representative of the major political parties shape organizational functioning and dynamics of central government ministries, centering on the relations between politicians and bureaucrats.

4.3. Politician-bureaucrat relations shaping Nepal's water resources management
Operating within the context of political fragmentation in the past decades, a minister often holds his/her position for a very short duration (less than a year). This is because once the ruling party changes, both the new PM and each political party in the government would then appoint their respective ministers to hold different posts within the government offices, as their first point of contact to ensure the representation of their often competing political interests.

While they were in office, a minister would focus his/her leadership on initiating as many 'new' development initiatives and projects as possible, as a means to deliver political leverage, regardless of whether the defined plan can be implemented within the very short duration s/he is in office, or whether the plan corresponds with local community's development needs. As shared by one of our interview respondents: *"New ministers love to lay the foundation of the work, to show that his/her political party is doing something useful for the people, or at least plan to do so, regardless of how such plan would benefit local community. Not to mention the fact that they themselves know that they would never be able to complete the plan implementation, given their short time at the office"* (interview with civil society representative, February 2017).

Presenting the new sectoral development plan merely as his/her political leverage, a minister often would initiate new development projects in his/her area of origins. This way, the projects' implementation sites are defined as a means to gain and ensure electoral support for relevant political parties. As stated by official from Department of Irrigation (DoI): *"For example, one minister initiated a lot of small projects (hundreds of them) on pond rehabilitation and ground water lifting in Saptari, his home district. This way, he ensures that many people from his home district would get benefits from the projects and in doing so increase and strengthen his political power base"* (interview with official from DoI, February 2017).

Fragmented national development planning driven by political competition between the different political parties is translated into disjointed development activities. As shared by official from DoI: *"With ministers come and go every year and the pressure for each new minister to start a new projects and program rather than continuing and completing the ones initiated by his/her predecessor, result not only in piling up of number of unfinished development projects, but also disjointed development activities"* (interview with official from DoI, February 2017). While all these existing projects would continue, in the sense that the government cannot stop them once they have started, delay in project completion becomes the new development trend in the current political climate. Such delay is inevitable because when a new minister takes office, he will use most of development budget to fund his new projects, instead of using the fund to complete those started by his predecessors.

Political and bureaucratic fragmentation results in scattered decision-making and inconsistent development activities in water resources management across scales. For example, prior to the formation of Ministry of Energy, Water Resources and Irrigation (MoEWRI) in 2017, the Ministry of Energy (MoE) was developing a plan to build a hydropower dam with 1200MW capacity (Budi Gandaki dam). This is despite the fact that IBN is formally in charge for hydropower development projects with electricity generating capacity larger than 500MW. Moreover, focusing mainly on the water use for hydropower electricity generation purposes, MoE overlooks the benefits that can be gained from regulating water flow for both electricity generation and irrigation purposes. Technically, they would release the remainder of the water (which can be used to irrigate more than 1 million ha of agricultural land in Nepal) to India for free. Similarly, in terms of design, if the dam is designed as a multi-purpose dam, this will result in a reduced dam height. Currently, the dam is at its maximum height.

Similarly, prior to the formation of MoEWRI, Ministry of Irrigation (MoI) was working on a new large irrigation system (Mega Dang Valley Irrigation Project), taking the water from Se river to irrigate 50,000 ha agricultural land as its command area, MoE is building a hydropower dam (100MW) upstream of the irrigation system intake. Once noticing this problem, MoI informed MoE minister. Following this flagging, the hydropower dam construction activities were halted. Yet, they still do not know what will happen with it (e.g. cancelled altogether or resume later on). MoE plans and constructs this hydropower dam without informing and consulting other sectoral ministries. So, they are aware about this problem only after construction occurred. As stated by official from MoFSC: *"This sectoral approach is applied not only by MoE, but all sectoral ministries. If they have to build any physical infrastructure, they will just build it without informing or consulting with others"* (interview with official from MoFSC, February 2017). At present, MoI is merged with MoE into MoEWRI. This merge could technically strengthen the overall sector coordination; though bureaucratic rivalries could also shift to department level.

At the department level, government staff struggle with this inconsistent development planning and disjointed activities. As shared by official from Department of Irrigation (DoI): *"We as technical staff could not cope with the fact that each year, the new minister would start with a new development project, knowing that the project implementation would be delayed the next year, following the change in political leadership"* (interview with official from DoI, February 2017). DoI has applied two strategies to deal with the problem. First, it will focus on activities that will not be affected by new projects, such as system O&M to improve the irrigation system's overall productivity. As this activity does not depend on new projects, DoI can still do their work in this regard. Second, it will propose to the new minister that it first conducts feasibility study and detailed assessment before proceeding with the proposed new project initiatives. If the feasibility study is favorable, it can proceed, but it should not proceed without any feasibility study. As shared by official from DoI: *"This way, at least DoI can prevent any possible damage if government budget is spent for development projects that are not economically feasible"* (interview with official from DoI, February 2017).

This highlights how government bureaucracy could to a certain extent resist political domination, by relying on their technical expertise to direct the overall sector development. Nonetheless, it also reveals how political actors cripple the administrative government system, as the political domination limits and reduces sectoral ministries' ability to formulate long-term sectoral development plans and programs. Here, political fragmentation results not only in scattered development plans and activities, it is also translated into an ineffective and inefficient development approach, where resources are wasted on new projects, while knowing that these projects will not be completed before other new projects come.

5. Discussions and Conclusion

Linking water resources management with the ongoing process of state transformation in Nepal, the paper highlights the importance of power relations and political forces shaping and reshaping water governance structures, processes, and outcomes. It shows how the ruling and major political parties could predetermine the overall performance of administrative government, while ensuring that national development plan and programs are formulated and implemented in line with the defined political agenda, neither incorporating the country's long-term development vision nor coinciding with local community's and the wider society's development needs and aspirations.

It illustrates how political fragmentation contributes to the preservation and reproduction of sectoral egoisms, rooted in bureaucratic rivalries between central government ministries responsible for water resources management. Here, political fragmentation works in tandem with sectoral development planning approaches centered on government ministries' bureaucratic interests to deliver political leverage, not necessarily linked with local community's views and perceptions and/or the grass roots realities. Thus, it presents the underlying rationale behind the current inconsistent and disjointed development planning and activities as well as internal power struggles between major political parties, sectoral ministries, and how such struggles manifest in politician-bureaucrat relations. It sheds light on the overall shaping of politician-bureaucrat relations and how the latter strategically maneuver political domination at ministerial and/or departmental level, while relying on their technical expertise in the sector development.

The country's systemic failure in development planning provides the rationales and justifies the current move towards federalism. Following federalism, decision making authority and responsibility will be transferred from central government to elected local governing bodies. Responding to this, central government ministries often raise the issue of lack of capacity, including the local government's inability to plan and implement, as key foundation to halt the transfer of tasks and responsibilities. In practice, however, our study shows that central government themselves are perhaps not in any better position than their governing counterparts at the local level. We argue that while transfer of tasks and responsibilities would not automatically solve the problem of sectoral development planning in the country, it will certainly increase the level of accountability between political party representatives and their political constituents. As stated by civil society organization: "*There will be a lot of cases where local governing bodies would misuse their authority. Yet, local community would also have more direct access to demand clarification from these local bodies. The accountability line will be more straightforward*" (interview with civil society organization, May 2018). Similarly, while this transfer would certainly involve a certain degree of power struggles, positioning these struggles as spaces to influence (Dikec, 2005), we argue that they will provide a space for civil society and local community to play more active role in the country's water resources development and management.

In the context of river basin planning, the political move towards federalism and the establishment of local governing bodies connect the idea of river basin planning with the overall notion of political representation and social justice (Clement et al. 2017). Prior to federalism, river basin planning was driven mainly by central government ministries in charge for water resources management. Here, the idea to have river basin plan is derived from central ministries' objective to control, develop, and manage the country's water resources to be economically viable and environmentally sustainable. Amidst the ongoing discussion on federalism, central government ministries have strategically position river basin planning as a means to preserve their bureaucratic power, that is by emphasizing the need for centralized planning in water resources development and management (Suhardiman et al. 2018). Following federalism, river basin planning can no longer overlook local governing bodies' roles and responsibilities, and local community's development needs. This brings to light the need to incorporate grass-roots development perspectives in the formulation of river basin plan. It also highlights how the planning process will require a lot of consultations with various key stakeholders, as more actors and institutions are participating in the overall decision-making processes.

From a policy perspective, the question remains as to how to harmonize and link the need for basin level planning with local people's development needs and aspirations. The way fiscal decentralization is designed, implemented and monitored will play a key role in ensuring smooth transfer of roles and responsibilities following federalism. Rules and procedures defined in fiscal decentralization will predetermine the pathway for transfer, and how the latter will ensure transparency and accountability. Similarly, the way local community and the wider society shape and reshape their access to decision making processes as a space to influence would also determine as to whether local governing bodies could represent local community's views and thus serve as more accountable people's representatives.

Acknowledgements: This study is made possible by the generous support of the American people through the United States Agency for International Development (USAID) under the Digo Jal Bikas (DJB) project (http://djb.iwmi.org). The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government.

References

Allan, J. A. 2003. IWRM/IWRAM: A new sanctioned discourse? SOAS Occasional Paper no. 50. London: SOAS

Asia Foundation. 2012. A Guide to government in Nepal: Structures, functions and practices. The Asia Foundation, Kathmandu, Nepal.

Bhandari, R., Lama, N. 2016. Dam Sanctioning Process in Nepal. International Rivers. Oakland, USA.

Biswas, A. K. 2008. Integrated water resources management: Is it working? *International Journal of Water Resources Development* 24: 5-22.

Biswas, A. K. 2004. Integrated water resources management: A reassessment. *Water International* 29: 248-256.

Blomquist, W., Schlager, E. 2005. Political pitfalls of integrated watershed management. *Society and Natural Resources* 18: 101-117.

Chikozho, C. 2008. Globalizing integrated water resources management: A complicated option in Southern Africa. *Water Resources Management* 22: 1241-1257.

Clement, F., Suhardiman, D., Bharati, L. 2017. IWRM discourse, institutional Holy Grail and water justice in Nepal. *Water Alternatives* 10(3): 870-887.

Cohen, A., Bakker, K. 2014. The eco-scalar fix: Rescaling environmental governance and the politics of ecological boundaries in Alberta, Canada. *Environment and Planning D: Society and Space* 32: 128-146.

Dikec, M. 2005. Space, politics and the political. *Environment and Planning D: Society and Space* 23: 171-188.

Dombrowsky, I. 2008. Integration in the management of international waters: Economic perspectives on a global policy discourse. *Global Governance* 14: 455-477.

Espeland, W. N. 2000. Bureaucratizing democracy, democratizing bureaucracy. *Law and Social Inquiry* 25(4): 1077-1109.

Furlong, S. R. 1998. Political influence on the bureaucracy: The bureaucracy speaks. *Journal of Public Administration Research and Theory* 8(1): 39-65.

Gaventa, J. 2009. Finding the spaces for change: A power analysis. IDS Bulletin.

Gyawali, D., Allan, J. A., Antunes, P., Dudeen, B. A., Laureano, P., Fernandez, C. L., Pahl-Wostl, C. 2006. EU-INCO water research from FP4 to FP6 (1994-2006): A critical review. Luxembourg: Office for Official Publications of the European Communities.

Katus, S., Suhardiman, D., Sellamuttu, S. 2016. When local power meets hydropower: Reconceptualizing resettlement along the Nam Gnouang River in Laos. *Geoforum* 72: 6-15.

Lautze, J., de Silva, S., Giordano, M., Sanford, L. 2011. Putting the cart before the horse: Water governance and IWRM. *Natural Resources Forum* 35(1): 1-8.

Lawoti, M., 2012. Ethnic politics and the building of an inclusive state. In: von Einsiedel, S., Malone, D., Pradhan, S. (Eds.) *Nepal in Transition: From People's War to Fragile Peace*. Cambridge University Press, Cambridge, pp. 129-152.

Lecours, A., 2013. The question of federalism in Nepal. *The Journal of Federalism* 44, 609-632.

McDonnell, R. A. 2008. Challenges for integrated water resources management: How do we provide the knowledge to support truly integrated thinking? *International Journal of Water Resources Development* 24: 131-143.

Merrey, D. J. 2008. Is normative integrated water resources management implementable? Charing a practical course with lessons from Southern Africa. *Physics and Chemistry of the Earth* 33: 899-905.

Middleton, T., Shneiderman, S., 2008. Reservations, federalism and the politics of recognition in Nepal. *Economic and Political Weekly* 39-45.

Miller, G. J. 2005. The political evolution of principal-agent models. *Annual Review of Political Science* 8: 203-225.

Moe, T. 2002. Political control and the power of the agent. Paper presented at the conference for controlling the bureaucracy. Texas A&M University. College station. Texas.

Molle, F., Mollinga, P., Wester, P. 2009. Hydraulic bureaucracies and the hydraulic mission: Flows of water, flows of power. *Water Alternatives* 2(3): 328-349.

Molle, F. 2008. Nirvana concepts, narratives and policy models: Insights from the water sector. *Water Alternatives* 1: 131-156.

Mollinga, P., Bolding, A. 2004. *The Politics of Irrigation Reform: Contested Policy Formulation and Implementation in Asia, Africa and Latin America.* Global Environmental Governance Series. London: Ashgate.

Mosse, D. 2004. Is good policy unimplementable? Reflections on the ethnography of aid policy and practice. *Development and Change* 35(4): 639-671.

Niskanen, W. 1971. *Bureaucracy and Representative Government.* New York: Aldine-Atherton.

Olsen, J. P. 2008. The ups and downs of bureaucratic organization. *Annual Review of Political Science* 11: 13-37.

Paudel, D., 2016. Ethnic identity politics in Nepal: Liberation from, or restoration of, elite interest? *Asian Ethnicity* 1-18.

Quarles van Ufford, P. 1988. The hidden crisis in development: Development bureaucracies in between intentions and outcomes. In P. Quarles van Ufford, D. Kruijt, T. Downing (eds), The hidden crisis in development: Development bureaucracies, pp. 9-38. UN Publications.

Rourke, F. E. 1984. *Bureaucracy, Politics, and Public Policy*. Boston, Little Brown.

Shneiderman, S., Tillin, L.,2015. Restructuring states, restructuring ethnicity: Looking across disciplinary boundaries at federal futures in India and Nepal. *Modern Asian Studies* 49, 1-39.

Stepan, A., 1999. Federalism and democracy: Beyond the US model. *Journal of Democracy* 10(4), 19-34.

Suhardiman, D., Bastakoti, R. C., Karki, E., Bharati, L. 2018. The politics of river basin planning and state transformation processes in Nepal. *Geoforum* 96, 70-76.

Suhardiman, D., Nicol, A., Mapedza, E. 2017. Introduction. In: Suhardiman, D., Nicol, A., Mapedza (eds), *Water Governance and Collective Action: Multi-scale Challenges.* Earthscan, London, pp. 1-8.

Suhardiman, D., Mollinga, P. 2017. Institutionalized corruption in Indonesian irrigation: An analysis of the upeti system. *Development Policy Review* 35(S2): 140-159.

Suhardiman, D., Clement, F., Bharati, L. 2015. Integrated water resources management in Nepal: Key stakeholders' perceptions and lessons learned. *International Journal of Water Resources Development* 31(2): 284-300.

Suhardiman, D., Giordano, M., Molle, F. 2012. Scalar disconnect: The logic of transboundary water governance in the Mekong. *Society and Natural Resources* 25(6): 572-586.

Varis, O., Keskinen, M., Kummu, M. 2008. Mekong at the crossroads. *Ambio* 37: 146-149.

Wade, R. 1982. The system of administrative and political corruption: Canal irrigation in South India. *Journal of Development Studies* 18(3): 287-328.

Warner, J., Wester, P., Bolding, A. 2008. Going with the flow: River basins as the natural units for water management? *Water Policy* 10: 121-138.

Waterman, R., Meier, K. 1998. Principal agent models: An expansion? *Journal of Public Administration Research and Theory* 8(2): 173-202.

Weingast, B., Moran, M. 1983. Bureaucratic discretion or congressional control: Regulatory policy making by the Federal Trade Commission. *Journal of Political Economy* 91(2): 765-800.

Wester, P., Merrey, D. J., de Lange, M. 2003. Boundaries of consent: Stakeholder representation in river basin management in Mexico and South Africa. *World Development* 31: 797-812.

Wittfogel, K. 1967. *Oriental Despotism: A Comparative Study of Total Power.* New Haven: Yale University Press.

Annex 3-3

World Development 122 (2019) 525–536

Contents lists available at ScienceDirect

World Development

journal homepage: www.elsevier.com/locate/worlddev

Spatial politics and local alliances shaping Nepal hydropower

Diana Suhardiman [a,*], Emma Karki [b]

[a] International Water Management Institute, Southeast Asia Regional Office, P. O. Box 4199, Vientiane, Lao Democratic People's Republic
[b] International Water Management Institute, Kathmandu, Nepal

ARTICLE INFO

Keywords:
Power relations
Hydropower decision making
Private sector actors
Spatial alliances
Nepal

ABSTRACT

This paper investigates the spatial dimension of power relations and the shaping of local alliances through a hydropower development project in Nepal. It provides a grass-roots illustration on the role of space in shaping and reshaping power relations, and how it manifests in the formation of local strategic alliances. Taking the Upper Karnali hydropower project as a case study, the paper highlights: 1) the role of private sector actor as an ad-hoc decision maker in hydropower development in the country; 2) how hydropower development is perceived by those who will be most affected; and 3) how the two shape the localized dynamics in hydropower decision making, while also sheds light on some of the key gaps in hydropower decision-making landscape and processes. Viewing space as a process and a product of socio-political interface, it shows how local communities living along the Karnali River view the planned hydropower project differently, how these views are rooted in their relationship with the hydropower company, and how such relationship is predetermined by local communities' bargaining power in relation to the proximity of their respective villages to the planned hydropower dam site, and vice versa. Unpacking the power relations shaping and reshaping spatial politics in hydropower decision making, it presents the concept of spatial alliances as a theoretical underpinning to unpack the question on why and how power relations emerge, are sustained and reproduced.

1. Introduction

Over the past decades, Nepal has experienced a rapid period of political reform as it has transitioned from a democratic government with a constitutional monarchy towards a democratically elected federal government. Driven by the need to move towards federalism, to place greater decision-making authority to local governing bodies, this period has also been characterized by power struggles between major political parties, government agencies, civil society organizations, and local communities competing for decision-making power across scales. This paper looks at the shaping of these power struggles from the lens of spatial politics in hydropower decision making. Taking the Upper Karnali hydropower project as a case study, it looks at: 1) the spatial dimension in hydropower decision-making processes; 2) how spatial politics shapes and reshapes the different power relations between respective local community and the hydropower company; and 3) how these relationships reflect back and influence local community's views on the planned project. It illustrates how local community along the Karnali River in Far Western Nepal negotiated their respective development needs and concerns with the hydropower company. It brings to light their different views and perceptions on the planned project, how the latter is derived from their spatial-based power relations with the company, and how these relations emerge partly as the company's response to the existing policy and institutional gaps in hydropower decision making.

Building on Lefebvre's theory of the production of space (Lefebvre, 1991; Chung, 2012) and Pierson's conceptualization of placing politics in time (Pierson, 2004), we argue that space plays an important role not only in shaping local community's view on the planned hydropower project, and how this view evolves over time, but also in determining their bargaining power, and how the latter (re)shapes the first. The importance of understanding the spatial dimension and how it shapes decision-making processes in natural resource management has been brought up by commons scholars looking at the role of local community in common pool resources management (Agrawal, 2014; Agrawal & Benson, 2011; Agrawal & Gibson, 1999; Ostrom, 2011; Varughese & Ostrom, 2001). Ostrom (2011) illustrates how unequal access to water and the power asymmetry between upstream and downstream water users in an irrigation system influence the process of rule shaping and proximity for collective action. Varughese and Ostrom (2001) show how locational differences to forest areas

* Corresponding author.
E-mail addresses: d.suhardiman@cgiar.org (D. Suhardiman), e.karki@cgiar.org (E. Karki).

https://doi.org/10.1016/j.worlddev.2019.06.022
0305-750X/

shape power relations and the rules of the game in forest conservation.[1]

Rather than portraying local communities as homogenous entity with a unified voice, we show how their views and perceptions on hydropower development are diverse and spatially fragmented, as they are shaped by their close or distant relationships with the company, the company's view on local community's importance in relation to the planned hydropower project, and how this view is partly derived from the respective village location, in proximity of the planned hydropower dam site. Building on earlier work that challenge the overall notion of community as homogenous social structure sharing common interests and norms (Agrawal et al., 2013; Agrawal & Gibson, 1999)[2], we illustrate how shared norms and common interests can change depending on how different members of local community perceive benefits and impacts from the planned hydropower project. Agrawal and Benson (2011) highlight the challenge of ensuring equity between upstream and downstream water users in an irrigation system, while referring to their differential benefits.

The paper contributes to current discourse on spatial analysis and hydropower decision-making processes in two ways. Firstly, it presents the concept of spatial alliance as a theoretical underpinning to unpack why and how power relations emerge, are sustained, and reproduced. Current literature on socio-political production of space has highlighted the importance of power analysis surrounding the logic of inclusion and exclusion (Low, 2008). Scholars have also discussed how spatial imagination can be deployed as a method to negotiate the overall distributions of costs and benefits in urban planning (Visser, 2001; Massey, 1995; Merrifield & Swyngedouw, 1996). Building on these works, the paper illustrates how spatial imagination can be (re)produced to redefine the spatial connections between local communities living along the river. The creation of these new spatial connections takes place through the process of disconnecting, when the company 'divides' the river into different sections (e.g. villages upstream of the dam that will be inundated by the dam development; villages downstream of the dam) while presenting the planned dam site as the epicenter of the new spatial imagination. The process of reconnecting began, when the company spatially reconnected these upstream and downstream villages, but only in relation to the planned dam site. Unlike before, when the river directly connects upstream with downstream villages, the new spatial imagination does not recognize the inter-villages direct spatial relations.

We argue that the production of these new spatial connections redefines villages' power relations with each other and vis-à-vis the company. The paper brings to light the shaping of spatial alliances between the company and upstream villages. It shows how the new spatial connection reduces downstream villages' bargaining power and their room for maneuver to negotiate their concerns with the company. Here, negotiated development visions and imagined spatial disconnect between upstream and downstream villages serve as the company's device to proceed with the planned hydropower project while removing key foundations for local community to reconcile their differences and come up with a unified voice. The shaping of these alliances shows local community's fragmented bargaining power and the company's ability to strategically use it as its entry point to proceed with the planned dam project. It illustrates the messy realities where hydropower decision-making domains overlap and intersect, and how they are in fact shaped and reshaped by a continuous negotiation process and alliance formation between various actors across the different domains (Lord, 2014; Dixit & Gyawali, 2010).

Secondly, it unpacks the local community's diverse views and perceptions on hydropower development and how these are shaped and reshaped by spatial-based alliance formation between respective local community and the company (Harvey, 1996)[3]. Linking the concept of spatial imagination with the actual shaping of spatial politics, it argues that while local community's views and perceptions on hydropower development could serve as potential grass-roots forces for more inclusive development, there is a need to place these views within the broader context of social justice (Sen, 2009; Fraser, 1998; Young, 1990; Pirie, 1983). Building on Agrawal and Gibson (1999) earlier work that highlights the need to broaden our understanding of local community, from small spatial units towards an inter-connected spatio-political and institutional network shaped by actors' multiple interests and strategies, we illustrate how local community's diverse views are partly rooted in how they identify themselves as either affected people or project beneficiaries, and how these identities are sustained or evolved through their respective relationship with the company.

We conducted an in-depth case study research (Burawoy, 1991; Yin, 1994) from January to June 2018, looking at how power dynamics is shaping and reshaping hydropower decision-making processes in Nepal, while focusing on the Upper Karnali hydropower project in particular. We focus on two elements: 1) how spatial politics shape strategic alliances formation in hydropower decision making; and 2) how these alliances shape local community's views on the planned hydropower project, and vice versa.

To understand how local community perceives the planned hydropower project, we conducted a series of focus group discussions with various Upper Karnali Concerns Committee (UKCC) members and villagers from 8 villages along the Karnali River, followed by in-depth semi-structured interviews with 5 UKCC members and 15 farmers. UKCC was formed by the hydropower company as a means to establish better line of communication between the company and the villagers. We gathered information on how UKCC members and villagers perceive the planned hydropower project, how their different perceptions are linked to their relationship with the hydropower company, and how such relationship partly derives from the spatial location of their respective villages. As part of this field research, the second author interviewed the company representative in Kathmandu. Placing the information and insights into the wider context of water governance in Nepal, we link our field data collection with an institutional analysis of hydropower decision making at national level. As part of this institutional analysis, we conducted a series of in-depth interviews with 8 government officials from various sector ministries, 7 political party representatives, as well as 9 representatives from donor agencies, international organizations and civil society groups. We complemented this institutional analysis with a policy review on the hydropower sector, looking at various policies and regulations (e.g. licensing system, cross-border power trade agreement, power purchase agreement).

In the following sections we highlight the central positioning of hydropower development in Nepal for the country's economic development. We then present some of the key concepts in socio-political production of space before moving to the case study presentation of the Upper Karnali hydropower project. We discuss and analyze the overall shaping of spatial politics in hydropower decision-making processes at the local level, centered on the company's strategic alliances with UKCC members from upstream villages, on the one hand, and their neglect for UKCC members

[1] See also Amirova et al. (2019) for determinants of cooperation in irrigation systems in Kazakhstan and Uzbekistan, and Cody (2018) for the role of water rights in shaping upstream-downstream relations in an irrigation system in Colorado basin.

[2] See McCord et al. (2019) on how farm households' heterogeneity shapes water delivery outcomes in irrigation systems in Kenya.

[3] For understanding how people-place connections are shaped and differentially experienced see Dukpa et al. (2018).

from downstream villages, on the other hand. We conclude with discussion on the need to recognize how spatial politics shapes localized dynamics in hydropower decision making, and its implications for social justice.

2. Hydropower development in Nepal: linking dominant narrative with local community's views

Following the country's local and national elections held in respectively mid 2017 and early 2018, Nepal entered a new chapter in a process of state transformation. Since the country's decade long civil conflict ended in November 2006, Nepal has been struggling to make the move to the federal system (Shneiderman & Tillin, 2015). Consensus on federalism is hard to achieve as political actors hold not only different but also conflicting ideas about what federalism should entail (e.g. by ethnicity, and/or by means of political recognition) and what it should achieve (Lawoti, 2012; Lecours, 2013; Middleton & Shneiderman, 2008; Paudel, 2016). Nonetheless, in 2017 political parties agreed that the federal system would be comprised of three levels of administrative governments at respectively central, provincial, and local or municipality level.[4] The elected local bodies would serve for 5 years.

Throughout the years of political turmoil, hydropower development remained a central piece in every government's economic development strategies. This is most apparent from the government's massive efforts to promote the sector development over time. As stated by Dixit and Gyawali (2010: 106–107): *"Since the end of World War II, it has been a political truism in Nepal that the country's problem is poverty and its greatest asset is its enormous hydropower potential, estimated at 83,000 MW. This figure, known to almost any school child, is repeated endlessly in the media as Nepal's passport out of poverty*". In 2014 the Nepal Electricity Authority (NEA) with support from the Japan International Cooperation Agency (JICA) developed the nationwide master plan study, highlighting Nepal's hydropower potential while outlining areas in the country's major rivers where hydropower development should be done. Currently, there are 56 hydropower projects in different phases of planning and construction in the country, representing over 20,279 MW potential power generating capacity, compared to the current installed capacity of 986 MW available to meet the electric demand (Alam et al., 2017; IHA, 2018). The central positioning of hydropower development as one of the key pillars to promote economic growth, and achieve national socio-economic development is not a new phenomenon in many developing countries in the Global South (Sneddon & Fox, 2012; Bakker, 1999; Molle, Foran, & Kakonen, 2009). Driven by rapid pace of industrialization, many developing countries worldwide have positioned hydropower development as the dominant pathway to respond to growing demand for electricity for both export-led economic growth and expanding domestic consumer markets.[5]

As Nepal embarked on hydropower development pathway, the government formulated a series of policies and legal frameworks to regulate and manage hydropower development projects. Hydropower development is featured prominently in both Water Resources Strategy (2002) and the National Water Plan (2005), formulated by Water Energy Commission Secretariat (WECS). The Hydropower Development Policy (2001) outlines hydropower decision-making steps (e.g. licensing[6], feasibility study, Environmental Impact Assessment or EIA review[7], Project Development Agreement) and covers the financial aspects in hydropower development, including royalty fee, income tax exemption rule, customs duty levy, and selling rate of electricity. In practice, however, it is unclear how the different government agencies in charge to approve each step of hydropower decision making will coordinate among themselves or monitor and evaluate the company's engagement with local communities. Similarly, while the policy mentioned the idea of benefit sharing, it does not specify the institutional set up, processes, and procedures that need to be followed to ensure its effective application. The Government of Nepal (GoN) has come up with various benefit-sharing modalities in hydropower development (Lord, 2016; Murton, Lord, & Beazley, 2016), including a royalty mechanism that provides a share of revenues to local government as well as the sale of publicly traded equity or shares to affected local community. Nonetheless, in most cases, the company would define benefit-sharing modalities, often without any prior consultation with local governing bodies and local communities. How benefit-sharing mechanism can be hindered and/or supported by existing institutional set up and legal framework, and how local communities could have more say in designing benefit-sharing modalities, remain obscure.[8]

Despite its central positioning, many have also raised concerns on how hydropower decision-making processes have been done through top-down approaches, centered on the government and the relevant company, with local community coming into the picture only during project implementation or after all the paper works are done (Lord, 2016; Baruah, 2012). Widespread resistance to hydropower development was most apparent in the case of the Arun 3 hydropower project, which resulted in the World Bank's withdrawal from the project (Dixit & Gyawali, 2010).[9] At the local level, rapid pace of hydropower development has resulted in an increase in the number of people and local community affected by dam projects (Lord, 2014; Subba, 2014), increase in socio-economic inequity and further marginalization of the poorest and most marginalized groups (Baruah, 2012; Arora, 2009).

3. Spatial politics and strategic alliances shaping hydropower decision making

The concept of the production of space (Lefebvre, 1991) posits a theory that understands space as fundamentally bound up with socio-political reality. As stated by Schmid (2008: 28): *"Space does not exist in itself, it is produced*". As socio-political construct, space

[4] Local governing bodies include 6 metropolises, 11 sub-metropolises, 276 municipalities and 460 rural municipalities. These local governing bodies are part of district and formed primarily based on population size and annual revenue. For example, each metropolis has minimum population of 280 thousand and annual revenue of at least 100 million NPR. Each sub-metropolis has minimum population of 150 thousand and annual revenue of at least 400 million NPR. Further, each municipality has minimum population of 20 thousand and annual revenue of at least 4 million NPR.

[5] Nationally, hydropower development is often positioned as the government's primary means to achieve its economic development targets through industrialization and as a means for government revenue generation. Regionally, international financial institutions such as the Asian Development Bank and the World Bank present the need for hydropower development as an integral part of regional economic integration.

[6] From a river basin planning perspective, little information is available with regard to how the licensing systems and process will be linked to various sectoral ministries development planning (e.g. master plans for hydropower and irrigation), and the overall basin planning.

[7] While EIA is included in the Environment Protection Act (1997) and Environment Protection Rules (1997) both documents do not specify on what the EIA should entail in the context of hydropower development.

[8] According to the policy, half of royalties coming from hydropower projects are shared with the district development committee (12%) and other districts in the area (38%) where the project was located (Sikor et al., 2018; Dixit & Gyawali, 2010). In practice, however, each company would apply different benefit sharing arrangements, as the policy is hardly being monitored or enforced.

[9] The 900 MW project was revived recently and is being developed by Satluj Jal Vidyut Nigam (SJVN) as another large-scale export-oriented project. SJVN is subsidiary of Indian government-owned Satluj Jal Vidyut Nigam Ltd.

and time do not exist universally, but are produced and reproduced by social constellations, and power relations embedded in the wider socio-political landscapes. Lefebvre (1991) discussed the three dialectically interconnected dimensions or processes of space (re)production. These refer to: 1) spatial practice or networks of interaction and communication; 2) representations of space, which emerge at the level of discourse; and 3) spaces of representation, which concerns the symbolic dimension of space (e.g. divine power, organizational logos). Bringing to light the importance of temporality in shaping socio-political processes and their complex dynamics, Pierson (2004) highlights the need to place politics in time, which means looking at the circumstances under which certain processes emerge and understanding why they unfold in particular period of time. It highlights the importance of temporality and path dependence, and their role in the overall shaping of social and political outcomes. As stated by Sewell (1996: 262-63): *"[Path dependence suggests] that what happened at an earlier point in time will affect the possible outcomes of a sequence of events occurring at a later point*".

As a central theme in the reconceptualization of the nature-society relation, the concept of the production of space has incorporated a relational conception of space and time, thus highlighting the need to understand space as an integral part of socio-political practice, or so-called spatial politics, in which power relations, competing interests and conflicts play an important role in shaping and reshaping the overall constellation of spatial interests and alliances (Soja, 2010; Pirie, 1983). Here, space becomes the key decisive factor shaping actors' and institutions' bargaining power and negotiation strategies, as these defined the overall process of alliances forming, and vice versa. Scholars have also discussed the logic of inclusion and exclusion through institutionalized orderings, while positioning space as a product of societal interaction and structures. They have shown how social inequity is produced and reproduced through spatial relations across scales (Berking, Frank, Frers, & Low, 2006; Mayerfeld-Bell, 1997). As stated by Low (2008:26): *"While it cannot be often enough stressed that no space imposes specific action (pedestrian tunnels need not necessarily engender fear, however empirically frequently this occurs), highly elaborated know-how has been developed about how deliberately to generate atmospheres in spaces*".

The paper unpacks the spatial politics (re)shaping the production of power relations in hydropower decision making at the grass-roots level. It illustrates the shaping of everyday politics in hydropower decision making (Huber & Joshi, 2015). It shows how the company's strategy to gain local community's support to proceed with the planned development has resulted in the fragmentation of local community's bargaining power and their ability to negotiate. Here, the basic spatial logic in hydropower decision making is constituted not by the company-local community dichotomy and/or opposition, but by how the company strategically formed alliances with upstream villages, while ignoring downstream villagers' concerns and needs. Or, as stated by Low (2008: 26): *"Heterogeneity and homogeneity are tied to competing space logics*". By ignoring downstream villagers' concerns on how the dam would impact the downstream fishing community and farmers, the company applied a spatial exclusion logic, knowing that they could proceed with the dam construction without downstream villagers' support. Similarly, by acknowledging and accepting upstream villagers' demand on land compensation payment for the land that will be inundated by the dam construction, the company employed a spatial inclusion logic, knowing that they could not proceed with the dam construction without upstream villagers' support. While the company's strategy to form strategic alliances with upstream villagers is key, the timing and sequence of how these spatial alliances are constructed also matter. Once alliances are made, there is a path-dependent quality that would sustain such alliances and make it difficult to change. For example, following both the company and upstream villages agreement on the land compensation value, it would be very difficult for upstream villagers to change their view on the planned hydropower project, regardless of how downstream villagers' strategies to convince them to do otherwise. Similarly, the company lacks any incentive to improve its relationship with downstream villages, as the latter's objection would have very little significance for the company's interest to continue with the planned hydropower project following the company's alliance with upstream villages.

Linking this spatial logic in hydropower decision making with the central positioning of local community as grass-roots forces for inclusive development, the paper unveils local community's different and sometimes conflicting views on the planned hydropower projects. Scholars have discussed how hydropower development in Nepal would affect local community and/or how they would benefit from the dam development (Lord, 2016; Rest, 2012; Dixit & Gyawali, 2010; Armbrecht, 1999). According to Lord (2016), not only that the majority of local community agree on the importance of hydropower development, they are also very much inclined to getting recognition as affected people, in order to be heard, consulted and represented. As stated by Lord (2016: 151): *"For many people, being classified as a project affected person is also a means of gaining entitlements to services that the government of Nepal has failed to provide, a more promising and immediate avenue for recognition*". This shows how local community views the company as an agent for development to whom they could convey their development needs and concerns. Nonetheless, we argue that local community's desire for development (Rest, 2012; de Vries, 2007) should not be viewed as something static, or unchanging over time. Most importantly, we highlight the need to understand the rationales behind local community's different views, how these views are (re)produced through the shaping of spatial alliances, how such alliances change the existing power relations, and thus others' ability to negotiate, and vice versa. What are key decisive factors shaping and reshaping local community's views on hydropower development? How do these views relate to local institutional arrangements, both formal and informal, pertaining to resettlement and compensation? How do these arrangements come to stand in relation to local community's bargaining power and ability to negotiate their development needs and concerns through their relationship with the company? These are questions explored here.

4. Putting local communities' views central in Nepal hydropower

This section starts with some background information of the Upper Karnali hydropower project. It continues with the company's strategy to form the Upper Karnali Concerns Committee (UKCC) in each of the 4 municipalities and 3 rural municipalities[10] that would be affected by the project. Further, we discuss local community's different views on the planned hydropower project, while putting their diverse views central in the overall shaping of hydropower decision-making processes at the local level.

4.1. The Upper Karnali hydropower project

The Upper Karnali hydropower project is set to be the largest hydroelectric power station in Nepal with power generation capacity of 900 MW. Nepal will receive 12% of generated electricity, with the remaining 88% going to India and Bangladesh. Commissioned

[10] According to the previous administrative divisions, these represented 12 Village Development Committees (VDCs) in three districts.

by the Investment Board of Nepal (IBN)[11], the Nepal Electricity Authority (NEA) will have 27% free equity stake in the project, while the private Indian company covers 100% of the total investment. Located in Far Western Nepal, the Upper Karnali hydropower project is located in Karnali river, flowing through three districts of Achham, Dailekh and Surkhet. The dam will be 150 m high, 207 m long. Technically, the project will use water from the Karnali River to generate electricity, while taking significant amount of water from one side of the river and channel it through a tunnel to another side of the river.

While the company presented the dam as run-of-the river dam, because water is returned to the same river lower down, the dam design still have a socio-environmental impact, though the latter is relatively smaller compare to a traditional impoundment dam (Burrier, 2016). While the technical characteristic might indeed result in fewer number of households being resettled, this does not mean that the dam would have less impact on local communities living along the river. In contrast, it would impact a significant number of villagers who rely on fisheries and farming activities for their livelihoods. Following its construction, the dam would reduce water flow in a stretch of around 50 km downstream, thus disrupting the river ecology, sediment flow and fish migration, leading to potential loss of fisheries and farming activities.[12] In total, the planned dam will affect 426 farm households and local community out of which 56 households need to be resettled across the three districts. Moreover, the dam will also impact thousands of farming households and fishing community living downstream of the dam. Despite the dam's limited storage capacity, key socio-economic and environmental impacts associated with a reservoir scheme are likely to be present. Fig. 1 gives an overview of the planned dam location on the Karnali river, administrative boundaries of the three districts and affected villages across the districts.

In 2008 the project was started with the signing of cross-border power trade agreement signed by the Government of Nepal (GoN) and the Government of India (GoI) and power purchase agreement between the two countries. In line with the cross-border power trade agreement, Nepal government placed a call for foreign company to bid for the project. In the same year, an Indian company, GMR Upper Karnali Hydropower Limited (a subsidiary of GMR Energy) won the bid to develop the project. GMR group is one of the largest conglomerates in India and is viewed as a key player in the infrastructure and energy sector with experience in generation and sale of power. Currently it is developing plants both in India and Nepal with a generation capacity of over 2300 MW.[13] For the import of electricity generated from the project, the company has ensured a long-term license from the Directorate General of Foreign Trade of GoI, valid for 30 years. The Project Development Agreement (PDA) states that GMR needs to comply with the relevant policies and legal frameworks of GoN when preparing and implementing its various plans (IBN, 2014). These included local benefit sharing, employment and skills training, industrial benefits, and disaster management plans, which will be jointly developed within the 12 months of the agreement date.[14] The company will also develop the rehabilitation and resettlement plans within 6 months of the agreement date.[15]

While the formulation of these plans urges the company to comply with existing rules and regulations, the latter do not provide a clear guideline on how the company has to formulate and implement the plans in relation to local community's development needs and aspirations. For example, with regard to the benefit-sharing plan, GMR will share 1% of the total project budget and spend it for community-based development including supporting infrastructure. As outlined in the PDA (IBN, 2014), this budget will primarily be spent on construction of a suspended bridge, child care centers, health post, mobile network tower, vocational training for youth, as well as, investment in education, health, empowerment, community development in the to be affected villages. Moreover, GMR would provide 2 MW rural electrification, 12% royalty to the project affected areas, shares for local community and 3000 direct employment during the construction phase. Nonetheless, it is unclear as to how and when the company has to do this in terms of institutional set up and consultation and negotiation with local governing bodies and local community (Jones, 2012).

All projects are also required to conduct an EIA following the guidelines (MoEST, 2006; MoFE, 2018) and seek approval from the Ministry of Forests and Environment (MoFE).[16] This is to be done during the feasibility study phase and submitted along with the license application.[17] According to the Hydropower EIA Manual (2018) the company should consult the affected communities during the pre-construction phase. It requires developers to engage with stakeholders during the EIA process. This is to provide information to the community regarding the project activities and ensure the community is in a position to take informed decisions. During this phase, discussions on land compensation also take place to plan and prepare a land acquisition, resettlement and livelihood restoration plan based on the feedback provided by the community and local authorities. The stakeholder consultation is expected to be a continuous and extensive process to ensure valuable inputs. Public hearings are required to be published 15 days prior inviting participants to partake in the EIA process.

In line with this general guideline, in 2012, the company formed Upper Karnali Concerns Committee (UKCC) in each of the villages that would be affected by the planned hydropower project to liaise with the larger community and channel information about the hydropower project. In practice, however, the company would focus the overall discussions on compensation mainly with upstream UKCC leaders and villages. As shared by UKCC leader from Saurat village during an interview: *"Initially the company would arrange a big meeting involving all UKCC members. Later, however, the company would focus the consultation and engagement*

[11] The IBN was established in 2011 to attract, accelerate and facilitate foreign direct investments in Nepal, while providing one window service to projects of national priority. It is in charge for hydropower project with power generation capacity above 500MW. The Prime Minster heads the board while the Chief Executive Officer heads the office.

[12] With minimum resettlement impacts and other socio-economic and environmental impacts spread throughout the basin, this makes it more difficult for local communities living along the river to organize and mobilize large-scale protests (Burrier, 2016; Klein, 2015).

[13] The Indian government's own experience with the Sardar Sarovar Project and the subsequent criticism and rejection by the government to the guidelines proposed in the 2000 report by the World Commission on Dams provides significant background on the socio-economic impact of large dams and how this has resulted in widespread social movements (Thakkar, 2008).

[14] GMR is expected to provide half yearly reports for the first 3 years of construction followed by yearly reports to inform the GoN on the implementation of the trainings and programs.

[15] In addition, GMR is required to consider the impact of the irrigation projects in the downstream impact study, which includes the Bardia and Karnali corridor lift irrigation projects with a total command area of 15,000 ha and water requirement of 42 m^3/s.

[16] Previously known as Ministry of Environment, Science and Technology.

[17] Generally, a developer must obtain a license from the Department of Electricity Development (DoED) prior to conducting a survey. The survey license can be used either for electricity generation, transmission or distribution. A development license is also required after the survey is conducted and can be categorized for generation, transmission and distribution of electricity. The application is to be submitted to the Secretary of the Ministry of Energy, Water Resources and Irrigation (MoEWRI) through DoED following the Electricity Rules (1993) for both types of licenses. The licensee is required to start the physical work within three months for the survey and within one year for the generation, transmission or distribution, though these can be extended if the licensee submits an application explaining reasons behind the delay (MoEST, 2006). For Upper Karnali project in particular, the IBN is in charge for issuing the license, due to its power generation capacity (above 500 MW).

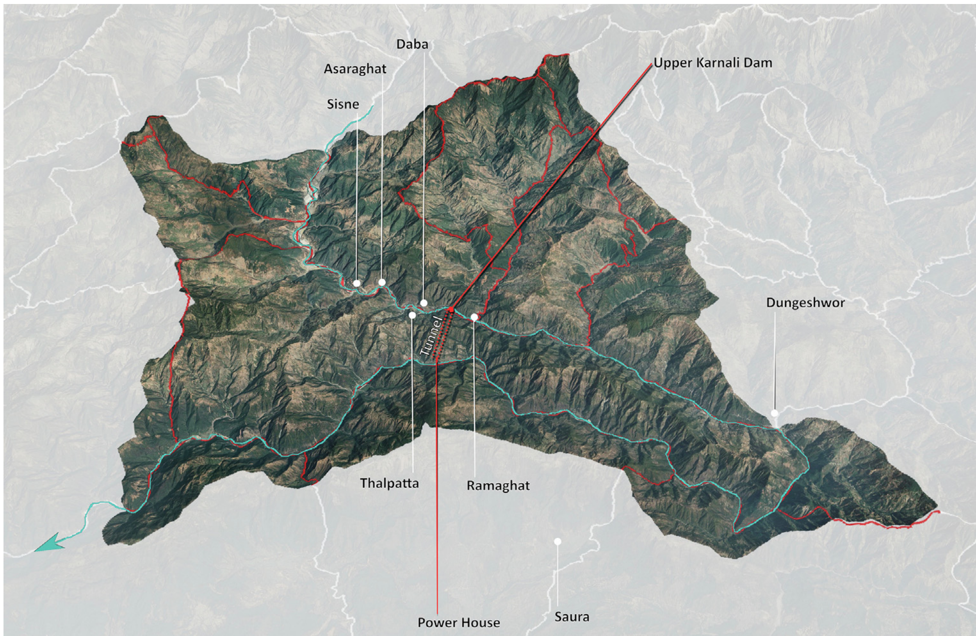


Fig. 1. Overview of Upper Karnali hydropower dam and administrative boundaries of affected villages across the three districts.

process with upstream UKCC members, due to their villages' location, close to the planned dam site, and their role in mobilizing protest against the company" (interview with UKCC leader from Saurat, May 2018). While consultation meetings with affected local communities were conducted in public spheres, the company could shape these meetings to include and exclude different UKCC members and local community.

Consequently, the subsequent EIA report would delve into the timeline for the construction of the project and expected land to be acquired for the purposes of the project, without much clarification as to whether affected community share common view with regard to the compensation, or how agreement on land compensation value was reached. Similarly, while the Resettlement Action Plan (RAP) provides key socio-environmental impacts and how the company would address these, the plan does not elaborate on the dam's downstream impacts and how the company would address these. Besides, while the company could only proceed with the dam construction after the government's approval of the RAP, the latter does not necessarily include a concrete timeline on when the company would provide affected households with compensation and any other entitlements. Obviously, while the company is required to consult and engage with affected community prior to the dam construction, the outcome of the process is very much defined by how the company convened the EIA process and implemented the RAP.[18] This highlights the problem of poor compliance in hydropower development, due to the government's lack of monitoring and evaluation mechanisms (Dixit & Gyawali, 2010) and the company's interest to shape the process to their advantage. This reflects key challenges in the country's hydropower governance, and how they are linked with the government's dependency on foreign direct investment and private sector actors for hydropower development (Sikor, Satyal, Dhungana, & Maskey, 2018).[19]

In 2018, the company is supposed to finalize the financial closure to get the final license and start with the dam construction. The financial closure report would have to outline the company's financial capacity to build the dam, which will be then reviewed and verified by the government. In order to acquire funding from the lenders, the hydropower company must secure the market to sell the generated electricity.[20] The Bangladeshi government has already signed and approved the MoU with NTPC Vidyut Vyapar Nigam (NVVN) to import 500 MW electricity from the Upper Karnali.[21] The plan is to complete the dam construction in 5–6 years from now (2024/2025). Once constructed, the company would have a 25-year concession time to operate the dam, after which they have to return to the GoN.

4.2. Upper Karnali concerns committee

Following the signing of the Memorandum of Understanding (MoU) between the GoN and the hydropower company in 2008 and the completion of the detailed project report in 2011, local community remained unaware about the plan to build the Upper Karnali hydropower dam. During that time, villagers would see the company staff coming to the area to conduct some topographical survey and measurement, but they hardly knew anything about the planned dam project. Local community heard about the planned hydropower project and how the project would impact their farming practices for the first time from their respective Village Development Committees (VDC) in 2012.

In the same year, the company proposed to form the Upper Karnali Concerns Committee (UKCC) in each of the 12 VDCs that would

[18] Jones (2012: 9) discusses how consultation processes at VDC level are 'either not happening or being run as a formality'. For the Upper Karnali hydropower project, the company never publicly disclosed the RAP.

[19] Policy mechanisms to ensure inclusive and sustainable hydropower development in Nepal have come under pressure as they are not always in favor of the government's goal to attract foreign direct investment. This is most apparent from the challenges to implement the International Labour Organization Convention 169 on indigenous rights in a series of hydropower projects (Jones, 2012).

[20] For GMR to lend money from the bank, it has to guarantee that a market exists to purchase the generated power. Since the company is responsible for this task, it is up to them to work with the Indian government to ensure the power purchasing agreement goes through. The Nepali and the Bangladeshi government are not influential in the settlement process. Once the bank releases the funds GMR can start acquiring land and pay the villages the promised amount.

[21] The MoU is between Bangladesh and NTPC Vidyut Vyapar Nigam (NVVN) since private developers are not allowed to sell electricity generated in a third country using transmission lines in India. This is part of the larger plan to purchase 9000 MW electricity from Nepal until 2040 from Upper Arun and Dudhkoshi hydropower projects.

be affected by the planned hydropower dam project (see Fig. 1). The idea to form the UKCC is that the company would then be able to communicate the planned hydropower project to local community, discuss key challenges and find ways as to how address these challenges together, while also ensuring that the proposed solution captures local community's development needs and concerns. Ideally, the UKCC would serve as both the company's first point of contact to reach out to local community, while communicating their development plans, especially pertaining to resettlement, compensation and other support it can provide for the affected community, as well as local community's means to negotiate their conditions and needs in relation to how the planned hydropower project would impact and/or benefit their livelihoods. The absence of government in the negotiation process can be attributed to the lack of elected representatives and a sense of mistrust amongst the community members to allow the government officials to negotiate on their behalf (Lord, 2016).

Starting from 2012, the company formed UKCC at each village that will be affected by the dam development. UKCC members were selected from households that would be affected by the planned hydropower project. In 2012, UKCCs were formed in respectively the upstream VDCs, as three upstream villages where farmers' farmland will be inundated following the hydropower dam construction. There are respectively 48.85 ha of private farmland and 207.75 ha of communal forest[22] that will be inundated in Thalpatta village alone. In Accham and Dailekh, there are respectively 35.61 ha and 15.26 ha of private farmland that will be inundated.

Unlike upstream villages UKCC that were formed first in 2012, UKCCs from downstream villages were formed only later in 2013. At that time, they were informed by their VDCs that their villages will be ones among those impacted by the planned hydropower project. Unlike upstream villages where the planned hydropower dam would result in villagers' agricultural farmland being inundated, the dam would not inundate any land in downstream villages. Rather, the planned dam would negatively impact local community's livelihoods in terms of reduced amount of water for their farming activities, while severely impacting the wider fishing community. Following the formation of the UKCC, the UKCC members raised their concerns on the dam's negative impacts to the company. However, at the time of writing, UKCC members remain uncertain as to whether the company would provide compensation for their loss of livelihoods following the construction of the dam.

Unlike in upstream villages where UKCC was formed in each of the villages that would be affected by the planned hydropower project, in downstream villages only one UKCC was formed out of the three villages that would be impacted by the dam. The UKCC formation in Pokharikanda and Chappre rural municipalities was halted by internal conflict between villagers, with each group wanting the UKCC chairperson representing the fishing community to be chosen from their respective group. As both villages comprise of local community living in the hilly and lowland area, each group wanted to have their respective leaders to be the UKCC chair person. As the group who lives at the hilly area would also represent the fishing community, as the one would be most affected by the hydropower dam, the idea is to assign their leader as the UKCC chairperson. However, the other group did not find this proposition acceptable as they wanted to also propose their own leader as the UKCC chair person, despite the fact that many of them are not fishermen. In the end, no UKCC was formed in these villages.

Thus, while the fishing community along the Karnali river would be the most affected by the planned hydropower project, they are not part of any of the UKCCs formed. While the fishing community could convey their concerns through general meeting organized by the company prior to the UKCC formation in 2012, following the formation of UKCC in each of the affected villages, their ability to raise the concerns is significantly reduced by each UKCC's focus to represent local community's needs and concerns in their respective villages. Moreover, the fishing community, comprised mainly of Dalit households, one of the poorest and most marginalized group, are without land registration papers. Perceived as untouchable, the group's ability to convey their concerns with regard to the planned hydropower project is very much limited by the existing power structure that does not always allow them to socialize and converse with others. As shared by one of Dalit fishermen we interviewed: *"I was in the big meeting arranged by the company. However, during the meeting I could only listen as I do not feel right to enter the discussion without anyone asking me to do so in the first place*" (interview with Dalit fisherman, May 2018). Hence, not having land registration papers to seek compensation and an UKCC that could represent their voice is a major blow.

While the company has formed and set up the UKCC as its point of contact, negotiation processes between the company and UKCC members are driven mainly by the company's and UKCC's interests, as most apparent from the negotiation on land compensation value, and thus not necessarily guided by the existing policies and legal frameworks in hydropower decision making. In instances wherein a parcel of land has to be acquired, the company is obliged to follow the government's policies and legal frameworks. Nonetheless, it is unclear as to whether the company should refer to the Land Acquisition Act (LAA) (NLC, 1977), the Land Acquisition, Resettlement and Rehabilitation Policy for Infrastructure Development Projects (LARRPIDP) (2014), or both. While the Act outlines the process to be followed to acquire and compensate land as defined by the government[23], its land classification system (e.g. agricultural, commercial and residential land) does not take into account people's livelihood options and strategies, and the overlapping boundaries between these different types of land use (Sharma & Khanal, 2010). Recently, the government has aimed to address these gaps through the introduction of new criteria to evaluate the existing land use and the application of 5 years of revenue in cash as a compensation measure, as stated in the LARRPIDP.[24] Yet, it is unclear how this policy will relate with the LAA and whether it can actually be implemented, when it concerns alternative measures to address the current gaps in the Act. This highlights the problem of overlapping policies and legal frameworks and its implications for the hydropower sector development in particular. As government agencies formulate laws and policies as a means to create spaces of power, overlapping policies and legal frameworks reveal not only bureaucratic fragmentation within the government, but also cross-sectoral competition and power struggles (Suhardiman, Bastakoti, Karki, & Bharati, 2018).

[22] While the forest land acquisition requires clearance from the Ministry of Forest and Environment, local community and UKCC members are not part of this discussion.

[23] Landowners are expected to seek compensation along with proof of land ownership within 15 days of issuing public notice indicating land acquisition by the government. An evaluation committee, comprised mainly of relevant government officials and rural municipality representatives, is responsible for determining the value of the land parcel as well as any house constructed in the premises. The Act also allows unsatisfied landowners to complain to the Chief District Officer for a final say. Section 27, however, states that the government may negotiate directly with the landowner, in which case, the above mentioned procedures are not applicable.

[24] The policy also envisions the compensation determination committee to work closely with the affected families and ensure mechanisms are in place to address complaints. It is unclear as to how the Act and the policy would include market price as part of the land valuation. Being largely unregulated, the market price for land can potentially inflate in situation wherein an infrastructure project is planned.

4.3. UKCC members' and local community's different views

4.3.1. Upstream view: the centrality of land compensation payment

UKCC members and local community from upstream villages (Thalpatta, Sisne and Daba) view that the planned hydropower project should continue as this would bring development to the area and improve local community's standard of living. They are aware about the negative impact the dam might give in terms of reducing their ability to produce sufficient food from their agricultural land, as they have to rely on their only farmland in the hilly area, which is much less fertile than the lowland, inundated one. Nonetheless, they think the immediate and long term benefits they could get from the dam development would exceed the costs.

Central in shaping the UKCC members and local community's view is the negotiated land compensation value, in which the company had agreed to pay for farmers' farmland that would be inundated following the hydropower dam construction. The incentive to support the project despite the significant loss to the farmland stems from the expected monetary benefit during the land acquisition process. The company has agreed to a land compensation value of 0.8–0.9 million NPR/ropani[25] for any loss of farmers' land. This value is very high, not only compared to the expected government compensation of 10,000 NPR/ropani derived from the land classification registration fee, but also with regard to the current land market value, usually set by the transaction rates in the last 6 months.[26] Villagers view the land compensation payment as additional benefit they could use to improve their livelihoods (e.g. for opening new shop and businesses, buy residential land elsewhere). As said by one of farmer from Sisne village: *"At present, we can rely on agricultural production to suffice our food consumption for 5–6 months in a year. Once part of our lowland farmland is inundated, we could only suffice for 2–3 months with regard to home consumption. But if you are poor, it does not really matter as to whether the dam will affect your livelihoods, you will still be poor. The most important thing is that I can now use the money from the land compensation payment to invest in my son's education to be land surveyor and works and earns money from the company later. Hence, I am willing to take the risk. Without the project, nothing will happen in the area and people will remain poor*" (interview with villager from Sisne, May 2018).

Throughout the years, upstream villages UKCC members negotiated with the company on terms and conditions for resettlement and compensation for agricultural land that will be inundated by the hydropower dam construction. In 2016, the company and upstream villages UKCCs agreed on the defined land compensation value of 0.9 million NPR/ropani payable for each household for land inundated to construct the dam. Initially, the company informed the villagers that they would complete land compensation payment in June 2017. In practice, however, the company only started with the actual distribution of the payment to affected villagers in September 2017. According to the new plan, the company would complete the payment process to all affected villagers in March 2018. As in May 2018, however, the company had only acquired approximately 12 percent of the total land and made the payment to the villagers.[27] This illustrates not only the company's inability to acquire the land needed for project development according to the defined plan, it also shows the government's lack of power to enforce the plan implementation. According to Section 8.2 of the PDA, upon approval by the government, land needed for project development will be acquired within the 12 months thereafter. The company's agreement on the land compensation value, on the other hand, shows how upstream UKCC members have been able to negotiate their interests simply by focusing on their role in mobilizing protests at the planned dam site and the company's field office in Surkhet (McAdam, McCarthy, & Zald, 1996), and without any reference to existing policies and legal frameworks.

When the company halted their land compensation payment due to recent attack on the company field office in March 2018, affected villagers and local community from the three upstream villages insisted that the company continue with the planned project, as only the latter would ensure the completion of villagers' land compensation payment. Anticipating the land compensation payment, some villagers had already closed the deals to buy land elsewhere while using the money from the compensation payment to purchase the land. As said by one of the villagers from Daba: *"I have purchased a residential land in Surkhet, where I will build our family home later. As part of the deal, I have given a down payment for the land and six months after that I would have to complete the final payment. For the latter, I would use the money from the land compensation payment. Hence, if the company delays the payment, this will affect my land deals*" (interview with villager from Daba, May 2018).

The local community has routinely voiced their concerns regarding the politicization of the Upper Karnali despite the significance of the project on the entire nation (IBN, 2015). During our interactions and discussions with several members of the upstream UKCC there was a strong unified voice to ensure that our field work and subsequent report does not hamper the project. Given the larger national level debate surrounding the politics and environmental concerns of the Upper Karnali voiced by civil societies residing in urban areas, upstream UKCC members wanted to ensure we would present our findings supporting the construction of the dam. It was clear that UKCC members from Dailekh and Accham have a very different view and stake in the completion of the project compared to the civil society members and conservationists critical of the project. As said by one UKCC member from Thalpatta: *"Many have come from Kathmandu to conduct research only to go back to write a report that talks about the negative effects of the project. They stay in their air-conditioned offices and nice homes and criticize the dam. Do they not see how we are living here? Our villages have never seen development; the government has not developed our area. Finally, we have some jobs coming and now the so-called experts want to stop that as well.*" (phone interview with UKCC member from Thalpatta, June 2018).

UKCC members from Thalpatta and Sisne view that the company has also provided them the opportunity to gain experience in hydropower decision-making processes, improve their negotiation skills, through for instance providing them the opportunity to visit hydropower projects in the country, to learn from past experiences. As said by UKCC member from Thalpatta village: *"Throughout the negotiation process with the company we tried to get all the needed information, for example on how past projects had been done, issues that need to be brought up as to better represent local community's needs and concerns to the company. We would collect this information from the Investment Board of Nepal (IBN), the media, through interaction with other members, and also through study tour to other affected villages*" (interview with UKCC member from Thalpatta village, May 2018). This brings to light as to how in the context of upstream villages, the UKCC has gained its power through its relationship with the company, as the company put UKCC central with regard to their role to communicate and negotiate local community's needs and concerns to the company, and vice versa.

[25] 1 Hectare = 19.965 Ropani.

[26] An official land valuation system does not exist in Nepal and valuation of compensation is conducted on project basis with the developers and government agencies determining compensation package (Ghimire et al., 2017).

[27] According to upstream villages UKCC members, the delay is rooted in the ongoing discussion to adjust the Power Purchase Agreement. Initially, the company would channel the generated power from the hydropower project to India, to ensure the country meets its electricity demand. At present, however, the discussion is to also sell this electricity from India to Bangladesh, as the first faces the issue of electricity over supply.

The case illustrates how power relations are shaped and reshaped following the company's spatial inclusion logic, to ensure it can proceed with the planned hydropower dam while also ensuring local community's concerns are addressed. The applied spatial logic not only result in the formation of strategic alliance between the company and upstream villages, it also ensures that the latter supported the newly produced spatial imagination, centered on the newly defined spatial connection between the planned hydropower dam site and its vicinity with upstream villages. Similarly, the timing when and the sequence of how the strategic alliance is formed ensure that the company could proceed with the planned hydropower project, while relying on upstream villages' support, with or without addressing the consent from downstream villages, which will be discussed next.

4.3.2. Downstream view: is the planned hydropower project worthwhile in the absence of any compensation mechanism?

UKCC members and local community from downstream villages (Ramaghat, Saura, and Dungeshwor) view that the planned hydropower project should be halted. While villagers would not directly lose their land due to inundation from hydropower development, the dam would negatively affect their livelihoods due to reduced water quantity leading to a loss of fisheries, loss of agricultural practices, loss of biodiversity as well as loss of communal land for livestock grazing near the river.

Back in 2016, the company informed UKCC members and local community that they would get access to electricity from the planned hydropower project. They have also provided school facilities and furniture to VDC offices to the respective villages. In practice, however, UKCC members and local community do not view this as a good enough benefit to outweigh their potential loss of farmland and fisheries resources. As said by one of the villagers from Saura village: *"I do not think that the planned hydropower project would benefit villagers. Even when we would get free access to electricity, this would not benefit us if it means we have to lose everything else related to our farming activities. At present we have sufficient water supply for our farming activities. When the dam is built, it would take all the water and impact 10,000 households in three villages in Surkhet district*" (interview with villager from Saura, May 2018). Similarly, as expressed by one of the Dalit fishing community from Ramaghat village: *"We have always been fishermen all our lives. When the planned dam would force us to stop fishing, we do not know as to whether we would be able to make the needed transition in our livelihood options, as we lack the skills needed for that*" (interview with Dalit fisherman, May 2018).

Central in shaping UKCC members' and local community's view is the fact that the company is not able to offer any clarity on compensation for the villagers' losses of livelihoods (e.g. farming and fisheries). As said by UKCC member from Saura village: *"We are not against the planned hydropower project, as we all know the country needs to develop. However, it is unclear as to how the company would compensate our losses of livelihoods following the dam construction. Before this is clarified, we could not support the dam construction*" (interview with UKCC member from Saura village, May 2018). Similarly, as expressed by one of the villagers from the same village: *"At present we are food secured. We do not have cash but we are fine. When the dam project comes, perhaps we would get cash for compensation of our loss of livelihoods. But we do not know how much and whether it will be enough to secure our food needs for the long term*" (interview with a farmer from Saura village, May 2018).

Unlike in the case of upstream UKCCs who have successfully negotiated with the company about the land compensation value, downstream UKCCs were able to voice local community's concerns on the negative impacts from the dam, though they lack any bargaining power to negotiate with the company on the compensation mechanism and arrangement. As the company did not depend on downstream UKCC members' and local community's support and acceptance for the construction of the planned hydropower dam, they could easily ignore their concerns. The company's unequal treatment towards respectively upstream and downstream UKCCs is captured in the following statement: *"I know farmers in Daba village would receive 0.9 million NPR/ropani for the inundated farmland. As for farmers in Saura village, the company did not even inform as to whether we would get any compensation for the loss of our livelihood options*" (interview with UKCC member from Saura village, May 2018).

As the company seems to be the one defining the space for negotiation in terms of compensation packages and other support, downstream UKCCs are left with very little chance to successfully negotiate local community's development needs and concerns in relation to the planned hydropower project. While downstream UKCCs could technically build alliance with upstream UKCCs to negotiate with the company, this potential alliance is undermined by the company's strategy to form alliances with upstream UKCC. While inter-UKCCs alliance is possible prior to the company's and upstream UKCC' agreement on the land compensation value, we argue that the agreement has put upstream UKCC and the company on a different negotiation path. Consequently, the establishment of this new negotiation path made it very difficult for upstream and downstream UKCC to join forces. Unlike before, they could no longer reconcile their concerns, as doing so would require upstream UKCC to break the agreement on the land compensation value they have just reached with the company.

4.4. Everyday politics and the shaping of local strategic alliances

UKCC members' and local community's different views on the planned hydropower dam show not only how the dam would impact local communities along the river differently, it also brings to light the spatial fragmentation and spatial politics shaping hydropower decision making at the grass roots level. This is most apparent from the formation of strategic spatial alliance between the company and upstream UKCCs on the one hand, and distance relationship between the company and downstream UKCCs on the other hand. As the company depends on upstream UKCCs' support before it can proceed with the dam construction, it is keen to make the negotiation works. Similarly, as the company does not depend on downstream UKCCs' support for the dam construction, they can ignore their concerns and/or decide to not enter into any negotiation with the UKCCs.

The (re)production of a new spatial imagination, centered on the planned dam site in the vicinity of upstream villages, has divided local community's standpoints with regard to the planned dam project. This fragmentation and division are most apparent from the way the company positioned upstream villages as strategic allies as compared to its view of downstream villages as affected people whose concerns can be ignored. Similarly, upstream villagers view themselves as direct beneficiaries from the hydropower project, instead of affected people. Here, the company did not only disconnect upstream and downstream villages spatial connection, it also undermined local community's ability to act collectively, while reconciling their differences. By forming UKCC at village level, the company has limited the UKCC's role and operational boundary to village level negotiation with the company, rather than through nested inter-village decision-making platform. The UKCC organizational design ensures that the company remains the key actors shaping and reshaping the new spatial imagination, while ensuring that inter-UKCCs platform never materialized. As expressed by UKCC member from Saura village: *"Initially, I and other UKCC members from Dungeshwor village proposed to the company to have an inter-UKCC committee, to ensure local community would have unified view on the planned hydropower project. When the company did not respond, this idea never materialized*" (interview with UKCC member from Saura village, May 2018).

Despite the lack of formal inter-UKCC organizational structure, the upstream and downstream UKCC members used to meet and came together initially, to discuss their concerns and reconcile them into a larger dam-affected people approach, while emphasizing on their unified position with regard to the planned dam project. However, this informal communication network became highly dysfunctional following the upstream UKCC members agreement with the company on the land compensation value. As shared by UKCC member from Dungeshwor village: *"In the past, upstream UKCC member (from Thalpatta) would inform us about their planned protests and encourage downstream villagers to join the protests to push for local community's demands for higher land compensation than initially proposed by the company. Yet, once the company agreed on the proposed land compensation value, upstream UKCC member did not communicate anything to downstream UKCC members. I heard about the agreement on land compensation value from my relatives living in upstream villages, and not from the UKCC member. This means that they have agreed on the company's plan to construct the dam, while overlooking how the latter would impact downstream villages*" (interview with UKCC member from Dungeshwor village, May 2018). The absence of inter-UKCCs platform and the company's strategic alliance with upstream UKCCs made it impossible for downstream UKCCs to rely on inter-UKCCs networks both formally and informally.

It also creates inter-UKCCs competition as evident in upstream UKCC members' lack of interest to support downstream UKCC members' role in negotiating compensation for the dam's downstream impact with the company. As expressed by UKCC member from Sisne: *"Everyone wants something different from the company. Upstream UKCC members and local community want to get land compensation payment, the fishing community downstream want to have training and employment opportunities, while farmers in downstream villages want to have irrigation systems. Nonetheless, the company has to do first thing first, that is ensuring land compensation payment for farmers in upstream villages*" (interview with UKCC member from Sisne, May 2018). Obviously, upstream UKCC members have little interest to support downstream UKCC's requests, fearing this would affect their own negotiation with the company on land compensation value. Some members of upstream UKCC deliberately kept relevant information on the negotiation processes concerning the land compensation payment to themselves, fearing that downstream UKCC's request might disrupt the negotiation process and affect the outcome. Here, relevant information on the planned hydropower project (e.g. compensation payment value and agreement) trickles down mainly through the strategic alliances formed by the company and the upstream UKCCs, while excluding downstream UKCCs access to information.

The strategic alliance between the company and upstream UKCC and villages results in further marginalization of the poor. In the absence of inter-UKCCs decision-making platform, the company could direct the entire discussions on compensation to local community living near the dam site, with very little attention, if any, to local community downstream who would be the hardest hit by the hydropower project. The significant stratification within Nepali society enables the company to divide and rule the affected communities, while ignoring the Dalit as the one who will be most affected by the dam development, but whose status in society renders them almost voiceless (Jones, 2012; Sikor et al., 2018).

5. Conclusion

The paper brings to light the spatial dimension in hydropower decision making, and the centrality of strategic alliances formation in the shaping of socio-political production of space, centering on the company's strategy to proceed with the planned hydropower project through the production of new spatial imagination (Low, 2008). It shows how local communities living along the river have different, oftentimes conflicting views with regard to hydropower development project. These views are derived from their relationship with the company, based on their village's spatial importance vis-à-vis the planned dam site, and how the latter predetermined their bargaining power, and thus their ability to negotiate their development needs and concerns.

Referring to the shaping of everyday politics as well as the formation of spatial alliances in hydropower decision making at the local level, the paper illustrates the shaping and reshaping of spatial logic driving hydropower decision-making processes, centering on the company's strategy to include and exclude local community's development needs and concerns, and how these coincide with its objective to proceed with the planned hydropower project. It argues that understanding this spatial logic is key to unpacking power relations (re)shaping hydropower governance landscapes, processes and outcomes.

The Nepal case study clearly shows how the company did not only form strategic alliances with the upstream UKCCs, it also undermined local community's potential ability to come with a unified voice demanding their collective needs and concerns. Lacking any spatial power to gain access to hydropower decision-making processes, downstream UKCCs' lack any bargaining power to push the company to agree on the negotiated terms or even start with the negotiation processes, as the latter is sidelined by upstream UKCCs' support to the planned dam project. While the central government has formulated and implemented various policies and legal frameworks to regulate and manage hydropower development in the country, our case study highlights key policy and institutional gaps in hydropower decision making. As various government agencies are competing for decision-making space, and bearing in mind the country's dependency on foreign direct investments and private sector actor for the sector development, there is a tendency to give the company some leeway to create their own decision-making space, resulting in the latter taking the center stage in hydropower project implementation at the grass-roots level.

The paper argues that the current discourse on anti-dam movement cannot be framed without including local community's diverse views on hydropower development, their dynamic standpoints, how this evolves over time, and its implications for social justice (Sen, 2009; Visser, 2001; Young, 1990), while asserting that *'notions of justice are more likely to be plural than converge on a single meaning'* (Sikor et al., 2018: 14). Moving beyond distributional and procedural justice (Schlosberg, 2007), it highlights the need to *'recognize that justice has different meanings for different people in different places'* (Tschakert, 2009: 731), while unpacking the processes that (re)produce misrecognitions, exclusions, through which injustices are created and sustained. For the Upper Karnali case in particular, this means connecting upstream UKCCs' negotiated demand for land compensation payment with downstream UKCCs' concerns on how the planned hydropower project would negatively impact their agricultural and fisheries resources. Upstream UKCC and villagers view justice as getting the agreed land compensation value. Downstream UKCC and villagers view justice as getting their concerns heard and addressed by the company. Putting these different perceptions of justice within the context of hydropower decision making, the paper highlights how views of justice can be contradictory, as this manifested in upstream and downstream UKCC and villagers' negotiation strategies with the company, and how the latter defines their respective position to support and oppose the planned hydropower project. [28]Or, as stated by Walker (2009: 40): *"as different groups will resort to different*

[28] On challenges for cross-scale collective action and stakeholder representation in river basin management see Swallow et al. (2006) and Wester et al. (2003).

conceptions of justice to bolster their position, so will different groups work with different understandings of the spatiality of the issues at hand".

Placing this within the context of state transformation and the current move towards federalism, it highlights the need to understand the overall shaping of spatial politics and broaden the overall notion of accountability of elected local governing bodies, beyond their respective administrative and political units (e.g. village, municipality), as it is pertinent that the planned development captures development needs and concerns of the poorest and most marginalized groups of the society. From a policy perspective, this highlights the role that can be played by local governing bodies in shaping the country's development in general and with regard to hydropower development in particular. Following federalism, local governing bodies could ensure that local community's negotiation with hydropower company is not based only on the relations between certain UKCC with the company, but most importantly driven by the need to distribute benefits and impacts of hydropower development more equally. This highlights the need to develop policy framework and mechanisms to govern and direct hydropower development practices at local level, to ensure that hydropower project captures local community's diverse development needs and aspirations.

Declaration of Competing Interest

None.

Acknowledgements

We would like to thank Prof. Arun Agrawal, World Development Editor in Chief and two unanimous reviewers for their valuable comments and feedbacks. The study is made possible by the generous support of the American people through the United States Agency for International Development (USAID). The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government.

References

Agrawal, A. (2014). Studying the commons, governing common pool resource outcomes: Some concluding thoughts. *Environmental Science and Policy, 36*, 86–91.
Agrawal, A., & Benson, C. (2011). Common property theory and resource governance institutions: Strengthening explanations of multiple outcomes. *Environmental Conservation, 38*, 199–210.
Agrawal, A., Brown, D. G., Rao, G., Riolo, R., Robinson, D. T., & Bommarito, M. II, (2013). Interactions between organizations and networks in common pool resource governance. *Environmental Science and Policy, 25*, 138–146.
Agrawal, A., & Gibson, C. (1999). Enchantment and disenchantment: The role of community in natural resource conservation. *World Development, 27*(4), 629–649.
Alam, F., Alam, Q., Reza, S., Khurshid-ul-Alam, S. M., Saleque, K., & Chowdhury, H. (2017). A review of hydropower projects in Nepal. *Energy Procedia, 110*, 581–585.
Amirova, I., Petrick, M., & Djanibekov, N. (2019). Long and short-term determinants of water user cooperation: Experimental evidence from Central Asia. *World Development, 113*, 10–25.
Armbrecht, A. (1999). The importance of being local: Villagers, NGOs and the World Bank in the Arun Valley, Nepal. *Identities, 6*(2–3), 319–344.
Arora, V. (2009). They are all set to dam(n) our future: Contested development through hydel power in democratic Sikkim. *Sociological Bulletin, 58*(1), 94–114.
Bakker, K. (1999). The politics of hydropower: Developing the Mekong. *Political Geography, 18*(2), 209–232.
Baruah, S. (2012). Whose river is it anyway? Political economy of hydropower in the Eastern Himalayas. *Economic and Political Weekly, 47*(29), 41–52.
Berking, H., Frank, S., Frers, L., & Low, M. (2006). *Negotiating urban conflicts. Interaction, space and control*. Bielefeld: Transcript.
Burawoy, M. (1991). The extended case method. In M. Burawoy (Ed.), *Ethnography unbound: Power and resistance in the modern metropolis* (pp. 271–287). Los Angeles: University of California Press.
Burrier, G. (2016). The developmental state, civil society and hydroelectric politics in Brazil. *Journal of Environment and Development, 25*(3), 332–358.
Chung, H. (2012). The spatial dimension of negotiated power relations and social justice in the redevelopment of villages-in-the-city in China. *Environment and Planning A, 10*(45), 2459–2476.
Cody, K. C. (2018). Upstream with a shovel or downstream with a water right? Irrigation in a changing climate. *Environmental Science and Policy, 80*, 62–73.
de Vries, P. (2007). Don't compromise your desire for development! A Lacanian/Deleuzian rethinking of the anti-politics machine. *Third World Quarterly, 28*(1), 25–43.
Dixit, A., & Gyawali, D. (2010). Nepal's constructive dialogue on dams and development. *Water Alternatives, 3*(2), 106–123.
Dukpa, R. D., Joshi, D., & Boelens, R. (2018). Hydropower development and the meaning of place: Multi-ethnic hydropower struggles in Sikkim, India. *Geoforum, 89*, 60–72.
Fraser, N. (1998). *Social justice in the age of identity politics: Redistribution, recognition, participation. Discussion Paper*. Berlin: WZB Berlin Social Science Center.
Ghimire, S., Tuladhar, A., & Sharma, S. R. (2017). Governance in land acquisition and compensation for infrastructure development. *American Journal of Civil Engineering, 7*(3), 169–178.
Harvey, D. (1996). *Justice, nature and the geography of difference*. Cambridge: Blackwell Publishers.
Huber, A., & Joshi, D. (2015). Hydropower, anti-politics and the opening of new political spaces in the Eastern Himalaya. *World Development, 76*, 13–25.
IBN (2014). *Project development agreement Upper Karnali hydropower project*. Kathmandu: Investment Board of Nepal.
IBN (2015). *Upper Karnali field visit report*. Kathmandu: Investment Board of Nepal.
IHA (2018). *Hydropower Status Report: Sector trends and insights 2018*. London: International Hydropower Association Limited.
Jones, P. S. (2012). Powering up the people? The politics of indigenous rights implementation: International Labour Organisation Convention 169 and hydroelectric power in Nepal. *International Journal of Human Rights, 16*(4), 624–647.
Klein, P. (2015). Engaging the Brazilian state: The Belo Monte dam and the struggle for political voice. *Journal of Peasant Studies, 42*, 1137–1156.
Lawoti, M. (2012). Ethnic politics and the building of an inclusive state. In S. von Einsiedel, D. Malone, & S. Pradhan (Eds.), *Nepal in transition: From people's war to fragile peace* (pp. 129–152). Cambridge: Cambridge University Press.
Lecours, A. (2013). The question of federalism in Nepal. *The Journal of Federalism, 44*, 609–632.
Lefebvre, H. (1991). *The production of space*. Cambridge: Blackwell.
Lord, A. (2014). Making a hydropower nation: Subjectivity, mobility and work in the hydroscapes of Nepal. *Himalaya, 34*(2), 111–121.
Lord, A. (2016). Citizens of a hydropower nation: Territory and agency at the frontiers of hydropower development in Nepal. *Economic Anthropology, 3*, 145–160.
Low, M. (2008). The constitution of space: The structuration of spaces through the simultaneity of effect and perception. *European Journal of Social theory, 11*(1), 25–49.
Massey, D. (1995). Space/power, identity/difference: Tensions in the city. In A. Merrifield & E. Swyngedouw (Eds.), *The urbanization of injustice* (pp. 1–17). London: Lawrence and Wishart.
Mayerfeld-Bell, M. (1997). The ghosts of place. *Theory and Society, 26*(6), 813–836.
McAdam, D., McCarthy, J. D., & Zald, M. N. (1996). *Comparative perspectives on social movements: Political opportunities, mobilizing structures, and cultural framings*. Cambridge: Cambridge University Press.
McCord, P., Angelo, J. D., Gower, D., Caylor, K. K., & Evans, T. (2019). Household-level heterogeneity of water resources within common pool resource systems. *Ecology and Society, 22*(1), 48.
Merrifield, A., & Swyngedouw, E. (1996). *The urbanization of injustice*. London: Lawrence and Wishart.
Middleton, T., & Shneiderman, S. (2008). Reservations, federalism and the politics of recognition in Nepal. *Economic and Political Weekly, 43*(19), 39–45.
MoEST (2006). *A handbook on licensing and environment assessment processes for hydropower development in Nepal*. Kathmandu: Ministry of Environment Science and Technology.
MoFE. (2018). *Hydropower environmental impact assessment manual*. Kathmandu: Ministry of Forest and Environment.
Molle, F., Foran, T., & Kakonen, M. (2009). *Contested waterscapes in the Mekong region: Hydropower, livelihoods and governance*. London: Earthscan.
Murton, G., Lord, A., & Beazley, R. (2016). Handshake across the Himalayas: Chinese investment, hydropower development, and state formation in Nepal. *Eurasian Geography and Economics, 57*(3), 403–432.
Ostrom, E. (2011). Reflections on some unsettled problems of irrigation. *American Economic Review, 101*, 49–63.
Paudel, D. (2016). Ethnic identity politics in Nepal: Liberation from, or restoration of, elite interest? *Asian Ethnicity, 17*, 1–18.
Pierson, P. (2004). *Politics in time: History, institutions, and social Analysis*. Princeton: Princeton University Press.
Pirie, G. H. (1983). On spatial justice. *Environment and Planning A, 15*, 465–473.
Rest, M. (2012). Generating power: Debates on development around the Nepalese Arun 3 hydropower project. *Contemporary South Asia, 20*(1), 105–117.
Schlosberg, D. (2007). *Defining environmental justice: Theories, movements, and nature*. Oxford: Oxford University Press.
Schmid, C. (2008). Henri Lefebvre's theory of the production of space: Towards a three-dimensional dialectic. In K. Goonewardena, S. Kipfer, R. Milgrom, & C. Schmid (Eds.), *Space, difference, everyday Life: Reading Henri Lefebvre* (pp. 27–45). New York and London: Routledge.

Sen, A. (2009). *The idea of justice*. Harvard: Harvard University Press.
Sewell, W. H. (1996). Three temporalities: Toward an eventful sociology. In T. McDonald (Ed.), *The historical turn in the human sciences* (pp. 245–280). Ann Arbor: University of Michigan Press.
Sharma, K., & Khanal, S. N. (2010). A review and analysis of existing legal and policy issues related to land tenure and agriculture in Nepal. *Kathmandu University Journal of Science, Engineering and Technology., 6*(2), 133–141.
Shneiderman, S., & Tillin, L. (2015). Restructuring states, restructuring ethnicity: Looking across disciplinary boundaries at federal futures in India and Nepal. *Modern Asian Studies, 49*, 1–39.
Sikor, T., Satyal, P., Dhungana, H., & Maskey, G. (2018). Brokering justice: Global indigenous rights and struggles over hydropower in Nepal. *Canadian Journal of Development Studies*, 1–19.
Sneddon, C., & Fox, C. (2012). Water, geopolitics and economic development in the conceptualization of a region. *Eurasian Geography and Economics, 53*(1), 143–160.
Soja, E. (2010). *Seeking spatial justice*. Minneapolis: University of Minnesota Press.
Subba, T. (2014). Power projects, protests and problematics of belonging in Dzongu, Sikkim. In G. Toffin & J. Pfaff-Czarnecka (Eds.), *Facing globalization in the Himalayas: Belong and the politics of the self* (pp. 326–343). New Delhi: Sage Publications.
Suhardiman, D., Bastakoti, R. C., Karki, E., & Bharati, L. (2018). The politics of river basin planning and state transformation processes in Nepal. *Geoforum, 96*, 70–76.
Swallow, B., Johnson, N., Meinzen-Dick, R., & Knox, A. (2006). The challenges of inclusive cross-scale collective action in watersheds. *Water International, 31*(3), 361–375.
Thakkar, H. (2008). *India's dam building abroad: Lessons from the experience at home? New financers and the environment*. Berkeley: International Rivers.
Tschakert, P. (2009). Digging deep for justice: A radical re-imagination of the artisanal gold mining sector in Ghana. *Antipode, 41*(4), 706–740.
Varughese, G., & Ostrom, E. (2001). The contested role of heterogeneity in collective action: Some evidence from community forestry in Nepal. *World Development, 29*(5), 747–765.
Visser, G. (2001). Social justice, integrated development planning and post-apartheid urban reconstruction. *Urban Studies, 38*, 1673–1699.
Walker, G. (2009). Beyond distribution and proximity: Exploring the multiple spatialities of environmental justice. In R. Holifield, M. Porter, & G. Walker (Eds.), *Spaces of environmental justice* (pp. 24–46). New Jersey: Wiley-Blackwell.
Wester, P., Merrey, D. J., & de Lange, M. (2003). Boundaries of consent: Stakeholder representation in river basin management in Mexico and South Africa. *World Development, 31*(5), 797–812.
Yin, R. K. (1994). *Case study research: Designs and methods* Applied social research methods series no. 5. London and New Delhi: Thousand Oaks: Sage Publications.
Young, I. M. (1990). *Justice and the politics of difference*. Princeton: Princeton University Press.

Annex 4-1

Water Policy 21 (2019) 1017–1033

Unravelling gendered practices in the public water sector in Nepal

Gitta Shrestha[a,*] and Floriane Clement[a,b]

[a]*International Water Management Institute (IWMI), GPO Box 8975, EPC 416, Kathmandu, Nepal*
**Corresponding author. E-mail: g.shrestha@cgiar.org*
[b]*DYNAFOR, Université de Toulouse, INPT, INRA, Toulouse, France*

Abstract

Despite decades of gender mainstreaming in the water sector, a wide gap between policy commitments and outcomes remains. This study aims at offering a fresh perspective on such policy gaps, by analysing how gendered discourses, institutions and professional culture contribute to policy gaps. We rely on a conceptual framework originally developed for analysing strategic change, which is used to analyse gender in the public water sector in Nepal. Our analysis relies on a review of national water policies and a series of semi-structured interviews with male and female water professionals from several public agencies. Our findings evidence how dominant discourses, formal rules and professional culture intersect to support and reproduce hegemonic masculine attitudes and practices of water professionals. Such attitudes and practices in turn favour a technocratic implementation of policy measures. We argue that gender equality policy initiatives in the water sector have overly focused on local level formal institutions and have not adequately considered the effects of masculine discourses, norms and culture to be effective in making progress towards gender equity. We conclude with policy recommendations.

Keywords: Discourse; Gender; Institutions; Nepal; Professional culture; Water

Introduction

Gender, along with other social identities, is a critical determinant and characteristic of water–society relationships. Gender shapes inter alia who benefits and who loses from water resource development (Carney, 1993; van Koppen, 1998) or from water privatisation (Harris, 2008) as well as one's vulnerability to water-related disasters (Enarson & Fordham, 2001). Yet over a long period, gender was considered irrelevant to water management in most policy spheres. Since the 1990s, the inclusion of

doi: 10.2166/wp.2019.238

gender equality in international water governance agendas[1] marks a formidable step forward in acknowledging gender as a legitimate policy issue in the water sector. Many governments have initiated institutional reforms to meet their policy commitments on gender, including quotas to ensure equal gender representation in water user associations (WUAs) and the allocation of formal individual water rights to women.

Yet these efforts have not, as a whole, profoundly challenged existing gendered patterns of water planning, management and decision-making, as documented in South Asia (Zwarteveen *et al.*, 2014). For instance, increased women's membership in WUAs has neither challenged traditional gender roles (Elias, 2017) nor led to legitimate and meaningful inclusion of women's interests in decision-making processes, as documented in South Africa and Kyrgyzstan (Kemerink *et al.*, 2012; Nixon & Owusu, 2017). Similarly, individual water rights have often not adequately supported women to meet their specific water needs and even reinforced existing gender inequities as observed in South Asia and elsewhere (Meinzen-Dick & Zwarteveen, 1998; Ahlers & Zwarteveen, 2009; Harris, 2009).

The processes and factors creating a gap between policy intentions and outcomes are multiple and intertwined. Policies are interacting with other strong drivers of change, some of which have aggravated gendered inequities, such as neoliberal reforms favouring water privatisation and marketisation (Ahlers & Zwarteveen, 2009; Harris, 2009; O'Reilly, 2011) and other political economic and environmental changes (Buechler & Hanson, 2015). Gender intersects with other social markers such as caste, ethnicity, class, age or religion in water injustices (Harris, 2008; O'Reilly, 2011; Leder *et al.*, 2017). Several scholars have also pointed to how water management is embedded in day-to-day norms, social relations and practices (Joshi, 2005; Vera Delgado & Zwarteveen, 2007; Ahlers & Zwarteveen, 2009; Sultana, 2009). As the latter depend on ecological and socio-cultural contexts, institutional panaceas are unlikely to produce expected policy outcomes across settings (Meinzen-Dick, 2007; Zwarteveen & Boelens, 2014). A relatively under-explored but growing area of scientific enquiry has been that of masculinities and gendered culture in water organisations, and how the latter influences the attitudes and practices of water professionals (Laurie, 2005; Zwarteveen, 2008; Liebrand & Udas, 2017).

We built on this recent scholarship, using the case study of water bureaucracies in Nepal. Nepal offers an interesting case study as national irrigation and drinking water policies are relatively progressive in terms of gender and social inclusion. Our objective was to explore how gendered discourses and institutions shape the attitudes and practices of professionals in water bureaucracies and the ability of public organisations to reach gender policy goals. By institutions, we consider the formal rules and informal rules, norms and strategies embedded in the professional culture. We add to earlier research by adapting an integrated organisational management framework, called the technical, cultural, political framework (Tichy, 1983). This allows a relatively comprehensive analysis of multiple organisational components and of their interactions, therefore supporting the design of actionable policy recommendations. We hope thereby to reach a broader audience of policy-makers, development practitioners and scholars.

[1] These include Agenda 21 of the Earth Summit in Rio (1992), the Dublin Principles of 1992. The UN Water for Life Decade 2005–2015 likewise emphasised the necessary involvement and participation of women to achieve international commitments on water and water-related issues.

Background

Gender in water policies in Nepal

In Nepal, policy attention to gender and development started in the 1980s as gender became increasingly prominent in international development debates. A landmark study on 'The status of women in Nepal' (Acharya & Bennett, 1981) made women's contribution to the national economy more visible on the policy stage[2]. In particular, there was an increasing recognition of women's role and responsibilities in the management of natural resources and, in particular, forest. Efforts to address gender equality in water resource management came later and can be dated back to the early 2000s, under the Ninth Five-year Plan (1997–2000). The Plan recognised women's development and empowerment as a key tenet of development. It indicated that all national development programmes would adhere to Nepal's National Plan of Action for Gender Equality and Women's Empowerment, formulated to implement the Beijing Platform for Action.

Donors have also strongly pushed gender mainstreaming as part of development initiatives, across several sectors. Gender mainstreaming debates have largely relied on a monolithic framing of 'the Nepali woman' as 'patriarchically oppressed, uniformly disadvantaged and Hindu' (Tamang, 2011: p. 281), ignoring the diversity of gender relationships and gendered experiences, needs and subjectivities across Nepal. In the water sector, gender mainstreaming efforts have resulted in the creation of a gender and social inclusion (GESI) unit in most ministries and line departments, as a requirement of the Gender Responsive Budgeting and Planning Directive (Government of Nepal, 2012). The latter was issued by the Ministry of Finance to fulfil Nepal's international commitments to gender equality, e.g., the Commission for Elimination of Discrimination Against Women (CEDAW), the Beijing Platform for Action and the Millennium Development Goals (MDGs). Furthermore, several gender equality initiatives are tied to donor-supported projects, e.g., from the Asian Development Bank or the World Bank, and many of them become dysfunctional as soon as the project phases out.

Policy initiatives towards gender equality in water management have, since their earliest stages, focused on enhancing the participation of women in formal WUAs. Although we could not specifically track donors' influence on gender mainstreaming debates in the water sector in Nepal, this focus is in line with international development discourses on gender equity and water (Cleaver, 1999; Wallace & Coles, 2005; Singh, 2008). The Irrigation Policy 1992 stipulates 20% of women members in WUAs (Ghimire, 2004) while recognising and institutionalising the participation of farmers in irrigation management. Nepal's Water Resource Strategy, a landmark cross-sectoral water policy document, stressed the importance of 'balanced gender participation and social equity' (HMGN, 2002) in the use and management of water resources. The National Water Plan (HMGN, 2005) similarly recommended the inclusion of women in integrated river basin water management (e.g., involvement of women in river bank protection, conservation of watershed, operation and management of irrigation systems, in electricity distribution programmes, etc.).

Sectoral policies include concrete policy measures to achieve these goals, namely, fixed quotas (33%) for women in the executive committees of formal WUAs, e.g., as specified in the Irrigation Regulation (HMGN, 2000) and the Irrigation Policy (HMGN, 2003; Government of Nepal, 2013). In addition, the

[2] Source: Interview.

latest irrigation policy (Government of Nepal (2013)) includes a specific section on gender that acknowledges the gender bias in the irrigation sector and proposes to address this bias through other specific interventions for gender equality and women's empowerment, e.g., the provision for financial concession and technical support to women and disadvantaged groups for irrigation facilities.

In the Water Supply, Sanitation and Hygiene (WASH) sector, the consideration of gender is central to the Rural Water Supply and Sanitation National Strategy and Policy (His Majesty's Government, 2004). These policy documents mandate inclusive and meaningful participation in terms of gender, caste and ethnicity, not only in the operation and maintenance of water supply and sanitation infrastructures, but also in local planning and budgeting and service delivery, with a quota of 30% women in water user committees. A second major component relates to capacity building, e.g., of women as health and village maintenance workers. A third key objective is to reduce the time and labour to fetch water through targeting disadvantaged groups for the provision of subsidised WASH facilities. The more recent Nepal WASH Sector Development Plan (SDP) (2016–2030) includes a specific section on GESI that defends 'the need to move beyond technical solutions towards more GESI-oriented approach that considers existing power relations between men and women, and between social groups, and how these influence access to resources and participation in decision-making process' (Government of Nepal, 2016: p. 55). It builds on earlier policies around the three components identified above: increased participation of disadvantaged groups, enhanced access to WASH facilities (notably through subsidies) and capacity building.

Gender is absent from watershed management, water-induced disaster management and groundwater resource development policies, but some of these sectors are gradually moving towards greater consideration of issues of social inclusion, e.g., the current draft of the National Watershed Management Policy (Government of Nepal, 2017). A draft version of the Government of Nepal's National Integrated Water Resources Policy that we reviewed in 2017 also identified women's participation in water management across decision-making levels as the main means to achieve gender equality.

In this paper, we focus on one policy measure: the legal quota for women's participation in formal[3] WUAs. It is of particular interest as it is the most central policy measure on gender equity in Nepal, which cuts across the irrigation and WASH sectors. Its implementation, however, has led to disappointing outcomes. It has also been widely adopted beyond Nepal and has attracted feminist scholars' attention, but the latter has mostly been limited to its implementation at the operational community level. We add to this debate by exploring how norms of masculinities have an effect on policy implementation at higher institutional levels. After reviewing current assessments of the policy gap between intentions and outcomes in Nepal and reviewing a range of causal factors and mechanisms, we will then broaden our analysis to consider the organisational factors that have hindered progress towards greater gender equity in the public water sector in Nepal.

Policy gaps

Our knowledge of the extent of the policy gap in regard to legal quotas on women's participation in WUAs is patchy – to our knowledge, there has not been any large-scale study on this issue in Nepal. Consequently, it is difficult to assess its outcomes and impacts across diverse contexts and to identify in a comprehensive manner the causal factors and mechanisms participating to the policy gaps. However, all published case

[3] By formal, in this case, we mean registered with the government.

studies point to their limited impact, whether in the irrigation or in the WASH sector – so do the observations of the water professionals we have met, including civil servants. In the irrigation sector, a survey conducted in the Second Irrigation Sector project, a large-scale irrigation development and rehabilitation project financially supported by ADB and implemented by the Government of Nepal, reports that 27 of the 108 WUAs created had reached the earlier policy quota of 20% of women (SILT, 2002 in Udas & Zwarteveen, 2005). Some scholars indicate that in the WASH sector, women are still insufficiently included at the planning stage (Bhandari *et al*., 2005). More recent studies in the irrigation sector also remark that the later quota of 33% has largely not been met (Udas, 2014; Pradhan, 2016), even though many young and middle-aged men are absent from villages, due to long-term or seasonal migration.

Even when the quota is met on paper, i.e., on the list of the executive committee members, women's participation is often considered as tokenism. Of course, there are large variations in women's participation in natural resource management across Nepal, as gender norms vary across agro-ecological regions and ethnic groups (Agarwal, 2010). Yet the available evidence indicates that overall, the legal quotas have fallen behind in empowering women in decision-making and enhancing gender equality. First, women are still not recognised as legitimate irrigators in their family (Panta & Resurrección, 2014). In many cases, either their husband, father in-law or brother in-law participates in the meetings (Ghimire, 2004; Pradhan, 2016). Second, cases where women do have a real influence on decisions and represent other women's interests are even rarer (Regmi & Fawcett, 1999; Upadhyay, 2003). Women participating are mostly from higher caste, thereby not necessarily defending the interests of women from other castes (Ghimire, 2004; Panta & Resurrección, 2014).

As a result, women's water multiple uses and specific needs are often ignored. For instance, women's uses of the water for domestic (washing clothes) or other needs (cattle bathing, vegetable gardening) are either ignored or viewed as secondary and rarely considered during canal design and operation (Lahiri-Dutt, 2007). Furthermore, the increasing number of women who are in charge of crop farming in the absence of their husband – as well as widows – have to rely on male relatives to secure access to irrigation water and often get less water than male irrigators (Panta & Resurrección, 2014).

Current understanding of policy gaps

Looking at the broader literature on women's participation in WUAs, earlier scientific studies show similar gaps between policy expectations and actual women's participation, e.g., in India (Meinzen-Dick & Zwarteveen, 1998; Singh, 2008). Women have faced multiple barriers to become active members of these associations, such as a lack of legal land titles, gender norms influencing their mobility or simply a lack of time to attend meetings due to domestic chores (Ghimire, 2004). Attending public meetings is under many socio-cultural contexts not considered socially appropriate for women and women's legitimacy and capacity to be involved in irrigation management is often questioned.

Even when women attend meetings, they might not have sufficient knowledge or confidence to speak up and their views or interests might be systematically ignored. Hence, women might not be able to draw any benefit from their participation, because of entrenched social hierarchies, gender norms and unequal power relationships, as shown in studies conducted across a variety of socio-cultural and ecological contexts (Adams *et al*., 1997; Meinzen-Dick & Zwarteveen, 1998; Cleaver, 1998). Several studies conclude that women might have a greater ability to claim access to water informally, through negotiation with family members and relatives, than by participating in formal groups. It might thus simply not be in their interest to take part in such groups and committees, where their legitimacy to voice their concerns is low (Cleaver, 1998; Jackson, 1998).

In Nepal, case studies analysing women's participation in WUAs in the irrigation sector indicate similar findings, e.g., the role of patriarchal norms (Chhetri *et al*., 2008; Panta & Resurrección, 2014). Some studies have evidenced the instrumentalisation of women's participation, showing how male WUA leaders allowed or supported women's participation in the executive committee in order to get government registration or to attract external funding (Udas & Zwarteveen, 2005; Chhetri *et al*., 2008). A study conducted in Tukucha Nala irrigation system, in Kavre district, indicated that most women felt that they would not have much to gain from their participation in WUAs, because most decisions were decided informally outside of WUA meetings by a few male members (Udas & Zwarteveen, 2005). A few women, those whose husband had migrated or who were widows, found it useful to become members of the executive committee as an effective means to network with government and development actors.

Understanding masculinities

This analysis of policy gaps points to the need for policy-makers and bureaucrats to understand local power relationships – and how these relationships are shaped by gender, caste, ethnicity and class. Most scholars indeed call for structural changes that would address the politicisation of WUAs, consider local informal rules and norms for water management, and initiate critical reflections on unequal gender norms (Udas & Zwarteveen, 2005; Panta & Resurrección, 2014). In other words, a technocratic application of quotas is alone unlikely to trigger a remarkable change in gendered patterns of water management.

Moving beyond a technocratic application of quotas requires identifying, questioning and challenging current practices, attitudes and organisational culture in water bureaucracies. Across countries, water bureaucracies are firmly embedded in a masculine professional culture (Zwarteveen, 2008), and Nepal is no exception (Udas & Zwarteveen, 2010; Liebrand & Udas, 2017). Men hold power, authority and expertise in irrigation organisations and what is deemed as a successful performance for a civil servant in the water sector is generally associated with masculine traits of characters and behaviours (Liebrand & Udas, 2017). Almost a decade ago, Udas & Zwarteveen (2010) unpacked how particular incentives and the masculine professional culture affected practices of civil servants at the Department of Irrigation (DOI) of Nepal. For example, promotion and performance evaluation are mainly associated with engineering achievements and level of expenditure, and efforts towards gender equality in projects are seldom incentivised. The engineering professional culture values attributes and skills such as technical competence, physical strength, being in command and rationality, which are commonly associated with hegemonic forms of masculinity and manhood. Almost a decade later, we revisit some of their findings, in a context where young female engineers have been recruited and GESI units created in public water agencies, and extend the study beyond the DOI to the public water sector in Nepal.

We propose a joint examination of the gendered nature of discourses, institutions and professional culture in the water sector, with the objective to expose how gendered everyday practices in public agencies affect policy implementation and policy outcomes on the ground.

Methods

We started with a comprehensive review of public policies in the water sector. We draw on a series of semi-structured interviews with water professionals from public agencies operating in the water sector, namely, government line agencies: DOI, Department of Water Induced Disaster Management

(DWIDM), the Department of Soil Conservation and Watershed Management (DSCWM), Department of Water Supply and Sanitation (DWSS), and planning bodies: The Water Energy and Commission Secretariat (WECS) and the Nepal Energy Authority (NEA). We also interviewed representatives from the civil society and non-government organisations (NGOs), either operating in the water sector (e.g., the Federation of Drinking Water and Sanitation Users (FEDWASUN) or advocating for gender equality. Interviews were conducted in Kathmandu in February–March 2017. Respondents represented a mix of engineers and sociologists, at different seniority levels. We also interviewed social inclusion experts working in international NGOs interacting with water bureaucrats to get external views. Altogether, 21 interviews (12 females, 19 males) were conducted in February and March 2017. The detailed notes from the interviews were coded and analysed manually. In addition, our analysis benefited from observations and insights drawn from regular interactions and engagement on gender with water professionals in Kathmandu and in districts located in the Far-Western region of Nepal between 2013 and 2017.

To analyse our data, we relied on the TPC framework for strategic change management (Tichy, 1983). The TPC framework decomposes an organisation into three management tools, namely, mission and mandate, structure and staff, and proposes to examine each of these components from three management areas: technical, political, and cultural (Table 1). It was adapted for gender mainstreaming by Oxfam Novib (2010).

While we were inspired by Oxfam's gender adaptation of the TPC framework, we kept the original nine components of the TPC framework (instead of 12 as per Oxfam Novib's framework). We felt the components on programmes added by Oxfam Novib were less relevant to our analysis as we focused on organisations in the public water sector, which are not entirely driven by a programme-mode approach. For this reason, we also preferred to consider the 'professional culture' rather than the 'organisational culture' used in Oxfam Novib's framework. By professional culture, we mean a set of professional and ethical norms and values that people with certain functions will tend to share (Shahin & Wright, 2004). Most components, except staff capacity and expertise (component 7) and attitudes (component 6), represent a mix of formal and informal institutions. By institutions, we mean the 'prescription that humans use in all forms of repetitive and structured interaction…' (Ostrom, 2005). Policies and actions (component 1) are usually formal rules, whereas professional culture (component 3) is rather constituted of informal norms, although it can also be influenced by formal rules and by the language in use.

Lastly, we added to Tichy's framework an explicit analysis of public discourses. By discourses, we mean 'a specific ensemble of ideas, concepts, and categorisations that is produced, reproduced, and transformed in a particular set of practices and through which meaning is given to physical and social realities' (Hajer, 1995). Discourse analysis aims at revealing patterns and structures in discussions and debates – the latter including public talks, policy documents, or every day discussions. We are interested in how discourses shape the way gender and water issues are framed and how they give legitimacy to certain institutions and practices while undervaluing or silencing other.

Table 1. Components of the nine boxes framework used in this study.

	Mission and mandates	Organisation structure	Human resource management
Technical	1. Policies and actions	4. Tasks and responsibilities	7. Staff capacity and expertise
Political	2. Policy influence	5. Decision-making	8. Room for manoeuvre
Cultural	3. Professional culture	6. Co-operation and learning	9. Attitudes

Source: Adapted from Oxfam Novib, (2010).

Our presentation of findings starts with the overview of the national policies on gender and review of gender in national water policies. We examine dominant discourses before elaborating on the different components of the framework. In this paper, we do not review all the components of the framework but rather discuss what we feel are the most important components. We start with examining the dominant narratives that frame gender and water issues before moving to the visible organisational components that policy-makers are generally most attentive to, namely, policies and actions (component 1 in Table 1), decision-making (component 5) and staff capacity and expertise (component 7). Then, we explore less visible domains, namely, the professional culture and attitudes in the water sector.

Results

Policy narratives

We identified through our interviews and review of policies three dominant policy narratives and assumptions on gender and water. The first narrative is that 'since water is a natural resource, water management is a technical task, which benefits everyone, men and women, equally'. Those relying on this narrative were mostly engineers and professionals with a technical background. For instance, both respondents from the DWIDM and the DSCWM indicated that since their department's mandate is to protect lives from landslides, it directly supports vulnerable and marginalised communities, which naturally includes both men and women. When asked about how they address gender in their work, one of them answered: '*We do not deal with water consumption. Our aim is to preserve water and to secure life and property damage from water disasters. So landslide protection work and river training directly deal with lives of people'* (interview, male engineer, government line agency). Similarly, several of the male engineers we met perceived water management as 'gender-neutral' because for them, water was a natural, not a social, object: '*Water resources are not gender-specific. Water resources are natural resources. It is not relevant to gender. We cannot say that there should be gender-friendly water extraction'* (interview, male engineer, government line agency).

A second dominant narrative, visible both in policy documents and interviews, relates to women's 'natural' roles: water and development professionals have historically associated women with reproductive uses of water. Dominant framings take men's and women's roles in public and private spheres as 'natural' without acknowledging the social construction of these roles and preferences, which is deeply embedded in social norms and culture. These framings create a discursive closure that has limited the range of interventions and initiatives to support gender equity in the water sector. For example, the latest draft of the Integrated Water Resource Policy recommends improved access of women to drinking water. This clause shows policy-makers' concern to relieve women's burden to fetch drinking water but, at the same time, implicitly reaffirms that it is women's responsibility to do so, therefore holding the risk to legitimise interventions that reinforce traditional gender roles. Similarly, water policy discourses rely on the assumption that developing or rehabilitating local water supply infrastructures is a sufficient condition to improve women's livelihoods: '*the government stated: one house, one tap, if access to water supply is improved, then gender equity is addressed'* (interview, male sociologist, government line agency). Yet, intra-household negotiations (Regmi & Fawcett, 1999), as well as gender, caste and local power hierarchies intersect to shape access to water with large inequalities among women from different age, class and caste (Leder *et al*., 2017).

Lastly, a central assumption that dominates policy discourses on gender and water is that women's participation in WUAs is a sufficient and necessary condition for greater gender equity. This assumption is in line with the first policy narrative, which posits that water is a gender-neutral, physical resource, whose development does not raise gender-based distributive justice issues. This is visible in all the national sectoral and multi-sectoral water policies that include a statement or section on gender. In many water policy documents, gender equity is exclusively understood and considered as the inclusion of women in WUAs. Because of this discursive closure, policy discourses promote women's participation in WUAs without justifying under which conditions and why participation will contribute to greater gender equity in the water sector. Women's participation is framed as unproblematic and mechanical, as if increasing the number of women members in WUAs solely requires a policy statement and will automatically result in gender equity. Such narrative glosses over all the structural barriers and power hierarchies that might make women's (and low caste men's) participation ineffective. Other relevant initiatives that could contribute to greater gender equity, such as improving access to technologies for women and marginalised groups or organising critical discussions on traditional gender roles, are not considered. These points are further discussed in the following sub-section on organisational components.

Visible organisational components

Systems, policy influence and decision-making. The organisational structure in place both reflects and reinforces these three narratives. In public water agencies such as the DOI, Groundwater Resource Development Board (GWRDB), DWSCM, DWIDM, DWSS, the institutionalisation of gender in irrigation development is neatly delimited, falling under the role of sociologists and association organisers, who are in charge of the creation and capacity building of formal WUAs. Because water management is seen to be a technical task, gender issues are not to be dealt with or addressed by engineers. As most – if not all – senior functionaries in public water agencies are civil engineers, there is no serious organisational commitment for gender: '*If you go to the DOI they will tell you: it is not their job. If you start talking to the Director General about the role of gender, he will say: 'go talk to that person''* (interview, male consultant).

This renders the work of the recently created GESI units ineffective as they operate in a void, disconnected from other divisions. The GESI units are to implement a set of GESI guidelines in their organisation to enhance gender equality in water management. This often requires collaborating with engineers from their department. For instance, the Gender Equality and Social Inclusion mainstreaming guideline for Irrigation and Water Induced Disaster Prevention sectors (Government of Nepal, 2014/15) proposes that GESI aspects are integrated in project feasibility studies. Yet most engineers we met do not see the relevance of gender to their work, as illustrated by this quote from a female engineer working in a government line agency: '*there is no need to coordinate with the GESI department. I never coordinate with them. Our work is not related*'. As reported by Udas & Zwarteveen (2010), the performance evaluation of public engineers is based on a standardised form, reporting activities, costs and achievements in terms of financial and physical progress (budget spent/infrastructure built) – there are therefore no incentives for them to consider gender. The fact that attention to gender is not included in their performance evaluation form also signifies that this is not important for the organisation.

Lastly, the GESI units have been allocated neither sufficient resources nor sufficient authority to implement the GESI guidelines (interviews). In one of the units, only one junior sociologist was appointed and the two other posts below her had been vacant for a year. The gender focal points we met felt overburdened and powerless to ensure that GESI is adequately considered in their department's activities. The general assumption that technical activities (e.g., flood protection, physical access to groundwater) will benefit all equally, including poor and disadvantaged groups, has led to the belief that a gender-earmarked budget for conducting specific GESI activities is not required.

Staff and expertise. Having more women in an organisation does not necessarily result in more gender-sensitive organisational culture and practices but staff and expertise nevertheless can still have an influence, especially in cases of very unequal gender balance in staff, as a whole and across hierarchical levels. Water bureaucracies in most countries have largely been dominated by male engineers, even though this is slowly changing. Compared to the figures reported by Udas & Zwarteveen (2010), there has been a slight increase in the proportion of women staff at the DOI, from 13 to 18% of the total staff (Figure 1). This could be the result of the national reservation policy (Civil Service Act, second amendment, 2007), which secures 33% entry for women. In the public service as a whole in Nepal, there has been an increase of the proportion of female civil servants from 8% in 2007 to 15.3% in 2014 (Bajracharya & Grace, 2014). It is remarkable that the increase of female staff at the DOI has mostly taken place among engineers: in the T1 category, the percentage of women has increased from 2 to 34% (Figure 1).

In the DWSS, the proportion of female staff is similar to that of the DOI (interview). At the Groundwater Resource Development Board (GWRDB), male staff represent 93% of the total staff and almost all of the female staff fall in the support staff category (Table 2).

Another interesting trend is the proportion of technical/non-technical staff in these agencies. There is still a limited number (Figure 1) or absence (Table 2) of non-technical staff (NT category), despite the recent creation of GESI units. Non-technical staff are sociologists, who conduct the 'software' activities, mostly the organisation of training for members of WUAs, training that is conducted on the ground by association organisers. At the DOI, non-technical staff represents 6% of the total staff, with three sociologists posted in the central office in Kathmandu and four in the regional offices. Their number has remained stable between 2007 and 2017 (Figure 1).

Femininities and masculinities

Professional culture. The masculinity of the water sector goes beyond the number of male professionals. The attitudes and practices of water professionals are shaped by norms that are embedded in a masculine professional culture. A masculine professional culture values traits, skills and behaviours associated with masculinity over those associated with femininity. The construction of large-scale infrastructure, associated with manhood and masculine traits such as technical knowledge, physical strength and endurance, is the most rewarding and highly praised professional activity within the DOI. On the other hand, sociology, which is perceived to be 'soft'[4] and feminine is undervalued. This has very visible effects on the motivation and performance on the individuals working on the social and political implications of irrigation management: '*There is no motivation for us* […] *Engineering is valued more than social science subjects* […] *this is a policy issue that has been ignored for decades*' (interview, female sociologist, government line agency). The superiority of technical, masculine knowledge over 'soft', feminine knowledge is institutionalised: sociologists are third-class gazetted officers without

[4] In the water sector in Nepal, professionals commonly call 'software activities' the activities that are not technical. Technical activities are called 'hardware activities'.

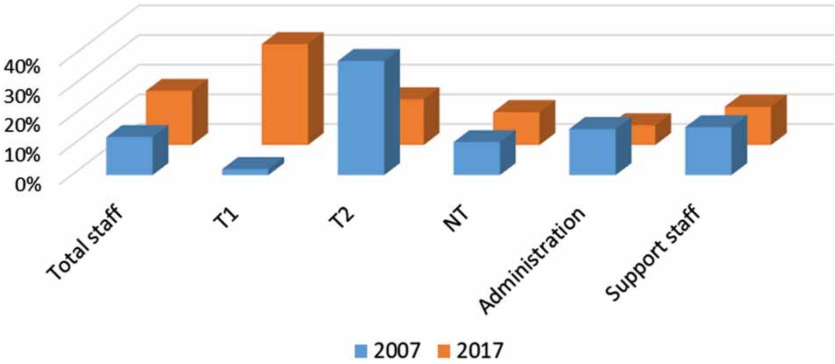


Fig. 1. Percentage of female staff across staff categories at the DOI in 2007 and 2017. T1: engineers, T2: technical staff not qualified as engineers, NT: non-technical professionals. *Sources*: Udas & Zwarteveen, 2010 for the 2007 data; administration section, DOI, for the 2017 data.

Table 2. Number of staff by category and sex in the GWRDB in 2017.

Staff type	Total staff	Female staff	Male staff
Total staff	127	10	117
T1	13	0	13
T2	0	0	0
T3	5	1	4
Support staff	109	9	100

Source: GWRDB administrative section, February 2017.

further chance of promotion. Therefore, male sociologists and even agricultural engineers do not conform to the hegemonic masculine model of a performant water professional.

> ‘*The Department mostly has positions for engineers and fewer positions for persons with a social science background. Therefore, even if a man had been in my position, he would be in a similar subordinate position. People don’t take these issues* [*gender*] *seriously. We cannot say that it is because a woman is holding the position, she is heard less by the group.* […] *it is basically about what skills and knowledge are valued by the organisation.* (Interview female sociologist, government line agency)’

Being in the field is associated with masculine traits of physical and mental strength, and the ability to give preference to work over family life. Positions in field offices are preferably reserved for men, whereas women’s capabilities to occupy such positions are routinely questioned. Male staff see women’s presence in the field as a hassle.

> ‘*People complain when a woman is posted in duty stations that require staffs.* […] *It is not about pointing at the capacity of the woman employee, but maybe it is their household roles and responsibilities that act as an obstacle.* […]. *We are regular to job, but it is important to understand the*

context and why some women side-track themselves from professional life. (Interview female sociologist, government line agency)'

Whereas masculine traits are valued, signs of femininity are ignored, undervalued or despised. Many women staff reported they had to silence physical feminine traits, especially in the field, seen as a masculine working space:

'*There is not much improvement in logistical issues. It was difficult for women during those days to be in the field. In my case, I would be the only woman in a men's group. Just think: how would you tell your male boss that you want to go for a pee? I think these things are still as it is in this sector*. (Interview, female sociologist, government line agency)'

Although this quote might raise a smile with readers, silencing embodied femininity can actually have far-reaching consequences on maternal and child health, as this quote indicates: '*You never know what kind of health issues they* [*female staff*] *are facing – pregnancy, menstruation etc. It is difficult for them to travel on motorbikes. This has led to many cases of miscarriage and immature babies*' (interview, female sociologist, government line agency). Another example below evidences how the specific professional needs of female staff, who form a minority, are often not adequately considered by their senior male counterparts, who are in a decision-making position.

'*If the Department has the resources to buy vehicles, no one will think of buying a scooter that could be used by female staff. Everyone will vote for buying a motorbike, which is mostly used by male staff. It is also because women do not hold positions at the decision-making level. Decision-makers make consultations at the last minute – they quickly ask among themselves who needs what and decide on the resources to allocate*. (Interview female engineer, government line agency)'

This quote evidences the intersection of institutions and professional culture. On the one hand, decision-making is relatively closed and rules do not leave space for staff to voice their requests. On the other hand, the professional culture privileges male over female needs, reproducing female exclusion from male spaces (field offices).

Lastly, several female informants felt female staff need to double efforts to prove themselves as competent as men. They reported how male and female staff are judged differently on similar achievements. While men's successes are attributed to their skills and competencies, women's successes are attributed to luck or institutional favours: '*When a young female gets promotion, people say that she was promoted due to quota but when a young male is promoted, people say that he got promotion due to his intelligence'* (interview, female engineer, government agency). Again, this shows that changing formal institutions without changing the professional culture might be counterproductive – women might get better chances of promotion but in a masculine professional culture, the legitimacy and authority associated with their new position are, at the same time, undermined.

The professional culture subtly favours male career advancement through the differentiated capabilities that men and women have to access knowledge, information and to network: '*Working in a male-dominated profession, men have advantages, for instance, they can build networks. I have to rush after 5 pm to take care of my household responsibilities, but men stay back for more gossips. This way they access extra knowledge and information, which we cannot'* (interview female engineer, government line agency). For instance, another female staff reported that women were systematically not being informed about international visits and training, relatively prestigious components of functionaries.

Attitudes, practices and knowledge

The narratives, institutional arrangements and professional culture in the water sector have influenced the implementation of policy efforts towards gender equality in several ways. First, women's participation in WUAs is used as a panacea as reflected in discourses and institutions. Gender issues are neatly delimited to the 'WUA space', with well-delineated experts, the sociologists, institutional set-up, the GESI unit and activities (creation of WUA meeting quotas, training for women). There is no space or incentives to reflect and learn about GESI-related challenges in water management. Sociologists and community mobilisers do not have the resources, room for manoeuvre, legitimacy nor the authority to propose activities that go beyond quotas in WUAs. This has contributed to the technocratic implementation of democratic and participatory decision-making in water management – that is, an implementation limited to following fixed procedures that does not address the root causes of injustices. The narrow focus on WUA and the lack of involvement of engineers in improving gender equality means that many opportunities for more gender-sensitive interventions are lost: '*The issue they* [*engineers*] *ignore is the location of boys and girl's toilet during construction.* [...] *It might be uncomfortable for young female and male teenagers* [*to share the same toilets*]. *These issues are never considered'* (interview, female engineer, government line agency). As engineers do not consider gender relevant to their work, '*canals are designed in such a way that it makes water available during ploughing, which is a male job, but the design does not consider the distribution of water during transplantation and weeding, which are women's tasks*' (interview, male water institutional expert, civil society organisation).

Overall, the recent donor-driven formal institutional changes, such as the creation of GESI units and the development of GESI guidelines, have not been sufficient to influence the attitudes and practices of water professionals in a way that challenged the status quo. On the contrary, these efforts seem like a band-aid approach in the context of dominant narratives on gender and water and a strong masculine professional culture. The everyday attitudes of male water professionals towards women indeed continue reproducing unequal gender relationships at work. Two female informants shared anonymously how male staff ridicule new mothers by calling them '*jersey gai*' (in English: Jersey cows), a cow breed known for its fatty milk. Some respondents also reported that men assign inferior nicknames to their female colleagues, such as *maiya* (maiya is used for younger girl child in a family), *baini* (younger sister), *moti* (fatty). On the contrary, they always expect, regardless of the hierarchy, to be referred to with respect as 'Sir'. Attitudes towards women can be also expressed in subtle types of behaviour: '*Often, I feel if a male would have been in my position, people would have received him in a different way'* (interview, female engineer, government agency). On the other hand, women have developed an inferiority attitude. Many of our informants expressed they perceive themselves less successful in their career than their male counterparts.

Such attitudes are linked to broader social values. Yet they are also nurtured by the masculine professional culture of the water sector. In turn, they affect practices towards gender equality in water resource development and management in several ways. First, these attitudes demonstrate a profound disregard and disrespect towards women, thereby undermining the legitimacy and value towards gender equality initiatives. Second, they can affect the design of project activities, by relying on paternalistic assumptions. For example, when water programmes include capacity building activities, women are proposed training related to microcredit that conform to traits perceived as feminine, while men receive technical training, e.g., on the operation of water sluices in canals. This reinforces existing gendered roles and divisions of labour in water management.

Lastly, male engineers' attitudes of superiority, based on the supposedly superior nature of technical – masculine – knowledge, also affect policy design: '*practical experience does not count. The 'I know everything' attitude is widespread* [...]. *The problem with us is that policy is developed on the basis of assumptions*' (interview, male engineer, government line agency). Gender is perceived as a frivolous ethical gloss imposed by donors rather than as a technical subject. As a result, male engineers feel that achieving GESI targets does not require any specific skills or knowledge – and that anybody can 'do gender'. For instance, one informant reported that male engineers reviewed the gender documents submitted to a donor-funded project. Another case reported by a sociologist of a public line agency was that of engineers conducting the capacity building activities of WUAs, as they thought it did not require any specific expertise that they did not already have.

Conclusion

In Nepal, the central policy measure to enhance gender equality, the legal quota to include women in registered WUAs, has not challenged gendered norms and practices in the water sector. However, new drivers for more gender-equal water management and governance have recently emerged. Notably, male outmigration has made the gendered nature of water access and management more visible to non-gender experts – with a high proportion of young males absent in rural areas. There has also been a greater institutionalisation of gender in public organisations, with the recent creation of GESI units and guidelines in government line agencies and an increase of gazetted female staffs in the public irrigation sector.

Yet, our study shows that these factors alone are unlikely to trigger remarkable progress towards gender equality because the masculine professional culture of the water sector contributes to reproducing gendered inequalities across work spaces – in central or local-level offices, in development project units, in meetings, in the field, etc. Current gendered discourses and the masculine professional culture reproduces institutional rigidity to address gender inequality, namely, the reliance on a single institutional model (women's quota in the executive committee of WUAs) replicated across contexts. Policy discourses also rely on a monolithic and simplistic understanding of women and men's experiences, needs and values related to water, that does not acknowledge their spatial and temporal heterogeneity. Furthermore, gendered culture and practices in public organisations favour its technocratic implementation, with limited spaces for institutional learning.

Sociologists have very little space to study what works in which context and limited influence to bring changes in their organisations, due to their lower position in both the bureaucratic and knowledge hierarchy. Male engineers remain the legitimate providers of knowledge and expertise for water resource development – and most of them do not see gender relevant to their work but rather as a well-delineated side activity, related to the creation of WUAs. This has a bearing on how water resource development and management issues are framed, how programmes are designed and ultimately affects the capacity of public organisations to adequately understand and address gender and social equity issues on the ground. Even sophisticated and well-intentioned GESI guidelines have very little chance to make a difference.

Scholars have defended the need to move away from institutional panaceas towards more grounded and context-sensitive consideration of gender for water resource development and management. We contend that as long as water agencies do not acknowledge the social nature of water and the hegemonic masculinity of the professional culture, policy commitments towards greater gender equality will have little effect on the ground. It is important that water organisations pay attention to their own spaces, practices and attitudes, in order to address and achieve equity and justice issues in water resource management at the ground level. To this end, we recommend to simultaneously address: (1) policy discourses, (2) organisational components and institutions and (3) the professional culture. From a discursive perspective, this means extending current framings of water as a resource to water as 'a symbol of identity, power and citizenship' (Mosse, 2008: p. 948) to move away from the engineering approach that dominates the water sector. It also requires including a greater diversity of voices on water needs, experiences and subjectivities to move beyond simplistic representations of 'the Nepali woman'. From an institutional point of view, this implies ensuring gender, ethnic and class diversity at all levels of policy-making and implementation, allocating adequate financial and human resources for more socially just water management, and creating specific incentives towards this goal, by changing performance evaluation and promotion rules. Lastly, with respect to professional culture, it is important to institutionalise values that promote positive masculinities of empathy and respect within organisations. Opening spaces for male and female staff to discuss opinions and experiences on doing gender can be a first step towards enhancing their skills, sensitivity and capacity to understand and address gender and social hierarchies in their daily practices.

Acknowledgements

This study is made possible by the generous support of the American people through the United States Agency for International Development (USAID). The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government. We thank Diana Suhardiman, Kashmira Kakati and two anonymous reviewers for their valuable comments.

References

Acharya, M. & Bennett, L. (1981). The status of women in Nepal. Volume II. Field studies. In: *The Rural Women of Nepal. An Aggregate Analysis and Summary of Eight Village Studies*. The Status of Women in Nepal, Vol. 9, part II. CEDA, Tribhuvan University, Kathmandu, Nepal.

Adams, W. M., Watson, E. E. & Mutiso, S. K. (1997). Water, rules and gender: water rights in an indigenous irrigation system, Marakwett, Kenya. *Development and Change 28*, 707–730.

Agarwal, B. (2010). Does women's proportional strength affect their participation? governing local forests in South Asia. *World Development 38*(1), 98–112.

Ahlers, R. & Zwarteveen, M. Z. (2009). The water question in feminism: water control and gender inequities in a neo-liberal era. *Gender, Place & Culture 16*(4), 409–426.

Bajracharya, P. & Grace, C. (2014). *The Nepal Civil Service and Re-Structuring of the State*. Ministry of General Administration, Government of Nepal and UNDP, Kathmandu, Nepal.

Bhandari, B. S., Grant, M. & Pokharel, D. (2005). Sustainable community water: managing supply systems in the mid-hills of Nepal. *Water Policy 7*(2), 201–214.

Buechler, S. & Hanson, A. -M. (2015). *A Political Ecology of Women, Water and Global Environmental Change*. Routledge, Abingdon, UK. and New York, USA.

Carney, J. (1993). Converting the wetlands, engendering the environment: the intersection of gender with agrarian change in the Gambia. *Economic Geography 69*(4), 329–348.

Chhetri, R. B., Timsina, N. P., Luintel, H., Regmi, R., Bhattarai, B. & Magar, R. A. (2008). *Decentralization and Promotion of Women's Rights in Nepal: Exploring Constraints, Opportunities and Intervention Avenues*. Forest Action Nepal and HIMAWANTI, Kathmandu, Nepal.

Cleaver, F. (1998). Incentives and informal institutions: gender and the management of water. *Agriculture and Human Values 15*, 347–360.

Cleaver, F. (1999). Paradoxes of participation: questioning participatory approaches to development. *Journal of International Development: The Journal of the Development Studies Association 11*(4), 597–612.

Elias, F. (2017). The practice of integrated water resources management in South Africa: challenges of women in water user associations. *Geojournal 82*(6), 1165–1177. doi:10.1007/s10708-016-9736-9.

Enarson, E. & Fordham, M. (2001). From women's needs to women's rights in disasters. *Global Environmental Change Part B: Environmental Hazards 3*(3), 133–136.

Ghimire, S. (2004). Women and irrigation in Nepal: context, issues and prospects. *Water Nepal 11*(2), 45–61.

Government of Nepal (2012). *Gender Responsive Budgeting and Planning Directive*. Ministry of Finance, Kathmandu, Nepal.

Government of Nepal (2013). *The Irrigation Policy 2013*. Ministry of Irrigation, Kathmandu, Nepal.

Government of Nepal (2014/15). *Gender Equality and Social Inclusion Mainstreaming Guideline for Irrigation and Water Induced Disaster Prevention Sectors*. Ministry of Irrigation. Kathmandu, Nepal.

Government of Nepal (2016). *Nepal Water Supply, Sanitation and Hygiene Sector Development Plan (2016–2030)*. Ministry of Water Supply and Sanitation, Sector Efficiency Improvement Unit (SEIU), Kathmandu, Nepal.

Government of Nepal (2017). Draft on National Watershed Management Policy 2017. Kathmandu, Nepal.

Hajer, M. J. (1995). *The Politics of Environmental Discourse: Ecological Modernization and the Policy Process*. Oxford University Press, Oxford, UK.

Harris, L. (2008). Water rich, resource poor: intersections of gender, poverty, and vulnerability in newly irrigated areas of southeastern Turkey. *World Development 36*(12), 2643–2662.

Harris, L. (2009). Gender and emergent water governance: comparative overview of neoliberalized natures and gender dimensions of privatization, devolution and marketization. *Gender, Place & Culture 16*(4), 387–408.

His Majesty's Government (2004) Rural Water Supply and Sanitation National Policy 2004 & Rural Water Supply and Sanitation National Strategy 2004. Kathmandu, Nepal.

His Majesty's Government of Nepal (2000). *Irrigation Regulation*. Ministry of Water Resources, Kathmandu, Nepal.

His Majesty's Government of Nepal (2002). *The Water Resource Strategy 2002*. Ministry of Water Resources, Kathmandu, Nepal.

His Majesty's Government of Nepal (2003). *The Irrigation Policy 2003*. Ministry of Water Resources, Kathmandu, Nepal.

His Majesty's Government of Nepal (2005). *National Water Plan 2005*. Ministry of Water Resources, Kathmandu, Nepal.

Jackson, C. (1998). Gender, irrigation, and environment: arguing for agency. *Agriculture and Human Values 15*(4), 313–324.

Joshi, D. (2005). Misunderstanding gender in water-addressing or reproducing exclusion. In *Gender, Water and Development*. Coles, A. & Wallace, T. (eds). Berg Publishers, Oxford, UK, pp. 135–153.

Kemerink, J. S., Méndez, L. E., Ahlers, R., Wester, P. & van der Zaag, P. (2012). The question of inclusion and representation in rural South Africa: challenging the concept of water user associations as a vehicle for transformation. *Water Policy 15*(2), 243–257. doi:10.2166/wp.2012.127.

Lahiri-Dutt, K. (2007). *Diluted Citizenship: Women, Water and Rights in the Midst of Inequities in India. (No. 07/02)*. Participatory Development Working Papers.

Laurie, N. (2005). Establishing development orthodoxy: negotiating masculinities in the water sector. *Development and Change 36*(3), 527–549. doi:10.1111/j.0012-155X.2005.00422.x.

Leder, S., Clement, F. & Karki, E. (2017). Reframing women's empowerment in water security programmes in western Nepal. *Gender & Development 25*(2), 235–251.

Liebrand, J. & Udas, P. B. (2017). Becoming an engineer or a lady engineer: exploring professional performance and masculinity in Nepal's Department of Irrigation. *Engineering Studies 9*(2), 120–139. doi:10.1080/19378629.2017.1345915.

Meinzen-Dick, R. (2007). Beyond panaceas in water institutions. *Proceedings of the National Academy of Science in the United States of America 104*, 15200–15205.

Meinzen-Dick, R. & Zwarteveen, M. Z. (1998). Gendered participation in water management: issues and illustrations from water users' associations in South Asia. *Agriculture and Human Values 15*(4), 337–345.

Mosse, D. (2008). Epilogue: the cultural politics of water – A comparative perspective. *Journal of Southern African Studies 34*(4), 939–948.

Nixon, R. & Owusu, F. (2017). Choice, inclusion, and access to information: understanding female farmers' participation in Kyrgyzstan's water-user associations. *Sustainability 9*(12), 15. doi:10.3390/su9122346.

O'Reilly, K. (2011). 'They are not of this house': the gendered costs of drinking water's commodification. *Economic and Political Weekly xlvi*(18), 49–55.

Ostrom, E. (2005). *Understanding Institutional Diversity*. Princeton University Press, Princeton, NJ, USA.

Oxfam Novib (2010). *Mainstreaming A Gender Justice Approach. A Manual to Support NGOs in Self-Assessing Their Gender Mainstreaming Competence*. Oxfam Novib, Den Haag.

Panta, S. K. & Resurrección, B. P. (2014). Gender and caste relations amidst a changing political situation in Nepal: insights from a farmer-managed irrigation system. *Gender, Technology and Development 18*(2), 219–247.

Pradhan, P. (2016). Gender issues and women participation in water users associations (WUAs) in irrigated agriculture in Nepal. *Journal of Graduate Volunteer Centre 12*(2), 261–297.

Regmi, S. C. & Fawcett, B. (1999). Integrating gender needs into drinking-water projects in Nepal. *Gender & Development 7*(3), 62–72. doi:10.1080/741923243.

Shahin, A. I. & Wright, P. L. (2004). Leadership in the context of culture: an Egyptian perspective. *Leadership & Organization Development Journal 25*(6), 499–511.

Singh, N. (2008). Equitable gender participation in local water governance: an insight into institutional paradoxes. *Water Resource Management 22*(7), 925–942.

Sultana, F. (2009). Fluid lives: subjectivities, gender and water in rural Bangladesh. *Gender, Place & Culture 16*(4), 427–444.

Tamang, S. (2011). The politics of 'developing Nepali women'. In: *Perspectives on Modern South Asia: A Reader in Culture, History, and Representation*. Visweswaran, K. (ed.). Blackwell Publishing Ltd, Oxford, UK, pp. 280–288.

Tichy, N. M. (1983). *Managing Strategic Change*. Wiley, New York, USA.

Udas, P. B. (2014). *Gendered Participation in Water Management in Nepal. Discourses, Policies and Practices in the Irrigation and Drinking Water Sectors*. PhD dissertation, Wageningen University, Wageningen, The Netherlands.

Udas, P. B. & Zwarteveen, M. (2005). Prescribing gender equity? The case of the tukucha nala irrigation system, central Nepal. In: *Liquid Relations: Contested Water Rights and Legal Complexity*. Roth, D., Boelens, R. & Zwarteveen, M. (eds). Rutgers University Press, New Brunswick, NJ, USA, pp. 21–43.

Udas, P. B. & Zwarteveen, M. Z. (2010). Can water professionals meet gender goals? A case study of the Department of Irrigation in Nepal. *Gender & Development 18*(1), 87–97. doi: https://doi.org/10.1080/13552071003600075.

Upadhyay, B. (2003). Water, poverty and gender: review of evidences from Nepal, India and South Africa. *Water Policy 5*(5–6), 503–511.

van Koppen, B. (1998). Water rights, gender, and poverty alleviation. Inclusion and exclusion of women and men smallholders in public irrigation infrastructure development. *Agriculture and Human Values 15*, 361–374.

Vera Delgado, J. & Zwarteveen, M. (2007). The public and private domain of the everyday politics of water: the constructions of gender and water power in the Andes of Peru. *International Feminist Journal Of Politics 9*(4), 503–511.

Wallace, T. & Coles, A. (2005). Water, gender and development: an introduction. In: *Gender, Water and Development*. Coles, A. & Wallace, T. (eds). Berg, Oxford, UK, 1–20.

Zwarteveen, M. (2008). Men, masculinities and water powers in irrigation. *Water Alternatives 1*(1), 111–130.

Zwarteveen, M. Z. & Boelens, R. (2014). Defining, researching and struggling for water justice: some conceptual building blocks for research and action. *Water International 39*(2), 143–158.

Zwarteveen, M. Z., Ahmed, S. & Gautam, S. R. (Eds.). (2014). *Diverting the Flow: Gender Equity and Water in South Asia*. Zubaan, New Delhi, India.

Received 10 December 2018; accepted in revised form 8 August 2019. Available online 27 September 2019

Annex 4-2

Women who do not migrate – Social interactions and participation in Western Nepal

Gitta Shrestha, Emily L. Pakhtigian, Marc Jeuland

Abstract

While evidence of a relationship between migration and agency among left-behind women exists, these linkages are not as straightforward as they may first appear. Oftentimes, it is the circumstances of migration, and particularly the complex and deeply-embedded socio-cultural dynamics that mediate this relationship, especially in the case of patriarchal institutions. Using quantitative and qualitative evidence from the Mid and Far-Western regions of Nepal—regions in which male migration is particularly common—we examine the correlations between migration and women's empowerment, specifically their abilities to interact and participate at both the household and community levels. Our data come from a representative survey of 3660 households living in the Karnali and Mahakali river basins, 18 focus group discussions held across locations in the same region, and 30 in-depth interviews from pilot study sites in the districts of Doti and Kailali. Our results indicate that migration may impact how women interact with their communities, in the sense that women from poor migrant nuclear families with fewer kinship and/or social ties suffer disadvantaged positions and face restricted access to spaces of empowerment. This is likely related to the highly structured patrilineal and male-centric social interactions within villages in this remote region.

Keywords: *Left-behind women, migration, social relations, gender, participation*

1. Introduction

Changes in the status-quo of the left-behind women in migrant households are central to debates in migration and gender research (Gartaula, Visser and Niehof 2012, Cortes 2016, Morokvašić 2014). There is growing recognition that the process of migration involves not only those who move, but also who stay behind – most often women, children, and the elderly (Ibid). Perhaps nowhere is the examination of migratory trends more relevant than in Nepal, where labour migration has become an increasingly prominent both economically, with roughly 30 percent of gross domestic product (GDP) coming from remittance payments, and socially, with migratory behaviours changing the age and gender compositions of rural communities across the country. Labour migration in Nepal is both age and gender specific, with the migrating population composed primarily of young males. According to the Central Bureau of Statistics (CBS, 2014), 47 percent of male migrants are between the ages of 15 and 34. This depicts an increasing trend of youth male migration, indicating an absence of agricultural labour in rural areas and changing social dynamics in migration-reliant regions. Given these trends, it is unsurprising that the feminisation of agriculture has been widely documented in Nepal (Gartaula, Niehof and Visser 2010). This has also been well recorded by national census which suggest an increase in the prominence and number of female-headed households from 15 percent in 2001 to nearly 26 percent in 2011(CBS 2014).

Studies indicate that while migration can help in improving the economic situation of the household (Dinkelman and Mariotti 2016, Theoharides 2017), it may also have negative repercussions on those left behind, especially on women (Maharjan, Bauer and Knerr 2012, Démurger 2015, Lokshin and Glinskaya 2008). While migration opens windows of opportunities for some women, these opportunities have not always translated into female empowerment (Lama, Kharel and Ghale 2017). Furthermore, there is evidence that the extent of improvements in female well-being and empowerment depends on the nature of migration itself—in terms of length and destination—and also on the socio-cultural context within which the migratory flows takes place (Kulczycka 2015, Gartaula et al. 2012).For example, Thieme and Boker-Muller (2009-2010) argue that women left-behind by migrating husbands actually become more dependent on their husbands' families due to the patrilineal and male-dominated networks that are dominant in those settings. Furthermore, they find that male migration does not increase bargaining power of left-behind women in the far-western region of Nepal. Thus, male migration need not be associated with female empowerment; rather, it is conditional on various factors such as the amount of remittances received, the duration of the migration, living arrangements in the home village, and other properties of the home production system, etc. (Gartaula et al. 2012, IBRD/WB 2018).

This paper examines the characteristics of households with migrating members as well as the relationships between migration and measures of social interaction and female participation We give particular attention to participation in natural resource management (NRM) groups, given the importance of these community groups in Nepal. In addition, we examine three mediating factors: (i) family structure, (ii) caste, and (iii) migration duration to provide a more nuanced discussion of relationships between migration and women's inclusion and participation at the household and community levels. The importance of social capital is widely acknowledged in shaping and sustaining migration, reducing risks, aiding accumulation of other types of capital, enhancing opportunities, increasing women's agency, and improving community well-being (Nega et al. 2010, Padmaja and Bantilan 2007, Dinda 2014, Thieme 2006). There is, however, less understanding of how social interactions and kinship networks, historically characterised as patrilineal and male-centric, shape the lives of women left behind by their migrating husbands, fathers, or sons. Social and kinship networks are forms of social capital acquired by individuals by virtue of their memberships in social institutions and structures. The benefits from such capital depend on the ability to mobilise networks and relationships, or members' abilities to maintain their networks through multiple forms of interactions (Bourdieu, 1983 in Thieme,2006). This paper's main contribution is in examining these gaps apparent in the literature.

The remainder of the paper is structured as follows. Section two provides additional background. Section three describes the conceptual framework. Section four outlines the study area and methodology used to collect and analyse data. Section five reports descriptive statistics and section six reports both quantitative and qualitative results. Finally, section seven concludes with a summary and discussion of policy implications.

2. Background

Several scholars have documented the positive impact of social capital on women's empowerment (Giraud et al., 2012).For instance, Maas et al. (2014) find that social capital enhances the legitimacy of women as rural entrepreneurs, helping them overcome poverty. A recent review also argued that social capital increases women's access to other forms of capital, forming the basis for inclusive growth (Mozumdar, Farid and Sarma 2017). Alternatively, others argue that social capital may also constrain individual action (Thieme 2006), particularly as it relates to adaptation to changing conditions (Paul et al., 2016). Das (2004), for example, outlines how inequalities perpetuate within situations of deep poverty – work-related time constraints, unequal participation in associations and networks of reciprocal help. This shows that while interactions could enhance opportunities, the ability to benefit from social resources again is highly imbued with unequal power relations, causing unequal social interactions, access to information and opportunities (Portes and Sensenbrenner 1993b). Moreover, groups embedded in tight networks dictated by caste or relational structures can be supportive but also constricting. They may pose limitations by putting excessive claim on group members, restricting individual freedom, or demanding conformity, thus excluding those who act against the normative order of the group (Portes and Sensenbrenner 1993a, Thieme 2006).

There is a growing literature that examines the links between migration, social networks, and women empowerment (Hadi 2001, Lodigiani and Salomone 2015, Yabiku, Agadjanian and Sevoyan 2010). Hadi (2001) and Yabiku et al. (2010) find evidence of increased female autonomy in household decision making among migrant households in Bangladesh and Mozambique, respectively, and argue that these impacts often last beyond the migration period. Lodigiani and Salomone (2015) consider migratory impacts on social norms and values, finding higher rates of female political participation among migratory populations. Other research indicates that male migration significantly increases the role of women in maintaining and reproducing patrilineal networks (Ismailbekova 2013). Migration may also reflect the process of empowerment and relations of dependence simultaneously(Cortes 2016).

3. Framework of women's empowerment

Sustainable Development Goal number five sets gender equality as a top development priority; female empowerment is the basis for achieving this goal. Conceptually, empowerment is a multifaceted and context-specific process. Here, we draw on Kabeer (1999) theorisation of empowerment to examine the relationship between gender and migration in western Nepal. Specifically, we adopt her characterization of empowerment as the process by which disempowered individuals acquire the capacity to make strategic life choices and exercise influence over decision making processes. Accordingly, this framework posits empowerment as a dynamic process in which the initially unempowered party—in this case, women—expand their capabilities to enjoy choice, voice, and agency in their life. The framework identifies three interrelated dimensions of empowerment: (i) resources, (ii) agency, and (iii) achievements.

Resources range across human (education, skill, labour) to social (relationships, networks, information, contacts) to economic (earnings, property and land) aspects. Resources enhance the ability to exercise choice; that is, they catalyse and facilitate empowerment (Kabeer, 1999). In many contexts, institutional structures and norms disempower women from taking leading roles in decision-making and disallow access to valuable resources. The State, family, community, market and NGOs represents key institutional sites with rules of resource allocation and distribution, which influence the ability of different groups of people to achieve the goals of survival, security and autonomy. Mobilisation of multiple social relations that people share in these key domains therefore facilitates an individual's access to resources, rights and responsibilities (Kabeer and Subrahmanian 1996).

Agency refers to the ability to define goals and act upon them (Kabeer, 1999). The framework presents a delicate connection between individual and collective agency, arguing that the latter would be more powerful to defy social norms subordinating women in a patriarchal system. It is measured through indicators including participation, decision-making, bargaining, negotiation, deception, manipulation, subversion and resistance. It also includes intangible, cognitive processes of reflection and analysis.

Finally, achievements demonstrate the extent to which an individual has been able to translate resources and agency into positive outcomes such as critical consciousness and control over resources.

4. Data and methods

The Karnali and Mahakali river basins in the mid and far-western development regions of Nepal (see Figure 1) were selected as the locations of this study due to their inclusion in the larger Digo Jal Bikas (DJB) research project, which aims at characterizing river-basin dependent activities in the region. [1] The study region covers 20 districts from three ecological regions (mountain, hill, and Terai). Livelihoods activities in these zones are dominated by farming, as well as high seasonal migration which provides supplemental income (CBS, 2011).

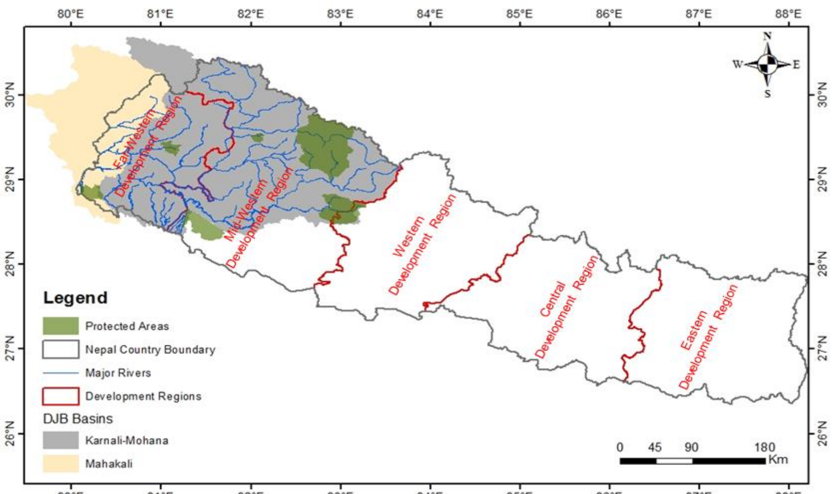


Figure 1: Locations of the Karnali and Mahakali River Basins in the Mid and Far Western Development Regions of Nepal. DJB is

This paper draws on both quantitative and qualitative data. The quantitative data come from a representative household survey implemented across the region in 2017. The survey elicited a variety of data from 3,660 sample households covering agricultural and other livelihood practices, natural resource use and valuation, community participation, asset ownership, and migration. The sample was constructed using a two-stage sampling method. In the first stage, primary sampling units' village development committee (VDC) were identified using probability proportional to size. In the second stage, households in the selected primary sampling units were selected using systematic random sampling. Data were collected using a paper-based survey, and data entry was completed in CSPro 5.5. All quantitative data analysis was conducted using Stata statistical software.

The primary qualitative data were derived from focus group discussions (FGD), and semi-structured in-depth interviews (IDI). These qualitative data help to contextualize and understand the broader patterns observed in the quantitative data. Qualitative data collection was based on purposive sampling whereby selection criteria for participants were based on caste, gender, occupation, and economic well-being. While 18 FGD were conducted in 9 districts in the basin, the IDIs come from only 2 districts—Doti and Kailali, where pilot Digo Jal Bikas intervention sites were located. As such, the data from the latter should not be viewed as representative of conditions in the broader region. Qualitative data was translated, transcribed, and later coded using ATLAS.ti. Data were analysed using thematic analysis.

5. Quantitative methods

We examine the characteristics of households with migrating members as well as the relationships between migration and measures of social interaction and female participation using multivariate regression analysis. Specifically, we describe characteristics of households with migrant household members by implementing the following probit model

$$Y_i = \alpha + \beta X_i + \varepsilon_i \tag{1}$$

where Y_i is an indicator for a household with at least one migrant member and X_i is a vector of characteristics including respondent gender and age, household head gender, highest educational attainment within the household, monthly household income, household structure (i.e., nuclear family or extended family), caste, and geographical region. We also implement Equation 1 on a subset of the entire sample to characterize households with short term migrations. Here, Y_i indicates the household has a migrant member who migrates for a period less than six months; the model is only run among households with at least one migrant member.

Along with describing households with migrant members, we use OLS regression to estimate the relationships between migration and various measures of social interaction and female participation, controlling for household and respondent characteristics. We estimate

$$Y_i = \alpha + \beta M_i + \gamma X_i + \varepsilon_i \tag{2a}$$

where Y_i is an indicator of social interaction or female participation, M_i indicates the household has a migrant member, and X_i is a vector of controls. To gain further insight into how relationships may differ within the migrant household population, we implement equation 2b

$$Y_i = \alpha + \beta_1 M_i + \beta_2 P_i + \beta_3 M_i \times P_i + \gamma X_i + \varepsilon_i \tag{2b}$$

Here, all variables are defined as in equation 2a, and P_i is an indicator for nuclear family structure, Dalit caste, or migration lasting fewer than six months.

In equations 2a and 2b we consider multiple measures of social interaction and female participation. Importantly, they combine both revealed and as stated measures. Given the importance of agriculture and natural resources to the livelihoods of the population in our sample, most of the social interaction measures are tied to these concepts. We also measure female-specific outcomes including female participation in household and community decision making and collective action. We examine four measures of social interaction: (i) shock assistance, as indicated by a binary indicator for whether the household has received support for climate, disease, or market shocks in the past five years; (ii) NGO presence, as indicated by local NGO involvement in the community; (iii) NGO support, as indicated by a binary indicator for whether a household could go to a local NGO for support; and (iv) average trust in natural resource and other community groups among female respondents. We also analyse five measures of female participation: (i) agricultural participation, which indicates female participation in trainings or meetings with extension officers; (ii) NRM meeting attendance, which indicates female attendance at natural resource user group meetings; (iii) other meeting attendance, which indicates female attendance at other community group meetings; (iv) remittance decisions, which indicates female participation in household decisions about the use of remittances; and (v) irrigation negotiations, which indicates female participation in renting and lending of irrigation machinery. Finally, we examine female participation in collective action using one outcome which indicates female participation in community-benefiting activities in the past year.

6. Socio-demographic characteristics

We first consider socio-demographic characteristics of our sample (Table 1). Seventy-one percent of respondents were male, with the average age being about 43 years old. Within the sample, the mean household education was secondary school, although many households had members who had not attended school or had only primary school education. Over 80 percent of households had male household heads, and the mean monthly income was found to be about 2330 rupees. Nearly half of the sample lived in households with a nuclear family structure—parents living with their children—while the other half lived in extended family households. Almost half of the sample was from the hill geographical region, with about 30 percent from the Terai and 20 percent from the mountain region. Finally, nearly 60 percent of the sample belongs to either the Brahmin or Chettri caste; indigenous and the Dalit caste groups comprised 20 percent each; and less than 1 percent are Muslim or other unidentified caste groups.

Table 1: Socio-demographic characteristics

	Mean	Standard Deviation	Observations	Minimum	Maximum
Male	0.71	0.45	3660	0	1
Age	42.5	13.5	3660	14	90
Highest Education[a]	4.8	1.4	3659	1	9
Male Household Head	0.84	0.36	3660	0	1
Monthly Income (NRs[b])	2331	71380	3660	0	3143753
Nuclear Family	0.47	0.50	3660	0	1
Region					
Mountain	0.22	0.36	3660	0	1
Hill	0.46	0.50	3660	0	1
Terai	0.32	0.47	3660	0	1
Caste					
Brahmin/Chettri	0.59	0.49	3660	0	1
Indigenous	0.22	0.42	3660	0	1
Dalit	0.18	0.38	3660	0	1
Muslim	0.004	0.07	3660	0	1
Other/Unidentified	0.009	0.09	3660	0	1

Source: Authors' calculations.

[a]: Education ranges from illiterate to graduate level education. The mean of 4.8 indicates an average education level of secondary school.

[b]:Exchange rate at time of survey was 103 NRs to 1 USD.

7. Migration characteristics

Unsurprisingly, given trends in migration evident throughout Nepal, levels of migration among sample households are high (Table 2). Over 37 percent of households have at least one migrant member, with the vast majority of households citing temporary or seasonal migration of members rather than permanent migration; the mean duration of migration is just over one year. The distribution of migrant sending and receiving locations varies. The majority of migrant households are from the hill region (57 percent), followed by the Terai (28 percent), and lastly the mountain region (15 percent). In terms of destination, 70 percent of migrants go to India; 16 percent to Gulf countries; 10 percent to domestic destinations; and 3 percent to non-India or Gulf-region countries. Within our sample, almost all sample migrants are men, with only 5 percent of households with migrants having female migrants and 98 percent of households with migrants sending male migrants. [2]

Table 2: Migration

	Mean	Standard Deviation	Observations	Minimum	Maximum
Migrant Member	0.37	0.48	3660	0	1
Seasonal Migrationa	0.98	0.15	1367	0	1
Permanent Migrationa	0.03	0.16	1367	0	1
Migration Durationa	13.86	10.47	1366	1	96
Male Migranta	0.98	0.13	1367	0	1
Female Migranta	0.05	0.21	1367	0	1
Regiona					
Mountain	0.15	0.36	1367	0	1
Hill	0.57	0.50	1367	0	1
Terai	0.28	0.45	1367	0	1
Destinationa					
Within Nepal	0.10	0.30	1367	0	1
India	0.71	0.45	1367	0	1
Gulf Countries	0.16	0.37	1367	0	1
Other International	0.03	0.16	1367	0	1

Source: Authors' calculations

a: All statistics calculated within migrating households

We also describe households with migrant members using multivariate probit regression; the marginal effects are reported in Table 3. Column 1 reports characteristics of households with at least one migrant member; column 2 describes households with migrant members who leave for six months or fewer. We find that migrant households are more likely to be male-headed and have an extended family structure. Additionally, they are more likely to be from the Dalit caste and the hill region. While these trends hold in describing short term migrant households as well we also find evidence of a negative relationship between monthly income and short term migration and higher rates of short term migration from the Terai region.

Table 3: Characterizing households with migrant members

	Migrant HH member	Short term migrant
Male respondent	-0.28***	-0.06***
	(0.02)	(0.01)
Male HH head	0.12***	0.05***
	(0.02)	(0.02)
Respondent age	0.0022***	0.0005
	(0.0007)	(0.0004)
Highest HH education	0.002	-0.002
	(0.007)	(0.004)
Monthly income	-0.00000009	-0.0000009***
	(0.0000001)	(0.0000003)
Nuclear family	-0.20***	-0.05***
	(0.02)	(0.01)
Dalit	0.09***	0.007
	(0.03)	(0.02)
Regiona		
Hill	0.15***	0.10***
	(0.05)	(0.02)
Terai	0.04	0.05***
	(0.05)	(0.01)
Observations	3649	3659
Pseudo R2	0.11	0.06

Source: Authors' calculations. Marginal effects are reported. Standard errors, clustered at VDC level, in parentheses.

*p< 0.10, **p< 0.05, ***p< 0.01

a: Mountain region is omitted category.

8. Analysis and results

Multivariate regression provides key insights into the relationships between migration and social interactions, female participation, and collective action in western Nepal. We begin our analysis broadly, considering relationships between migration and social interactions at the household level. As the analysis progresses, we included gendered results, specifically examining migration within the context of gender. In the subsections to follow, we outline the descriptive statistics of our measures of social interaction, female participation, and collective action, respectively, as well as report regression results. Given the wealth of qualitative data available from FGDs and IDIs throughout the region, we contextualize our quantitative findings with qualitative evidence from the basins.

Social Interactions

Throughout the basins, social interactions that involve trainings and NGO interactions are uniformly low. As indicated in Table 4, only three percent of the sample had received assistance related to environmental, disease, or market shocks they had faced; the majority of this assistance is from government or NGOs. Given that over 80 percent of the sample experienced some type of shock in the previous 5 years, these rates of assistance are quite low. More of the sample had interacted with community NGOs, with 20 percent of the sample recognizing local NGO activity in their communities and 7 percent indicating that they personally know NGO staff to whom they could reach out for support if it were needed. While social interactions appear quite low on the indicators measured, we do find that female respondents exhibit high levels of trust in the NRM or community groups of which they are a part.

Table 4: Social interactions

	Mean	Standard Deviation	Observations	Minimum	Maximum
Shock assistance	0.03	0.18	3660	0	1
NGO presence	0.19	0.40	3652	0	1
NGO support	0.07	0.25	3660	0	1
NR group trusta	2.29	0.52	1134	0	3
Community group trusta	2.28	0.50	1509	0	3

Source: Authors' calculations

a: Trust measured on 0 to 3 scale with 0 indicating no trust and 3 indicating complete trust.

Panel A of table 7 reports multivariate regression results related to social interactions.

We find that households with migrant members exhibit negative relationships with each of these social interaction measures, indicating lower levels of social interaction compared to non-migrant households. While migrant households exhibit significantly lower levels of trust in natural resource groups and other community groups, the negative relationships with shock assistance, NGO presence, and NGO support are not significant at conventional levels. We also find that male respondents and households with male household heads exhibit positive relationships with our social interaction measures, providing suggestive evidence of a gendered component of social interaction within our sample. Thus, men may have access to the benefits of more social interaction relative to women.

FGDs and IDIs revealed that men, usually those who do not migrate, act as initial contacts for project staff, who, in rural areas, are primarily high caste men. This is largely because of the normative dimensions of social interactions, which dictate the tendency to interact with members of the same social group. This is particularly true in the case of NRM. Therefore, women's ability to access information on trainings, meetings, intervention programs, and services is shaped by their social positions and the natures of their social relationships. Our qualitative interviews further suggest that households without men have fewer interactions with project staff, unless women share strong social or kinship ties with the staff. While this is the dominant narrative, we do find that women in nuclear families with migrant members may have greater interactions with NGOs and their activities in the community than women in households without migrant members or in extended family structures. These women's increasing interactions with NGOs could also be attributed to project requirements of compulsory female participation.

Based on the qualitative evidence from the FGDs and IDIs, we suspected that different household and migration characteristics may mediate the relationship between migration and social interactions; we investigate three possibilities using multivariate regression methods—family structure, caste, and migration duration—in Tables A1, A2, and A3 (panel A). With regard to family structure, when considering the interaction between a nuclear family structure and a migrant household, we find that nuclear family-structured migrant households have received more assistance related to economic, disease, or climatic shocks and are more familiar with local NGOs and NGO staff, compared to others. While not all of these positive relationships are significant, we do find that migrant nuclear family households are significantly more likely to feel they can reach out to local NGOs for support if necessary. With regard to caste, we find that Dalit households demonstrate lower levels of social interaction on average. This trend is even more salient among Dalit households with migrant members. Finally, with regard to migration duration, we find largely positive relationships between short-term migrating household members and social interactions. None of the latter relationships are significant at conventional levels, however.

9. Female Participation and decision making

In addition to understanding the relationships between households' social interactions and migration, we investigated the correlations between migration and female participation. Table 5 reports the descriptive statistics from our sample. Overall, female participation and decision making is quite low. Only 19 percent of women are active participants in decisions around use of remittances, and only 2 percent participate in irrigation negotiations. Furthermore, only 3 percent have attended agricultural trainings or met with extension officials [3]; while 13 percent regularly attend natural resource group meetings; and 19 percent regularly attend other community group meetings. This trend of unequal female participation in trainings and in meeting extension officers is also reflected in qualitative interviews. We found a few women attending several trainings while others had attended none. Furthermore, some households appear to meet extension officer several times, while other had never attended, which further demonstrates the inequitable distribution of resource and information access within a community.

Table 5: Female participation

	Mean	Standard Deviation	Observations	Minimum	Maximum
Agriculture participation	0.03	0.17	3660	0	1
NR meeting attendance	0.13	0.33	3660	0	1
Other meeting attendance	0.19	0.40	3660	0	1
Remittance decisions	0.19	0.40	3660	0	1
Irrigation negotiations	0.02	0.13	3660	0	1
Source: Authors' calculations					

Panel B of Table 7 reports multivariate regression results for our participation variables. With the exception of agricultural participation, there are higher levels of female participation from migrant households, with the relationship demonstrating statistical significance for all outcomes except negotiation decisions. That is, women from migrant households are more likely to participate in natural resource and community group meetings as well as to make decisions regarding the use of remittance payments. Panels B of Tables A1, A2, and A3 (in the appendix) demonstrate, however, there is heterogeneity in female participation based on family structure, caste, and migration duration. First, we find that female household members of migrant nuclear families are less active in community groups (although the negative relationship is not significant) and more active in remittance decisions, a contrast to results found when not considering family structure explicitly. These trends are supported by our qualitative findings which indicate that women from nuclear families are more time constrained, and, accordingly, less able to allocate time to community groups. Second, we find that among Dalit households, the relationship between female participation and migration is less clear and imprecisely measured. Finally, we find that long term migration appears to drive the positive relationship between female participation and the presence of household migrants. Table A3, demonstrates that among households with migrants who leave for 6 months or less, female participation is lower, particularly with regards to participation in irrigation negotiations and community group meetings. This result is perhaps unsurprising. While long term migration may require women to participate more actively in the community, short term migration likely maintains traditional gender roles through frequent migrant return.

The qualitative data reveal that female participation is more common when groups are exclusively for women or when there is compulsory female participation. For example, some community forest user groups or savings groups are entirely composed of women. There are also NRM groups that require female membership and participation, with policies stipulating that, for example, a third of participants must be female to encourage a more equal gender distribution within the group. Furthermore, many NGOs in rural areas strive to reach women, targeting female-dominated groups for vegetable farm trainings and female empowerment.

While intentions to include women in community groups and decision making exist within many of the communities in our sample, our data show that compulsory participation does not always lead to transformative participation. Particularly in mixed NRM groups where women are selected from close relational network, exhibit tokenistic participation. For instance, in a hamlet in Kailali, we found four women with close kinship ties to men on the committee, who were also members of an irrigation user committee. None of these women irrigated fields themselves, whereas female irrigators, a majority of whom have smaller landholdings and migrant husbands or sons, were much less aware of the existence of the irrigation user committee. Accordingly, these women irrigators faced immense challenges in securing irrigation services. A widow with two migrant sons shared her hardships in these words:

> "It [busy schedules of men who help in operating engines] delays irrigation. The seeds don't sprout and dry in the absence of water. This year I could get no help. My son was far and he could not come. Crop in 10 khatta (3386.21 Sq meters) of land was destroyed. All men were busy. My plot is near Mohana river and at comparatively higher elevation. The road is uneven and the engine was heavy. It is difficult for me to carry it alone in the 'dunlop (bullock cart)'. I could not water my fields."
>
> (In-depth Interview, Kailali, 30.10.2017)

As this interview excerpt illustrates, gender relations play a role in irrigation negotiations and determine access to irrigation equipment. While these challenges are faced by many women, they are particularly burdensome for women from migrant nuclear families. In the case of joint families, many women receive assistance in negotiating irrigation equipment from their fathers-in-law or other male relatives.

We observed similar arrangements in community forest user groups (CFUGs). In one mixed CFUG, the daughter of a local politician was nominated as a treasurer; however, this position was in name only and she was not informed about committee decisions. In two locations in the basin (Doti and Kailali), only one household member could be a member of the CFUG, and male household members generally hold this role. Sometimes women attended meetings if men were temporarily away from the community; however, upon their return, men would typically resume their participation.

Women acknowledged that family structure was important in their participatory activities. For example, in extended family structures, mothers-in law often take responsibility for caring for infants and young children, while daughters-in-law take responsibility for other household and farm tasks. Accordingly, mothers-in-law have more time to attend community meetings and trainings.

Interviews indicated that traditional gender roles and conceptions of work thus continued to act as an obstacle to women's participation. For example, male focus group participants in Jumla shared:

> "In each committee if the president is a male then the vice president is a female. Comparatively the participation has increased but it is not equal to the men yet. The other thing is they are too busy with their household work to participate in such committees."
>
> (FGD, Jumla, 14.2.2017)

Women-only savings groups were among the most popular groups in which women in the Karnali and Mahakali River Basins participate. These groups facilitate women's access to finance; however, since a majority are illiterate and immobile, financial inclusion and empowerment varies based on other characteristics as well. For example, in the mountains and the Terai, women-only savings groups usually form along caste/ethnicity lines, and membership for women from other castes is seldom acceptable. For example, in one village there was a Dalit woman from a migrant family who had been removed from the saving group because her brother-in-law's son had married a non-Dalit girl.

In addition, remittances from migration do enable women to more actively participate in these groups; however, their participation may remain constrained by family structure. In Kailali, where large joint family structures are dominant, female savings group participants were primarily older women. Here we observed a monthly meeting of a women's' savings group and found that few young women with infants participated. Intra-household gender dynamics, therefore, are an important factor determining women's participation in savings groups and their financial empowerment.

10. Female participation in collective action

Finally, we consider individual participation in collective action, as indicated by a binary variable for whether the female respondent participated in community efforts in the year prior to the survey (Table 6). Overall, collective action is quite low in the sample, with only 17 percent of female respondents indicating they had participated in at least one such activity in the prior year, compared to 28 percent among male respondents. In the sample of female respondents as well as the entire sample, the most common form of collective action was contribution to road improvement.

Table 6: Collective action

	Mean	Standard Deviation	Observations	Minimum	Maximum
Female participation	0.17	0.37	1053	0	1

Source: Authors' calculations

Table 7: Multivariate regression

	Panel A: Social Interactions					Panel B: Female Participation					Panel C: Collective Action
	Shock assistance	NGO presence	NGO support	NR group trust	Community group trust	Agriculture participation	NR meeting attendance	Other meeting attendance	Remittance decisions	Irrigation negotiations	Participation
Migrant HH	-0.0013	-0.0008	-0.0083	-0.13***	-0.13***	-0.012	0.054***	0.055**	0.48***	0.0052	-0.057**
	(0.01)	(0.02)	(0.01)	(0.04)	(0.04)	(0.01)	(0.02)	(0.02)	(0.02)	(0.00)	(0.03)
Male	0.0011	-0.020	0.033***			-0.016	-0.14***	-0.064**	-0.14***	-0.023***	
	(0.01)	(0.02)	(0.01)			(0.01)	(0.02)	(0.03)	(0.02)	(0.01)	
Male HH head	0.0067	-0.0050	0.0022	0.0069	0.031	-0.011	-0.084***	0.034	-0.052***	-0.031***	0.089***
	(0.01)	(0.02)	(0.01)	(0.05)	(0.05)	(0.01)	(0.02)	(0.03)	(0.01)	(0.01)	(0.03)
Nuclear family	-0.0043	-0.023	-0.0056	0.036	0.035	-0.0072	0.021*	-0.047**	0.049***	0.0082	-0.029
	(0.0`)	(0.01)	(0.01)	(0.03)	(0.03)	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.02)
Constant	0.056	0.083	-0.020	2.01***	2.27***	0.043**	0.22***	0.53***	0.30***	0.031**	0.056
	(0.04)	(0.05)	(0.03)	(0.12)	(0.13)	(0.02)	(0.04)	(0.08)	(0.04)	(0.01)	(0.11)
Observations	3649	3641	3649	1129	1506	3649	3649	3649	3649	3649	1050
R^2	0.02	0.06	0.03	0.04	0.05	0.02	0.08	0.04	0.45	0.06	0.05

Source: Authors' calculations. Standard errors, clustered at VDC level, in parentheses. All regressions control for respondent age, household education, monthly income, caste group, and geographical region. NR group trust, community group trust, and collective action participation are measured at the respondent level; all other outcomes at the household level.

$^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$

With regards to migration, Table 7 (panel C) demonstrates that female respondents from households with migrant members less commonly participate in collective action; this result is significant at the 5 percent level. We again find some heterogeneity within our sample with regard to this relationship, as demonstrated by Panels C in Tables A1, A2, and A3. First, we find that female respondents from migrant nuclear families and female respondents from migrant Dalit households are more likely to participate in collective action, although these results are not significant at conventional levels. Second, we find that the negative result observed in the entire sample is driven by long-term migration; women in households with migrants who are gone for less than 6 months are more likely to participate collectively although this result is also not significant at conventional levels.

11. Discussion and conclusion

This study examines the relationships between social interactions and women's participation at household and community levels, within a context of very prevalent, male-dominated migration. We consider a variety of indicators that represent social interaction, female participation, and collective action. Our results indicate that migration may impact how households and individuals interact with their communities. Migration not only reconfigures gender roles and relations, it also interacts with local norms and networks within and beyond the community, therefore playing an important role in access to resources, information, training, services, and income opportunities among left-behind populations. In our study context in western Nepal, these left-behind individuals are primarily women. Our results suggest that women from poor migrant families with fewer kinship and social ties owing to their subordinate structural position (caste, class, ethnicity) may face restricted access to spaces of empowerment. This restricted access may stem from the fact that social interactions in the villages are highly structured by patrilineal and male-centric networks that exclude households with male migrants, although it is also possible that households with migrants begin with reduced social capital and empowerment independent of the migration status of their members. While migration and gender have this interconnected role, we also find that other household and migrant characteristics are related to women's interactions in community participation and decision-making. Indeed, our qualitative evidence suggests that family structure often dictates the time female household members have to dedicate to non-household responsibilities, such as participation in community groups.

Unequal social interactions shaped by gender and social norms are key components of many social theories. Consequently, men, who often enjoy positions of power based on social and cultural norms, are able to seize more opportunities from their social relationships (Smith-Lovin and McPherson 1991, Lin 1999, Ridgeway and Smith-Lovin 1999). Our study confirms this finding and suggests patterns of unequal gender interactions, opportunities, and participation. Low levels of social interactions by female household members echo gendered and male-centric interactions, as also observed by previous studies. Furthermore, the difference in interactions is also stark along caste/ethnicity lines, as social spaces are generally dominated by high caste men (Lin 2000). In this context, as our qualitative data indicates, dependency on men may be amplified among left-behind women from marginalised groups.

Considering the NRM sector more specifically, we observed in our data and fieldwork that resource management in rural Nepal is highly male dominated, particularly in more remote areas where male community members enjoy stronger social bonds and networks with project staff. There are two sides to this: female staff is also less likely to be involved in project interventions in remote areas, and where traditional gender roles are also much stronger. Influential men, mainly from higher castes, thus act as particularly strong gate keepers and play vital role in disseminating information on projects, trainings, and meetings in these settings (Lama and Buchy 2002, Agrawal 2001). Consequently, unless women from migrant households share strong kinship relations with men, they have lower access to information about trainings, opportunities, and are less involved in NRM executive committee (Lin 2000, Nightingale 2002). This is clearly evident in our data, which indicates that higher caste women from migrant household demonstrate higher rates of NRM group participation compared to women of lower castes. Furthermore, consistent with existing findings (Subedi, 2008), our results show mobile, less burdened, and rich women participating more than those who are immobile, busy, and poor. In both Doti and Kailali, the majority of women from marginalised groups, particularly those in nuclear families, are not educated, and busy with household and agricultural responsibilities. Accordingly, when these women are left behind by (primarily male) migrating household members, they experience increased responsibilities at home, reducing the time they have to participate in trainings and community groups. Unsurprisingly then, women who do participate are close relatives of influential men, who themselves do not migrate. The participation of these more highly-connected women is often tokenistic and not transformative, since it mostly benefits specific ethnic groups and disregards the needs and experiences of the marginalised groups of women (Tamang 2011, Shrestha Forthcoming.). In our qualitative data, we observed the exclusion of women irrigators from irrigation user groups at the expense of well-connected women who were not involved in irrigation. As such, women's irrigation needs are not reflected in user group decisions and women face challenges in accessing irrigation equipment, meaning they are often the last to irrigate their fields. As argued by Mehta (2014),formal and informal rules and norms support powerful groups' interests, rather than those of the weak and marginalised.

Our study also aligns with other research that argues that women participate most in issues surrounding children's education and nutrition (Quisumbing, et.al., 1995; Khalaf, 2009). Scholars argue that improvements in these spheres are evidence of increased efficacy in pre-assigned roles rather than of female agency or empowerment (Kabeer 1999). Even when structure is imposed on community groups to expand women's roles in the community, the outcomes do not always meet these objectives. In Kailali, for example, a registered women's savings group had a formal rule that members could loan money only against agriculture expenses. While members do officially state agriculture related expenses as loan rationale, they often use the funds for other purposes including household necessities, education, marriage, and even to repay migration debt. Although such savings groups may provide women with the ability to support family needs when male household members migrate, they often increase debt liabilities, leading to future financial challenges. Moreover, these groups do not challenge the status quo of unequal gender relations because these responsibilities fall firmly within the realm of domestic boundaries.

Second, while participation provides an opportunity to work towards shared goals and objectives, without literacy skills and required capabilities to maintain records, women remain largely dependent on men. In Doti, we met the chairwoman of a woman's savings groups who was part of a migrant, nuclear family. She was a close relative of the secretary of men's savings group, who would advise and help her with accounts. Her ability to maintain these accounts depended on her male family member's assistance, demonstrating the dependence of female groups on men in the community.

Finally, challenges remain regarding the reliability of these groups, as their ability to provide loans depends on active member participation and savings. When this participation is not maintained, members must turn to other sources for loans such as relatives and friends. As shown by our quantitative data, decisions regarding expenses are determined by family structure. Women from migrant households who live with their-in-laws are less likely to exercise agency owning to position subordinate to senior female members (Kabeer 1999).

Migration is an increasingly dominant feature of the Nepali economy, particularly in western Nepal. As migration becomes more commonplace, policy concerns arise regarding both migrants themselves and the families they leave behind. In Nepal, left-behind family members, who are primarily female, face many challenges; however, migration also offers a potential pathway for women's empowerment as women step in to fulfill the roles and responsibilities of migrating men. Still, many societal and household characteristics play a role in the relationship between migratory households and female empowerment, and empowerment should therefore not be assumed. In this paper, we examined three mediating factors: (i) family structure, (ii) caste, and (iii) migration duration, and found that increases in female participation at both the household and community levels are largely driven by women living in joint families, women of higher caste, and women who are left-behind for longer durations. These patterns reinforce and reproduce social and gender inequalities. With regard to policy, this study highlights the need to go beyond measurement of the direct impact of male migration on migrants themselves, and instead calls for examination of patterns and processes of social interactions that may restrict or facilitate the abilities and agency of left-behind women to participate in spaces of empowerment. This requires recognising women as heterogeneous group with unequal links, capabilities, and access. It also points to a particular need for supporting interventions that help lower status left-behind women. Accordingly, advancing women's empowerment will entail intentional, policy efforts that address gender and social inequalities.

Acknowledgements: This study is made possible by the generous support of the American people through the United States Agency for International Development (USAID) under Digo Jal Bikas (DJB) project.

Disclaimer: The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government. All research conducted with permission of the Institutional Review Board (IRB) of Duke University.

Endnotes

[1]More information about the Digo Jal Bikas project is available at http://djb.iwmi.org/.

[2] Some households send more than one migrant, which is why the sum of the percentages of migrants who are male and female is greater than 100 percent.

[3] Attending agricultural trainings and meeting with extension officers is quite rare within our sample. In fact, while slightly more than 3 percent of men in the sample participated in these activities, there is no statistically significant difference in participation between genders

References

Agrawal, B. (2001). Participatory Exclusions, Community Forestry, and Gender: An Analysis for South Asia and a Conceptual Framework. World Development, 29, 1623-1648.

CBS. (2014). Population Monograph of Nepal. Retrieved from Kathmandu:

Cortes, G. (2016). Women and Migrations: Those Who Stay. from Pole de recherche pour l'organisation et la diffusion de l'information geographique (CNRS UMR 8586)

Das, R. J. (2004). Social capital and poverty of the wage-labour class: problems with the social capital theory. Transactions of the Institute of British Geographers, 29(1), 27-45. doi:10.1111/j.0020-2754.2004.00112.x

Démurger, S. (2015). Migration and families left behind. from IZA World of Labor

Dinda, S. (2014). Inclusive growth through creation of human and social capital. . International Journal of Social Economics, 41(878-895.).

Dinkelman, T., & Mariotti, M. (2016). The long-run effects of labor migration on human capital formation in communities of origin. American Economic Journal: Applied Economics, 8(4), 1-35.

Gartaula, H. N., Niehof, A., & Visser, L. (2010). Feminisation of Agriculture as an Effect of Male Out-migration: Unexpected Outcomes from Jhapa District, Eastern Nepal. International Journal of Interdisciplinary Social Sciences, 5(2), 565-577.

Gartaula, H. N., Visser, L., & Niehof, A. (2012). Socio-Cultural Dispositions and Wellbeing of the Women Left Behind: A Case of Migrant Households in Nepal. Social Indicators Research, 108(3), 401-420.

Giraud, G. C., H. Renouard, R. D. L'Huillier, L. Martini`ere & C. Sutter. 2012. Relational capability: A multidimensional approach., ed. H. Universit´e Paris1 Panth´eonSorbonne (Post-Print and Working Papers) halshs-00827690.

Hadi, A. (2001). International migration and the change of women's position among the left-behind in rural Bangladesh. International Journal of Population Geography, 7(1), 53-61.

IBRD/WB. (2018). Male outmigration and women's work and empowerment in agriculture: the case of Nepal and Senegal. 2018. . from The international Bank for Reconstruction and development/ The world Bank

Ismailbekova, A. (2013). Migration and patrilineal descent: the effects of spatial male mobility on social female mobility in rural Kyrgyzstan. In: .

Kabeer, N. (1999). Resources, Agency, Achievements: Reflections on the Measurement of Women's Empowerment. . Development and Change, 30, 435-464.

Kabeer, N., & Subrahmanian, R. (1996). Institutions, Relations, and Outcomes: Framework and Tools for Gender Aware Planning. from Institute of development Studies

Kabeer, N. (2005). Gender equality and women's empowerment: A critical analysis of the third millennium development goal. Gender & Development, 13(1), 13-24.

Khalaf, M.C., 2009. Male Migration and the Lebanese Family: The Impact on the Wife Left Behind. Journal of Middle East Women's Studies 5, 102–119. doi:10.2979/MEW.2009.5.3.102

Kulczycka, K. (2015). Left behind women and empowerment: consequences of male labour migration on the economic and social polistion of left behind women in Nepal. (Bachelor of Science in Development Studies), Lund University, Sweden.

Lama, A., & Buchy, M. (2002). Gender, Class, Caste and Participation: The Case of Community Forestry in Nepal Indian Journal of Gender Studies, 9.

Lama, A. S., Kharel, S., & Ghale, T. (2017). When the Men Are Away Migration and Women's Participation in Nepal's Community Forestry. Mountain Research and Development, 37(3), 263-270.

Lin, N. (1999). Social Networks and Social Attainment. Annual Review of Sociology, 25, 467-487.

Lin, N. (2000). Inequality in Social Capital. Contemporary Sociology, 29(6), 785-795. doi:10.2307/2654086

Lodigiani, E., & Salomone, S. (2015). Migration-Induced Transfers of Norms. The Case of Female Political Empowerment (June 23, 2015). (Publication no. http://dx.doi.org/10.2139/ssrn.2622394). (19/WP/2015). from University Ca' Foscari of Venice, Dept. of Economics https://ssrn.com/abstract=2622394

Lokshin, M., & Glinskaya, E. (2008). The effect of male migration for work on employment patterns of female in Nepal. from The world bank

Maas, J., Seferiadis, A., F. G. Bunder, J., & Zweekhorst, M. (2014). Bridging the disconnect: how network creation facilitates female Bangladeshi entrepreneurship. International Entrepreneurship and Management Journal, 10(3), 457-470.

Maharjan, A., Bauer, S., & Knerr, B. (2012). Do Rural Women Who Stay Behind Benefit from Male Out-migration? A Case Study in the Hills of Nepal. Gender, Technology and Development, 16(1), 95-123. doi:10.1177/097185241101600105

Mehta, L. (2014). Water and Human Development World Development, 59, 59-69.

Morokvašić , M. (2014). Gendering Migration. Migracijske i etničke teme, 30(3), 355-378. doi:10.11567/met.30.3.4

Mozumdar, L., Farid, K. S., & Sarma, P. (2017). Relevance of social capital in women's business performance in Bangladesh (Vol. 15).

Nega, F., Mathijs, E., Deckers, J., & Tollens, E. (2010). Gender, social capital and empowerment in northern Ethiopia. from MPRA

Nightingale, A. J. (2002). Participating or Just Sitting In? The Dynamics of Gender and Caste in Community Forestry Journal of forest and livelihood, 2.

Padmaja, R., & Bantilan, C. (2007). Empowerment through Technology: Gender Dimensions of Social Capital Build-up in Maharastra, India. . from CAPRi

Paul, C. J., Weinthal, E. S., Bellemare, M. F., & Jeuland, M. A. (2016). Social capital, trust,

and adaptation to climate change: Evidence from rural Ethiopia. Global Environmental Change, 36, 124-138.

Portes, A., & Sensenbrenner, J. (1993). Embeddedness and Immigration: Notes on the Social Determinants of Economic Action. American Journal of Sociology, 98(6), 1320-1349.

Quisumbing, A. R., Brown, L. R., Feldstein, H. S., Haddad, L., & Pena, C. (1995). Women: The key to food security (p. 22). Washington, DC: IFPRI.

Ridgeway, C. L., & Smith-Lovin, L. (1999). The Gender System and Interaction. Annual Reviews, 25, 191-216.

Shrestha, G. (Forthcoming.). Our women are not yet ready: An Ethnography of emerging.female leadership in transitional Nepal – A Local Perspective. Chakra: A Nordic Journal of South Asian Studies. Under Review

Smith-Lovin, L., & McPherson, J. M. (1991). You are who you know : a network perspective on gender. In P. England (Ed.), Theory on Gender/Feminism on Theory (pp. 223-251). New York: Aldine.

Subedi, R. (2008). Women Farmer's participation in agriculture training in Kavre District of Nepal. . (Degree of Master in Training Rural Extension and Transformation.), Larenstein University of Applied Sciences, Wageningen, The Netherlands.

Tamang, S. (2011). The politics of developing nepali women: Wiley-Blackwell.

Theoharides, C. (2017). Manila to Malaysia, Quezon to Qatar: International migration and its effects on origin-country human capital. Journal of Human Resources(0216-7714R1).

Thieme, S. (2006). Social Networks and Migration: Far West Nepalese Labour Migrants in Delhi. Münster.

Thieme, S., & Boker-Muller, U. (2009-2010). Social Networks and migration: Women's livelihoods between Far West Nepal and Delhi. European Bulletin of Himalayan Research, 35-36, 107-121.

Yabiku, S. T., Agadjanian, V., & Sevoyan, A. (2010). Husbands' labour migration and wives' autonomy. . Population studies, 64(3), 293-306.

Appendix

Table A1: Nuclear family interactions

	Panel A: Social Interactions					Panel B: Female Participation					Panel C: Collective Action
	Shock assistance	NGO presence	NGO support	NR group trust	Community group trust	Agriculture participation	NR meeting attendance	Other meeting attendance	Remittance decisions	Irrigation negotiations	Participation
Migrant HH	-0.0076	-0.015	-0.020	-0.10**	-0.10***	-0.012	0.058***	0.057**	0.40***	0.0042	-0.082**
	(0.01)	(0.02)	(0.01)	(0.04)	(0.04)	(0.01)	(0.02)	(0.03)	(0.02)	(0.01)	(0.03)
Nuclear family	-0.0094	-0.035**	-0.015	0.058	0.054	-0.0075	0.024*	-0.045*	-0.015**	0.0074	-0.055
	(0.01)	(0.02)	(0.01)	(0.04)	(0.03)	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.04)
Migrant × NF	0.015	0.034	0.027*	-0.080	-0.073	0.0010	-0.0093	-0.0059	0.19***	0.0025	0.047
	(0.01)	(0.03)	(0.02)	(0.08)	(0.06)	(0.01)	(0.03)	(0.04)	(0.03)	(0.01)	(0.05)
Male	-0.00021	-0.018	0.035***			-0.015	-0.14***	-0.065**	-0.13***	-0.023***	
	(0.01)	(0.03)	(0.01)			(0.01)	(0.02)	(0.03)	(0.02)	(0.01)	
Male HH head	0.0063	-0.0059	0.0015	0.0041	0.028	-0.011	-0.083***	0.034	-0.057***	-0.031***	0.087***
	(0.01)	(0.02)	(0.01)	(0.05)	(0.05)	(0.01)	(0.02)	(0.03)	(0.01)	(0.01)	(0.03)
Constant	0.057	0.087*	-0.017	2.01***	2.27***	0.043**	0.22***	0.53***	0.32***	0.032**	0.071
	(0.04)	(0.05)	(0.03)	(0.12)	(0.13)	(0.02)	(0.04)	(0.08)	(0.04)	(0.01)	(0.10)
Observations	3649	3641	3649	1129	1506	3649	3649	3649	3649	3649	1050

R2	0.02	0.06	0.03	0.04	0.05	0.02	0.08	0.04	0.46	0.06	0.05

Source: Authors' calculations. Standard errors, clustered at VDC level, in parentheses. All regressions control for respondent age, household education, monthly income, caste group, and geographical region.NR group trust, community group trust, and collective action participation are measured at the respondent level; all other outcomes at the household level.

*p< 0.10, **p< 0.05, ***p< 0.01

Table A2: Dalit interactions

	Panel A: Social Interactions					Panel B: Female Participation					Panel C: Collective Action
	Shock assistance	NGO presence	NGO support	NR group trust	Community group trust	Agriculture participation	NR meeting attendance	Other meeting attendance	Remittance decisions	Irrigation negotiations	Participation
Migrant HH	0.00019	0.0020	-0.0042	-0.13***	-0.11***	-0.013	0.048**	0.066***	0.47***	0.0078	-0.067**
	(0.01)	(0.02)	(0.01)	(0.01)	(0.04)	(0.01)	(0.02)	(0.02)	(0.02)	(0.01)	(0.03)
Dalit	0.053	-0.022	-0.0086	0.012	0.11	-0.020**	-0.015	-0.0052	-0.021**	0.013**	-0.012
	(0.05)	(0.03)	(0.02)	(0.08)	(0.08)	(0.01)	(0.02)	(0.04)	(0.01)	(0.01)	(0.05)
Migrant × Dalit	-0.016	0.0078	-0.011	-0.047	-0.14*	0.015	0.034	-0.061	0.031	-0.0069	0.042
	(0.03)	(0.04)	(0.02)	(0.11)	(0.08)	(0.01)	(0.03)	(0.05)	(0.03)	(0.01)	(0.05)
Male	-0.00083	-0.020	0.033***			-0.016	-0.14***	-0.064**	-0.14***	-0.023***	
	(0.01)	(0.02)	(0.01)			(0.01)	(0.02)	(0.03)	(0.02)	(0.01)	
Male HH head	0.0077	-0.011	-0.0005	0.029	0.051	-0.012	-0.084***	0.032	-0.052***	-0.033***	0.091***
	(0.01)	(0.02)	(0.01)	(0.05)	(0.05)	(0.01)	(0.02)	(0.03)	(0.01)	(0.01)	(0.03)

Constant	0.060*	0.060	-0.030	2.08***	2.33***	0.038**	0.22***	0.53***	0.30***	0.027*	0.062
	(0.04)	(0.05)	(0.03)	(0.12)	(0.13)	(0.02)	(0.04)	(0.08)	(0.04)	(0.01)	(0.11)
Observations	3649	3641	3649	1129	1506	3649	3649	3649	3649	3649	1050
R2	0.02	0.06	0.02	0.03	0.04	0.01	0.08	0.04	0.45	0.06	0.05

Source: Authors' calculations. Standard errors, clustered at VDC level, in parentheses.All regressions control for respondent age, household education, monthly income, caste group, and geographical region.NR group trust, community group trust, and collective action participation are measured at the respondent level; all other outcomes at the household level.

*p< 0.10, **p< 0.05, ***p< 0.01

Table A3: Short-term migration

	Panel A: Social Interactions					Panel B: Female Participation					Panel C: Collective Action
	Shock assistance	NGO presence	NGO support	NR group trust	Community group trust	Agriculture participation	NR meeting attendance	Other meeting attendance	Remittance decisions	Irrigation negotiations	Participation
Migrant HH (short term)	0.020	0.0055	0.0093	-0.027	0.018	0.0016	-0.023	-0.071**	-0.035	-0.015*	0.034
	(0.02)	(0.03)	(0.02)	(0.07)	(0.06)	(0.01)	(0.03)	(0.04)	(0.03)	(0.01)	(0.04)
Male	-0.0022	-0.050	0.035**			-0.011	-0.17***	-0.051	-0.27***	-0.019*	
	(0.01)	(0.03)	(0.02)			(0.02)	(0.03)	(0.04)	(0.04)	(0.01)	
Male HH head	0.013	-0.035	-0.027	0.016	0.087	-0.025	-0.098**	0.0079	-0.16***	-0.037**	0.025
	(0.01)	(0.03)	(0.02)	(0.09)	(0.11)	(0.02)	(0.04)	(0.04)	(0.03)	(0.02)	(0.03)
Constant	0.060	-0.034	-0.039	1.71***	1.85***	0.040	0.37***	0.64***	1.12***	0.0089	-0.063
	(0.04)	(0.09)	(0.04)	(0.22)	(0.22)	(0.04)	(0.09)	(0.11)	(0.09)	(0.02)	(0.12)

Observations	1367	1364	1367	384	479	1367	1367	1367	1367	1367	590
R2	0.03	0.07	0.03	0.04	0.06	0.02	0.09	0.02	0.23	0.08	0.03

Source: Authors' calculations. Standard errors, clustered at VDC level, in parentheses.All regressions control for respondent age, household education, monthly income, caste group, and geographical region.NR group trust, community group trust, and collective action participation are measured at the respondent level; all other outcomes at the household level.

*p< 0.10, **p< 0.05, ***p< 0.01

Annex 4-3

Gender, Social Capital, and Collective for Sustainability of Water Resources in West Nepal

Gitta Shrestha, Floriane Clement

Abstract

The importance of social capital in enhancing collective management of the commons have been increasingly sought in diverse disciplines. Nevertheless, the connection between gendered social capital and its impact on differentiated capabilities of women and men to partake in collective management of water resources remains an under investigated area. Drawing on capabilities approach by Sen (1990) and literatures on social capital, we investigate the interlinkages between social capital, capabilities and collective management of water resources in two hamlets, one each in Doti and Kailali districts in Nepal. Qualitative methods were used to collect the data. The respondents were sampled purposively from different caste, class, gender, age, education and social positions. The findings suggest social capital influential in shaping capabilities, which in turn creates new connections, access and networks which again allow individuals to attain new capabilities and functioning. However, social capital is influenced by gender and other social identities such as caste, class, and age thereby, disassociating women and the marginalized groups from being integrated into men dominated water networks and governing mechanisms, which reinforce gender inequality and affect women's wellbeing adversely. This study further identifies that, women's social capital and capabilities must increase, a process which builds individual capacity and enables collective action in the community.

Keywords: Capabilities, collective commons, gender, social capital, water

1. Setting the Context

> *"I wish I could work like you. We have a different life. We work in the fields, in the forest and in the filth. I wish I was educated like you'*. Doti, 2017

This is the common response we had received in remote hills of Doti when we approached women, mainly young and mid-aged [30-40] for informal interactions, while we accompanied them in their walks to the fields, animal sheds, water springs or to the forest. It was late November when conducted second phase of field work in Doti. In the village, it is only possible to meet aged men and women. Most of the young and mid-aged men were away to work in India. The recently implemented community forest rules in the village had fixed days to collect forest products and women did not want to miss it. Women would be busy early morning till late evening. This is the everyday life of a rural women, no matter what season it is. To hold them for interviews is difficult and at the same time I am filled with a feeling of guilt. While they continue doing their work, I pose questions: *Do you regularly interact with people (outsider, female) like us?* Some would answer no and some would say – '*yes sometimes. Two madam (female staffs) was here to help us to form women's saving groups".* Do you meet male staffs (outsiders)? *Yes, if they are from the village. We meet male outsiders very less; they [men staffs] meet men in the market. Even if we meet them, it is always in groups, not one to one. Sometimes they call us for meetings. What if I was accompanied by a man? Would that have made any difference to my status?* The women smiled, stayed silent for a while and answered – *niko mandeinan* (it will not be considered good). After talking for a while, they tell me – *if we continue talking with you, we will get late for our work'*, and in groups, they rush towards the forest.

> *"Women in groups, walk to the forest. They walk far chatting about their lives, help each other with making bundles, and relax with a puff of smoke in the bush! "From Authors' field diary, Doti, 2017.*

These field interactions/observations strongly indicate women not only as a diverse group – the differences among us as urban and rural women [in terms of mobility and capabilities], but also evidence gendered spaces of interaction and exclusion. Although male-migration has caused shifts in gender roles (reference), places of meeting, persons to meet and one's responsibility is strongly defined by gender and cultural norms [relational spaces] in rural areas. My interactions with these women also exhibit changing aspirations of rural women who wish to be mobile, independent and economically empowered, however, lack spaces, capabilities and are overburdened [entangle] with gendered roles to work towards individual well-being (reference).

In this paper, I basically draw attention to gendered social capital that shape women's capabilities and functioning in relation to water resources in the hills and tarai regions, marked by high seasonal/circular male migration. Women in these areas are the target groups of various development projects including collective water management. The projects aim to empower these women by including them in the water user groups, and ultimately aiming towards the overall goal of sustainable management of water resources (SDG[1] 6) and gender equality (SDG 5). While importance of women has been increasingly emphasised in policy and practice in the water sector [(e.g. The Nepal Irrigation Management Transfer Project (IMTP) (1995-2002)], a number of empirical literature documents 'business-as-usual 'approaches and less/passive participation of women in water user associations (Shrestha and Clement, forthcoming). The methods and strategies adopted to overcome gender based obstacles in water resource management related projects remain vague, (Sülün, Emine Eminel, 2018) paying no/less attention to social spaces and social processes that creates pathways, social capital in this research's context and facilitate [capabilities] access to resources.

2. Background: Gender, Social Capital and collective water sustainability in Nepal.

In the context of increasing water scarcity, a number of water agencies have adopted collective model[2] under Integrated water resource management (IWRM)[3] in Nepal (Ratner et al. 2017). Collective engagement to manage scare water resources is considered critical to sustainable, equitable and efficient use of scare and depleting water resources. Collective action implies sense of ownership, joint responsibility, informed decision making that are owned by involved stakeholders, motivation to support water resource management improvements, share risks, and pool expertise, capacity and finance to deal with water related social, environmental and economic consequences [reference]. Gender, often acts as an organising principle for community action, thus may have implications for the efficiency and effectiveness of collective action (Pandolfelli, Lauren., Meinzen-Dick, Ruth., and Dohrn, Stephan, 2005).

[1] Sustainable Development Goals, 2030.

[2] A master plan for integrated watershed development in the Siwalik (Chure) Hills region in FY 2015.
3 integrated water resources management (IWRM) has been defined by the Global Water Partnership (GWP) as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems".

Several water agencies are engaged in installing water supplies and irrigations schemes in rural areas such as tapping stream flows, building community ponds in villages, constructing tanks, building reservoirs for increase drinking and irrigation water. Participatory approach and gender and social inclusion (GESI) is integral to collective model of water management that aim to benefit both men and women especially from the marginalised communities in equal terms (GoN, 2014). Nevertheless, data shows that a majority of disadvantaged groups are yet devoid of improved access to water services including water for irrigation (Regmi, Chandra Shibesh and Fawcett, Ben. 2001). Moreover, non-functionality of water infrastructure after completion of the project pose serious sustainability[4] questions (performance of irrigation systems), which further push marginalised households at the verse of resource poverty.

Existing research evidence structural factors such as caste/ethnicity, landholdings etc., leading to inequitable distribution of benefits from and contributions towards, the operation and management of irrigation canals. Discriminatory norms, and unequal power relations influence access to information, knowledge, participation and impact negotiating capabilities of marginal farmers (Chambers, 1977)[5]. As a result, they constitute a disincentive for collective action of natural resources. Social capital has been documented one among various factors for enhancing collective action for managing irrigation resources. A recent research in Nepal indicates that the absence of trust within community members result in conflict and non-contribution to maintenance of field channels and control structures, which in turn lead to increased unequal access to irrigation water (Pariyar, Lovett and Snell 2018). Women, from marginalised families suffer most in such situations. Deficiency of trust among community members stemmed from non-inclusion in decision making impacts sustainability of the project. The literature on the community management of natural resources indicates - to build sustainability of various water management approaches needs interventions that encourage reciprocity and cooperation among community members. Lam (1998)[i], Sara and Katzi, (1998), Harvey et. al., (2004) and Vaidya (2015) insist on importance of the active participation of local users in decisions related to water allocation and community services in community managed water supplies. According to Hodgkin (1994) if communities are not well represented on the design process, not well educated on technical know-how of the technologies and their selection, if they find themselves limited to interests and powers of the facilitators/donors, ultimately, beneficiaries disown the projects and this hinders sustainability. Research shows if the beneficiaries participate fully in the process of identifying and selecting the appropriate and affordable water supply technology, then there is a great chance to enhance project ownership and hence its sustainability.

In this article, we draw attention to the gendered social capital that factor from 'gendered social relations and networks', - socially constructed by dominant cultural and social institutions [carry profound consequences for women] consequently deciding 'capabilities and functioning of individuals, which we hypothesize impact the sustainability (performance) of water distribution systems in rural areas [equity debate]. While various interventions increasingly recognise the importance of gender equality and women empowerment, less attention have been paid to the processes [and relationships, values, norms] [spaces] applied to engage men and women in

[4] Water projects lack sustainability component. (Hodgkin, 1994, Baumann, 2005, Water Aid, 2006).
[5] *Chambers, R. (1977). Men and water: The organisation and operation of irrigation. In B. H. Farmer (Eds.), Green revolution? Technology and change in rice-growing areas of Tamil Nadu and Sri Lanka. Boulder: Westview Press.*

transformation process. By doing so, this paper contributes and add to the ever growing sustainability and equity debates in the field of sustainable water resource management.[6]

3. Conceptual framework: Gendered Social Capital, Capabilities and Functioning

The concept of social capital emerged in the wake of weakening community ties, well-being and economic efficiency in the later decades of 19th Century (Norris and Inglehart, 2003). Since then it has been theorised in multiple ways by various disciplines, in different contexts to understand causes of behaviour and collective social outcomes. Despite criticism and inconsistency regarding its meanings and use, literature on social capital has grown extensively in recent years. Many see it as a popular yet elusive since there exits not a single definitional concept and approach for it. In this research, we conceptualise social capital rooted in social relations, embedded in normative structure (Reimer, 2007). We adapt the definition provided by Ostrom, 2008 – i.e., social capital as an attribute of individuals and of their relationships that enhance their ability to (*sic*) [p5] coordinate action and achieve desired goals. It is through such relationships that people reassert and renegotiate the rules governing the access to resources in society and influence the distribution, control and transformation of assets (Bebbington 1999, 2035).

Social relations are organised by normative structures [1].[7] Benefit from the social capital largely depends on the ability of an individual to mobilise social relations, i.e., proper investment is required to build and maintain it and secure benefits; which largely is influenced by social (gender, class, caste) and cultural (values, norms) attributes.[8] Therefore, not everyone has equal access and possession of social capital, neither social capital could bring equal benefits to all. In this sense, it is more helpful to see social capital as the social relations of inclusion and exclusion and how individuals in networks relate to each other and the norms which maintain and organise the connections (Reimer, 2008).

Existing research indicates the ability to mobilise social capital can enhance other forms of capital (such as human) (Dinda, 2014) and therefore improve people's capabilities (Migheli, 2011).[9] Capabilities, as Sen (1990) defines – 'what people are able to do', determines 'functioning' – what people want to be i.e., capabilities [freedom, opportunities] direct the choices about their life. The capability approach respects people's different ideas of the good life, and their capacity to achieve it. Social relation is central to capability approach by Sen (1990) and Nassbaum (2000). Sen define social relations as part of an entitlement set, which are used as means by individuals to achieve their own way of life. Similarly, affiliation is the 7th central human functional capability listed by Nassbaum, 'Being able to live with and toward others, to recognize and show concern for other human beings, to engage in various forms of social interaction; to be able to imagine the situation of another' (*sic*) P

[6] The majority of sustainability programs to-date have been gender blind, and have thus ended up working primarily with men, who are more often recognized as farmers, fishers, irrigators, or foresters and who are more likely to occupy public spaces.

[7] Normative structure are relatively comprehensive ways in which people organise their interactions, each with its own general set of associated norms that condition the co-ordination of social behaviour (Fiske, 1991 in Reimer, 2008). P9.

[8] In summary, these three elements – resources, entitlements and functions of utilization – will determine the extent of choices open to an individual (his options for being and doing). The more curtailed the capability extent is, the poorer an individual will be in terms of life choices. Therefore, poverty is not a lack of resources anymore, but rather a lack of capabilities [Sen, 1990).

[9] Communities with social capital had more prerequisites to respond and prepare to the challenges and reach for external support.
https://jyx.jyu.fi/bitstream/handle/123456789/50552/Thesis_Pesonen_FINAL_2016.pdf?sequence=5

41.Migheli (2011) presents a dynamic connection between social capital, capabilities and functioning. According to his theory, the ability to attain new capabilities is enhanced by the possession of social capital; hence investing in its accumulation allows individuals to improve their welfare. Furthermore, new capabilities allow the individual to create new connections and access new networks, accruing his or her stock of social capital and opening the door to the possibility of attaining new capabilities.[10] Inequality in social capital across social groups has been widely documented. Historically, gender constitute an integral social construction causing significant differences in the social networks and embedded resources between males and females. While men are usually connected to resourceful and geographically dispersed social networks, women are limited to kin based and geographically close networks with fewer resources; While men network with economic institutions, women popular networks are focused on domestic and community affairs. Such inequality in social capital increases along lines of social differences. For instance, differences in social capital between women with infants and women with adult children. Similar has been document in the context of natural resource management which shows that for certain groups to build and maintain a social network is costly in terms of both time and other resources, imposing a barrier to social capital accumulation (Dasgupta 2005; Ioannides and Loury, 2004). For instance, Meinzen-Dick and Zwarteveen 2003 shows high opportunity cost of time for women that reduces their incentives to participate in certain social networks. In the context of severe resource constraint, women usually join groups that mobilize fewer resources than men (Maluccio et al 2003). Meinzen-Dick and Zwarteveen (2003) demonstrate how barriers faced by women in their participation in water management user groups in South Asia may stimulate use of alternative forms of social capital such as a network of friends and relatives.

Such differences offer different or unequal outcomes that could exacerbate disadvantages of women and minority groups in terms of resources and well-being. Gender scholars argue that the investigation of social capital is incomplete without investigating gendered hierarchies within which social networks are forged (Silvey and Elmhirst 2003). It has been argued that social capital that exists within a broader context of gender inequality can exacerbate women's disadvantages, as women remain excluded from the more powerful networks of trust and reciprocity that exist among men (Ibid). Westermann, Ashby and Pretty (2005) find significant differences in the gender aspects of social capital impacts the activities and outcomes for natural resource management groups. This research recognises the unequal human capabilities of men and women and also among women[11] due to unequal social and political circumstances (Nassubaum 2000), and ask – is social capital gendered? How social capital differs for men and women? How it shapes capabilities of men and women to benefit from water resources?

We have selected three types of social capital that are particularly important in the study of collective action: (1) Social network, (2) formal and informal rules, and (3) trust (Ostrom, 2008).

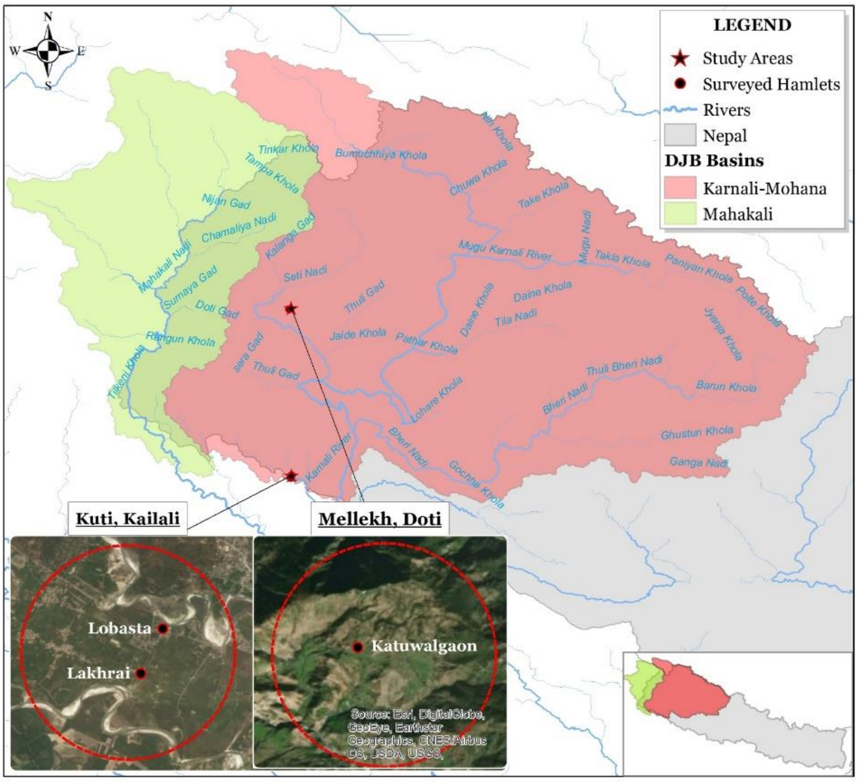
4. Study area

The study hamlets were selected on the basis of findings and observations from the first phase of field work under DJB project [Weblink of the project]. Katawalgaon in Mellekh, Doti was selected because of the examples of poor water governance which had left irrigation ponds dry and abandoned, while

[10] Communities with social capital had more prerequisites to respond and prepare to the challenges and reach for external support.
https://jyx.jyu.fi/bitstream/handle/123456789/50552/Thesis_Pesonen_FINAL_2016.pdf?sequence=5
[11] One cannot end gender oppression without ending caste oppression. One cannot smash patriarchy without the annihilation of caste.

Lobasta in Kuti, Kailali was selected because of the presence of strong local institutions that had glued members for collective resource management such as ground water irrigation, dam construction, path building and so on. These scenarios made us to go deeper into the question of social capital and collective commons, to critically explore the range of local institutions and investigate why some institutions sustain while others perish using gender lens, in this research, our concern relates to collective local water governance especially water for irrigation. Conducting parallel research in two different geographical settings with different bio-physical and ethnicity provided us with the scope to develop cross culturally comparable research[12].

Map 1. Location of the study areas.



Source: IWMI-Nepal

5. Research Methods

The research is exploratory and qualitative in nature. Methods of data collection included well-being ranking, village mapping, in-depth interviews, key informant interviews, institutional Venn diagram and participant observation. The respondents were selected purposively in both the hamlets. Respondents from different caste, class, gender, age, education, social position, household migration status were interviewed. Efforts were made to interview members and non-members of community groups uniformly in order to gather different perspective on social capital and collective action. Altogether 30 respondents in Kuti and 20 respondents in Katwalgoan were interviewed. Interviewing respondents from diverse groups enabled data credibility and verification. To ease the language constraint especially with women who do not speak Nepali in Doti and Kailali, a local translator was

[12] Write briefly about study areas, what kind of community is it.

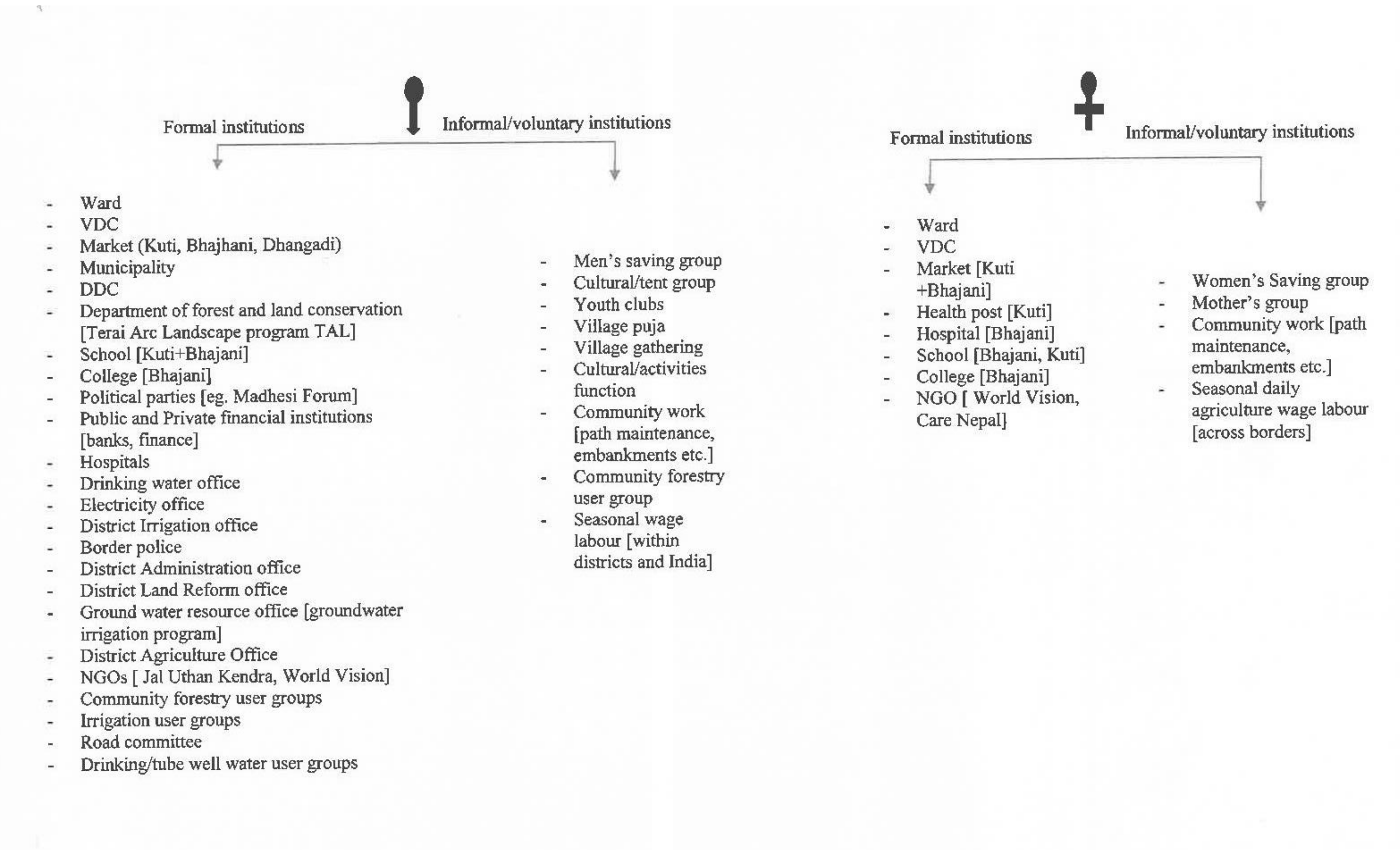
hired at both research sites. Notes were taken in Nepali which was later transcribed in English and coded under emergent research themes. Field work in Kuti was conducted in October 2017 and field work in Katawalgon was conducted in November 2017.

6. Findings

The gender dimensions of group membership and social networks (relationships)

We conducted Venn institutional diagrams as participatory visual method separately with men and women groups in each hamlet in Kailali and Doti. This was conducted to explore types of spaces that men and women in the community interacts with. The group was mixed in terms of age and caste. We specifically asked questions on organisations or groups which they interact on frequent basis. The participants were asked to sketch both formal and informal groups on a piece of paper. Participants identified institutions that were assigned circles of different sizes based on their perceived importance, as larger circles mean more important institution. The distance of the circle from the centre indicate the nearness of their relations and accessibility.

Figure 1 Formal and Informal Spaces of interaction and participation



Source: Field work, 2017,2018.

Our data indicate clear gender differences in spaces and groups where men and women interact. As could be seen from figure 1, while men interact with a varied number of formal and informal spaces women's interactions are limited to immediate spaces, mostly informal. Everyday lives in both study areas is strongly dictated by traditional gender roles [Tharu/Rajhi and Chettri], which promote limited mobility among women outside the community. Men as the household head interact with officials at the community, village and district level, offices mostly dominated by men. Women travel furthest to VDC or Ward office, specially from households with no men. In Kuti, the offices are half an hour walking distance from the village, while in Mellekh it is located at the other side of the mountain which is approximately located at 4 hours by walk. Therefore, in case of Mellekh distance to VDC offices is also one factor limiting frequent travel to government offices. This difference in mobility among women in the hills and in the mountains due topography was also visible from the differences in involvement of female wage labour. In Mellekh, women mostly perform unpaid labour exchange (perma) in the farms, whereas in Kuti, women are engaged both in perma and in seasonal daily wage labour across borders. Majority of households in Kuti are joint households, which make possible among women of the household to divide work among themselves and take part in economic activity. In most cases, daughter-in-law would join other women for wage labour and older women in the household take part in caring responsibilities such as looking after children in the household. Such mobility however is popular among poor household. Women from well-off households seldom participate in such activities for it symbolise low status. Also, women are only allowed to be mobile in groups. We heard stories where women engaged in wage labour are considered not good by the community. Therefore, class factors into loosening gender constructions to some extent. In Mellekh, on the other hand, family breakdown has become a norm. Happening changes in the family structure however, have not brought any changes in the traditional way of living lives. Male migration and nuclear family structure is becoming a norm however, women are still caught with traditional farming, households and caring responsibilities which take a toll on their time. Changing forest and water resources have further increased their work time, for they walk further than before to access forest resources. Water facilities have come closer due to modern infrastructure such as taps and ponds, yet competition for water resources has increased due to decrease in flow and quantity of water. In most cases women have to wait long for their turn. Therefore, due to time constraints which is directly related to traditional gender roles, women are seldom involved with formal spaces.[13] Similar reasons apply in informal spaces such as village meeting, unless women face mandatory clause of participation [in village meetings, community work (e.g. labour contribution) mainly in case of households with migrant men. Such households as our data shows are usually assisted by male relatives to access formal services such as relief aid, widow pension etc. Female reservation has successfully brought women in user committees (water, forest) however, as we observed, their participation is tokenistic and dominated by women closely related to influential men in the villages. Hence, poor women farmers are not benefited by such reservations [Discussed in later sections].

Interactions in formal spaces also differ in terms of age and ability. Young, old and differently able enjoy limited interactions in formal spaces. It is similar in informal spaces such as participation in voluntary organisations. In Mellekh, since meetings are held normally in market area, old and differently abled were found not participating since they are required to walk quite a long distance to reach market. In Kuti, elderly participation is absent in formal spaces and passive in informal spaces. With youths, we found youth clubs run and dominated by young boys. Similarly, in other cultural and village activities, it is male youths and adult men who look after management issues; female youths

[13] men walk far mending the sources

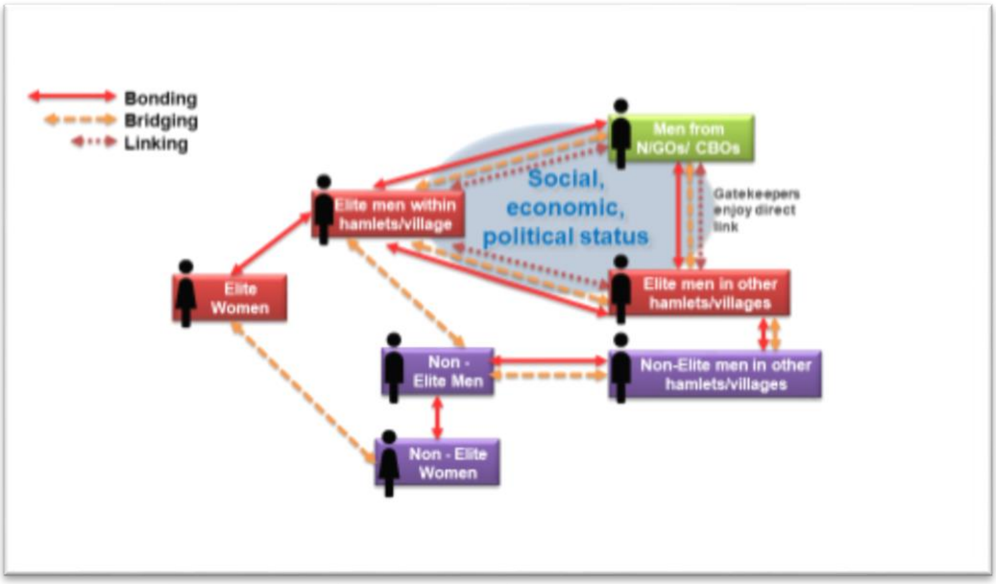
and women are limited to cultural performance (eg. dance), cooking and other feminine activities.[14] [15]

In the study areas, mostly women interact in spaces created and are being led by women and which mostly focus on women's issues. For instance, mother's group created by District women and children office, run as monthly saving groups; involvement in school committees which is mainly seen as feminine spaces; interaction with NGOs which works with child education, nutrition and health. Spaces where important resources are discussed and managed such as forest, water, politics, road, market is dominated by men. In both hamlets, there were only few women who were had extended networks. [women health volunteers].

Social spaces are shaped historically by unequal caste and class relations and the patrilineal networks

In view of exploring social spaces that result in differentiated social capital for men and women, it is also important to ask what mediates such spaces and what exclusionary impacts such capital may possess for men and women from the marginalised communities. In our study hamlets, we find that social spaces are shaped historically by unequal caste and class relations and the patrilineal networks that maintains men's control and domination over resources.

Figure 2: Figure showing pathways to networks between different groups of people



Source: Field work, 2017, 2018.

As described in the previous section, since women in majority share networks close in family and kinship, women links to the members outside of the family is marked via their relations with men in the family and kinship networks. While this is true for women from all backgrounds, women from higher class and caste enjoy comparative advantage owing to extended networks, men in their family share with the outside world. These men, categorically educated, with comparatively large landholdings, owning

[14] that create differences in social networking that can be deployed to build further social capital.

[15] Ethnic community organisations provided limited opportunities for women to be involved in activities and programs.

local jobs-businesses-leadership positions and who seldom migrate for labour jobs, share ties with men both inside and outside the village. Gender and social position provide men with the advantageous links to access information and opportunities related to development projects including water. Male domination in water projects particularly from high [similar] caste also factors in the production of gendered social capital. We observed men staffs deployed in the field connect with local men not only on the basis of gender but also on caste lineage. We did not come across any women staffs in the study area working on water issues. As stated in the previous sections, women staffs are deployed and women from the village are mobilised for issues such as maternal health, child education, nutrition etc. The absence of female staffs in the field discourage women in the village to build alliances to access opportunities and information related to water projects. Socially embedded as a default practice, local men usually act as the first contact of men staff from the water projects. This arise from two main factors – [a] owing to traditional culture and gender roles, men are perceived as knowledgeable, and [b] social and gender norms dictate behaviours that disapprove male-female interaction and between other groups [e.g. Dalit and non-Dalit]. Project staffs rely on local men for selecting women representatives for user committees. Women[16] in close contacts are recommended for jobs, membership in user committees, meetings and trainings [refer example below]. In the hamlet, some women had attended several trainings and some had attended none.

Case 1. Woman A lives in X hamlet, not far from her paternal home, her house located alongside the main blacktopped road. Her family owns large plots of land however, the family themselves does not cultivate the lands. She is a sister of a well-respected, educated local leader who played a major role to bring groundwater shallow irrigation project in the village and who is positioned as a secretary of the irrigation user group. A is in irrigation user group and also in drinking water user group [hand pump]. The hand pump has been installed in the courtyard of her house. She does not irrigate the farms.

Case 2. Woman B, a widow lives alone in Y hamlet. She has two migrant sons who are engaged in daily wage labour jobs in other districts. They visit home very rare particularly to help her during plantation season. She owns marginal plots of lands alongside river, however, does not hold land entitlement yet. The land still in the name of her brother in-law. She borrows pipes, pumps and exchange labour in the fields. She irrigates farm herself, face uneasy access to irrigation water however, she is not even aware of the existence of the irrigation user groups in the community.

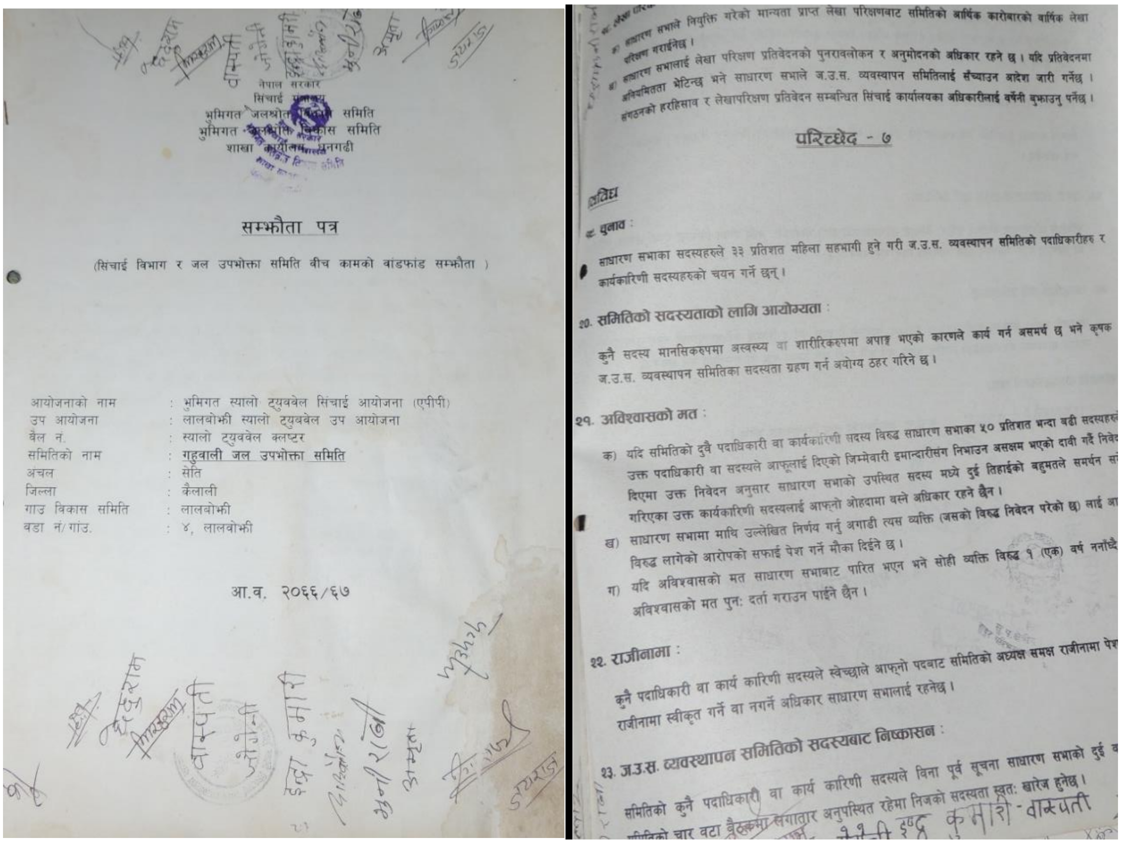
These case studies of two women with different social identities from the same community demonstrate a) the characteristics of women who are involved in the user groups often b) that even if 33 percent provision stated in the agreement [Photo 1] has been met, involvement of women through patrilineal linkage has not benefited poor women farmers. Following examples one each from Doti and Kailali exemplifies how such links [shaped historically by unequal caste and class relations and the patrilineal networks], benefit one single group and carry a risk of aggravating social and gender inequalities.

Groundwater Shallow Tube-well Irrigation scheme in Kailali

Under a government scheme that introduces groundwater shallow tube well irrigation, a group of farmers collectively received a grant to install electric infrastructure for water pumping in 2010. Users

[16] In other projects, female staffs not oriented on gender and power relation issue.

have expressed how using electric pumps as opposed to diesel pumps is a welcome relief because they are cheaper and lighter to carry. While the heavy weight of diesel pumps required a bullock cart to be transported, electric operated pumps can be carried even on bicycles. Moreover, using electric pumps eliminates the burden of having to travel to far away markets in Nepal and India for diesel. Lastly, electricity is also much less expensive than diesel.



नेपाल सरकार
सिंचाई
भुमिगत जलश्रोत समिति
भुमिगत विकास समिति
शाखा कार्यालय, धनगढी

सम्झौता पत्र

(सिंचाई विभाग र जल उपभोक्ता समिति बीच कामको बांडफांड सम्झौता)

आयोजनाको नाम	: भुमिगत स्यालो ट्युववेल सिंचाई आयोजना (एपीपी)
उप आयोजना	: लालबोझी स्यालो ट्युववेल उप आयोजना
वैल नं.	: स्यालो ट्युववेल क्लष्टर
समितिको नाम	: गहुवाली जल उपभोक्ता समिति
अंचल	: सेति
जिल्ला	: कैलाली
गाउ विकास समिति	: लालबोझी
वडा नं/गांउ.	: ४, लालबोझी

आ.व. २०६६/६७

परिच्छेद - ७

१८. चुनाव :

साधारण सभाका सदस्यहरुले ३३ प्रतिशत महिला सहभागी हुने गरी ज.उ.स. व्यवस्थापन समितिको पदाधिकारीहरु र कार्यकारिणी सदस्यहरुको चयन गर्ने छन्।

२०. समितिको सदस्यताको लागि आयोग्यता :

कुनै सदस्य मानसिकरुपमा अस्वस्थ्य वा शारीरिकरुपमा अपाङ्ग भएको कारणले कार्य गर्न असमर्थ छ भने कृषक ज.उ.स. व्यवस्थापन समितिका सदस्यता ग्रहण गर्न अयोग्य ठहर गरिने छ।

२१. अविश्वासको मत :

क) यदि समितिको दुवै पदाधिकारी वा कार्यकारिणी सदस्य विरुद्ध साधारण सभाका ५० प्रतिशत भन्दा बढी सदस्यहरु उक्त पदाधिकारी वा सदस्यले आफूलाई दिएको जिम्मेवारी इमान्दारीसंग निभाउन असक्षम भएको दावी गर्दै निवेदन दिएमा उक्त निवेदन अनुसार साधारण सभाको उपस्थित सदस्य मध्ये दुई तिहाईको बहुमतले समर्थन गरिएका उक्त कार्यकारिणी सदस्यलाई आफ्नो ओहदामा बस्ने अधिकार रहने छैन।

ख) साधारण सभामा माथि उल्लेखित निर्णय गर्नु अगाडी त्यस व्यक्ति (जसको विरुद्ध निवेदन परेको छ) लाई विरुद्ध लागेको आरोपको सफाई पेश गर्ने मौका दिईने छ।

ग) यदि अविश्वासको मत साधारण सभाबाट पारित भएन भने सोही व्यक्ति विरुद्ध १ (एक) वर्ष ननाँघ्दै अविश्वासको मत पुन: दर्ता गराउन पाईने छैन।

२२. राजीनामा :

कुनै पदाधिकारी वा कार्य कारिणी सदस्यले स्वेच्छाले आफ्नो पदबाट समितिको अध्यक्ष समक्ष राजीनामा पेश राजीनामा स्वीकृत गर्ने वा नगर्ने अधिकार साधारण सभालाई रहनेछ।

२३. ज.उ.स. व्यवस्थापन समितिको सदस्यबाट निष्कासन :

समितिको कुनै पदाधिकारी वा कार्य कारिणी सदस्यले विना पूर्व सूचना साधारण सभाको दुई लगातार अनुपस्थित रहेमा निजको सदस्यता स्वत: खारेज हुनेछ।

Photo 1: The agreement between irrigation department and water user association showing 33 per cent compulsory participation of women in the association.

However, not all farmers were able to benefit from the electric pumps scheme. The irrigation user group was formed following certain government clauses that mandate that members of the group hold legal land titles. This causes the majority of the farmers in the municipality to be excluded from the scheme because most farmers are beneficiaries of land reform in the 1960s, and have yet to receive legal land entitlement papers from the government. As a result, only farmers with large landholdings with adjoining land have been able to benefit from the scheme. The virtue of requiring land tenure de facto excludes women and other disadvantaged groups.

The Irrigation Policy (2003, 2013) has a clause that stipulates that 33 percent of the programme beneficiaries must be women. Four out of the 11 members of the irrigation group are indeed women. But, after meeting these four women, it became clear that some of the women were unaware of their membership in the group, and the other women members either did not farm or irrigate lands. Most women members are wives or sisters of men whose lands are located close together. When men in the group were asked about the inclusion of women in the scheme, they openly expressed that women were included solely because of the clause.

The scheme has benefited farmers, but not poor women irrigators. Most of the poor farmers still rent and carry diesel pumps in bullock carts to fields that are located far from their houses. Some farmers joined the groups later, yet pay a high cost per unit of electricity. The gendered distribution of responsibilities in the field poses a challenge for women whose husbands have migrated. Driving bullock carts and operating water pumps is traditionally a man's job. Women whose husbands have migrated are thus dependent on men for irrigation.

When asked why women find it difficult to operate engines, they stated it needed strength, and they often broke down and needed regular maintenance in which women were not skilled. Moreover, most women do not wish to take on a role that is traditionally male. Women wait for men to operate engine pumps, resulting in late seedling and in some cases, no seed germination at all. When the men are done, the women irrigate the fields with their help. Some women irrigate the fields at night, but only when there are no men at home, and they would return home no later than 11 pm or 12 am while men can irrigate the whole night.

A widow with migrant sons shared how this year she could not irrigate 10 kathas of land because there was no one to help her to carry the engine to her fields, located in the elevated lands near the Mohana River. Her crops were destroyed. Similarly, another woman with a migrant husband said*, "It is difficult to arrange everything. I was busy arranging the 'dunlop' (the cart) all morning, now I need to arrange bullocks and then I have to worry about getting a man to drive the cart and plough the fields. To get things done is not straightforward. We have to request several people, several times."* For women farmers like her, irrigation itself entails a series of negotiations in the absence of access to the required resources and technology. For women irrigators, irrigation is not only economically expensive but also emotionally challenging.

Devisthal Community Group: Traditional local decision making power structures

Photo 2: Devisthal Community Group Building in Katawalgoan, Doti.

In order to know governance structure in Mellekh, it is important to understand the local history, culture, political and economic developments. Historically, the place is dominated by Chettris and informal institutions are institutionalised as per the pre-conflict state political systems and ideology that had elements of social exclusion and caste based discrimination. Founded in 1998, in the same year when the local self-governance act was implemented, Devisthal community group is a historical remnant, hidden but strong informal institution, which has kept historical decision making and power structures intact. It could be defined as a new form of customary local self-governing system led by Mukhiya and the family members in the initial years of formation. Some changes could be seen from the inclusion of the youths partially due to political divides owing to several years of political upheavals and recent political transformations in the country and mainly due to the need of skills and networks that is needed to prepare and maintain records/documents and to win local budget for the community. Young males appointed as local staffs by I/NGOs act both as networks and skilled human resources in this regard. Outwardly, the group is presented as men's saving group however, manage and decide on important issues such as forest, water, conflicts and other village issues.

Caste and social hierarchies define settlement and landownership history, marginal lands [pakho] basically owned by the lower caste members. The new developments such as Silgadi-Kalena-Mellekh road has caused migration within villages with comparatively well-off families moving alongside or near the roads. Prominent male members of the group reside in this area and hold local business or jobs such as teaching, and development, who seldom migrate for seasonal labour jobs and control major decision spaces. A passive membership of a single male Dalit metalsmith who was sheltered by the community for meeting the requirements of agriculture equipment was observed. Since it is all men group, women are not invited to the meetings. When asked on the reason men stated women have their own saving groups and men do not join those meetings. Of several ponds, we observed only two ponds in use and functioning which is used and managed by Devisthal Community Groups. Other irrigation pond user groups as informed and observed become dysfunctional soon after the project phase out. The men in the Devisthal members dominate and influence other user groups formed by development organisations – diversion of funds and benefits to their own ponds; capture and control on resources, information, services, trainings, extended network.

The rules of game: Formal and Informal Institutions [17]

As evident from the previous sections, formal and informal rules, when ignore gender power hierarchies cause disadvantage for women's individual and collective agency. While informal and traditional gender and social norms de facto excludes women from men controlled spaces where important decisions are made, formal rules for example 33% reservation in user committees highly influenced by patrilineal networks favour women in close contact of the men gatekeepers [explained in figure 2, Section 6.2.1.]. Moreover, the project criteria for the selection of women –good hold in Nepali language, ability to spend time for meetings and discussions, ability to keep records, mobility, place and time of meetings etc., automatically filter women from the marginalised households and especially single women without male in the house and with limited social networks. Other factors which impacts equal opportunities for participation includes - Intra-household relations [influence

[17] No gesi orientation, No women staff

which women [mother-in-law/daughter-in-law] participates from joint families], migrant vs. non-migrant[18] households and differently abled/special needs individuals.

While the rules encourage female participation, no time and budget are devoted by the water project on addressing root causes of unequal choices of participation, information and resource use and to strengthen women capabilities. For instance, one of the reasons for ineffectiveness of 33 percent involvement of women in water user groups as existing studies and our previous field experiences in the water sector suggest also arise from the absence of awareness on gender and power relations issues among staffs who are actually responsible to develop and implement GESI activities in the field. In the field, we found staffs although responsible for considering GESI in their work rarely mingle with women outside the market areas and their understanding of gender is mostly limited to ensuring 33 percent involvement of women in the user groups. We have also experienced from our field observations in other areas of far-west Nepal, that even though local female is selected in the position of community mobiliser however, even such appointments are not free from power networks. In addition, owing to position low in organisational hierarchy, they receive no opportunity of learnings on how gender and power relations impact their efforts to ensure gender equality in groups and project activities [reference]. This has major implications on unequal access to information, opportunities, and services and add to the vulnerability of those less capable of dealing with water stress. In other hamlets of the study area, ignoring complex social dynamics has led to the privatisation of water sources and infrastructure and thus, denied marginalised access to water (Shrestha and Clement, 2018).

7. Discussion

The study found differences in social capital and capabilities of men and women, which depend in turn, on their access to information, knowledge and opportunities. Men and women differ in number of groups they join, also there are clear gender differences in the types of groups to which men and women belong. While men obtain these through a variety of formal and informal interactions, women are limited to mostly informal activities, which they create and lead, with a primary focus on women's issues (e.g., health and nutrition). Men, in contrast, dominate discussions and management of key resources, like water, thus putting women at a disadvantage.

Our study confirms findings from previous studies[19] which demonstrate women's networks to be largely comprised of informal support from family or local friends. Although these connections offer companionship, practical assistance and emotional support, these are limited in terms of larger access to information, opportunities and access. that can be deployed to build further social capital.

The analysis reveals the ways in which social network assets are conditional on socioeconomic and gender circumstances. Gendered social capital is shaped by unequal class, caste/ethnic and patrilineal or male-centric networks. In addition, the gathered data reveals that a strong social connection depends on common caste/ethnicity people share in the village. For instance, Chettris have close social bonding with Chettis than with Dalits. This finding was similar in case of Kailali. For instance, Tharus share a strong social bond with Tharus and strongly disassociate themselves from Madhesi and Dalits, Pahadis. Since Chettri is high in caste hierarchy than Dalit, in the hills Dalit was underprivileged.

[18] Shrestha, Pakhtigian and Jeuland, 2019 shows at times, household migration status and family structure interact and shape participation.

[19] The Sociological Quarterly 47 (2006) 497–520 © 2006 Midwest Sociological Society

[20] Similarly, in Kuti tharus are close knit indigenous community with comparatively large landholdings than other groups in the village.

Women's links with formal and informal networks depend on their relations with men in the family. Therefore, women from poor and marginalized households, with fewer kinship and social ties, have fewer opportunities for building capabilities to benefit from water resources. Male migration further complicates the situation, making women dependent on men relatives for work that is socially defined as masculine (such as transporting and operating water pumps). These women's access to information remains restricted as well, since outmigration leaves male "gatekeepers" largely in control of major decisions in the village. Our findings reiterate findings from other parts of the world [reference] and in similar sectors [farming, sweet potato] which highlights how information and services is dominated by men. Women in the study areas are involved in farming and irrigation however, interventions in these areas mostly reach men. In this regard, the interventions cause unintended outcomes because the women who irrigates the land are not having access to and left behind in terms of water knowledge, trainings, technologies and market.

Formal rules of selection of women in the water user committees have basically encouraged patronage women participation which is passive and tokenistic and have not benefitted the overall issue of women's access to water. Men dominated water projects and men centric formal and informal networks has further aggravated women's unequal access to benefit from the collective water resources.

8. Conclusion

In this article, we demonstrated how gendered social capital emanating from unequal social process and normative structures facilitate unequal capabilities to access and benefit from water resources. Another pertinent and long standing question in the literature of social capital includes impact of gendered social capital on the sustainability of the collective commons. Our examples from Kailali on groundwater shallow water irrigation and from Doti on Devisthal community group managing two irrigation pond shows smooth functioning of the only those irrigation systems which is used and managed by the elite[21] men of high caste and class, at the expense of unsustainability of the other ponds or irrigation systems in the region which is used by the marginalised groups of the community. Such systems are not inclusive, encourage distrust and exclude women and the poor. In the longer run pose risk of aggravating water conflicts and social inequalities. Trust promotes cooperation and contribution in collective management of resources. Future interventions should ensure participation of women through institutional arrangements of reciprocity, trust and cooperation (Vaidya 2015). Social relations to water is equally important as that of relations of water to technology for efficient and sustainable use and management. Focus on either will create imbalance and resource conflict causing unsustainable use of water by the communities. Moreover, women's increased access to information, resources, technologies are important for increased women's capabilities to participate,

---

[20] In the case below, a Dalit woman was boycotted and lost membership in social groups because a boy from her family married a Chettri girl.

[21] Elite: a select group that is superior in terms of ability or qualities to the rest of a group or society. English oxford dictionary. A group or class of people as having the most power and influence in a society, especially on account of their wealth or privilege.

decide and benefit from water resources and projects. Social capital – networks, rules and trust - plays big role in building on capabilities which in turn enhance self-esteem, confidence, knowledge, and women's access and control over resources. Such gaps must be addressed in project implementation to ensure women are not left behind when it comes to trainings, new technologies and knowledge to increase capabilities, adoption and water and farm productivity.

Acknowledgements: This study is made possible by the generous support of the American people through the United States Agency for International Development (USAID) under Digo Jal Bikas (DJB) project. The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government.

We are grateful to all the respondents in Katawalgoan in Doti and Lobasta and Lakhrai in Kailali districts in far-west Nepal, who shared their lives and made this research possible. We would also like to acknowledge the field translation provided by Ms. Bina Chaudhary in Kailali and Mrs. Shanta Bhandari in Doti. Also, deep appreciation to the team leader, DJB Dr. Luna Bharati for her continuous support for research on gender and water management in Far West Nepal. We thank ------- their valuable comments.

9. References:

Bebbington, A. (1999) Capitals and Capabiltiies: A framework for analyzing peasant viability, rurual livelihoods and poverty. World Development 27, 2021- 2044.

Migheli, M. (2011) Capabilities and Functionings: The Role of Social Capital for Accessing New Capabilities. Review of Political Economy, 23, 133-142.

Nassubaum, M. C. 2000. Women and Human development: The Capabilities Approach. Cambridge University Press.

Pariyar, B., J. C. Lovett & C. Snell (2018) Inequality of access in irrigation systems of the mid-hills of Nepal. Area Development and Policy, 3, 60-78.

Ratner, B. D., R. Meinzen-Dick , J. Hellin , E. Mapedza , J. Unruh, W. Veening, E. Haglund, C. May & C. Bruch (2017) Addressing conflict through collective action in natural resource management. International Journal of the Commons. , 11, 887-906.

Silvey, R. & R. Elmhirst (2003) Engendering Social Capital: Women Workers and Rural-Urban Networks in Indonesia's Crisis. World Development, 31, 865-879.

Vaidya, R. A. (2015) Governance and management of local water storage in the Hindu Kush Himalayas. International Journal of Water Resources Development, 31, 253-268.

Westermann, O., J. Ashby & J. Pretty (2005) Gender and Social Capital: The importance of gender differences for teh maturity and effectiveness of natural resoruce managment groups. World Development.

Sülün, Emine Eminel, 2018. Women, Water Resource Management, and Sustainable Development: The Turkey-North Cyprus Water Pipeline Project. Resources, 7, 50 MDPI doi:10.3390/resources7030050

Pandolfelli, Lauren., Meinzen-Dick, Ruth., and Dohrn, Stephan, 2005. Gender and Collective Action: A Conceptual Framework for Analysis. International Research Workshop on 'Gender and Collective Action' October 17-21, 2005 •Chiang Mai, Thailand CAPRi Working Paper No. 64 • MAY 2007

Government of Nepal. (2014). Budget speech of fiscal year 2014/15. Ministry of Finance 13 July. Retrieved from http://www.mof.gov.np/uploads/document/file/Budget%20Speech%20Final%20English_20140727050302.pdf.

Oad, R., & Sampath, R. K. (1995). Performance measure for improving irrigation management. Irrigation and Drainage Systems, 9, 357–370. doi:10.1007/BF00881621

Renault, D., & Vehmeyer, P. W. (1999). On reliability in irrigation service preliminary concepts and application. Irrigation and Drainage Systems, 13(1), 77–105. doi:10.1023/A:1006232705161

Lam, W. F. (1998). Governing irrigation systems in Nepal: Institutions, infrastructure, and collective action. Oakland, CA: ICS Press.

Ostrom, E. (2010). Beyond markets and states: Polycentric governance of complex economic systems. American Economic Review, 100, 641–672.

Pradhan, P. (1989). Patterns of irrigation organization: A comparative study of 21 farmer managed irrigation systems. Colombo: International Irrigation Management Institute.

---

[i] Lam 1998. Governing irrigation systems in Nepal: Institutions, infrastructure, and collective action. Oakland, CA: ICS Press. [Google Scholar]

Annex 5-1

Dealing with variations in access to water: An assessment of challenges and coping strategies in Far-Western Nepal

Ram Bastakoti[1], Emma Karki[1], Bhesh Raj Thapa[1], and Vishnu Prasad Pandey[1]

[1] *International Water Management Institute, Pulchowk, Lalitpur, Nepal*

**Corresponding Author: v.pandey@cgiar.org*

Abstract
The Far-Western region of Nepal, which covers Province-6 and 7, is sensitive and vulnerable to changes in the monsoonal weather patterns. This study therefore focused in the Far-Western Nepal and assessed variations in water availability and access; evaluated determinants facilitating or constraining availability and access to water; and analyzed institutional arrangements for water governance at community level. The study was carried out at three sites, namely, Kuti village in Kailali district, and Punebata and Mellekh villages in Doti district, representing diverse agro-ecological zones. Data and information were collection from focus group discussions (FGDs) and key informant interviews (KIIs) at community level and then supplemented with household surveys. Observed trends showed annual and seasonal variations in rainfall and temperature, as well as extremes such as flooding and long dry spells that affected water availability. The access to water also varies according to the type of source for irrigation. In hill/mountain, irrigation sources mainly include stream/spring, but in Tarai, groundwater is the primary source of irrigation. In hill/mountain, water availability is in decline in stream/springs, whereas in Tarai, access to groundwater is constrained by energy cost/availability and fragmented land size. Results indicate that tubewell and pump ownership is very low in Tarai indicating dependency on rental market. Overall, the access to irrigation water is constrained by several factors such as topographic variations, land access and cropping pattern, climatic variations, socio-economic variations, and institutional arrangements. The findings of this study helped gain insights to plan techno-social interventions (e.g., optimizing water use, efficient irrigation technologies, collective approaches, etc.) for addressing such challenges.

***Keywords**: climate shocks, coping strategies, Nepal, perceptions, water access and management*

1. Introduction

Nepal is rich in water resources and biodiversity, however, lags behind in terms of development. Nearly a quarter (or 28.6%) of its population is living below the poverty line (NPC/GoN, 2018). Water resources remain a key area of focus with the government prioritizing it as an important resource for development and economic growth (WECS/GoN, 2011). The 224 billion cubic meters (BCM) of water available per year in Nepal remains underutilized with only less than 7% used for economic and social uses (WECS/GoN, 2005). Despite high level of dependency of a large section of population in subsistence farming, only 40.8% of arable land is irrigated (DWRI/GoN, 2019). It has brought down the crop productivity significantly in comparison to other countries in the region. Therefore, there is a high reliance on food imports, mainly from India, to fulfill the growing demand.

Water availability in the country is distributed unevenly over spatial and temporal scales because of high dependence on monsoonal weather patterns. Heavy monsoon precipitation in the months of June through September follows dry spells for the rest of the year. Monsoon flooding and erosion deposition from flash floods characterize the areas in the Tarai, the southern plain of the country, while landslides and heavy erosions affect the hills. During the dry spells, the Tarai areas rely heavily on river waters, where available, or pumped groundwater for domestic and agricultural uses. Access of irrigation water to marginal farmers is limited although they constitute the majority of cultivators (Suhardiman et al., 2015). Winter monsoon contributes to less than 40% of the total precipitation with monthly precipitation amounts around 50 mm or less (Wang et al., 2013). This precipitation is a critical source of irrigation for winter crops. On the other hand, the mountainous regions stake its survival on springs as the main water sources especially given the extreme topography that make river water withdrawal extremely difficult.

Nepal is particularly vulnerable to changes in climatic events (MoPE/GoN, 2016). Due to its dependence on natural resources coupled with extreme topography, any changes in climatic events may result in compromised livelihood for the people and country as a whole. The Far-Western region of Nepal is particularly sensitive and vulnerable compared to other regions of Nepal (Siddiqui, et al. 2012). Climate change affects water availability and access and reflects on the changes in rainfall intensity and duration (Siddiqui, et al. 2012). Anecdotal information indicates that rainfall in Far-Western region has not changed substantially in terms of absolute quantity but the rainfall intensity has increased; with shorter rainfall durations, thereby leading to reduced ability of already compromised land surfaces to affect recharge. An increase in consecutive dry days adds to the dry spells exposing vulnerability to floods, landslides and droughts (Karki et al., 2017). One of the worst winter drought was experienced in the far and mid-western region of Nepal in 2008-2009 leading to an acute food shortage (MOAAC/WFP/FAO, 2009). Building resilience of farming communities in the Far-Western region of Nepal thus calls for efforts at managing water in a range of scales from field to basin.

Gender and ethnicity also play a role in accessing water and participation in groups facilitating and managing water-related activities. Women are burdened with household and agricultural responsibilities (Tamang et al., 2014) both of which require extensive use of water yet different negotiating skills. Their household duties and lack of prior interaction sometimes prevent participation (Agrawal, 2001) hindering access to water. Women tend to seek help from other male members to raise concerns (Zwarteveen and Neupane, 1996). With the increasing male out-migration leading to a feminization of agriculture, women are now, by default, increasing participation and membership in irrigation and other water-related groups (Meinzen-Dick and Zwarteveen, 1998).

In this context, this study aims to unpack challenges and coping strategies by – i) characterizing the biophysical and other environments of water access and availability; ii) analyzing the institutional arrangements for water governance at local/community level; and iii) suggesting technologies and approaches to improve farm productivity and livelihoods. This study assessed the temporal and spatial variation in water availability at the selected areas in Karnali and Mohana basins of Nepal. By documenting the physical, social, economic, and institutional determinants supporting or constraining availability and access, this helped gain insights to plan approaches to alleviate the challenges.

2. Methodology

Figure 1 depicts the overall methodological approach adopted in this study. A combination of biophysical and social analysis, with primary and secondary data sources, were conducted. Sites were selected based on a set of selected indicators. The determinants of the access to water were identified based on literature review and relevancy to the study area. The determinants were quantified based on the data collected from primary and secondary sources. Daily rainfall and temperature were the secondary data used in this study. They were acquired from the Department of Hydrology and Meteorology (DHM), the Government of Nepal. In case of primary data, a combination of participatory approach (e.g., focus group discussion, FGD, and key informant interview, KII), field observation, guided transect walk, and household surveys were carried out. The FGD included a set of open-ended questions that aimed to capture perceptions of people on various aspects of the determinants that affect the access to water.

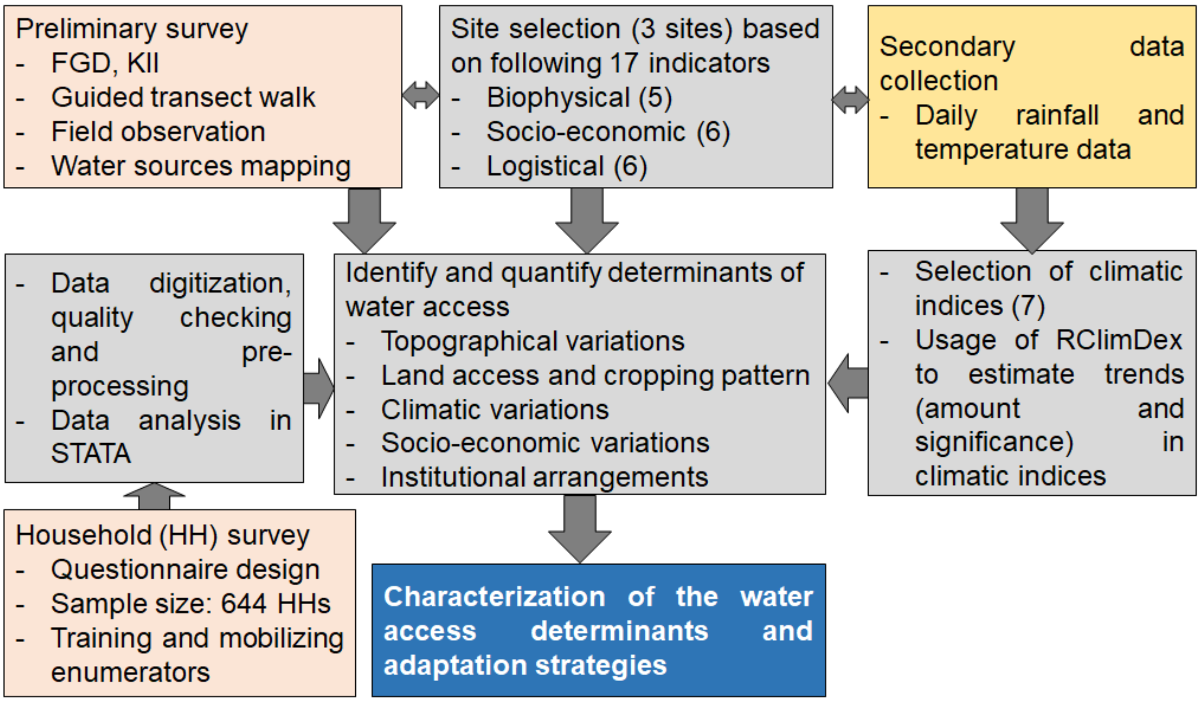


Figure 1: Methodological framework adopted in this study.

2.1 Site selection

Three sites/villages from the Karnali and Mohana river basins were selected to represent various diversities in the basin, such as ecological, socio-economic, and topographical, among others. The sites were identified based on analysis of 17 indicators related to biophysical (five indicators), socio-economic (six indicators), and logistical (six indicators). The indicators also included aspects like landholding and composition of social groups, especially ethnic and disadvantaged groups, as well. The indicator values for the purpose of site selection were collected through a set of participatory techniques such as FGD and KII. In addition, field observation and a guided transect walk was also conducted. After careful analysis, following three sites/villages were identified/selected as the study area: Kuti village in Kailali district, and Punebata and Mellekh villages in Doti district (Fig. 2).

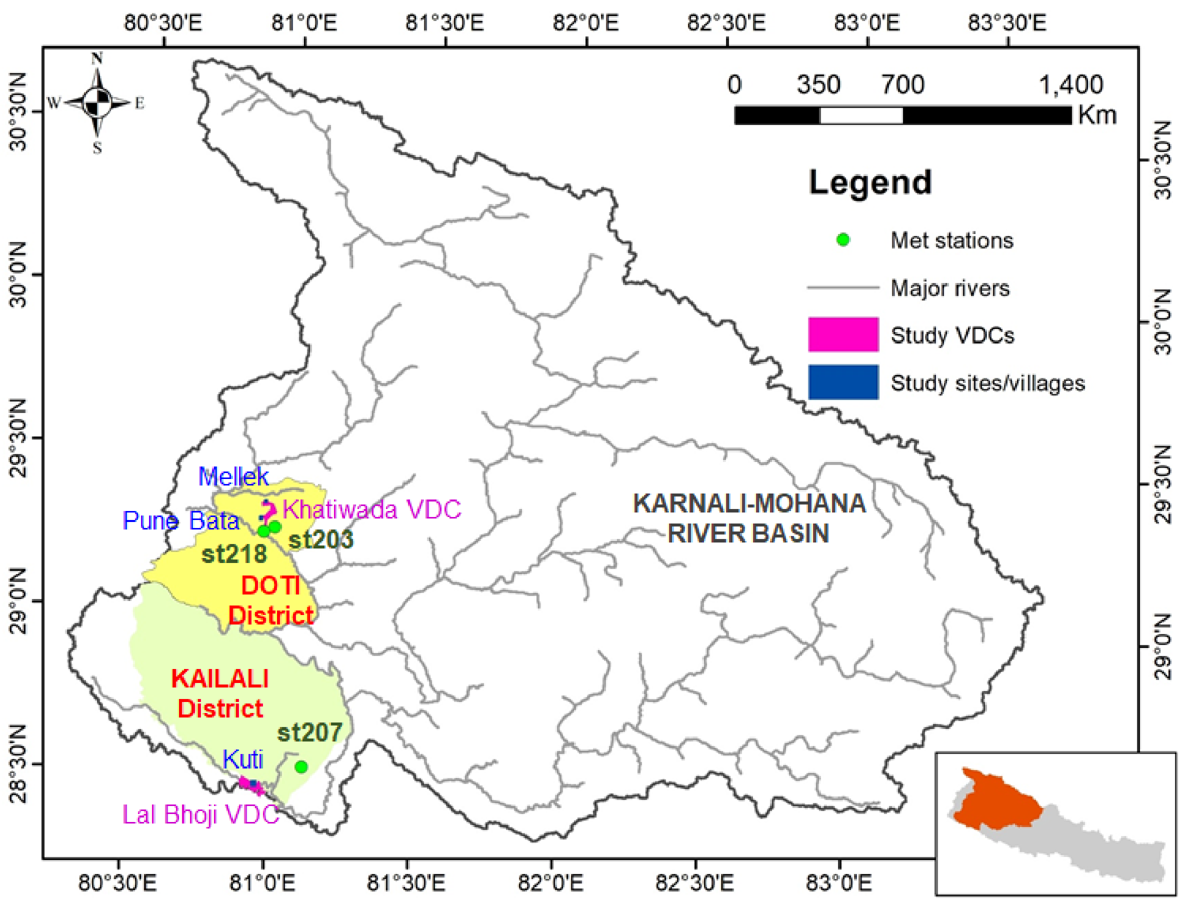


Figure 2. Locations of study villages in Karnali and Mohana basins, Nepal.

2.2 Identification of water access determinants

A literature review as well as field visit was conducted to identify the determinants that affect water access across the study sites. After critical review and in consideration of the study sites, following determinants were identified as relevant for this study. The determinants as well as their logical links to water access are shown in the Table 1.

Table 1: Determinants that makes differential access to water in the study areas.

Determinants	Indicator	Logical link to water access
Topographical variations	Elevation range (masl), derived from digital elevation model (DEM)	Water at lower elevations are rather readily available from ground or surface sources compared to high elevation hill slopes. Therefore, water access is likely to be better in lower elevation (e.g., Tarai)
Land access and cropping pattern	Access to land; Cropping intensity and patterns	Water-intensive cropping patterns are likely to impact water availability to others. (people/area/future time)
Climatic variations	Various (7 nos.) indicators related to temperature and precipitation (please refer Table 3 for the list and	More precipitation is likely to enhance water availability, which, depending upon other conditions, may help enhance access to water. Higher temperature may result more water loss due to evapotranspiration and therefore may adversely affect access as well as demand

	description of indicators)	Shift/variation in temperature and precipitation have impact on vegetation patterns, which affects agricultural production in Nepal.
Socio-economic variations	Demographics, gender, age, migration/mobility; and cast groups	Higher cast groups and/or those with better economic conditions (either by remittance or other sources of income) are likely to have better access to water
Institutional arrangements	Participation, water allocation, decision-making and collective action	Existing practices for water allocation and decision-making mechanism constitute institutional arrangements for water management and thereby influence access to water

2.3 Field surveys

Community level data were collected through a series of field surveys using a combination of participatory techniques and field observations. At the beginning, the research team conducted a participatory resource mapping, wellbeing ranking and wealth ranking with men and women separately to identify water resources, settlements, distribution of *khet land*[1] and households. Crop calendar exercise was conducted in each study village to get an overview of cropping patterns and engagement in farm labour. Two separate FGDs were also held in each village with men and women to get an overview of land ownership trends, migration, livestock and current water use and management. FGD participants represented heterogeneity of the village. The FGDs also attempted to get an understanding of the success and failures of past water management interventions in the study villages. Concurrently, a guided transect walk was conducted to identify available water sources in each village. In a later visit, a FGD was conducted in each village to specifically understand the current practices on land tenancy, water use and collective action to inform potential approaches and adaptation strategies.

A household survey was carried out with all 644 households (HHs) in each study village. Out of 644 HHs, 220 were from Kuti, 179 from Punebata and 245 from Mellekh villages. Household survey was conducted by experienced enumerators using a set of pre-tested questionnaire.

2.4 Data analysis

The survey data were digitized and stored in MS Excel and STATA for further quality checking and pre-processing. Data quality was assessed, usable data were screened, and then used for further analysis. Then the status on key aspects of the study villages were described based on descriptive statistics. The collected data was analysed using STATA, a statistical analysis software. Climatic data (temperature and rainfall) were collected from secondary sources. Daily data from three representative stations located nearby the three sites (Table 2), owned and administered by DHM, were used for climatic trend analysis. The stations represent three physiographical regions of Nepal, namely, Mountain, Hill, and Tarai. The data were collected, assessed for quality, and pre-processed before using for further analysis. The quality was assessed based on length of the historical data, percentage of missing data, and existence of outliers. The characteristics of the stations are shown in Table 2.

[1] *Khet land* refers to irrigated flat land.

Table 2. Representative climate stations used for the climatic trend analysis.

District	DHM stations		Data length	Location		Altitude (masl)
	Index	Name		Lat.	Lon.	
Doti	203	Silgadi	1980-2015	29.267	80.983	1360
	218	Dipayal	1980-2015	29.252	80.946	617
Kailali	207	Tikapur	1980-2015	28.533	81.117	140

Three indicators related to precipitation and four related to temperature (Table 3) were selected from the list of 27 climate indices prescribed by the Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI). The thresholds adopted here were 45°C and 20 °C for the upper and lower daily maximum temperatures; 20 °C and -20 °C for the upper and lower daily minimum temperatures; and 20 mm for daily precipitation. RClimDex (Zhang and Yang, 2004) was used for analyzing trends in the selected climate indices. Eventhough the input data were in daily time setps, the indices were calculated either on a monthly or annual time setp depending on their type. Furthermore, people's perception were also evaluated.

Table 3. Climate indices considered for the trend analysis (Source: Adapted from Zhang and Yang, 2004)

ID	Index name	Description	Units
PRCPTOT	Annual total precipitation	Annual total precipitation in wet days when daily rainfall >= 1 mm	mm
CWD	Consecutive wet days	Maximum number of consecutive days with daily rainfall >= 1 mm	days
CDD	Consecutive dry days	Maximum number of consecutive days with daily rainfall < 1 mm	days
TXx	Maximum of Tmax	Monthly maximum value of daily maximum temperatures	ºC
TNx	Maximum of Tmin	Monthly maximum value of daily minimum temperatures	ºC
TXn	Minimum of Tmax	Monthly minimum value of daily maximum temperatures	ºC
TNn	Minimum of Tmin	Monthly minimum value of daily minimum temperatures	ºC

3. Status of water access

Water availability and access varied considerably across the study villages. In terms of sources of irrigation, it varies from stream/spring as primary source in hill/mountain to groundwater in Tarai villages (Table 4). In Mellekh, the hilly village, 84.5% of the irrigation requirement is covered by river/stream where as in Kuti, the Tarai village, 93.2% of the irrigation requirement covered by groundwater. In Punebata, another hilly village, surface pond is also an important source of irrigation given the abundancy and proximity to the *khet* lands.

Table 4. Sources of irrigation in study villages (% area coverage).

Villages	River/stream	Springs	Groundwater	Pond	Others
Mellekh	84.5	3.6	0.0	0.0	11.9
Punebata	63.7	2.9	0.0	26.9	6.5
Kuti	3.4	0.6	93.2	0.0	2.8

Even though most of the land (88.7%) had some level of access to irrigation, it is limited to monsoon/early winter only. In hill/mountain villages, water availability declines in stream/springs. In Tarai village, access to groundwater is constrained by energy cost/availability and fragmented land size. Tubewell and pump ownership is very low in

Tarai village indicating the dependency on rental market. Only 29.1% households have tubewells installed in their fields, out of which 76.6% are shallow tube wells.

In Mellekh, there are several spring sources surrounding the village which are used for domestic and livestock requirements. However, the rough terrain and fragmented farm land limits access to irrigation facilities. Agriculture is primarily rainfed since the village lacks pumps and irrigation canals. Irrigation ponds built by development agencies are either unused or require extensive repair while one hamlet has a small canal sourced from a spring via a pond. The community manages the canal informally and farmers agree to share water turn-by-turn. Irrigation in dry season preceding the monsoon in June is particularly difficult due to reduced flow in the springs and often leads to conflicts within the community.

In Punebata, there are also several natural water sources used for domestic and agricultural requirements. The topographical variation and fragmented farm land in Punebata adds to the burden of managing irrigation. *Naulas* (springs), protected and unprotected, are rarely developed due to low flows and financial limitations. A large pond serves as the primary irrigation source in several hamlets and water is distributed on a rotational basis. The community manages water allocation and besides minor conflicts on the timing, the farmers largely follow the arrangement. Secondary storage tanks and pipe networks also provide water for domestic, animal and irrigation uses. Several concrete and plastic lined ponds and smaller streams distributed around the village also provide water via interconnected pipes or canals for private as well as communal use. Given the variety of irrigation sources available throughout the village, conflicts around water access are largely related to distribution timing. The large pond, once built under a development project, requires significant repair work and proper maintenance. The lack of formal body to oversee such work affects the efficiency of the system, leads to more conflicts, and ultimately limits the potential to increase productivity.

In Kuti, households access groundwater via deep bore wells for drinking purpose. Besides concerns regarding Arsenic contamination, the community is largely water sufficient all the year round. Shallow tubewells, powered via electricity or diesel, are common in some agricultural fields. Men are largely responsible for operating pumps and there is a high prevalence of pump rental, either individually or communally. Two rivers adjoining the village and groundwater are the main sources for irrigation providing abundant water for irrigation. Despite the water availability, constrains in accessing irrigation facilities limit the potential for intensive farming. The limited number of tubewells installed by landlords/farmers are unable to meet the demand during peak season. Farmers are also discouraged by the high costs of fuel and pumps. Women find it difficult to rent pumps since they are usually excluded from the negotiation process and have limited knowledge of prices and operation of pumps. There are instances of Indian farmers leasing land to grow wheat in Kuti and have been quite successful due to their use of large irrigation pumps and agricultural inputs.

It is necessary to mention that Punebata and Mellekh are located in the region with high penetration of local water infrastructure development projects putting the onus on the next incoming agency to either repair or build new taps/ponds. Frequent but short-term projects in both villages and a lack of ownership from the community have resulted in subsequent failure of some projects. The high structural failure and poor user group associated with the existing irrigation infrastructures support the opinion that sustainable management of natural resource common goods must be supported by a functional community participation (Coward 1984, Oad and King 1991).

4. Determinants of water access

4.1 Topographical variation

The status of water access is determined by topographical diversitym which indicates level of proximity to the water sources. The Karnali-Mohana River basin has a distinct variation in topography with elevation varying from 69 masl to 7,726 masl, ecology, climate, culture, and access to physical infrastructure. In this context, three villages at different physiographic zones, Mellekh (Mountain), Punebata (Hill), and Kuti (Tarai) were considered for evaluating the water access situation.

Mellekh lies in a rugged mountain terrain with elevations ranging from 1,265 to 1,980 masl. It extends horizontally over Sayal Rural Municipality (former Khatiwada village development committee, VDC) and vertically down till the river as shown in Fig. 1. As discussed in previous section, only few spring sources exist in Mellekh village, which is not sufficient for both drinking and irrigation purpose. Water for domestic/household purpose is brought from a source located outside the village at a distance of about 5 km upstream. Sources within the village are getting drying and insufficient for agriculture use. Despite the construction of overflow recharge ponds, the access to water for agriculture use is poor in terms of quantity. The unfavorable terrain and poor infrastructure further hinders water access.

Punebata lies on an elevation range of 640 – 1,190 masl in Dipayal-Silgadi Municipality (former Khatiwada VDC) as in Fig. 1. The village has mild slope terrain with several springs located in northern part as well as at the centre of village. Several springs and ponds are well maintained to provide water for domestic and agriculture use. Ponds owned privately are mostly concrete and provide sufficient water. Communal ponds are poorly maintained and unable to meet the demand, especially during dry season. Public sources are mainly located in the northern part of the village and require pipe or canals to transport water to the agricultural fields, adding to the overall cost and thereby limiting access. Given the topographical variation, activities aimed at enhancing water yield from the catchment such as landscape management through bioengineering, and activities aimed at reducing demand such as water efficient irrigation techniques may help to improve water access and then enhance agricultural productivity in the village.

Kuti lies in the lower region in Bhajani Municipality in the Tarai district, Kailali. The village is situated on the floodplains of Mohana and Kandra rivers with elevations between 145-155 masl. Due to the flat terrain and close proximity to Mohana and Kandra rivers, the village is prone to flooding during the monsoon, followed by two-months of waterlogging after the monsoon. The lack of a bridge severely limits the access to the village, especially during monsoon and post monsoon period. Major deterring factors for water access for agricultural purposes in the area are limited number of pumps and tubewells and high cost associated with rental and physical infrastructure. In this context, environment-friendly irrigation systems driven by electric or solar could be the viable option for a long-run.

4.2 Land access and cropping pattern

4.2.1 Access to land

Land ownership and tenure characteristics also affect access to water as fragmented land makes it difficult to invest in irrigation facilities. Household survey revealed that overall about 12.1% HHs are landless, with the highest proportion in Kuti (Table 5). There is a wide range of variation in terms of land holdings in the study villages. The average landholding is 0.47 ha, slightly more in Kuti compared to other two villages while average cultivable land is slightly less, 0.44 ha. Large number of HHs have holdings below average, whereas few HHs have significantly larger sized land parcels.

Land tenancy is common in all the sites ranging from *batiya* to *thekka* to *tamsuk*[2]. Overall, about 15.2% of households rented-in land for cultivation whereas 14.8% households rented-out land to others (Table 5). Large proportion of tenant farmers was found in Punebata village whereas large size of rented in/out was in Kuti village. Overall, average rented-in land size was 0.31 ha whereas average rented-out land size was 0.49 ha. Land holdings varied significantly across the hamlets within all three villages.

Table 5. Land ownership, landholding size and land tenure characteristics in study villages.

Villages Parameters	Mellekh	Punebata	Kuti	Overall
HH with land (%)	86.90	91.60	85.90	87.90
HH without land (%)	13.10	8.40	14.10	12.10
Average land owned (ha)	0.40	0.40	0.60	0.47
Average cultivable land (ha)	0.38	0.34	0.60	0.44
HH who rent-in land (%)	7.80	29.60	11.80	15.20
HH who rent-out land (%)	4.10	23.50	19.50	14.80
Average land rented-in (ha)	0.24	0.17	0.53	0.31
Average land rented-out (ha)	0.42	0.25	0.80	0.49

Given the high altitude and topography, land in Mellekh is dry and fits mostly for wheat and millet. Agricultural land most suitable for paddy cultivation is located downhill from the settlements. Leasing land is fairly common, and sharecropping was the most common form of land tenancy in this village, though other forms also exist. Given the wide geographical distribution of land significant portion of land are left abandoned or fallow. Many farmers have land fragmented throughout the village making investing in irrigation difficult and expensive. Lack of labour, limited irrigation facilities, and short cropping season due to high altitude further limits the agricultural production.

The land characteristics in Punebata are similar to Mellekh in term of fragmented farm land spread across the village. The presence of ponds and canals in Punebata do provide better access to water for most households in comparison to Mellekh. Households with absent male members prioritize fertile land with available water access for paddy cultivation. *Parma*, a system of a mutually beneficial labor sharing, is practiced during paddy cropping and harvesting season.

In Kuti, growing population, river flooding and sand deposition, landlessness are the major constraints in accessing land for agriculture. There is a high variation in land size given the

[2] *Batiya* is sharecropping. *Thekka* is commonly used when the landowners require emergency cash. The owner receives a fixed amount set based on the size and quality of land. This agreement usually lasts for 1-3 years or longer depending on when the owner is able to give the initial amount back to the tenant. *Thekka* is similar to *maat* but in this arrangement there is a fixed time limit of a year. In case the landlord is unable to pay back the initial amount back to the tenant then the land is transferred to the tenant.

traditional land ownership structures. There are instances of HHs from the Far-Western hilly region who have recently settled in this village and have claimed public land for agricultural use informal ownership rights. This has resulted in increased demand for irrigation water. Several HHs, including Dalit families, have access to land but lack formal title despite paying taxes. Plots are frequently bought and sold without formal paperwork and indicating a sense of actual ownership. Land tenancy is common in Kuti and farmers practice three types of tenancy agreements ranging from *batiya* to *thekka* to *tamsuk*. Sharecropping is the most common type of tenancy and the sharecroppers typically lack invest in irrigation equipment. Most sharecroppers are landless and lack financial capacity to invest in water technology or even determine crop choices.

4.2.2 Cropping patterns

Cropping pattern varied across the study villages given the diverse topography, climate and land availability. In Mellekh, farmers practice two-crop system. During monsoon paddy is planted in *khet* land while maize, barley and soybeans are grown in *pakho* land. During winter, wheat is grown in khet land while mustard is planted alongside it. Lentils are also grown during winter season. Farmers have not changed their cropping patterns and they follow the same pattern regardless of any weather changes. Different vegetables, particularly tomato and potato, are commonly grown in the village. A few privately owned greenhouses were noted in the village; in which vegetables such as tomatoes, onions, cauliflower and eggplants are grown. The owners of the greenhouses were found to use the piped water from the community domestic water systems for irrigation, a practice that is not approved but is not restricted either. Such practice demands more water but access is limited.

In Punebata, paddy and wheat are grown during summer and winter seasons, respectively. Farmers have been growing vegetables for decades and almost every HH sells vegetables in the local markets of Dipayal and Pipalla. One common phenomenon is the shift to water-intensive cropping pattern, which will demand more water, but access is limited or what is constraining to access required amount of water. Although the land in Punebata is highly fertile there is low productivity due to water insufficiency.

Similar to other parts of Western Tarai, farmers in Kuti also plant two crops a year, paddy and wheat. Paddy is planted in the monsoon season whereas wheat is planted in the winter season, alongside mustard and pulses. Given the higher winter rainfall in Kailali district, wheat is irrigated by rainwater. However, irrigation is required during both wheat and paddy season given frequent dry spells. Given the lack of labour in the village, farmers limit cultivation to the “high-fertility” areas, with areas with less fertile soil and insufficient water being left fallow. On the other hand, water-intensive cropping pattern, such as vegetables in dry seasons, in some parts of the village face constrained water access.

4.3 Climatic variations

Seasonal fluctuation of water availability depends on the fluctuation of temperature, precipitation, and evapotranspiration, which finally governs the access to water for the different water uses. In this context, trend on precipitation and temperature were analyzed to understand the implication on agricultural production. Shift/variation in temperature and precipitation have significant impact on vegetation patterns (Anyamba, 2014), which significantly affects agricultural production in Nepal (Malla, 2008).

A summary of the estimated trends in precipitation indices (PRCPTOT, CWD, and CDD) is presented in Table 6. The total annual precipitation (PRCPTOT) in all the three station shows a decreasing trend, albeit statistically insignificant at 95% level of confidence. Similarly, the consecutive wet days (CWD) and consecutive dry days (CDD) are insignificantly increasing at all the three stations. It reflects increase in duration of no-rain period as well opportunity for constructing water storage infrastructures to store water during wet season and use for dry season to enhance access to water. In terms of topography, amount of rise in CDD is increasing from mountain terrain (Mellekh) to hill (Punebata) and Tarai (Kuti). Increasing CWD and CDD in hills imply for the increased occurrence of floods and droughts. In case of Mountain, total annual precipitation has been found slightly decreasing in trend with the number of consecutive wet, dry days are increasing, implying the increased occurrence of both flood, and droughts. In case of Tarai, total annual precipitation is slightly decreasing with the number of CWD is decreasing, whereas the number of CDD is increasing, implying that it is getting dryer with risk of drought. This implies less access to water in dry season both in terms of total water received and timing of water application may alter. This may lead to possible crop damages due to dry spell.

Table 6. Trends in precipitation and temperature indices at meteorological stations nearby the study sites.

Indices	St203 (Mellekh)		St218 (Punebata)		St207 (Kuti)	
	Trend	p-value	Trend	p-value	Trend	p-value
PRCPTOT	-2.25	0.59	-7.14	0.09	-3.35	0.57
CWD	0.08	0.19	0.03	0.56	0.00	0.94
CDD	0.04	0.93	0.91	0.06	0.77	0.08
TXx	0.08	0.11	0.05	0.08	0.00	0.93
TNx	0.04	0.28	0.02	0.46	0.00	0.96
TXn	0.09	0.20	0.07	0.11	-0.05	0.25
TNn	0.04	0.28	0.01	0.46	-0.02	0.52

In terms of temperature, four temperature indices (TXx, TNx, TXn, TNn) were analyzed as summarized in Table 6. The monthly maximum of daily maximum temperatures (TXx) and the monthly maximum of daily minimum temperatures (TNx) are slightly increasing at all three stations, but the increase is statistically insignificant at 95% level of confidence. Similarly, monthly minimum of daily maximum temperatures (TXn) and monthly minimum of daily minimum temperatures (TNn) are also insignificantly increasing trend in two stations (Hill and Mountain). These results indicate that Hill and Mountain are getting hotter. In case of Tarai, the maximum of both maximum and minimum are increasing whereas the minimum of both maximum and minimum temperature are decreasing in trend. These values indicate that the variability range of both maximum and minimum temperature are widening. Across all the three sites, temperature is increasing in summer, which ultimately affect the access to water for agricultural use. Farmer has perceived that, the changes in precipitation (i.e. erratic rainfall) and changes in temperature also shifted the cultivation time of crop, which significantly reduces the production. Those anomalies on climatic variable and effect on crop production can be addressed through introduction of new agro-technology, climate resilient better seeds, better crop management practice, and use of fertilizer. In addition to analyzing trends in climatic data, the variations/changes/shifts perceived in spatial and temporal water availability was analyzed based on perception survey and results are presented in Table 7. Out of the three study sites/villages, Mellekh has experienced progression of land erosion, flash floods and reduced rainfall events. Despite these noted developments, the respondents generally agreed that rainfall reduction has not been severe enough to meet categorization as drought, except in 2015. Changes in rainfall patterns (shifts in rainfall dates and higher rainfall intensities) however are the major concerns. The respondents also highlighted the warming temperatures in the village. They note that years past the village received snow but this has not occurred within the last 4 years.

Table 7. Perceptions on spatial and temporal variations in water availability

Key issues	Mellekh	Punebata	Kuti
Climate Shocks	Progression of land erosion, flash floods and reduced rainfall events.	Landslide events resulted in displacement of several households	Floods have become a more common and intense occurrence
Precipitation Variability	Shifts in rainfall dates and higher rainfall intensities. No snow in the last 4 years.	Variability of start and end dates of rains with increased intensity. No significant reduction in rainfall	Prone to flooding during monsoon and waterlogging for two to three months after the monsoon
Temperature Variability	Warming temperatures in the village	Warming temperatures in the village	Warming temperatures in the village
River Bank Erosion	-	-	Kandra river channel has undergone severe bank erosion due to deforestation.

The community members in Punebata informed that there has been no significant reduction in rainfall within the last 5-10 years. In the recent past (2015), there was a once off drought. Despite this, they have experienced a continued increase in the variability of start and end dates of rains as well as increased intensity. This has led to a few instances of flooding (2000 and 2008) and increased erosion. Due to the high rainfall intensities, the community has experiences landslides periodically (major events occurred in 1984, 1993 and 2000). The landslide events resulted in displacement of several households. In case of Kuti, due to the flat terrain of the village and its location between Mohana and Kandra Rivers, it is prone to flooding during the monsoon and waterlogging for two to three months after the monsoon. This is a normal occurrence, which has been getting extreme in the recent past. In recent years' floods (from Mohana and Kandra rivers) have become a more common and intense occurrence with Kuti being cut off from rest of the districts for several weeks. Flooding normally lasts for one month with about 40% crop destruction depending on when the flood occurs. The Kandra river channel has undergone severe bank erosion due to deforestation. An embankment constructed along the Kandra River in 2013 through a government program has helped reduce the extent of flooding but some low-lying *khet* land still gets flooded. The village also experiences the double impact of both too much and too little water with some fields experiencing water logging especially in the monsoon and post-monsoon periods.

All three study villages experience either too much or too little water affecting their overall agricultural production. People in Mellekh reported high water insufficiency in both monsoon and winter seasons (Fig. 3). Result showed diverse range of water sufficiency in Punebata due to imbalance in accessing water from ponds. In overall, Kuti is water sufficient all year round. Farmers, especially in Mellekh, have reported high water insufficiency in both monsoon and winter seasons. Farmers in Punebata have access to three canals yet farmers experience a range of diversity in terms of water sufficiency. This can perhaps be explained by the imbalance in accessing water by farmers who rely on ponds located in private land.

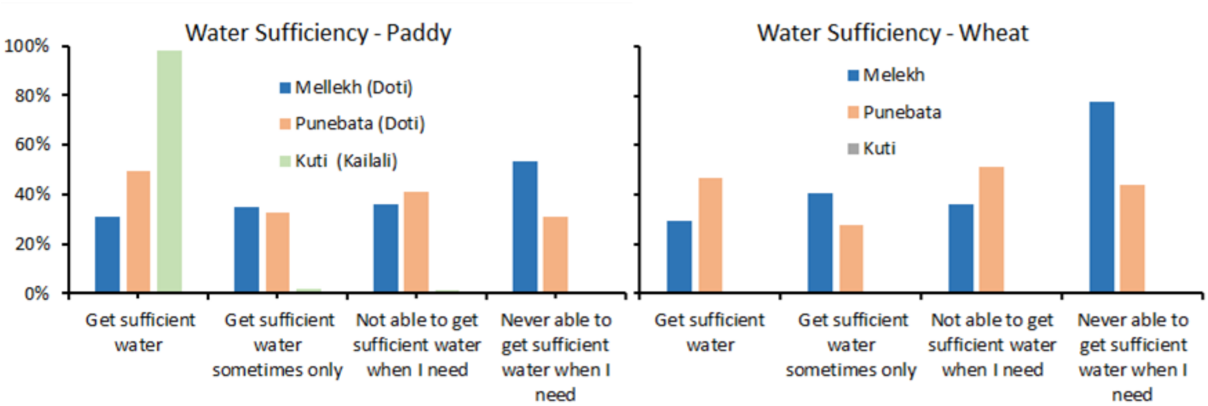


Figure 3. Water sufficiency situation in study villages

4.4 Socio-economic status and implication to water access

Composition of socio-economic characteristics have differential effect on access to water. Three study villages included a total of 644 HHs, the number varied across the villages (Table 8). Total population of three villages is 3,888 with slightly more percentages of male population than female. Number of HHs and population varied across the study villages. A large proportion of population included below 18 years' age group in all three villages.

Table 8. Overview of study villages

District	Municipality/Rural municipality	Village	No of HH	Population	Male %	Female %
Doti	Syayal	Mellekh	245	1440	51.3	48.8
Doti	Dipayal Silgadi	Punebata	179	1103	50.0	50.0
Kailali	Bhajani	Kuti	220	1345	50.6	49.4
Total			644	3888	50.7	49.3

In terms of ethnic composition, majority of HHs in Mellekh are Chettri, followed by Dalits and Brahmins. Dalit HHs are clustered in the North-Western part of the village which is also farthest away from the water sources. Hamlets have access to their respective community forests. In Punebata, most of the HHs comprise of Chettri and Dalit castes. The community manages the forests while the committee members manage issues related forest access for fodder and firewood. Kuti has five hamlets spread across the village. The indigenous Raji community makes up the majority of the HHs, followed by the Danguara Tharus who migrated from Dalit and indigenous Chaudhary community in Dang district. Some of them have migrated from neighboring hilly districts after the government's malaria eradication program in the 1960s. This has also contributed to the clearance of forested land for households and *khet* land. The community has access to three community-managed forests surrounding the village.

Agriculture is the major occupation with 29% engaged in agriculture in both Mellekh and Kuti and 31% in Punebata. A fairly large percentage of young men and women currently enrolled in school or colleges. Migration is prominent phenomenon in all study villages though the destination and nature varied. Migration in general has resulted in labor shortage and feminization of agriculture. All three villages have high out-migration with at least one migrant from each HH in Punebata and Mellekh. In Kuti, migration is endemic with most men aged 16-55 migrating seasonally to India for jobs. About 40% of the migrants, mainly men, are seasonal who go to India and return during the peak agriculture seasons.

Farmers in all three sites are primarily dependent on subsistence agriculture. Given the climate variability, farmers and limited irrigation facilities, many farmers opt to migrate, either seasonally or temporarily, to diversify their livelihoods. Seasonal migration to India is common with 1% in Mellekh, and 7.4 % Kuti, respectively. Kuti is located at the border, which allows for easy access to the market in India. Many men travel to India for seasonal labour, returning during cropping season each year to support the family. Women from Kuti also travel to the neighboring Indian villages in search of work and return home at the end of the day. All three villages have a high rate of male out-migration, beyond India to other countries such as Malaysia, Qatar and others in the Gulf region. The numbers are particularly high in the hilly village with 26% in Mellekh and 28.6 % in Punebata. Kuti is low in terms of foreign employment at only 5.3%. Men who travel beyond India tend to return after a few years, owing to higher travel costs. In Mellekh the rate of male out-migration is relatively less compared to the other two villages.

The out-migration of young male members has had a depressing impact on the intensity of agricultural cultivation. Women are responsible for managing agricultural land which is often fragmented and scattered throughout the village. With a shortage of labour within the family, women have an additional burden to manage farming activities. Farming is limited to the 'high-fertility' areas while the less fertile land and/or land without irrigation facility is left fallow.

Out-migration pressure has resulted in lack of labor for agricultural activities with women, children and older men being the main labor pool for farming. Migration is a trend unlikely to change but empowering the women and those who have stayed back to invest in technical solutions that reduce the drudgery of farm work and/or reduce the amount of work will make agriculture easier and more productive. It is imperative to ensure suggested technologies are user friendly to ensure easy uptake by women farmers as well. Promoting and implementing water efficient irrigation methods and practices and improving on-farm water management would also help lower the pumping requirements, consequently improving the water productivity and hence the profit margins of the farmers.

4.5 Institutional arrangements: Participation in water allocation process

The existing practices for water allocation and decision-making mechanism constitute institutional arrangements for water management and thereby influence access to water. For example, social norms and practices for water allocation decision-making also matters to water access. Water allocation for drinking and irrigation is usually conducted through the formation of water user groups. The group ensures funds are collected for future repair and maintenance work and also provide a space for farmers to meet and share success and failures during monthly meetings. The funds for repair are collected when required and the lack of ownership proves difficult to solicit funding from all users. Community members tend to blame children for damaging taps but do not take responsibility for their own inaction in fixing the issue. During such events farmers rely on springs and even rivers to meet their domestic and agriculture water needs. This adds to the workload of women who are primarily responsible for collecting water. The primary goal of reducing the time and drudgery associated with procuring water by constructing communal taps remains largely unmet due to the lack of ownership from the community itself. On the other hand, there are issues related to participating in groups meetings itself. Household survey revealed that men make up the majority of participants in groups related to natural resources management (Fig. 4).

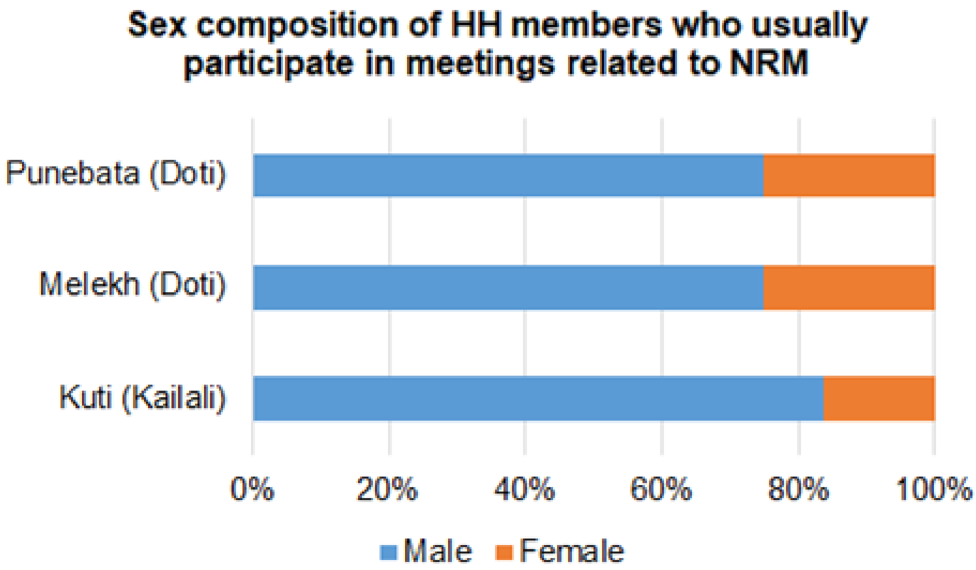


Figure 4. Participation of household (HH) members in natural resources management group meetings

In Punebata and Mellekh, participation of women in communal meetings is increasing, whereas in Kuti the overall participation is quite low. Participation can be an issue for women due to constraints ranging from household and childcare responsibilities, unsuitable timing of meetings and even lack of interest. In many meetings men tend to make decisions given the technical aspect of irrigation schemes involving construction and machine usage. In such instances women may find it intimidating to contribute their opinions due to their lack of technical knowledge. Households with only female members tend to depend on other male members or neighboring households for information sharing regarding water allocation, pump rental pricing and others. In overall, the institutional development, for water management, was inadequate. As a result of poor local institutions the level of collective action was low.

5. Coping/Adaptation strategies

Droughts, untimely rain, and floods are most common shocks dealt by farmers in all three villages (Fig. 5). Heavy reliance on rainwater at both sites in Doti leaves the farmers vulnerable during climatic shocks and untimely rainfall.

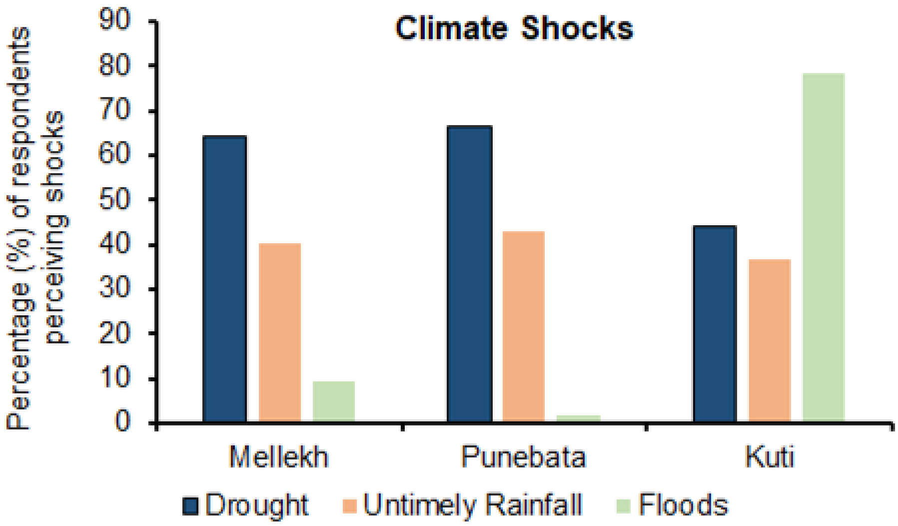


Figure 5. Occurrence of major climate shocks in the study villages in last five years.

Drought is common in all three study villages (Fig. 5), with Punebta and Mellekh experiencing moderate to severe affect. Mellekh experiences the highest income loss due to drought followed by Punebata and Kuti. The Far-Western region experiences winter drought which severely hampers wheat production. In response to the drought, majority of farmers have done nothing to change their farming techniques in all three sites. Farmers in Mellekh reported to leaving land fallow while farmers in Kuti either borrowed money or reduced overall food consumption (Fig. 6).

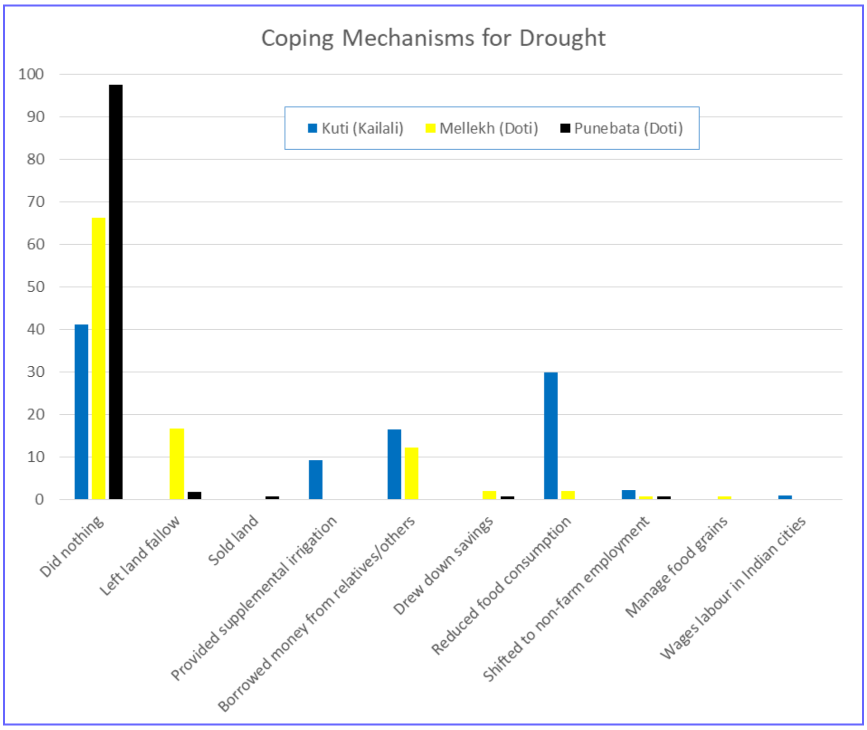


Figure 6. Coping mechanisms employed in response to drought.

In case of untimely rainfall, almost half of the respondents in all the three study villages reported untimely rainfall (Fig. 5) with a general consensus of moderate to severe affects on their agriculture production. Almost all farmers in Mellekh and Punebata reported a loss in income due to the untimely rainfall. However, similar to the drought situation, majority farmers reported to doing nothing in response to the untimely rainfall in all three sites (Fig. 7). Reducing food consumption and providing supplemental irrigation was used as a strategy in Kuti whereas farmers in Mellkeh left land fallow or borrowed money in response.

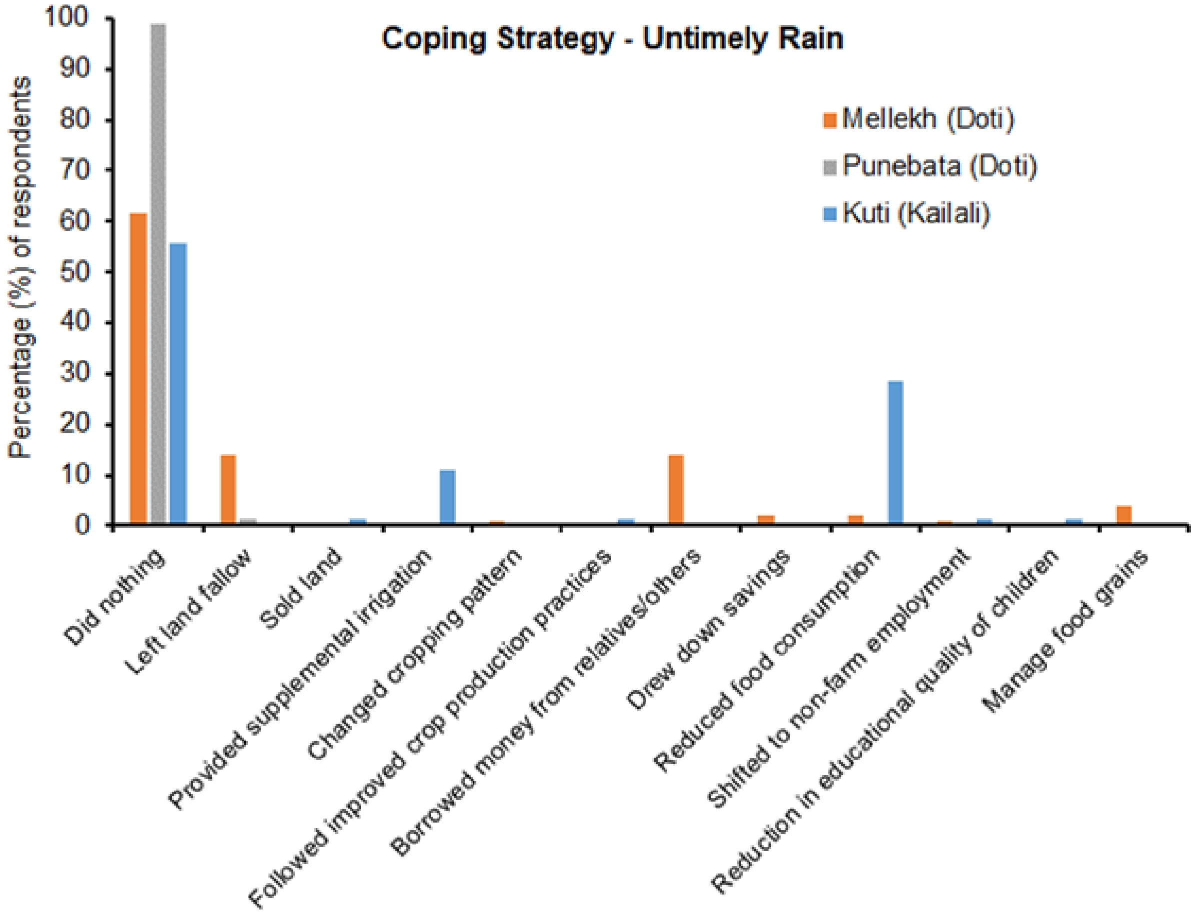


Figure 7. Coping strategies in response to untimely rainfall.

In regard to floods, it has been the most frequent and most devastating climatic shock in Kuti (Fig. 5). Every year the farmers are affected by floods from both Kandra and Mohana rivers. Farmers reported a mostly severe flood situation in Kuti resulting in a significant damage to income source. Given the frequency of floods, the community maintains an informal arrangement with the upstream community to provide information during monsoon seasons to prepare for any flood events. Punebata and Mellekh are not affected by floods due to their topographical location. Farmers in all three sites responded to doing nothing in the event of floods (Fig. 8). Leaving land fallow, borrowing money and outmigration to cities were some of the methods employed in response. It is interesting to note that migration to cities abroad was not a coping strategy employed in response to any of the abovementioned climatic shocks. This can be explained since male members of the family have been migrating for several years, especially to India, that it is not considered as a coping mechanism. Rather it is the only job opportunity available to the young men residing in the villages. A decreased interest of youth in agriculture coupled by the uncertaininty in agriculture has already forced a generation of young men to countries such as India and in the Gulf region.

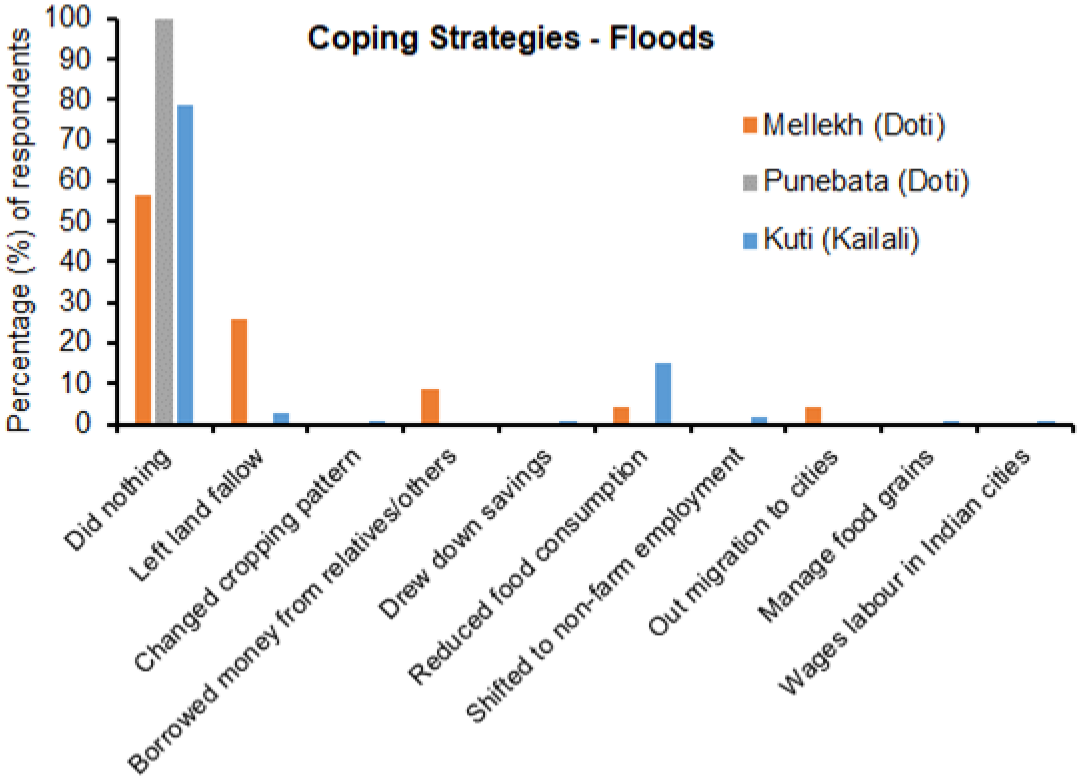


Figure 8. Coping strategies in response to floods.

Despite the knowledge of recurring floods, farmers have not changed their farming strategies. In Kuti, a number of HHs reported to have not planted crops during monsoon season but more than half of the farmers continue to plant paddy. Crop plantation in winter suffers the most in Kuti most probably due to the heavy sand deposits during monsoon floods. In the case of Kuti, the khets are rendered unfit for agriculture in spite of regular water supply. At both sites in Doti, canal and rainwater are the main irrigation sources for wheat. However, water availability decreases during pre monsoon dry months which hampers overall production. Farmers in Mellekh reported the highest water insufficiency but overall the farming strategy has remained unchanged. Farmers still plant using traditonal methods and restrict irrigaiton techniques to basin, flooding, and furrowing. Use of drip and sprinklers are negligent or non-exisitent in all three sites. Use of drip irrigaiton is restricted to Punebata where previous development projects have provided drip kits to farmers gorwing vegetables at a subsidized rate or for free for demonstration purpose. The longetivity of the drip method is cut short once the damanged pipes are unable to be replaced. In addition, there is a general understanding amongst farmers that crops will benefit the most from flooding the khet with water.

In terms of adaption strategy, very few farmers reported to getting any form of support in the aftermath of a climatic shock or stress. Among those who seeked support, none of the farmers reported receiving any immediate support from the government. Farmers received some immedaite support from the local level government in the form of cash, food. Community organizations also provided support in the form of cash and advice. Relatives and sometimes informal groups within the village also provide key support during such events.

Further to the aforementioned strategies, after careful analysis of the socio-economic and bio-physical assessment of the three study sites, the Digo Jal Bikas (DJB) project has designed a set of interventions as strategy to improve access to water. They are already implemented in the three sites and currently under monitoring stage for their evaluation. They key features of the intervention strategies and expected impacts for enhancing access to water are outlined in Table 9.

Table 9: Intervention strategies to enhance water access

Village	Problem	Intervention	Solution
Mellekh	Low water availability during dry season	Collective Farming approach, on farm water management solution (micro irrigation, improved seeds)	Source protection and pond rehabilitation with improved irrigation facilities
Punebata	Low water availability during dry season Source unavailable for use.	Collective Farming approach, on farm water management solution (micro irrigation, improved seeds)	Source protection or effective utilization of available water using improved tools and techniques
Kuti	Flooding	Sunflower pump with tubewell installation, collective vegetable farming, training, improved seed distribution	Embankment and artificial cutoff (long term) Increased water access in dry season (immediate solution)

6. Conclusions and policy implications

Although water is available all the year round in all three sites, there is variability depending on the season. Farmers are heavily dependent on rainwater in both villages in Doti, followed by streams and rivers. The summer monsoon is somewhat sufficient in meeting irrigation needs for paddy cultivation but the winter crop needs remain largely unmet. In addition, untimely rainfall and climatic shocks such as droughts add to the water availability. Crop plantation in winter, therefore, suffers due to the unavailability of water. Farmers face difficulties procuring water during the dry pre monsoon months as public taps tend to decrease in flow or dry up. Naulas, the most common alternative source in Mellekh during the dry months also experience a decrease in water flow. During these months the waiting time at *naulas* can extend to about 15 to 37 minutes. The case is similar in Punebata where ponds and rivers are the preferred alternative source during dry months. In Kuti, farmers rely mostly on groundwater followed by rainwater but floods in the monsoon season are the biggest perpetrators affecting both agriculture as well as livelihoods. Groundwater extraction in Kuti could provide constant supply of water throughout the year, but the access is constrained by factors such as land ownership/fragmentation and low investment capacity.

The spatial distribution and access to spring sources in mountains/hills (Mellekh and Punebata villages) shows the high need for water storage and distribution infrastructure that should be aimed at not just making water available where and when needed but that provides for equitable distribution to most areas. The aim should be to push towards not just supporting water management in areas with water sources but also areas with limited water sources. This calls for integrated spring source protection and development, water storage and distribution infrastructures and efficient water management practices.

In all three study villages (i.e., Mellekh, Punebata and Kuti), concerted efforts towards on-farm water management strategies to improve resilience of the domestic and agricultural water needs against the limited sources in necessary. Both traditional and modern soil and water management technologies and practices are to be implemented and/or supported. Implementing practices and infrastructure to promote spatially distributed springshed water retention, infiltration improvement and soil cover to conserve soil moisture, among others is necessary. Building the capacity of the communities to use of physical land terrain for rainwater harvesting and flood control through recharge ponds in the mid hills shall be a key priority, especially in Mellekh and Punebata.

Watershed management to build up resilience of community water resources is crucial for the long-term sustainability of such initiatives. The intervention should aim to sensitize the communities to the impacts of the interventions through trainings and exposure demonstrations. These activities should aim at not only building capacity within the community but also to promote community ownership and improve engagement of all stakeholders to the natural resource developments through robust management structures as suitable for each location.

The reality of the integration of water across all life areas especially in such communities demands the need of addressing water access in the context of the holistic community development. This calls for the integration of agricultural water development into multiple use systems/infrastructures, especially to harness the strength of domestic water user structures, which are generally more developed and better managed.

The high slopes of the mountainous watersheds offer limited ability to slow down the high intensity torrential monsoon rains. Supporting local communities to construct small ponds and diversion terraces can effectively check the surface runoff and store water in the catchment areas thereby facilitating recharge potential. The structures need to be integrated within normal farming layouts, such as bunding of contour fields, are also quite effective in reducing soil erosion from the watersheds.

Beyond relying on short-term flow measurements and technical design procedures, the development of mountain gravity flow irrigation schemes require participation and input by the target beneficiaries. Engineers need to collect as much information as possible from the community on issues such as historical stream flows, existing canal layouts, and types and locations of water sources. Such historical information should guide the development of socially acceptable and robust systems.

To avail the long-term value of the piloted activities and interventions implemented such small-scale catchments the balancing of the enabling environment for these activities should aim at the intended long-term ideals of legislation, policies and institutional structures. As highlighted by Anderson et al (2008), stakeholder engagements and dialogue at all levels of technical and management structures is important. The engagements should extend from community discussions, designs and capacity development to policy level workshops and dialogues.

Results showed that despite poor economic and financial capability the communities are willing to pay for water and other natural resource management and development. However, achievement of this relies on the ability towards motivation of the community as a whole, where all beneficiaries develop a sense of ownership under equitable access and use. Further, prioritization of natural resource development should be adapted to the community's level of resource utilization; for example, developing irrigation infrastructure will not succeed where domestic water facilities are not satisfactory.

Some of the community in hill villages already show a good understanding of implementing multiple use system for high water capture and productivity, and exemplify the unity of purpose and productive gains from a water as a common-pool resource. Realizing the physical limits of water availability, the community's traditional informal management system would need support and strengthening to help solve conflicts that may arise with increased intensification of agricultural activities. Likewise, in case of Tarai village, the community faces constraints associated with pumping infrastructure and efficient irrigation systems for intensive irrigation. In such case, affordable water lifting technologies, especially employing sustainable pumping technologies such as solar power and axial flow pumps are highly desirable for this community. Promoting and implementing water efficient irrigation methods and practices and improving on-farm water management would also help lower the pumping requirements, consequently improving the water productivity and hence the profit margins of the farmers.

Acknowledgements: This study is made possible by the generous support of the American people through the United States Agency for International Development (USAID) under Digo Jal Bikas (DJB) projected. The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government

References

Anderson, Aileen, Eiman Karar, and Stefano Farolfi. 2008. "Synthesis: IWRM lessons for implementation." *Water SA* 34 (6): 665-669.

Anyamba A, Small JL, Britch SC, et al. Recent Weather Extremes and Impacts on Agricultural Production and Vector-Borne Disease Outbreak Patterns. Ikegami T, ed. *PLoS ONE*. 2014; 9(3): e92538.

Coward, E. W. 1984. *Improving policies and programs for the development of small-scale irrigation systems.* Water Management Synthesis Project Report 27, Ithaca, New York: Cornell University, 25-36.

DWRI/GoN (2018). National Irrigation Master Plan, Draft Main Report. Department of Water Resources and Irrigation (DWRI), Government of Nepal (GoN). Unpublished.

Karki, R, Hasson, S, Schickhoff, U. (2017). Rising precipitation extremes across Nepal. Climate 5(1): 4. doi:10.3390/cli5010004.

Malla, G. (2008). Climate change and its impact on Nepalese agriculture. J. Agric. Environ. 2008, 9, 62–71

Meinzen-Dick, R. and Zwarteveen, M. (1998). 'Gendered participation in water management: Issues and illustrations from water users 'associations in South Asia'. *Agriculture and Human Values*, 15(4), pp. 337-345.

MOAAC/WFP/FAO. (2009). 2008/09 Winter Drought in Nepal-Crop and Food Security Assessment Joint Technical Report; Ministry of Agriculture and Cooperatives

(MOAAC), Government of Nepal, World Food Programme (WFP), Food and Agriculture Organization of the United Nations (FAO): Kathmandu, Nepal.

Siddiqui, S., Bharati, L., Gurung, P., Maharjan, L.D., 2012. Climate Change and Vulnerability Mapping in Watersheds in Middle and High Mountains of Nepal. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Suhardiman, D.; Clement, F.; Bharati, L. 2015. Integrated water resources management in Nepal: Key stakeholders' perceptions and lessons learned. Int. J. Water Resour. Dev. 2015, 31, 284–300

Tamang, S.; Paudel, K.P.; Shrestha, K.K. 2014. Feminization of Agriculture and its Implications for Food Security in Rural Nepal. J. For. and Livelihood 12 (1). Pp.20-32.

Wang, S. Y., J. H. Yoon, R. R. Gillies, and C. Cho. 2013. *What caused the winter drought in Western Nepal during recent years?*, *J. Clim.*, **26**, 8241–8256, doi:10.1175/JCLI-D-12-00800.1.

WECS/GoN (2005). National Water Plan. Water and Energy Commission Secretariat (WECS), Government of Nepal (GoN). Retrieved from: http://www.moen.gov.np/pdf_files/national_water_plan.pdf

WECS/GoN (2011) Water resources of Nepal in the context of climate change. Water and Energy Commission Secretariat (WECS), Government of Nepal (GoN): Kathmandu.

Zhang, X., and Yang, F. (2004). RClimDex(1.0) user manual. Downsview: Climate Research Branch, Environment Canada.

Zwarteveen, M. Z., and Nita Neupane. 1996. 'Free-riders or victims: Women's nonparticipation in irrigation management in Nepal's Chhattis Mauja irrigation scheme'. Research Report 7. Colombo, Sri Lanka: International Irrigation Management Institute.

Annex 5-2

climate

MDPI

Article

Climate Shocks and Responses in Karnali-Mahakali Basins, Western Nepal

Vishnu Prasad Pandey [1,*], Akriti Sharma [1], Sanita Dhaubanjar [1], Luna Bharati [1] and Indu Raj Joshi [2]

[1] International Water Management Institute (IWMI), Nepal Office, Lalitpur 44600, Nepal
[2] Square One Research and Training, Lalitpur 44700, Nepal
* Correspondence: v.pandey@cgiar.org or vishnu.pandey@gmail.com

Received: 12 June 2019; Accepted: 11 July 2019; Published: 18 July 2019

check for updates

Abstract: The Himalayas are highly susceptible to the impacts of climate change, as it consequently increases the vulnerability of downstream communities, livelihoods and ecosystems. Western Nepal currently holds significant potential as multiple opportunities for water development within the country are underway. However, it is also identified as one of the most vulnerable regions to climate change, with both an increase in the occurrence of natural disasters and exacerbated severity and impacts levels. Regional climate model (RCM) projections indicate warmer weather with higher variability in rainfall for this region. This paper combines bio-physical and social approaches to further study and understand the current climate shocks and responses present in Western Nepal. Data was collected from 3660 households across 122 primary sampling units across the Karnali, Mahakali and Mohana River basins along with focus group discussions, which provided a rich understanding of the currently perceived climatic shocks and related events. Further analysis of climatology was carried out through nine indices of precipitation and temperature that were found to be relevant to the discussed climate shocks. Results show that 79% of households reported experiencing at least one type of climate shock in the five-year period and the most common occurrence was droughts, which is also supported by the climate data. Disaggregated results show that perception varies with the region and among the basins. Analysis of climatic trends further show that irregular weather is most common in the hill region, although average reported frequency of irregular weather is higher in the mountain. Further analysis into the severity and response to climatic shocks suggest an imminent need for better adaptation strategies. This study's results show that a vast majority of respondents lack proper access to knowledge and that successful adaptation strategies must be adapted to specific regions to meet communities' local needs.

Keywords: adaptation; climate change; climate shocks; Karnali; Mahakali; Western Nepal

1. Introduction

Responding to climate change and developing resiliency has become a global priority. Climate action, however, is very context specific. Therefore, case studies that highlight better characterization and understanding of climate change/variability, severity of stresses and impacts, and response mechanisms and their effectiveness at basin or sub-basin levels are very important. Such studies from the Himalayan regions are of further interest as the Himalayas are highly sensitive to climate change and variability [1]. In the Hindu Kush Himalayan (HKH) region, climate change will have varying implications for various sectors such as agriculture, energy and water resources, among others [2]. Regional climate model (RCM) projections suggest that the future climate in the Karnali and Mahakali basins in the HKH region will be warmer with higher variability in rainfall dominated by sporadic high intensity rains [3]. Under such future climate, these Himalayan rivers flowing through Western Nepal are projected to see changes in water availability and its spatio-temporal distribution [4,5]. Furthermore, access to clean water, which is a prerequisite for peoples' health, will be a challenge. Changes in water availability and its access will therefore greatly affect peoples' health as well as the agricultural sector, which contributes to 39% of Nepal's gross domestic product (GDP) and employs nearly 75% of the country's workforce [6]. Therefore, impacts of climate change on water and agriculture sectors will affect the national economy.

Western Nepal spreads over 50,000 km^2 of the headwaters of the Ganges basin in South Asia. Any impacts in the headwater will have implications in the downstream communities and ecosystems in the Ganges basin as well. Western Nepal has high potential for economic development. However, the region is also vulnerable to climate change [7]. Under projected changes in future climate, people and ecosystems are likely to suffer even more, with or without further development of the region. New studies are emerging to understand and quantify the threats of climate change [5,8,9]. However, the consideration of climate shocks, defined here as the events that outstrip the capacity of a society to cope with it, including events such as drought, floods, irregular weather, etc.; as defined in [8], is still missing. Understanding the occurrence of climatic shocks, the stresses and risks induced by the shocks, and suitable set of adaptation strategies across different locations are necessary for enhancing climate-resilience of large underdeveloped basins like Karnali and Mahakali (please refer Figure 1 for their locations).

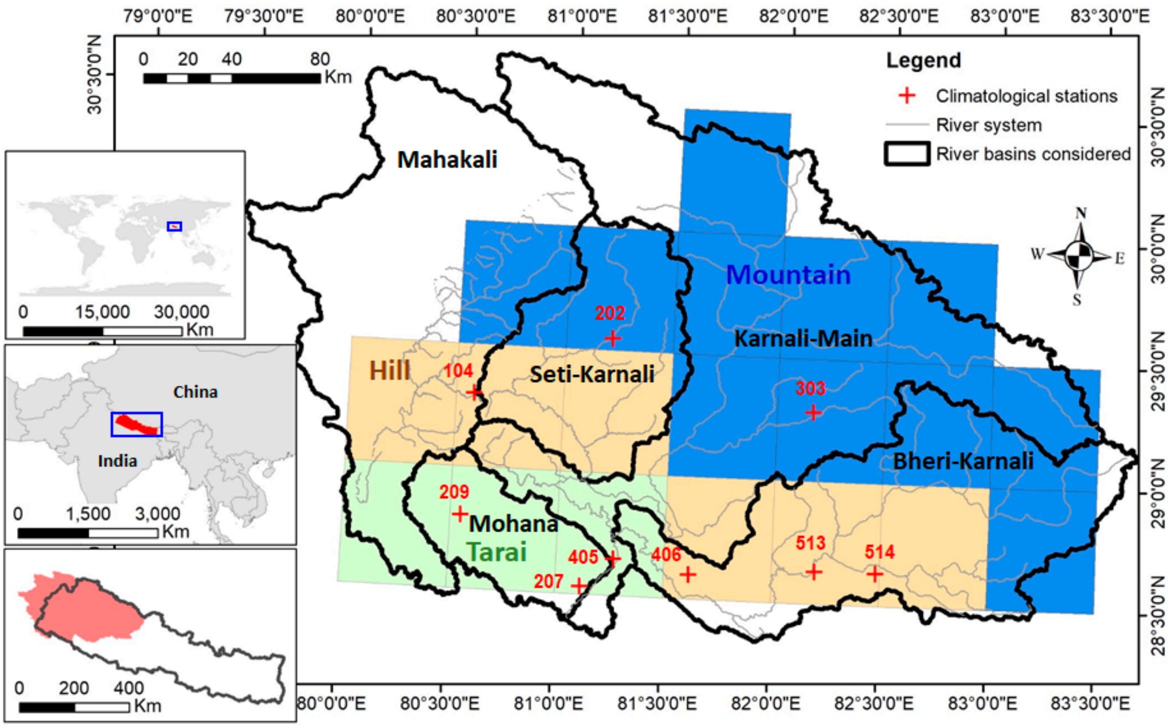


Figure 1. Location of study area in Western Nepal along with other relevant layers. Color squares are regional climate model (RCM) grid cells; blue indicating mountain grids, orange as hill, and green as Tarai grids for future climate projection.

Natural disasters such as flooding, droughts and untimely rains are natural weather events that communities have faced and dealt with for generations. However, over the past two decades, climate change/variability has accelerated the frequency, intensity and severity at which these natural disasters occur. Adaptation to climate change impacts is emerging as a key development agenda across the globe and in Nepal as well. The national adaptation plan of action (NAPA) and subsequent local adaptation plan of action (LAPA) are designed to provide a guiding framework for the mitigation and adaptation to climate change specific to Nepal [9]. However, there are missing links between the extent of climate change, level of impacts, and suitability of various adaptations strategies in the context of Nepal. Past studies narrowly focused on either a bio-physical approach (analysis of hydro-climatic data), or a social approach (analysis of perception of shocks based on social survey). This study aims to combine the two approaches, as was done in [10], and further elaborate with the aid of people's perception and traditional knowledge in the study area. We integrate data generated from both social and bio-physical studies to analyse different types of climate shocks, severity of stress and risks associated with the shocks, and evaluate response mechanism considering the case of Western Nepal. Such an inter-disciplinary approach is on rise in recent time recognizing the need to address the multitude of factors that define climate shocks and a community's adaptive capacity (e.g., [11–13]).

There is no universal response strategy and mechanism that works for all. Local response strategies and mechanism may vary across any basin depending upon frequency of stressors, awareness of community, and capacity (financial and technical) to recover from a shock. The strategies for coping with a climate shock can generally be categorized into structural, technical, management, socio-economic, and regulatory measures [9]. For example, when considering drought as the climate shock, potential structural measures could include construction of water storage reservoir and irrigation infrastructures [12]; whereas strategies geared towards developing drought-tolerant varies, such as promoting micro-irrigation, and changing crop patterns could be potential technical measures [14–16]. Similarly, economic measures against droughts are crop insurance, migration for supplementary income, and crop sharing [17,18]. In case of floods, the adaptation strategies could be the construction of dykes/weirs (structural measure); flood forecasting and construction of houses with a floodable ground floor (technical measure); building institutional capacity and improving institutional arrangements for flood response (management measure); insurances for damages to crops/property/lives (economic measures); and floodplain zoning and development of flood prevention standards (regulatory measures) [19–23]. Additionally, designing an appropriate set of strategies for any location should take peoples' perception of climate shocks and associated severity of the risks into account.

Some studies (e.g., [24–27] have highlighted potential adaptation options for Nepal. However, no studies explore the status of climate shocks and responses specifically for Karnali, Mahakali and Mohana basins in Western Nepal. More importantly, in order to design better strategies and create better policies, there is a need to understand the impacts of climate change/variability on people, the predicted worsening, local people's perception, and how they adapt. This study therefore aims to address the gap by answering the following four research questions: (i) What type of climate shocks have people perceived? (ii) What are observed climatological trends and their link to the perceived climate shocks? (iii) How severe are the risks of climate shocks that people have perceived? (iv) What are the existing response mechanisms to address the risks and how effective are they?

2. Materials and Methods

2.1. Study Area

The Karnali and Mahakali are the two largest basins located in Western Nepal (Figure 1). The Mahakali River descends from 3600 m at Kalapani in Nepal to 200 m as it enters the Tarai plains. The river flows through Uttaranchal in India, boarders between India and Nepal and continues to flow down India. Only 32.4% of the basin area falls within Nepalese territory. Two important tributaries of the Mahakali River in Nepal are Chamelia and Limpiyadhura rivers. The Karnali starts in the High Mountains at an altitude covering 5500 m up to 7726 m, with the headwater lying at about 230 km North from Chisapani (mainstream Karnali River length).

The Mohana River, lying in south of the Karnali Basin, descends from the Churia range, flows through the Tarai plain and meets with the Karnali River at the Nepal-India border. The watershed area of the Mohana delineated above the Nepal-India border is 3730.3 km^2. The combined basin area of Karnali-Mohana (KarMo) above the Nepal-India border is 49,889 km^2. About 6.9% of the KarMo basin lies in China. Major tributaries of the Karnali River are grouped in this study into Bheri-Karnali (comprising Thuli Bheri and Sani Bheri), Seti-Karnali (comprising West Seti and Budhi

Ganga) and Karnali-Main (comprising Mugu Karnali, Humla Karnali, and other remaining areas). Table 1 highlights the key bio-physical characteristics of Mahakali, Karnali and Mohana. Being largely snow-fed basins, they are also vulnerable to climate change impacts. These rivers see a short-term increase in water availability during the dry season followed by long bouts of dwindling water availability. Therefore, it is best that communities adopt locale specific adaptation strategies.

Table 1. Bio-physical characteristics of the three river basins in Western Nepal.

Characteristic	Karnali	Mohana	Mahakali
Originates in	Tibetan plateaus and high mountains	Nepalese Churia hills	High mountains
Basin area (delineated above Nepal-India border)	46,151 km^2	3730 km^2	17,371 km^2
Elevation range (elevation range as seen in ASTER GDEM V2 [28])	5500–7726 masl (upstream of Chisapani)	113–1928 masl	83–7378 masl
Location	Transboundary between China and Nepal (6.9% in China)	Nepal	Transboundary between India and Nepal (68% in India)
Stream network	Dendritic	Parallel	Dendritic
Glaciers and glacial lakes [29])	1361 glaciers over 1740 km^2 (127.81 km^3 of ice reserve) 907 glacial lakes over 37.67 km^2	-	87 glaciers over 143 km^2 (10.06 km^3 of ice reserve) 16 glacial lakes over 0.38 km^2
Hydropower projects in Nepalese territory	127 proposed projects ranging from 0.5–1000 Mega Watt (MW)	-	2 operational, 3 under-construction and 5 proposed projects ranging from 0.99–6720 MW

2.2. Methodology

The overall methodological flowchart adopted in assessing climate shocks and responses in the Karnali-Mahakali river basins are shown in Figure 2. It consists of identifying potential climate shocks in the study area through literature reviews, focus group discussions (FGDs) and key informant interviews (KIIs); designing and implementing questionnaire surveys for perception analysis; analysis of climate shocks and severity of risks; analysis of climatological trends and their links to the climate shocks; and evaluation of response mechanisms. The questionnaire used in basin-wide survey is available at http://djb.iwmi.org/outputs/. The methods used in this study are described in the following sub-sections.

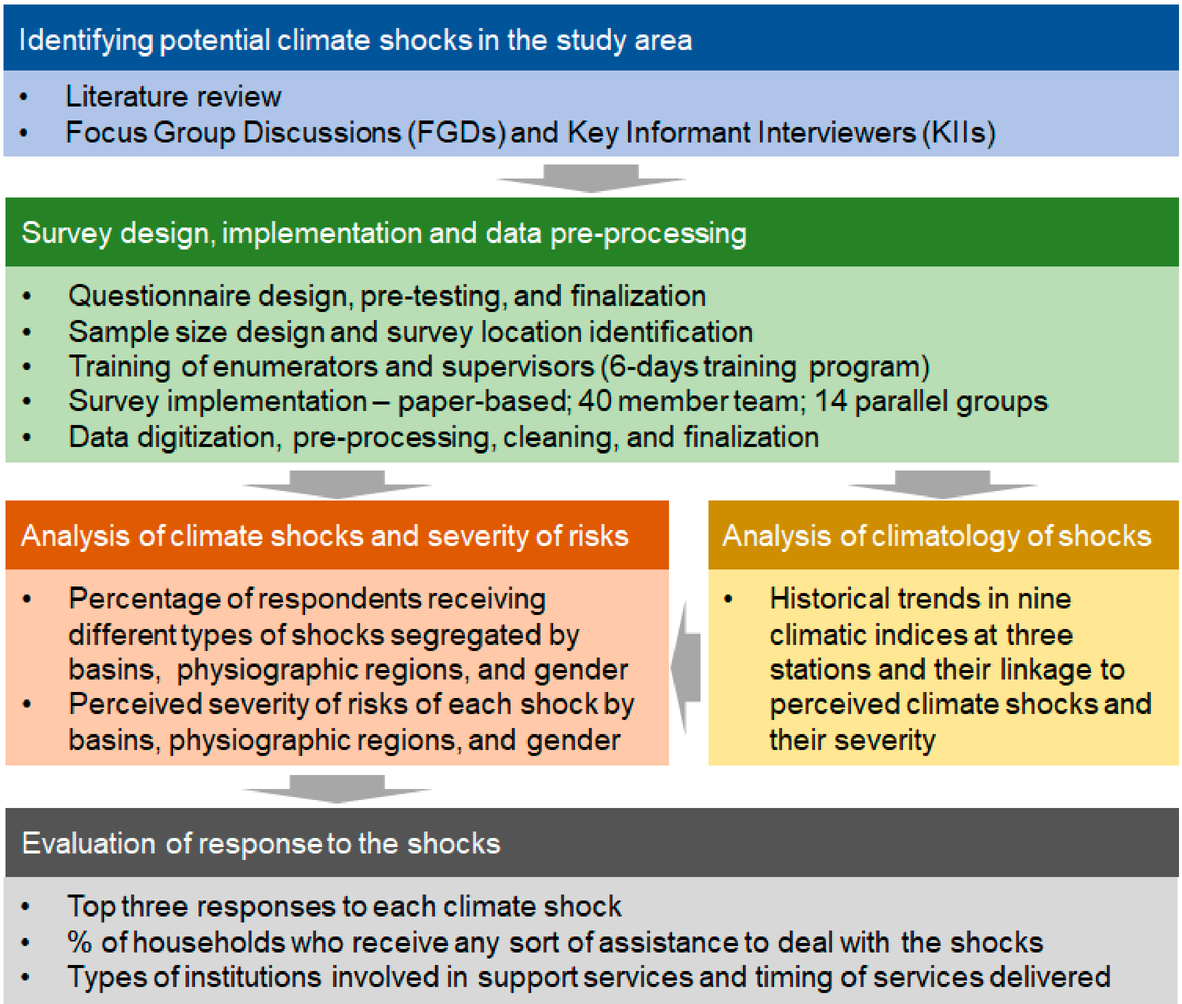


Figure 2. Methodological flow chart for assessing climate shocks and responses in Karnali-Mahakali basin.

2.2.1. Survey Design and Implementation

A structured questionnaire was designed utilizing prior experience of the authors (e.g., [13,15]) on designing a similar type of study. The draft questionnaire was further refined based on inputs from FGDs carried out in the region. The survey questions addressed various aspects of water and its uses, agriculture, climate shocks and responses, among others. The questions related to climate shocks and responses were included in Sections 13 and 14 of a larger basin-wide survey targeted at overall socio-economic characterization of water resource uses in the basins. These questions focused on perceived climate shocks, risks associated with the shocks, especially extreme events such as floods and droughts, and responses made to deal with the impacts.

The survey consists of a representative sample of 3660 households from 122 primary sampling units (PSUs), which are defined as wards that represent the lowest administrative unit in Nepal, applying multi-step sampling procedure. These PSUs were selected from 21 domains using probability proportional to size (PPS) sampling method, where size is measured based on the number of households. The domains were identified from five major river basins (i.e., Bheri-Karnali, Seti-Karnali, Main-Karnali, Mohana, and Mahakli), three ecological regions (i.e., mountain, hill and Tarai plains), and the presence/absence of hydropower projects. The disaggregation of the sample size across the 21 strata is summarized in Table A1.

From each PSU, 30 households were selected using systematic random sampling method. The sampling interval n depends on the number of households in a given PSU; that is, n = number of households/30. While selecting a random household, a landmark was identified and every *n*th household was selected for interview thereafter. Households were eligible for the sample if they were a permanent resident of the ward and if the chief wage earner or alternative knowledgeable house member was available and willing to participate. Respondents living in the ward for at least one year were considered permanent residents. If the sample household failed to meet the inclusion criterion or refused to participate, the next neighboring household was selected in its place.

The survey questionnaire, originally designed in English, was translated into Nepali for implementation. The survey was carried out during June–July 2017 through paper-based questionnaires simultaneously by 14 survey teams consisting of over 40 enumerators, supervisors and monitors trained by the Nepal Water Conservation Foundation (NWCF). A 6-day training period was conducted from 4–9 June 2017 for the enumerators and supervisors. No issues were reported during the survey. No refusal to participate cases were reported by the survey team. Supervisors coded and verified the collected data before entering into CSpro 5.0.

2.2.2. Analysis of Climate Shocks and Associated Risks

Eight climate shocks were identified as relevant to the region based on scoping studies and FGDs carried out by the research team across various locations in the study area. These eight climate shocks are therefore included in the questionnaire and are the following: droughts, untimely rains, irregular weather, hailstorm, floods, animal disease, serious pest damage to crops, and market shocks. Furthermore, an "other" category was also listed to allow for the identification of other climate shocks that people have perceived in the locality. Respondents were asked to answer the survey questions considering climate-related shocks they may have experienced in the last five years. Data gathered on perceived shocks was analysed in terms of type of shocks, quantified as percentage of respondents that have perceived specific type of shocks, and also discussed as frequency of occurrence of the shock as perceived by the respondents. The severity of the risks associated with the shocks were analysed in qualitative terms (i.e., low, medium, and high). Both frequency of shocks and severity of risks were disaggregated further by physiographic regions (i.e., mountain, hill, and Tarai), and river basins (i.e., Karnali-Main, Seti-Karnali, Bheri-Karnali, Mahakali, and Mohana) to understand the variation of perceived shocks across Western Nepal. Chi-squared test of independence was conducted to provide p-values to test statistical significance of the presented results. The p-value of $p < 0.005$ suggests the results to be significant (at 95% level of significance), while those with p-values of $p < 0.001$ (at 99.9% level of significance) suggest the results to be highly significant. The survey responses were analysed in STATA, a statistical analysis software.

2.2.3. Analysis of Climatology of Climate Shocks

Nine indices of precipitation and temperature relevant to the climate shocks considered here were identified from the comprehensive list of World Meteorological Organization (WMO) Commission for Climatology (CCl) expert team on Sector-specific Climate Indices (ET-SCI). Selected references are defined in Table 2. Literature review and expert opinion was used to subjectively relate the indices to five of the eight climate shocks considered here, namely: drought, irregular weather, floods, animal disease and serious pest damage to crops. The "untimely rain" is not considered as it cannot be sufficiently described by the climate change indices defined at annual scale here. Hailstorms are not considered as the formation of hails but are governed by the combination of thunderstorms, wind updrafts and freezing temperatures of clouds higher in the atmosphere. The ET-SCI indices only consider rainfall and surface temperatures, which are not sufficient to account for hailstorm conditions. Market shocks are also not directly related to the indices. Upholding the principal of parsimony, the 10 indicators were selected so that a minimum number of indicators relatable to multiple shocks may be considered.

The R-based ClimPACT2 tool developed by the ET-SCI was used to calculate the relevant indices at nine representative stations (shown in Figure 1) with good quality long-term data for 1980–2005 across Western Nepal. Two of the stations fall in the mountain region, four in the hill region and three in the Tarai region, the southern plains of Nepal, providing a basis for comparison of region-specific implications of the climate indices. Further discussion of selection of the nine stations for climate change analysis is provided in [30]. Quality of data at all nine stations were checked in ClimPACT2 and all identified outliers were reviewed prior to index calculation. Next, trends in the climatic indices were evaluated by calculating the Mann Kendall Trend (MKT) test [31,32] and Sen's slope statistics [31]. Further details on the implementation of the analysis is provided in [32].

Table 2. ET-SCI indices analyzed to understand trends in climate shocks in Western Nepal (Source: modified after [33]).

ET-SCI Index	Description	Related to
tmm	Mean annual daily temperature	Animal disease; serious pest damage to crops
tn90p	Annual percentage of days with warm nights (i.e., Tmin > 90th percentile)	Droughts; animal disease; serious pest damage to crops
r10mm	Annual number of days when precipitation ≥10 mm	Irregular weather; flood
wsdi	Annual number of days contributing to events where six or more consecutive days experience Tmax > 90th percentile	Droughts
r20mm	Annual number of days when precipitation ≥20 mm	Flood
cdd	Maximum annual number of consecutive dry days (when precipitation <1.0 mm)	Droughts; irregular weather
cwd	Maximum annual number of consecutive wet days (when precipitation ≥1.0 mm)	Flood; irregular weather
rx5day	Maximum annual five-day total precipitation	Flood; irregular weather
spei	Measure of "drought" using the standardised precipitation evapotranspiration index (SPEI) on time scales of 12 months	Droughts

3. Results

Figure 3 presents the coverage of the sampled households (HHs) in the survey. A total of 3660 HHs were surveyed across the Karnali, Mahakali and Mohana river basins. Respondents from the hill, mountain, and Tarai regions were 50%, 20%, and 30%, respectively. In terms of gender disaggregation, 71% of the respondents were male. The surveyed HHs have average population of seven persons/HH, with minimum of one (1) and maximum of 25. While the average HH size remains similar across all basins, results show that it is highest among the Dalit population, with a 7.5 average. Approximately 60% of the sample were either Brahmin or Chettri, followed by 20% of indigenous and 20% of Dalit and less than 1% of Muslim or other unidentified castes. The proportion of female-headed HHs were consistent across ethnicity stratification and ranged from 14% to 17%. Thirty-one percent of the population was between 0–14 years of age, 62% between 15–59 years while 8% were over 64 years. Details on perceived climate shocks, severity of risks, climatological analysis, and learnings from the responses are discussed in the following sub-sections.

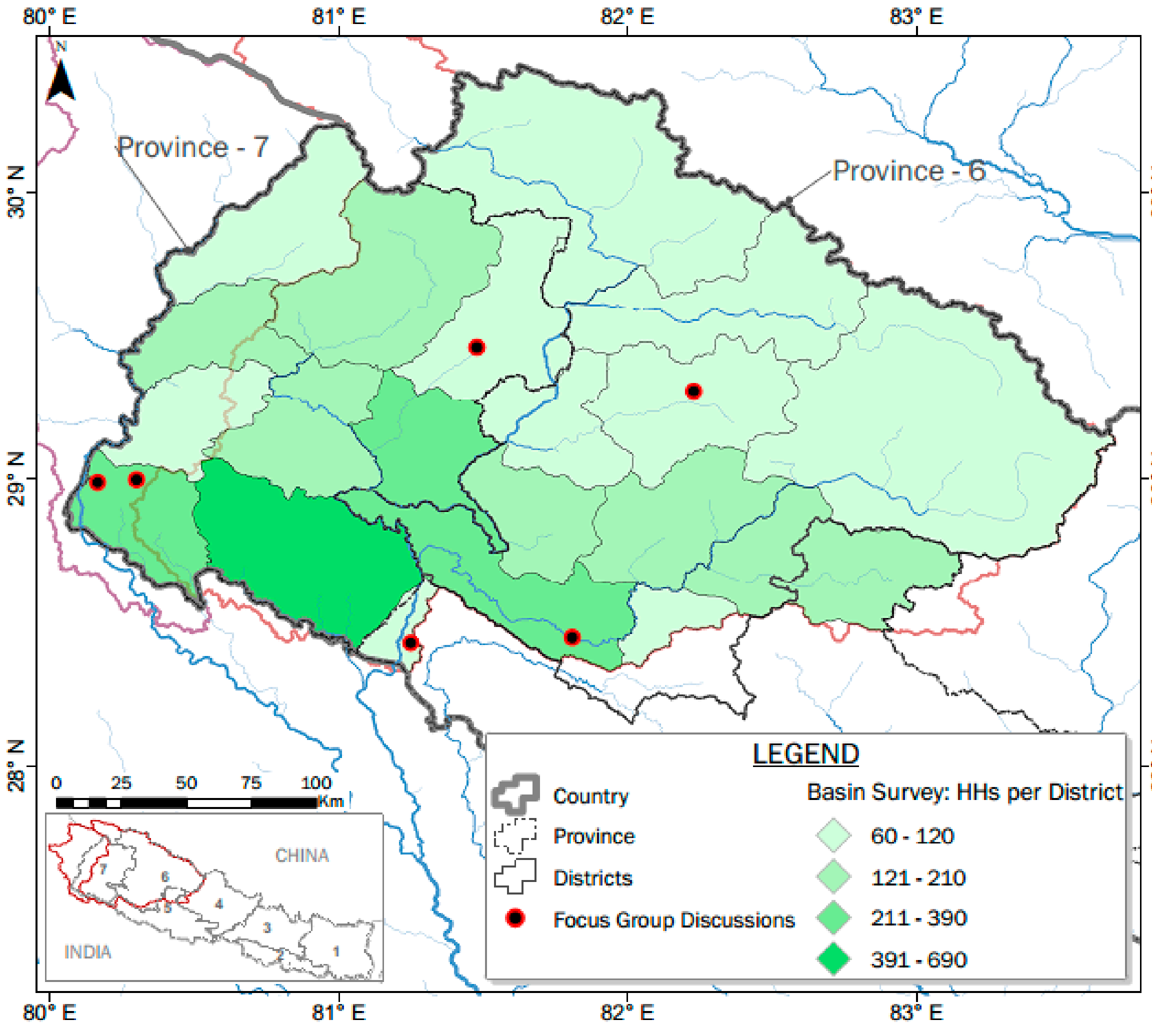


Figure 3. Spatial distribution of 3660 survey households across districts in Western Nepal based on stratification along 21 strata.

3.1. Perceived Climate Shocks

Figure 4 present the type of shocks perceived by HHs in the last five years across Western Nepal and disaggregated by the three eco-regions: mountain, hill and Tarai plains. Floods and droughts were identified as the two key climate risks that are affecting agriculture and livelihoods in the study region. The p-value based on Chi-squared statistic is also presented in the Table 3 as a measure of statistical significance as well as the goodness of fit of data, or the probability of the event occurring. Out of 3660 surveyed HHs across Western Nepal basin, 79% reported experiencing at least one type of climate shock. In an aggregate, 54% of the respondents have perceived drought, whereas hailstorm is experienced by 52%, untimely rain by 33%, and serious crop damage by some 24%. Though drought is the dominant shock at the scale of Western Nepal, it is not the dominant shock at the individual eco-region level.

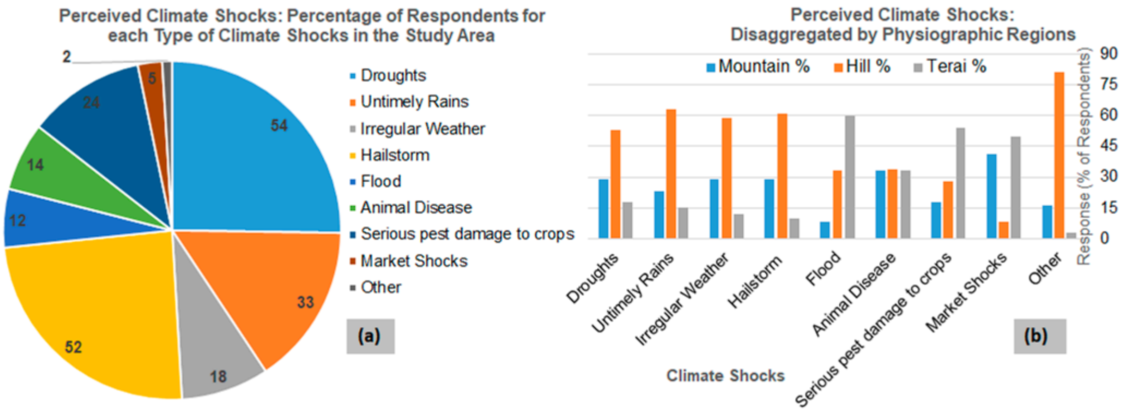


Figure 4. Percentage of respondents perceiving different types of shocks in the last five years—(**a**) across the entire Western Nepal; and (**b**) across the three ecological regions (i.e., mountain/hill/Tarai).

Table 3. Severity of the risks to shocks perceived by households in the Karnali-Mahakali Basins. The *p*-values are based on Chi-squared test.

Shocks	Severity of Risks	Basin						Total		*p*-Value
		Karnali		Mahakali		Mohana				
		n	%	n	%	n	%	n	%	
Drought	Low	332	24	40	12	41	17	413	21	0.00
	Medium	648	46	121	35	126	52	895	45	
	High	420	30	180	53	76	31	676	34	
Untimely rain	Low	260	30	15	6	16	17	291	24	0.00
	Medium	476	55	125	51	55	59	656	55	
	High	130	15	104	43	22	24	256	21	
Irregular weather	Low	180	42	18	9	17	38	215	32	0.00
	Medium	177	41	100	51	28	62	305	46	
	High	70	16	77	39	0	0	147	22	
Hailstorms	Low	449	30	53	17	14	14	516	27	0.00
	Medium	454	30	108	34	57	59	619	32	
	High	595	40	156	49	26	27	777	41	
Flood	Low	29	19	5	3	13	9	47	10	0.00
	Medium	48	32	53	35	65	44	166	37	
	High	73	49	94	62	71	48	238	53	
Animal disease	Low	59	17	12	18	18	23	89	18	0.63
	Medium	171	49	37	54	36	45	244	49	
	High	121	34	19	28	26	33	166	33	
Serious crop damage	Low	53	14	17	8	42	15	112	13	0.04
	Medium	244	63	145	65	159	56	548	61	
	High	90	23	60	27	82	29	232	26	
Market Shocks	Low	8	9	4	6	1	2	13	6	0.02
	Medium	54	59	29	40	17	41	100	49	
	High	29	32	39	54	23	56	91	45	

Disaggregated results show that perception varies with the region. A majority of respondents who had experienced most of the considered shocks came from the hill region (e.g., drought, untimely rain, irregular weather, hailstorm, etc.). Floods on the other hand, are the most common in Tarai. Due to the topography of the Tarai plains, the entire region is vulnerable to flooding and inundation.

Meanwhile market shock emerged as the dominant shock in the mountain region. The mountain region in Karnali is one of the poorest and remotest areas in Nepal with limited to no road access in many areas. Given the low income level in the region, accommodating to high fluctuations in market prices on top of the already high cost of air transport may be a high risk factor for mountain communities. However, it should be noted that the mountain region, comprising over 50% of Western Nepal, is not as densely covered by the surveyed sample as the Tarai which comprises about 15% (Figure 4).

Across the regional scale, the pre-dominant climate shocks were droughts (54%), hailstorms (52%), and untimely rains (33%) (Figure 4a). However, the results vary across the physiographic regions. For example, the climate shock pre-dominant in Tarai is the flood (60%) and followed by serious pest damage to crop (54%) and market shocks (50%) (Figure 4b). It is more likely for HHs in Tarai to have access to and own comparatively larger plots of land to undertake commercial farming. Agriculture in the hills and mountains, especially in Western Nepal are largely for subsistence farming, hence pest damage may not be as big of a concern. Additionally, tropical temperatures in the Tarai could also contribute to high amounts of pest infestation and damage. In case of the hill region, untimely rain is the pre-dominant climate shocks (63%) followed by hailstorm (61%), and irregular weather (59%) (Figure 4b); whereas for the Mountains, market shocks (41%), animal disease (33%), droughts (29%), hailstorm (29%), and irregular weather (29%) are the prevailing form of climate shocks (Figure 4b).

Survey results were also disaggregated by five sub-basins as shown in Figure 5. Among the five basins considered, respondents from the Karnali-Main, comprising largely of the mountain and hill regions, experienced hailstorms and droughts the most, while flooding (Figure 5a) was experienced the most in the Mahakali and Mohana basins. However, the dominance of specific shocks is not as persistent at basin scale as seen in regional scales with values lower than 40% reported for most shocks across the basins. Thirty percent and 17% of the respondents in Karnali-Main and Seti-Karnali basins have experienced droughts in the last five years, respectively. Drought, hailstorm, untimely rain and irregular weather were less prevalent in the Mohana basin compared to other basins. However, flood and serious pest damage to the crops are the most dominant in the Mohana, the basin originating in the mid-hills and most of the areas lying in southern plain of Nepal.

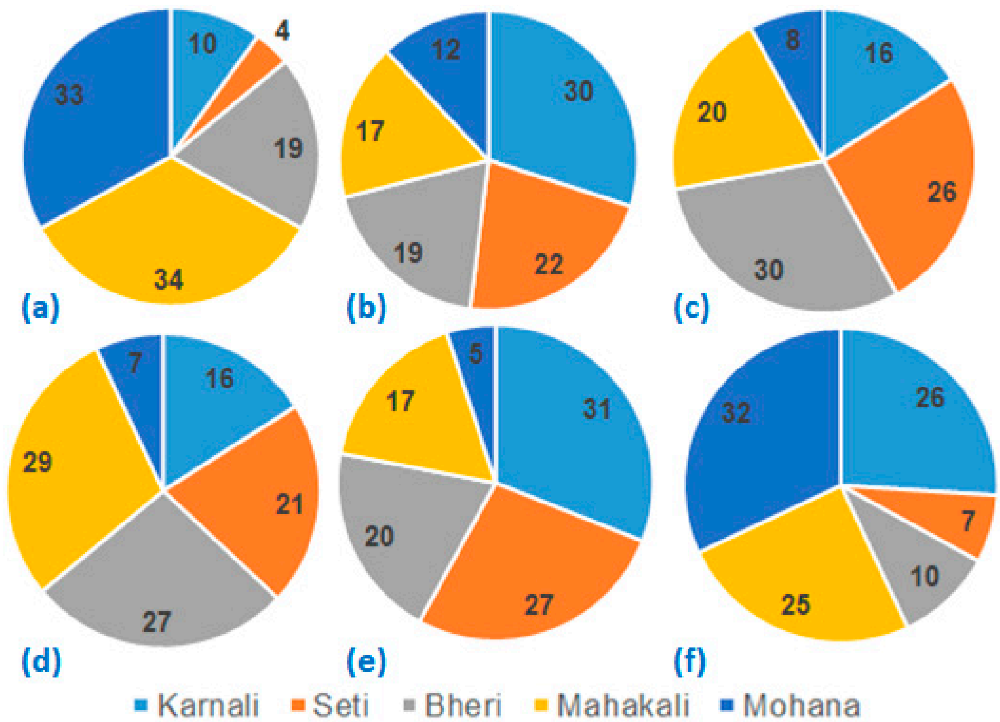


Figure 5. Percentage of respondents perceiving different types of shocks in the last five years disaggregated by sub-basins: (**a**) flood; (**b**) drought; (**c**) untimely rainfall; (**d**) irregular weather; (**e**) hailstorm; and (**f**) serious pest damage to crops.

In terms of frequency of climate shocks, as tabulated in Tables A2 and A3, floods were noted on an average of three times over the last five-year period, with some respondents saying they had experienced flooding events up to 65 times within the same time frame. Similarly, respondents noted that droughts occurred at least twice in the five years, with the maximum frequency reported at 36. Serious pest damage to crops followed closely at approximately three times over a five-year period. When observing this data through the regional and basin lenses it can be noted that both droughts and untimely rains were perceived to occur at similar frequencies across all three geographical regions. However, flooding was noticeably higher with the average frequency of flooding in the Tarai at 3.56 times in five years, while the hill respondents reported nearly 2.25 times. Across the sub basins we see that flooding was reported to occur most often in the Mohana and Seti-Karnali basins at 3.73 and 3.05 times, respectively.

Climate change/variability may lead to an increase in the occurrence of natural disasters like floods and droughts and exacerbates their risks and impacts. Climate extremes inducing climate shocks will continue to affect various sectors and communities. Survey results showed that HHs across the studied region have repeatedly perceived these shocks and felt their negative impacts even over the relatively short timeframe of the past five years.

3.2. Climatological Trends in Climate Shocks

Climatological trends at nine stations spread across three ecological regions and five basins were analysed based on selected climatic-indices and their linkage with perceived climatic shocks. Quality of time series data, both temperature and precipitation, were assessed using ClimPACT2. Nine ET-SCI indices summarized in Table 2 were identified as relevant to the shocks. Figure 1 shows the relative location of the nine stations while Figure 6 shows the trend values in terms of the *p*-value for the MKT and the Sen's slope. Tabulated values are provided as Table A4. The Sen's slope and MKT could not be evaluated for some stations due to gaps in the data. The stations spread over the three eco-regions provide a basis to compare the trends across the mountain, hill and Tarai stations. In Figure 6, nearly

80% of cases do not show statistical significance at 5% confidence level. The majority of the statistically significant p-values considering 5% confidence (or $p < 0.05$) appear in the mountain (two cases) and hill (eight cases) stations for the temperature parameters. Highly statistically significant trends with $p < 0.001$ are only reported six times. In Figure 6b, stations in the same regions are not always showing the consistent direction and magnitude for the Sen's slope.

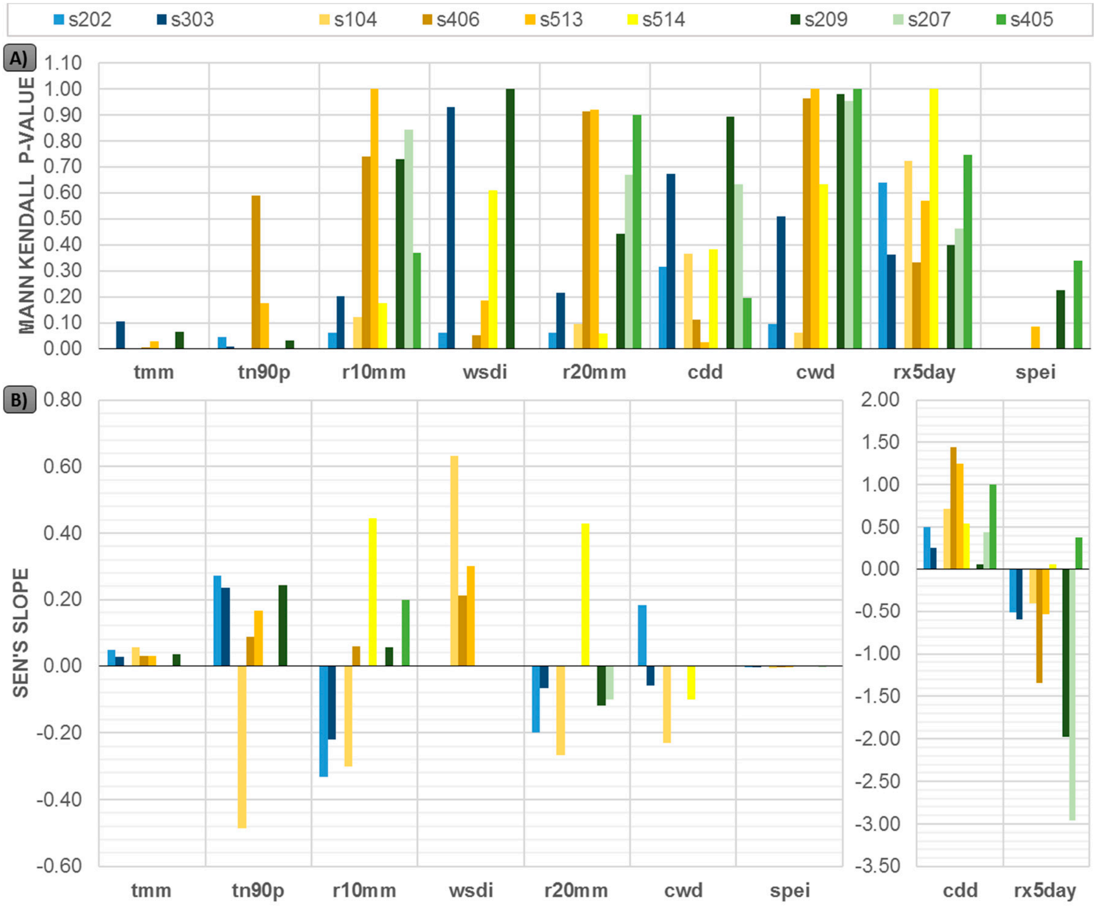


Figure 6. Historical (1980–2005) trends in nine selected ETCCDI indices across stations: two in mountain (blue), four in hill (yellow) and three in Tarai (green). (**A**) p-value for the Mann-Kendall test (**B**) Sen's slope value for each of the indices.

Six of the climate shocks considered here have been related to a subset of climate indices for the comparison of people's perception and historical data trends on climate extremes. Note that the trends are analysed for 1980–2005, whereas the survey conducted in 2017 represents the impression from the last five years; tentatively 2012–2017. Hence, people's perception and historic trends based on climate data may not match perfectly. Droughts were reported as the dominant shock which the majority of respondents experienced across Western Nepal.

Droughts represent conditions with extended periods of dryness with no rainfall and high temperatures. Thus, the temperature (*tn90p*, *wsdi*) and precipitation (*cdd*, *spei*) indices, indicative of such conditions, are related with drought here. The *tn90p* represents the percentage of days with high temperatures indicated by nights with minimum temperatures higher than the 90th percentile. The *wsdi* tracks the consecutive occurrence of days with maximum temperatures higher than the 90th percentile. Similarly, *cdd* represents occurrence of consecutive dry days with precipitation lower than 1 mm. *spei* is a standard measure of drought. The trend for *tn90p* indicated by Sen Slope in Figure 6b is positive across all stations except station 104 in the hills. For stations 202, 303 in the mountains, 194 in the hills and 209 in the Tarai, these positive trends are statistically significant. The trend in *wsdi* is highly positive for all hill stations, statistically significant for station 104 and zero for the rest. Similarly, *cdd* is highly positive across all stations and regions, with a statistically significant value in hill station 513. The *spei* values across all stations are near zero.

Irregular weather is related here to indices *r10mm*, *rx5day*, *cdd* and *cwd*. *r10mm* indicating number of days with rainfall exceeding 10 mm is selected to analyse deviation in occurrence of normal wet days. *rx5day* represents the quantity of the maximum annual five-day total rainfall, respectively. The *cwd* is similar to *cdd* but represents the occurrence of consecutive wet days. *Rx5day*, *cwd* and *cdd* are selected to capture the irregularities in weather pattern caused by extreme rainfall. *R10mm* has the positive trend for most of the hill and Tarai stations but a negative trend for mountain stations. *Rx5day* consistently shows an alarming negative slope across all stations, except stations 202 and 514 while *cdd* is consistently positive. The trend in *cwd* is not strong or consistent across the stations. As shown in Figure 4, irregular weather is perceived the most in the hills, with 59% respondents reporting it. However, the average frequency of irregular weather reported in the survey (Table A2) is the highest for the mountain. The four indices hint towards irregularity in terms of decline in rainfall. A tighter definition of irregular weather would help direct comparison of perceptions and climate data. Note however that trends in these four parameters are not statistically significant for all stations except for hill station 513 for *cdd*.

3.3. Perceived Severity of Risk from the Climate Shocks

Further information on the severity of risks to the shocks was gathered from the HHs that experienced shocks. In order to know the severity of the climate-induced shocks, respondents were asked to classify the impacts as either low, medium, or high. Severity is defined low if no major harm was done to the household, medium if manageable damage occurred and high if loss of land or life threating events occurred. Results disaggregated by basins are shown in Table 3 and with ecological regions are presented in Figure 7 (please refer Table A5 for data). The highest proportion of the HHs perceived medium severity of risks to the shocks for droughts (45%), untimely rain (55%), irregular weather (46%), animal disease (49%), serious crop damage (61%), and market shocks (49%). It is worthy to note that the most commonly reported shock earlier was droughts, with 54% of the respondents having experienced them, however, their perceived risks are medium across all regions. Over 53% reported high severity of the risks for flood and 41% for hailstorm. In the recent years within Nepal, especially in the Tarai, catastrophic flooding has left many people homeless, with a loss of resources and even the loss of lives. Still, little assistance has been provided to locals to help develop adaptation strategies against floods that in-evidently come with the monsoon every year.

Across the basin categories, it is observed that droughts were most commonly felt in the Karnali basin, with a majority (46%) of the respondents describing the severity as medium. The severity of risks from flooding is consistently considered as “medium” across all three basins with 32%, 35% and 44% of respondents in the Karnali, Mahakali and Mohana, respectively, experiencing medium severity of the risks (Table 3). However, respondents across the study area during the survey as well as FGDs perceive that the damage potential of the recent flood events are increasing. This further supports the need for better adaptation strategies from floods whose frequency might be relatively low, but impacts might be severe.

In general, perceived severity of risks associated with most of the climate shocks is medium. On average, over the past five years, a HH in the Tarai experienced flooding more frequently (3.56 times) than those households in the mountain (2.32 times) and hill (2.25 times) regions (Table A2). However, on further investigation we find that floods are ranked as a high risk shock in the Tarai region more often, while droughts and untimely rains are high impact shocks in the hill region. There is comparatively little dependency on rainwater in the Tarai than in the hills and mountain regions due to easy access to surface water in rivers or groundwater. As a result, untimely rains are less likely to affect communities in the Tarai as much. In the hill region, irrigation sources are mostly river water along with rainwater, and without the seasonal rains, the region is very vulnerable to harvest damage.

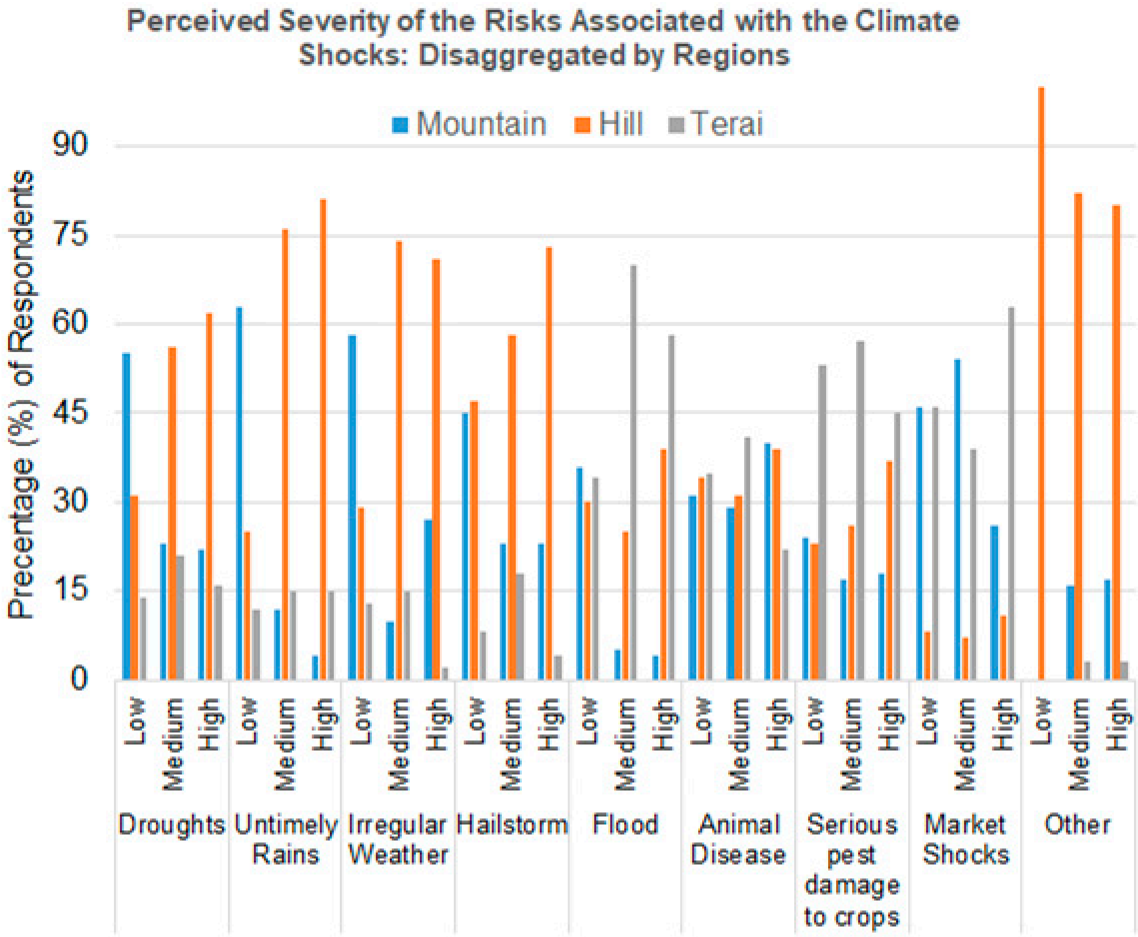


Figure 7. Severity of the risks to shocks perceived by households in the Karnali-Mahakali Basins—disaggregated by the type of shocks as well as physiographic regions.

3.4. Response to the Shocks

Sixteen potential responses to the climatic shocks, as can be seen in Table 4, were listed in the questionnaire. The respondents were requested to list their response (one or more) to different shocks from the list of 16. Despite the prevalence of climate shocks like floods and droughts in many parts of Western Nepal, communities lack measures for-post disaster recovery. Results showed that the most common response to the climatic shocks was "doing nothing". This further strengthens the argument that there is a knowledge gap amongst households on how to effectively adapt to the various climate risks that they face on a day to day basis. The only instance where the outcome was varied was for "serious pest damage to crops", where the response is "use of pesticides". Farmers have known how to combat pest damage for generations, making this climate shock one that they are familiar with, and well equipped for. The fear of financial loss or the threats to food security from "serious pest damage to crops" has potentially provided locals with the incentive to develop adaption measures that they can apply at individual level to curb such risks. Shocks like floods and droughts may not be similarly managed as easily and cheaply at the individual level.

Table 4. Top three responses for each shock.

Shocks and Responses	Respondents		Shocks and Responses	Respondents	
	Total	%		Total	%
Droughts	**1978**	**54**	**Flood**	**445**	**12**
● Did nothing	1386	70	● Did nothing	330	74
● Left the land fallow	409	21	● Left the land fallow	26	6
● Borrow money from others	71	4	● Reduced food consumption	21	5
Untimely rains	**1205**	**33**	**Animal disease**	**493**	**13**
● Did nothing	1018	84	● Did nothing	319	65
● Left the land fallow	81	7	● Sold livestock	84	17
● Borrow money from others	31	3	● Used pesticides	23	5
Irregular weather	**668**	**18**	**Pest damage to crops**	**892**	**24**
● Did nothing	525	79	● Used pesticides	481	54
● Left the land fallow	64	10	● Did nothing	342	38
● Borrow money from others	44	7	● Changed cropping patters	19	2
Hailstorm	**1910**	**52**	**Market shocks**	**202**	**6**
● Did nothing	1606	84	● Did nothing	156	77
● Borrow money from others	114	6	● Borrow money from others	16	8
● Left the land fallow	80	4	● Reduced food consumption	15	7

Top three responses for droughts, untimely rains, irregular weather, and hailstorm were doing nothing, left the land fallow, and borrow money from relatives/others (Table 4). The percentages of responses, however, varied for different shocks, even though doing nothing was reported by more than 70% in all these shocks. In case of flooding, in addition to doing nothing and leaving the land fallow, 5% of the respondents also answered "reduced food consumption". This could be due to several factors including crop damage, food rations ruined or depleted by the flood water, and delays in providing food supply or relief material to the affected communities. In case of animal disease, selling livestock and in case of pest damage to crops, changing cropping patterns are new types of responses compared to the other shocks that the community are practicing. When there are market shocks, 15% of respondents reacted by borrowing money from relatives/others and reducing food consumption.

In addition to self-responses, this study also analysed the pattern of support services provided by other agencies, including government, to assess the effectiveness of the provided services. A very low percentage, only 3.3%, of the sample households received support services of some form (Table 5). However, whether the post-disaster support was accessed with pro-activeness of community themselves or those of supporting agencies are not evident due to lack of adequate data. It was noted that a higher proportion of marginalized Dalit households (7.1%) said that they got support for aftershocks than other ethnic groups. Although the percentage of households receiving some support was very low, less than 10%, the level of support that mountain household received after the shocks was higher (6.4%) compared to hill (2.2%) and Tarai (2.9%).

Table 5. Percentage of households who received any sort of assistance to dealing with the shocks.

Category	% of Household	Category	% of Household
By basin		Region	
Karnali	3.4	Mountain	6.4
Mahakali	4.3	Hill	2.2
Mohana	2.4	Tarai	2.9
By gender of HH head		Ethnicity	
Male	3.4	Non marginalized	2.0
Female	2.8	Marginalized Janajati, and Madhesi	3.3
		Dalit	7.1
		Total	3.3

Furthermore, respondents who received any assistance were asked to indicate the agency responsible for aiding in the post-recovery process. More than two-thirds of the respondents (67%) indicated that the government agencies were major service providers for climatic shocks (Table 5). Other notable service providers included relief agencies, and groups in the communities. Table 6 summarizes the responsible party for providing support services across all climate-related events. However, support from family and local community groups were found to be the most time sensitive, occurring only at the time of the shock. Interestingly, saving community groups and friends are also the leading source for loans among the surveyed population, at 30% and 24%, suggesting a higher propensity to depend on these sources.

Table 6. Support services and timing of services received by households from different institutions.

HH Receiving any Support (*N* = 122)			**Timing of Services Received (%)**			
Supporting Agency	**n**	**%**	**At the Time of Shock**	**Within a Week**	**Within a Month**	**Within 6 Months**
National government agency (e.g., DADO, DOI, DWIDM, etc.) Government support	44	36	30	23	23	23
District-level government (i.e., DDC)	6	5	33	0	16	67
VDC-level government	32	26	0	3	16	81
Relief agency	29	24	48	28	21	3
Saving groups	7	6	29	71	0	0
Community/Social groups	4	3	75	25	0	0
Others in community	21	17	88	6	6	0
Extended family	3	2	100	0	0	0

Notes: DDC—District Development Committee; DADO—District Agriculture Development Office; DOI—Department of Irrigation; DWIDM—Department of Water-Induced Disaster Management; HH—household; VDC—village development committee.

Government agencies—National Government Agencies, District Development Committee (DDC) and Village Development Committee (VDC)—were noted to have delays when providing their relief services. In the past, the response lag time from the government agencies could be explained by the presence of bureaucracies, systematic nuances, and inadequate systems. Now that the municipalities hold more authority in the federal government, the documentation and relief efforts are expected to have a quicker response time. Only 30% of the respondents said that government agencies provide support services immediately at the time of the climatic shock. This highlights the need for better transfer systems as relief in the form of monetary funds, sustenance and transportation (such as boats) is the most crucial following the immediate onset of natural disasters. Communities within Karnali district lamented how boats were not provided as a timely response to the massive flooding that occurs each year with the monsoon rains, hereby restricting their mobility and hindering the process of ration collection. The current LAPAs have helped individuals across an array of thematic areas including agriculture, livestock, and food security. Incorporating resilience strategies prior to climate shocks can further help communities improve and protect their livelihoods. Further, NAPA and LAPA strategies must be gender-responsive and must incorporate local existing knowledge, innovations by communities through collective action and other local practices into its policies too.

4. Discussion and Conclusions

Nepal's geographical landscape already makes it vulnerable to an array of climate shocks. Over the past decades, climate-induced changes have contributed in increased frequency, duration and severity of the risks to many of the climate shocks experienced by communities in Nepal. Additionally, a large number of communities living in these flood and drought prone areas are low to middle income households, hereby having limited access to the necessary resources to equip them with relevant adaptation strategies. The increased risks to climate/non-climatic shocks on water and agriculture sectors are likely to have significant implications on communities, hereby affecting the national economy that relies so heavily on natural resources. It is imperative that Nepal also adopts necessary adaptation strategies to better equip communities with the tools and knowledge required to protect themselves against future climatic hazards.

Western Nepal has a significant potential to contribute to national prosperity with a variety of comparative advantages. However, the region is relatively more vulnerable to climate change impacts. Therefore, understanding the level of climate shocks/stress, severity of risks to the shocks, and the past responses across different locations are important for future climate-resilient development planning. This study assessed perceived climatic shocks, climatological trends and their links to the perceived shocks, perceived severity of risks, and responses in the Karnali-Mahakali river basin in Western Nepal. A large-scale (3660 household) basin-wide survey was carried out to assess perceptions on climatic shocks, perceived severity of risks to the shocks, and responses; and climatological data from nine stations were analysed for trends in climatic indices.

One or more kind of climate shocks are perceived by approximately 80% of the respondents. Droughts and hailstorms are perceived by more than half of the respondents, whereas 33% and 24% have perceived untimely rains and serious crop damage, respectively. A household in the Tarai experiences flooding more often (>3.56 times) than in the mountain (2.32 times) and hill (2.25 times) regions. Floods are a high-risk shock in the Tarai region, while droughts and untimely rains are high-risk shocks in the hill region. Previous research also highlighted that the Karnali and Mahakali, two out of the four largest rivers in Nepal, are comparatively less vulnerable to flooding in the mountain and hill regions, but more likely to create damage in the Tarai plains [34]. Such variation in perception of floods across the regions may also stem from communities in hill and mountain regions, residing largely in hill and mountain tops, where rising water levels in the river may not necessarily impact livelihoods. In contrast, agricultural lands in Tarai lie closer to riverbanks for easier access to water for irrigation, making them more susceptible to floods. Prevalence of rain-fed agriculture in the hill as compared to Tarai may explain the higher perception of untimely rains, hailstorm and irregular weather that directly impact crop production in the hills. The results also vary across the basins; respondents from the Karnali-Main comprising largely of the mountain and hill regions, experienced hailstorms and droughts the most, while most people in Mahakali and Mohana experienced flooding. Mohana basin, lying entirely in the Tarai, comprises of a parallel network of streams originating in the steep mid-hills and abruptly flattening into the plains. The streams are characterized by peak flows and flash floods during the monsoon. As a result, it experiences more flooding as well as serious damage to crops. As a majority of agricultural activities in Western Nepal rely on water resources, various climate shocks that directly and indirectly affect water availability can quickly ruin yield and disrupt crop harvesting. The impact of one shock can have differing levels of severity across the various ecological regions and basins. For instance, HHs in the Tarai have access to groundwater, making them less reliant on rainwater for agriculture than HHs in the hill and mountain regions. The Nepali agriculture industry contributes to 27.04% (https://www.statista.com/statistics/425750/nepal-gdp-distribution-across-economic-sectors/) of the GDP. As a result, the implications of climate change on agriculture in Nepal can have significant impacts on livelihood security of local communities and the national economy.

The climatological trends of nine selected indices at nine stations spread across the three ecological regions and five basins also complements the perceived climate shocks. The results indicate increases in dry and warmer conditions with a majority of the temperature indices trending towards rise in temperatures, while precipitation indices like *rx5day* and *cwd* indicate a decline in rainfall. More extreme events like floods and droughts are therefore already experienced, which are likely to increase in future as well. The positive historical trends in *tn90p* and *cdd* support the high perception of droughts. The positive trend in *wsdi*, which only occurred in the hills and higher Sen's slope for *cdd* in the hills, may support the perception of drought as the fourth most reported shock perceived by 53% of respondents in the hills. The higher frequency of occurrence of droughts in mountains than in the hills, however, cannot be supported by the trend data. Flood is related to *r20mm*, *cwd* and *rx5day*, all of which do not show statistical significance trends at 95% level of confidence. All three indices consider high rainfall situations that are likely to trigger floods. The highly negative trend in *rx5day* for Tarai stations 209 and 207 in comparison to the mountain and hill stations do not support people's perception of higher dominance and frequency of floods in the Tarai. The majority of the stations also have negative slopes for *r20mm*, except for station 514 in the hill. Climate shocks like animal disease and serious pest damage to crops have been related to the temperature indices *tmm* and *tn90p*, considering the higher likelihood of occurrence, growth and spread of disease causing pests and microbes in higher temperatures. The *tmm* represents mean temperature while *tn90p* is the percentage of warm days. Except station 514 in the hill and 207 and 405 in the Tarai, for which Sen's slope could not be evaluated, the trends in *tmm* and *tn90p* are significant or highly significant. All stations report a positive trend, except station 104 in the hill reporting a high negative value that is also statistically significant. There is no differentiable trend across the three ecological regions. However, the general rise in temperature across all regions supports the prominence of the pest damage to crops in Tarai where large scale and commercial agriculture is more common than in other regions. Overall, the emerging trends hint towards an increase in dry and warmer conditions with the majority of the temperature indices trending towards rise in temperatures while precipitation indices like *rx5day* and *cwd* indicate a decline in rainfall. Such historic trends can explain the survey reports on occurrence of droughts, temperature rise conducive to pest damage to crops, and irregular weather.

Perceived severity of risks from climate shocks were also analyzed. The highest proportion of households have perceived a medium severity for drought, untimely rain, irregular weather, animal disease, serious crop damage, and market shocks. More than half of the respondents have perceived high severity of the risks to flood and 41% for hailstorm. Literature supports that the topography of the Tarai plains makes the entire region more vulnerable to flooding and inundation [34]. A large proportion of households in Nepal, and the Tarai depend on agriculture and rural livelihoods for their income and food security. The susceptible geographical topography in the Tarai, coupled with the dependency on agriculture, further aggravates the severity risks to floods as families have a lot at stake. Research conducted by [34], highlights that the Karnali and Mahakali Rivers, two of the four largest in Nepal, are comparatively less vulnerable in the mountain and hill regions. Floods are more likely to create damage in the Tarai plains, and as the paper points out, this is further exacerbated by climate change.

Despite the prevalence of climate shocks like floods and droughts in many parts of Western Nepal, communities lack measures for post disaster recovery. With 70% of the households relaying that their response to climatic shocks has been "doing nothing", this study highlights the imminent need to better equip Nepalese communities to adopt adaptation strategies. A small percentage of respondents were forced to sell their productive assets, including livestock, while some reduced food consumption in response to flooding. Local communities frequently have limited access to resources and knowledge that can protect them against these climate risks. It is also more likely that these vulnerable communities do not have the required information to access available government or non-government- based assistances. As a result, more often than not, communities are unable to do anything in response to climate shocks. A small portion of the respondents, who potentially have access to information and resources, and have more flexibility in use of available resources, are responding in different ways such as selling livestock in case of animal disease, changing cropping patterns and using pesticides in case of pest damage to crops. There are also cases where farmers left their land fallow as it was damaged due to irregular weather. Some cases of "reducing food consumption" as a response for shocks was also reported, indicating the extreme response which is of concern on a humanitarian ground.

Climate change continues to be a challenge for development, and without building the resilience of communities and ecosystems, rural communities will continue to lose assets including land, crops, housing, livestock and health. The design of adaptation strategies and response mechanisms to deal with climate shocks and associated impacts will therefore need to take these aspects into consideration. In order to empower communities across Nepal with the necessary skillset, there should be improved access to resources, services, markets, technologies, and decision making agencies that are tailored to their local and physiographic needs.

Finally, the methodology adopted in this study is applicable to other areas as well. Depending upon location and dominance of issues, the questionnaire may need to be customized appropriately to ensure that adequate information is collected to support for appropriate interpretation of results.

Author Contributions: Conceptualization, V.P.P. and L.B.; methodology, V.P.P., S.D., and I.R.J.; software, A.S. and S.D.; validation, I.R.J. and V.P.P.; formal analysis, A.S., S.D. and V.P.P.; investigation; V.P.P. and I.R.J.; resources, L.B.; data curation, A.S., I.R.J. and S.D.; original draft preparation, V.P.P., A.S., and S.D.; review and editing, I.R.J. and L.B.; visualization, V.P.P. and L.B.; supervision, L.B.; project administration, L.B. and V.P.P.; funding acquisition, L.B.

Funding: This research was funded by the United States Agency for International Development (USAID), award number AIT-367-IO-16-00002.

Acknowledgments: This study is made possible by the generous support of the American people through the United States Agency for International Development (USAID) under Digo Jal Bikas (DJB) project. The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government. We also would like to acknowledge Nepal Water Conservation Foundation (NWCF) for helping with the basin-wide survey and data digitization and the local people/respondents for kindly agreeing to respond to the questionnaire.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations and Acronyms

CCI	Commission for Climatology
CDD	Consecutive Dry Days
CWD	Consecutive Wet Days
DADO	District Agriculture Development Office
DDC	District Development Committee
DOI	Department of Irrigation
DWIDM	Department of Water-Induced Disaster Management
ET-SCI	Expert Team on Sector-specific Climate Indices
FGD	Focus Group Discussion
GDP	Gross Domestic Product
HHs	Households
HKH	Hindu Kush Himalayan (HKH)
KarMo	Karnali-Mohana
KII	Key Informant Interview
Km2	Square Kilometers
LAPA	Local Adaptation Plan of Action
masl	Meters Above Mean Sea Level
MKT	Mann Kendal Test
MW	Mega Watt
NAPA	National Adaptation Plan of Action
NWCF	Nepal Water Conservation Foundation
PSUs	Primary Sampling Units
RCM	Regional Climate Model
SPEI	Standardised Precipitation Evapotranspiration Index
VDC	Village Development Committees
WMO	World Meteorological Organization

Appendix A

Table A1. Selected sample size by PSUs. HP is hydropower. PSU is primary sampling unit.

Basin	Eco-Region	Hydro Clusters	Population	Population Proportion	Sample Size	Sample PSUs	Adjusted Sample Size
Bheri-Karnali	Mountain	HP	8095	0.2	7	1	30
		None HP	24,281	0.6	21	1	30
	Hill	HP	241,428	5.8	209	7	210
		None HP	556,754	13.4	481	16	480
Main-Karnali	Mountain	HP	25,868	0.6	22	1	30
		None HP	376,937	9.1	326	11	330
	Hill	HP	138,480	3.3	120	4	120
		None HP	264,786	6.4	229	8	240
	Tarai	HP	6027	0.1	5	1	30
		None HP	17,0138	4.1	147	5	150
Seti- Karnali	Mountain	HP	87,602	2.1	76	3	90
		None HP	191,047	4.6	165	6	150
	Hill	HP	60,395	1.5	52	2	60
		None HP	362,092	8.7	313	10	300
Mahakali	Mountain	HP	51,719	1.2	45	2	60
		None HP	81,655	2.0	71	2	60
	Hill	HP	28,976	0.7	25	1	30
		None HP	254,117	6.1	220	7	210
	Tarai	HP	0	0.0	0	0	0
		None HP	281,129	6.8	243	8	240
Mohana	Hill	HP	0	0.0	0	0	0
		None HP	7436	0.2	6	1	30
	Tarai	HP	0	0.0	0	0	0
		None HP	920,830	22.2	796	26	780
Summary	12	21 valid clusters	4,139,792	100.0	3579	122	3660

Table A2. Frequency of climate shocks across the regions.

Climate Shocks	Statistics	Mountain	Hill	Tarai	Total
Droughts	Mean	2.61	2.17	2.33	2.32
	Minimum	1	1	1	1
	Maximum	36	32	8	36
Untimely rains	Mean	2.31	2.48	2.41	2.43
	Minimum	1	1	1	1
	Maximum	5	6	7	7
Irregular weather	Mean	2.51	2.26	1.92	2.3
	Minimum	1	1	1	1
	Maximum	5	5	12	12
Hailstorm	Mean	2.82	1.99	2.16	2.25
	Minimum	1	1	1	1
	Maximum	10	7	7	10
Flood	Mean	2.32	2.25	3.56	
	Minimum	1	1	1	1
	Maximum	5	65	12	65
Animal disease	Mean	1.96	1.66	1.98	1.866
	Minimum	1	1	1	1
	Maximum	5	5	10	10
Serious pest damage to crops	Mean	2.23	2.63	2.61	2.55
	Minimum	1	1	1	1
	Maximum	6	10	50	50
Market shocks	Mean	2.76	2.59	3.79	3.26
	Minimum	1	1	1	1
	Maximum	23	5	25	25
Other	Mean	2.18	3.8	3.5	3.54
	Minimum	1	1	1	1
	Maximum	4	15	5	15

Table A3. Frequency of climate shocks across the sub-basins.

Climate Shocks	Statistics	Karnali	Seti	Bheri	Mahakali	Mohana	Total
Droughts	Mean	2.41	2.38	1.93	2.63	2.18	2.32
	Minimum	1	1	1	1	1	1
	Maximum	32	36	5	5	8	36
Untimely rains	Mean	2.42	2.51	2.27	2.68	2.13	2.43
	Minimum	1	1	1	1	1	1
	Maximum	7	5	5	6	5	7
Irregular weather	Mean	2.29	2.6	1.87	2.57	1.87	2.3
	Minimum	1	1	1	1	1	1
	Maximum	5	5	5	5	12	12
Hailstorm	Mean	2.45	2.21	1.85	2.5	2.05	2.25
	Minimum	1	1	1	1	1	1
	Maximum	10	7	5	5	7	10
Flood	Mean	2.68	3.05	2.52	2.75	3.73	3.04
	Minimum	1	1	1	1	1	1
	Maximum	12	5	65	6	12	65
Animal disease	Mean	1.96	1.85	1.63	1.93	1.74	1.87
	Minimum	1	1	1	1	1	1
	Maximum	10	5	5	5	5	10
Serious pest damage to crops	Mean	2.25	2	3.4	3.26	2.09	2.55
	Minimum	1	1	1	1	1	1
	Maximum	10	7	5	50	5	50
Market shocks	Mean	2.48	3.78	2.67	3.75	3.51	3.26
	Minimum	1	1	1	1	1	1
	Maximum	5	23	5	25	11	25
Other	Mean	3.27	2.72	.	6.9	5	3.53
	Minimum	1	1	.	1	1	1
	Maximum	15	5	.	10	5	15

Table A4. Climatological trends in nine ET-SCI climatic indices. Slope is Sen's slope and *p*-value is MKT *p*-value. Red-shading indicate *p*-values < 0.001, which indicate a high statistical significance while yellow-shading indicate *p*-values < 0.05, which show a statistical significance at 5% confidence level.

Parameter Trend	s202 @ Mountain		s303 @ Mountain		s514 @ Hill	
Over [1980–2005]	Slope	*p*-Value	Slope	*p*-Value	Slope	*p*-Value
tmm	0.048	0.000	0.028	0.107		
tn90p	0.272	0.047	0.236	0.010		
r10mm	−0.333	0.061	−0.221	0.203	0.444	0.176
wsdi	0.000	0.062	0.000	0.931	0.000	0.609
r20mm	−0.200	0.063	−0.067	0.216	0.429	0.059
cdd	0.500	0.315	0.258	0.674	0.545	0.383
cwd	0.185	0.095	−0.059	0.510	−0.100	0.633
rx5day	−0.511	0.640	−0.596	0.362	0.058	1.000
spei	−0.003	0.000	−0.005	0.000		
Parameter Trend	**s104 @ Hill**		**s406 @ Hill**		**s513@Hill**	
Over [1980–2005]	**Slope**	***p*-Value**	**Slope**	***p*-Value**	**Slope**	***P*-Value**
tmm	0.055	0.001	0.030	0.005	0.029	0.028
tn90p	−0.487	0.001	0.088	0.591	0.166	0.176
r10mm	−0.300	0.122	0.059	0.740	0.000	1.000
wsdi	0.633	0.001	0.212	0.052	0.300	0.184
r20mm	−0.267	0.097	0.000	0.912	0.000	0.921
cdd	0.720	0.365	1.444	0.112	1.244	0.024
cwd	−0.231	0.063	0.000	0.965	0.000	1.000
rx5day	−0.400	0.724	−1.342	0.332	−0.528	0.568
spei	−0.007	0.000	−0.002	0.002	−0.001	0.086
Parameter Trend	**s209 @ Plain**		**s207 @ Plain**		**s405@Plain**	
Over [1980–2005]	**Slope**	***p*-Value**	**Slope**	***p*-Value**	**Slope**	***p*-Value**
tmm	0.034	0.065				
tn90p	0.243	0.032				
r10mm	0.056	0.730	0.000	0.842	0.200	0.369
wsdi	0.000	1.000				
r20mm	−0.118	0.441	−0.100	0.671	0.000	0.901
cdd	0.059	0.895	0.444	0.632	1.000	0.197
cwd	0.000	0.979	0.000	0.954	0.000	1.000
rx5day	−1.978	0.398	−2.958	0.463	0.378	0.747
spei	0.001	0.227	−0.003	0.000	0.001	0.339

Table A5. Perceived impacts of the climate shocks as per ecological regions.

Climate Shocks	Severity	Total		Region						*p*-Value
				Mountain		Hill		Tarai		
		No	%	No	%	No	%	No	%	
Droughts	Low	413	11	226	55	128	31	59	14	0.00
	Medium	895	24	203	23	502	56	190	21	
	High	676	18	149	22	422	62	105	16	
	Total	1984	54	578	29	1052	53	354	18	
Untimely rains	Low	291	8	183	63	72	25	36	12	0.00
	Medium	656	18	77	12	497	76	100	15	
	High	256	7	11	4	207	81	38	15	
	Total	1203	33	271	23	758	63	174	14	
Irregular weather	Low	215	6	125	58	62	29	28	13	0.00
	Medium	305	8	32	10	226	74	47	15	
	High	147	4	39	27	105	71	3	2	
	Total	667	18	196	29	393	59	78	12	
Hailstorm	Low	516	14	234	45	243	47	39	8	0.00
	Medium	619	17	145	23	361	58	113	18	
	High	777	21	176	23	570	73	31	4	
	Total	1912	52	555	29	1174	61	183	10	
Flood	Low	47	1	17	36	14	30	16	34	0.00
	Medium	166	5	8	5	41	25	117	70	
	High	238	7	9	4	92	39	137	58	
	Total	451	12	34	8	147	33	270	60	
Animal disease	Low	89	2	28	31	30	34	31	35	0.00
	Medium	244	7	70	29	75	31	99	41	
	High	166	5	66	40	64	39	36	22	
	Total	499	14	164	33	169	34	166	33	
Serious pest damage to crops	Low	112	3	27	24	26	23	59	53	0.00
	Medium	548	15	94	17	140	26	314	57	
	High	232	6	41	18	86	37	105	45	
	Total	892	24	162	18	252	28	478	54	
Market shocks	Low	13	0	6	46	1	8	6	46	0.00
	Medium	100	3	54	54	7	7	39	39	
	High	91	2	24	26	10	11	57	63	
	Total	204	6	84	41	18	9	102	50	
Other	Low	1	0	0	0	1	100	0	0	0.99
	Medium	38	1	6	16	31	82	1	3	
	High	30	1	5	17	24	80	1	3	
	Total	69	2	11	16	56	81	2	3	

References

1. Shrestha, A.B.; Aryal, R. Climate change in Nepal and its impact on Himalayan glaciers. *Reg. Environ. Chang.* **2011**, *11*, 65–77. [CrossRef]
2. Wester, P.; Mishra, A.; Mukherji, A.; Shrestha, A.B. *The Hindu Kush Himalaya Assessment*; Cham: Springer International Publishing: Basel, Switzerland, 2019.
3. Dhaubanjar, S.; Pandey, V.P.; Bharati, L.; Khadka, A.; Matheswaran, K.; Okwany, R.; Chinnasamy, P.; Shrestha, S.L. *Characterization of Spring-Dominated Micro-Watersheds in Western Nepal—The Case of Springs in Shikharpur and Banlek*; International Water Management Institute (IWMI): Colombo, Sri Lanka, 2019.
4. Pandey, V.P.; Dhaubanjar, S.; Bharati, L.; Thapa, B.R. Hydrological response of Chamelia watershed in Mahakali Basin to climate change. *Sci. Total Environ.* **2019**, *650*, 365–383. [CrossRef] [PubMed]
5. Pandey, V.P.; Dhaubanjar, S.; Bharati, L.; Thapa, B.R. Modeling hydrology in large basins using multi-site calibration approach: A case of Karnali-Mohana basin, Western Nepal. (Under Review). *Hydro-Environ. Res.* **2019**, under review.
6. NARC. *NARC's Strategic Vision for Agricultural Research 2011–2030*; Ministry of Agriculture Development (MoAD): Lalitpur, Nepal, 2010.
7. Siddiqui, S.; Bharati, L.; Gurung, P.; Maharjan, L. *Climate Change and Vulnerability Mapping in Watersheds in Middle and High Mountains of Nepal*; IWMI: Colombo, Sri Lanka, 2012.
8. Niles, M.T.; Salerno, J.D. A cross-country analysis of climate shocks and smallholder food insecurity. *PLoS ONE* **2018**, *13*, e0192928. [CrossRef] [PubMed]
9. Bastakoti, R.C.; Bharati, L.; Bhattarai, U.; Wahid, S.M. Agriculture under changing climate conditions and adaptation options in the Koshi Basin. *Clim. Dev.* **2017**, *9*, 634–648. [CrossRef]

10. Devkota, R.P.; Pandey, V.P.; Bhattarai, U.; Shrestha, H.; Adhikari, S.; Dulal, K.N. Climate change and adaptation strategies in Budhi Gandaki River Basin, Nepal: A perception-based analysis. *Clim. Chang.* **2017**, *140*, 195–208. [CrossRef]
11. Devkota, R.P.; Bhattarai, U. Assessment of climate change impact on floods from a techno-social perspective. *J. Flood Risk Manag.* **2018**, *77*, S186–S196. [CrossRef]
12. Turral, H.; Svendsen, M.; Faures, J.M. Investing in irrigation: Reviewing the past and looking to the future. *Agric. Water Manag.* **2010**, *97*, 551–560. [CrossRef]
13. Jongdee, B. *Agricultural Water Management*; Elsevier: Amsterdam, The Netherlands, 2006.
14. Waha, K.; Müller, C.; Bondeau, A.; Dietrich, J.P.; Kurukulasuriya, P.; Heinke, J.; Lotze-Campen, H. Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa. *Glob. Environ. Chang.* **2013**, *23*, 130–143. [CrossRef]
15. Conway, D.; Lisa, E.; Schipper, F. Adaptation to climate change in Africa: Challenges and opportunities identified from Ethiopia. *Glob. Environ. Chang.* **2011**, *21*, 227–237. [CrossRef]
16. Mwinjaka, O.; Gupta, J.; Bresser, T. Adaptation strategies of the poorest farmers in drought-prone Gujarat. *Clim. Dev.* **2010**, *2*, 346–363. [CrossRef]
17. Adger, W.N.; Arnell, N.W.; Tompkins, E.L. Successful adaptation to climate change across scales. *Glob. Environ. Chang.* **2005**, *145*, 77–86. [CrossRef]
18. Dawson, R.J.; Ball, T.; Werritty, J.; Werritty, A.; Hall, J.W.; Roche, N. Assessing the effectiveness of non-structural flood management measures in the Thames Estuary under conditions of socio-economic and environmental change. *Glob. Environ. Chang.* **2011**, *21*, 628–646.
19. Huntjens, P.; Lebel, L.; Pahl-Wostl, C.; Camkin, J.; Schulze, R.; Kranz, N. Institutional design propositions for the governance of adaptation to climate change in the water sector. *Glob. Environ. Chang.* **2012**, *22*, 67–81. [CrossRef]
20. Kuntiyawichai, K.; Schultz, B.; Uhlenbrook, S.; Suryadi, F.X.; van Griensven, A. Comparison of flood management options for the Yang River Basin, Thailand. *Irrig. Drain.* **2011**, *60*, 526–543.
21. Næss, L.O.; Bang, G.; Eriksen, S.; Vevatne, J. Institutional adaptation to climate change: Flood responses at the municipal level in Norway. *Glob. Environ. Chang.* **2005**, *15*, 125–138.
22. Bharati, L.; Gurung, P.; Jayakody, P.; Smakhtin, V.; Bhattarai, U. The Projected Impact of Climate Change on Water Availability and Development in the Koshi Basin, Nepal. *Mt. Res. Dev.* **2014**, *34*, 118–130.
23. Dixit, A.; Upadhya, M.; Dixit, K.; Pokhrel, A.; Rai, D.R. Living with water stress in the hills of the Koshi Basin, Nepal. In *Living Water Stress Hills Koshi Basin Nepal*; ICIMOD: Lalitpur, Nepal, 2009.
24. Manandhar, S.; Pandey, V.P.; Kazama, F. Hydro-climatic trends and people's perceptions: Case of Kali Gandaki River Basin, Nepal. *Clim. Res.* **2012**, *54*, 167–179.
25. Moors, E.J.; Groot, A.; Biemans, H.; van Scheltinga, C.T.; Siderius, C.; Stoffel, M.; Huggel, C.; Wiltshire, A.; Mathison, C.; Ridley, J.; et al. (Eds.) Adaptation to changing water resources in the Ganges basin, northern India. *Environ. Sci. Policy* **2011**, *14*, 758–769. [CrossRef]
26. Mann, H.B. Nonparametric Tests against Trend. *Econometrica* **1945**, *13*, 245–259. [CrossRef]
27. Kendall, M.G. *Rank Correlation Methods*, 4th ed.; Charles Griffin: London, UK, 1975.
28. National Aeronautics and Space Administration Jet Propulsion Laboratory. *ASTER Global Digital Elevation Model V002 [Data Set]*; National Aeronautics and Space Administration Jet Propulsion Laboratory: Pasadena, CA, USA, 2009.
29. Ives, J.D.; Shrestha, R.B.; Mool, P.K.P.K. *Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment*; ICIMOD: Kathmandu, Nepal, 2010; pp. 10–11.
30. Dhaubanjar, S.; Pandey, V.P.; Bharati, L. Climate futures for Western Nepal based on CORDEX South Asia Regional Climate Models. *Inter. J. Clim.* **2019**, in press.
31. Sen, P.K. Estimates of the Regression Coefficient Based on Kendall's Tau. *J. Am. Stat. Assoc.* **1968**, *63*, 1379–1389. [CrossRef]
32. Dhaubanjar, S.; Bharati, L.; Pandey, V.P.; Blauth, K. Unpacking climate change: Assessment of sector-wise impact in Western Nepal. *Manuscript*.

33. Zhang, X.; Yang, F. RClimDex (1.0) User Manual. Available online: http://etccdi.pacificclimate.org/software.shtml (accessed on 12 June 2019).
34. Adhikari, B.R. Flooding and inundation in Nepal Terai: Issues and Concerns. *Hydro Nepal* **2013**, *12*, 59–65. [CrossRef]

Annex 6-1

Ecological Indicators 108 (2020) 105735

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Water diversion induced changes in aquatic biodiversity in monsoon-dominated rivers of Western Himalayas in Nepal: Implications for environmental flows

Ram Devi Tachamo Shah[a,*], Subodh Sharma[a], Luna Bharati[b]

[a] Aquatic Ecology Centre, Kathmandu University, Dhulikhel, Nepal
[b] International Water Management Institute, Nepal

ARTICLE INFO

Keywords:
Himalayan headwaters
Rheophiles
Irrigation
Micro-hydropower
Water diversions

ABSTRACT

Water diversion projects across the world, for drinking water, energy production and irrigation, have threatened riverine ecosystems and organisms inhabiting those systems. However, the impacts of such projects on aquatic biodiversity in monsoon-dominated river ecosystems are little known, particularly in Nepal. This study examines the effects of flow reduction due to water diversion projects on the macroinvertebrate communities in the rivers of the Karnali and Mahakali basins in the Western Himalayas in Nepal. Macroinvertebrates were sampled during post-monsoon (November), baseflow (February) and pre-monsoon (May) seasons during 2016 and 2017. Non-metric Multidimensional Scaling (NMDS) was performed to visualize clustering of sites according to percentage of water abstractions (extraction of water for various uses) and Redundancy Analysis (RDA) was used to explore environmental variables that explained variation in macroinvertebrate community composition. A significant pattern of macroinvertebrates across the water abstraction categories was only revealed for the baseflow season. NMDS clustered sites into three clumps: "none to slight water abstraction (< 30% – Class 1)", "moderate water abstraction (> 30% to < 80% – Class 2)" and "heavy water abstraction (> 80% – Class 3)". The study also showed that water abstraction varied seasonally in the region (Wilk's Lambda = 0.697, $F_{(2, 28)} = 4.215$, $P = 0.025$, $n^2 = 0.23$). The RDA plot indicated that taxa such as *Acentrella* sp., *Paragenetina* sp., *Hydropsyche* sp., *Glossosomatinae*, Elmidae, Orthocladiinae and Dimesiinae were rheophilic i.e. positively correlated with water velocity. Taxa like *Torleya* sp., *Caenis* sp., *Cinygmina* sp., *Choroterpes* sp., Limonidae and Ceratopogoniidae were found in sites with high proportion of pool sections and relative high temperature induced by flow reduction among the sites. Indicator taxonomic groups for Class 1, 2 and 3 water abstraction levels, measured through high relative abundance values, were Trichoptera, Coleoptera, Odonata and Lepidoptera, respectively. Macroinvertebrate abundance was found to be the more sensitive metric than taxonomic richness in the abstracted sites. It is important to understand the relationship between flow alterations induced by water abstractions and changes in macroinvertebrates composition in order to determine sustainable and sound management strategies for river ecosystems.

1. Introduction

Freshwater ecosystems occupy < 0.1% of the Earth surface and yet provide habitats to about 10% of known biodiversity (Balian et al., 2008). In addition to being biodiversity hotspots, freshwater ecosystems also supply water for drinking, as well as for industrial uses and energy production. Today, humans have modified over three quarters of global large rivers and nearly no free flowing rivers exist in developed nations (Dynesius and Nilsson, 1994; Grill et al. 2019; Nilsson et al., 2005). River modifications alter flow regimes, causing a wide range of hydromorphological and ecological change (Caiola et al., 2014; Papadaki et al., 2016; Poff and Zimmerman, 2010; Schneider and Petrin, 2017). Alteration of stream flow characteristics due to water diversion projects may affect the health of river ecosystems and in-stream biotic communities, contributing to a loss of sensitive biota and enhancement of tolerant biota, sediment transport, and changes in nutrient availability and river beds (Bunn and Arthington, 2002; Poff et al., 1997; Tonkin and Death, 2013; Ward and Stanford, 1983).

In Nepal, water resource development is still underdeveloped. Though Nepal has nearly 42,000 MW of hydropower capacity, < 1000 MW has

* Corresponding author.
E-mail addresses: ramdevi.env@gmail.com (R.D. Tachamo Shah), subodh.sharma@ku.edu.np (S. Sharma), L.bharati@cgiar.org (L. Bharati).

https://doi.org/10.1016/j.ecolind.2019.105735
Received 19 October 2018; Received in revised form 9 September 2019; Accepted 12 September 2019
Available online 21 September 2019

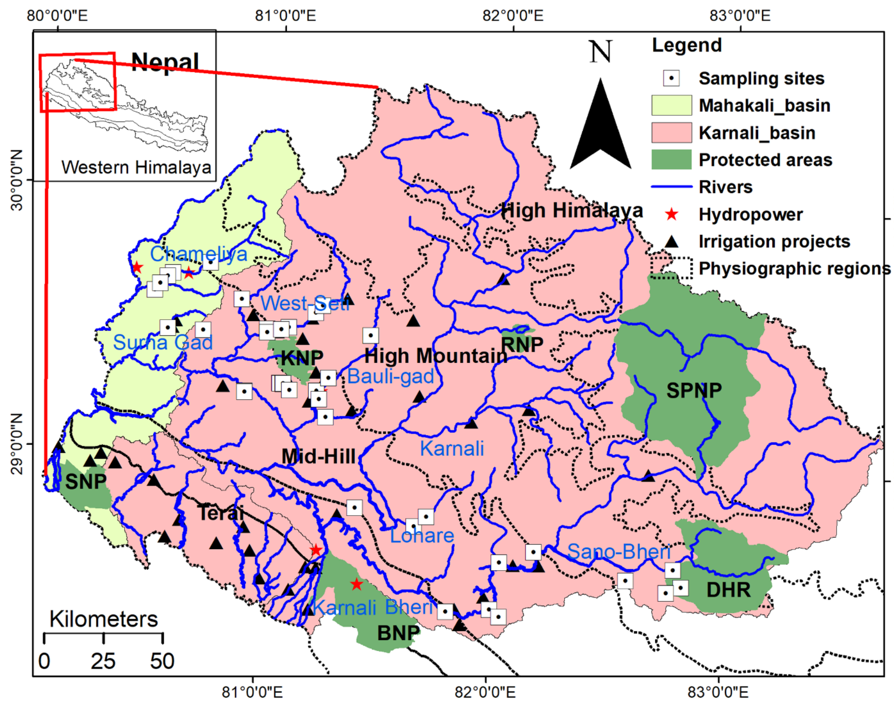


Fig. 1. Locations of sampling sites in headwaters of Mahakali and Karnali River basins. From left- right: SNP = Suklaphata National Park; KNP = Khaptad National Park; RNP = Rara National Park; BNP = Bardia National Park; SPNP = Shey-phoksundo National Park; DHR = Dhorpatan Hunting Reserve.

been realized hitherto. Considering the potential of water resource development to aid in social and economic development, Nepal has aimed to generate about 25,000 MW of electricity by the end of 2030 (GoN/WECS, 2013) and many of these projects are planned in the Karnali and Mahakali river basins of Western Himalaya. It seems likely that many tributaries and sections of large rivers will be dammed in the next couple of decades, which will alter river flows in downstream sections of dams and reservoirs. Currently, the headwaters of Karnali and Mahakali basins are relatively unaffected by large-scale development. However, water diversion projects are prolific, mainly for irrigation, water mills and micro-hydropower (Fig. 1). Water is tapped from the source causing downstream river sections to have little or no water, despite the "Irrigation policy of Nepal (GoN/WECS, 2002)" mandating that the minimum water level required for the conservation of aquatic organisms living in the river ecosystems needs to be maintained. The ecological consequences of these water abstractions, however, are poorly assessed. In river ecosystems, benthic macroinvertebrates are considered one of the best bio-indicators for assessing the impacts of wider ranges of water pollution, climate change and flow alteration as they respond positively or negatively to these stressors (Dewson et al., 2007a; Poff and Zimmerman, 2010). Biotic indices based on benthic macroinvertebrates are common around the world (*sensu* DePauw and Hawkes, 1993). The most common ecosystem changes associated with an observed negative response of these indicator species include a decline in taxonomic richness, shift in relative abundance of certain organisms and reduction in biomass production (Holt et al., 2014). With hydrological changes, many of these aquatic insects have been found to be less abundant in low flows (Lenat, 1993) as river flows exert physical forces that influence water chemistry, nutrient cycle and habitat availability (Dewson et al., 2007b). As reliable bio-indicators, orders Ephemeroptera, Plecoptera and Trichoptera (EPT) are useful for ecological assessment of rivers to understand impacts of development of water resources (Holt et al., 2014). In this study, we assessed the ecological consequences of water diversion projects (especially irrigation projects, water mills and micro-hydropowers) on river health, by observing how indicator species respond to the changes in flow regimes. We anticipated that the increasing degree of water abstraction would result in reduced taxonomic richness and abundance of indicator taxa. We tested this hypothesis by looking at responses of macroinvertebrate assemblages in abstracted stream reaches and compared them to that at natural (reference) sites.

2. Materials and method

2.1. Study area

The Mahakali and Karnali River basins are the least disturbed river basins in Nepal. The headwaters are free from modern urbanization, and although there is organic pollution and regular influx of sewage into the rivers, the amount is minimal, thus offering a relatively controlled environment to assess the effects of water diversion projects on biotic communities.

The Mahakali River flows from the northern part of India and only 34% of the basin lies within Nepal. The Karnali basin has a catchment area of 127,950 sq. km of which 55% falls in Nepal (WSHP, 2007). About 14% of the total basin is under protection as national parks (7%), wildlife reserves and conservation areas. The Karnali River originates from the southern part of the Tibetan Plateau and is one of the main tributaries of the Ganges River system. At 507 km, the river is the longest in Nepal. The entire western Nepal is also a rain-shadow area as Western Nepal receives less than half the rain (1,000 mm annual rainfall) that Eastern Nepal does (2,500 mm annual rainfall) (GoN, 2008). Therefore, the region is considered as an arid zone that lacks riparian vegetation and canopy coverage in the rivers (Tachamo Shah's field survey 2016–2017). About 80% annual rainfall occurs in four months of the year from June –September.

2.2. Sampling sites

A total of 33, 41 and 40 (excluded one dried river reach) river reaches were sampled for post-monsoon (November), baseflow (February) and pre-monsoon (May) seasons, respectively, in the headwaters of Mahakali and Karnali River basins in 2016 and 2017 (Fig. 1). The sampling sites were distributed in rivers of High-Mountain, Mid-

Hills and Lowland eco-regions with road accessibility. All sites were mostly free from direct industrial or sewage influxes and waste dumping. Screening protocols (Hartmann et al., 2010) an effective tool to assess impacts of organic pollution) consists of 4 components: Sensory features (ordor, non natural color, foam and solid wastes); Ferro-sulfide reduction; Algae and periphyton coverage; and richness and abundance of benthic macroinvertebrates, were filled in at each site and only River Quality Class (RQC) I and II (High and Good river quality status, respectively) were selected for this study. Rivers with and without water diversions were considered as disturbed and natural (reference) sites, respectively. At disturbed sites, rivers were run-of-the-river systems with weir height < 2 m diverted for domestic, agricultural, water-mill operation and micro-hydropower generation.

Physico-chemical parameters such as pH, water temperature, conductivity, total dissolved solids (TDS) and dissolved oxygen saturation (%) were measured by a HANNA multi-parameter probe on site. Velocity was measured at 0.6 times of total water depth from water surface by using Global Flow Probe (Xylem brand) at 1 m interval across the wetted river channel. Discharge was calculated from velocity and cross-sectional area of wetted river channel. Proportion of flow types such as %riffle, %run and %pool within sampling stream reach was visually estimated before sampling benthic macroinvertebrates.

2.3. Benthic macroinvertebrates sampling and processing

At each selected site, about 50–100 m river reach was sampled for benthic macroinvertebrates. A total of 10 sub-samples from different substrates were collected at each site and combined to make one composite sample (Tachamo Shah et al., 2015). The substrate coverage was estimated at 10% intervals. Increase in specific substrate coverage increased number of sub-samples from that particular habitat. Benthic samples were collected by placing a hand-net of mesh size 500 µm against the flow of the river and disturbing the substrate for a minute to dislodge macroinvertebrates attached to surfaces of boulder, cobble, stone, gravel or sand (Barbour et al., 1999). The collected benthic macroinvertebrates were preserved in a sample bottle containing 80% ethanol for further laboratory analysis. Substrate type, depth and velocity at the site were recorded for each sub-sample prior to benthic sample collection. In the laboratory, benthic samples were sorted and identified at genus (mainly Ephemeroptera, Plecoptera, Trichoptera, Mollusca and Oligocheata except for Tubificidae), family (Coleoptera, Heteroptera, Odonata, Diptera, Lepidoptera and Megaloptera) and subfamily (Chironomidae and Psephenidae) levels using available keys (Morse et al., 1994; Assess-HKH internal keys, 2006; Nesemann et al., 2007; Nesemann et al., 2011). Identified samples were preserved in vials containing 80% ethanol at the Aquatic Ecology Centre of Kathmandu University.

2.4. Statistical analyses

The crossed anova was carried out to check for the effects of seasons and sites in taxonomic richness and abundance of benthic macroinvertebrates. Package "car" (Fox and Weisberg, 2019) was installed to perform the analysis.

Non-metric Multidimensional Scaling (NMDS) was used to group the sites according to seasons. Another NMDS plot was developed to examine the impact of water abstraction on composition of benthic macroinvertebrates. Sørenson's distance measure was applied in the ordination plot in R software. NMDS ordination is a robust ordination technique for exploring similarities or dissimilarities in biological data as it does not require any assumptions of multivariate normality and yields good results even when large numbers of data sets have zero values (Clarke, 1993). Benthic macroinvertebrates abundance were transformed to log (x + 1) prior to NMDS analysis. The first NMDS was performed on data representing three eco-regions – High Mountain, Mid-Hills and Lowland. The second NMDS was carried out excluding lowland and dam sites. Rare taxon with ≤3 individuals were removed prior to data transformation, reducing the taxa count from 174 to 139. Permutational Multivariate Analysis of Variance (PERMANOVA) was carried out with the Adonis function in R/vegan to test to check whether benthic macroinvertebrate assemblages differed significantly among seasons, eco-regions and water abstraction classes. The Bray-Curtis distance was used as distance measure in the community data.

A detrended correspondence analysis (DCA) was performed on benthic macroinvertebrate abundance to determine whether the distributions of the datasets are linear or unimodal (ter Braak and Smilauer, 2002). As the length of the first DCA axis (longest gradient) did not exceed 3.0 SD in benthic macroinvertebrate data (2.34 SD), the linear ordination method, redundancy analysis (RDA), was applied to explore how much variance in the benthic data could be explained by environmental variables, such as pH, conductivity, water temperature, oxygen saturation (%), total dissolved solids (TDS), water depth, water velocity, % riffle, % run and % pool. Prior to RDA, multicollinearity test was conducted and "TDS" was removed due to high collinearity ($r > 0.70$) in the final RDA plot. R "vegan" package was used in multivariate analysis.

Indicator species (Ind Val) analysis is widely used in long-term environmental monitoring for habitat or species conservation. Indicator species analysis seeks the relationship between species occurrence or abundance values from a set of sampled sites and classification of sites, which may represent habitat types or disturbance states. Indicator species analysis requires two components, namely, the community data matrix and the vectors that classify sites into groups (De Cáceres, 2013). It calculates relative frequency of species within group (Fidelity) and concentration of abundance within particular groups (Exclusivity). The Ind Val indicates the state of ecosystems by determining the effects of environmental change on biotic community within the study area. The Ind Val requires a package "labdsv" for running indval function in R software. All the analyses were performed in R package (R Core Team, 2018).

A one-way analysis of variance (ANOVA) was conducted to evaluate seasonal variation in the three water abstraction categories: none to slight abstraction (< 30%), moderate abstraction (> 30 – < 80%) and heavy abstraction (> 80%) in sampling sites.

3. Results

3.1. Seasonal changes in macroinvertebrate community composition

A total of 112, 146, 119 taxa representing 68, 79 and 76 families of macroinvertebrates were recorded for post-monsoon (November), baseflow (February) and pre-monsoon (May) seasons, respectively. Families belonging to orders/classes: Ephemeroptera, Plecoptera, Trichoptera, Coleoptera, Diptera, Heteroptera, Odonata, Lepidoptera, Megaloptera, Oligochaeta and Mollusca were recorded in all three seasons while families representing Decapoda, Hirudinea, Hydrachnidia and Turbellaria were additionally recorded only in baseflow and pre-monsoon seasons. Overall taxonomic richness and abundances were not different among seasons at natural sites, but some groups were significantly different among seasons for abstracted sites.

The study revealed that Trichoptera was the dominant order followed by Diptera (Fig. 2). A total of 5 functional feeding groups (FFGs) were recorded in the study sites (Fig. 3a,b). Collector-gatherers and shredders shared over 30% and < 5% of taxonomic richness, respectively while predators and scrapers shared similar percentage (> 20%) of taxonomic richness for the seasons (Fig. 3a). Collector-gatherers were the most dominant taxonomic group and accounting for nearly 60% of overall benthic macroinvertebrates abundance. Shredders made up < 2% of overall benthic macroinvertebrates abundance across the three seasons (Fig. 3b). Collector-filterers were found to be more stable

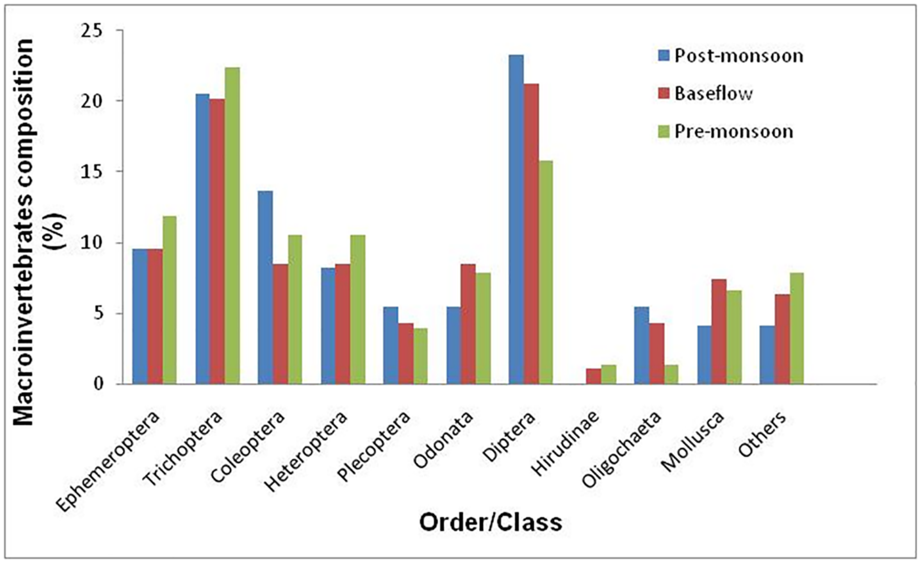


Fig. 2. Faunal composition of benthic macroinvertebrates across seasons. Others comprise of Lepidoptera, Megaloptera, Hydrachnidia and Decapoda.

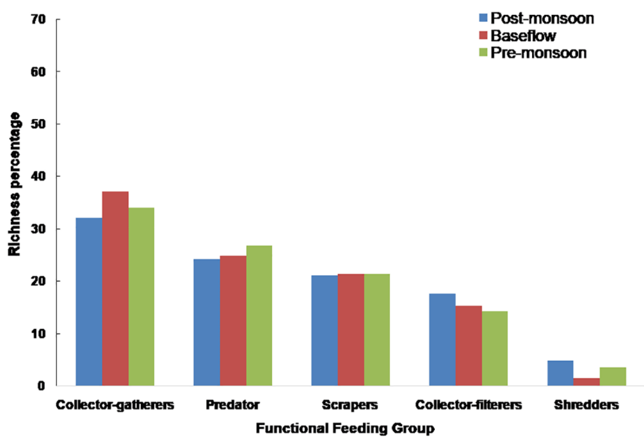


Fig. 3a. Functional Feeding Groups (FFGs) relative richness across seasons.

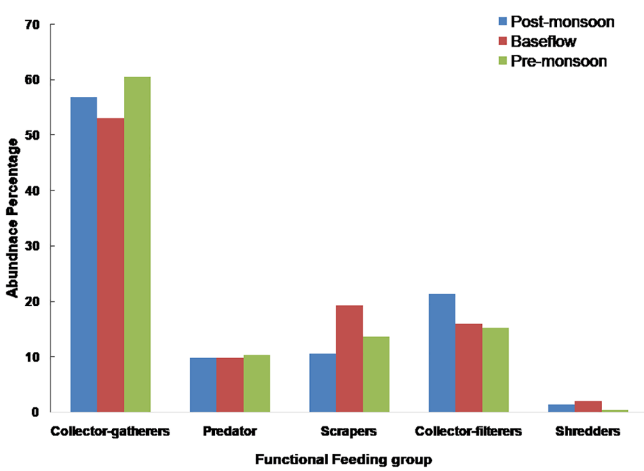


Fig. 3b. Functional Feeding Groups (FFGs) relative abundance across sampling seasons.

in terms of both richness and abundance (15–21%). No significant difference in composition and richness of FFGs between natural and abstracted sites were found for any of the seasons.

In the NMDS ordination for all sites, the distribution of sampling sites reflected both seasonality and eco-regions (stress = 0.175; Fig. 4).

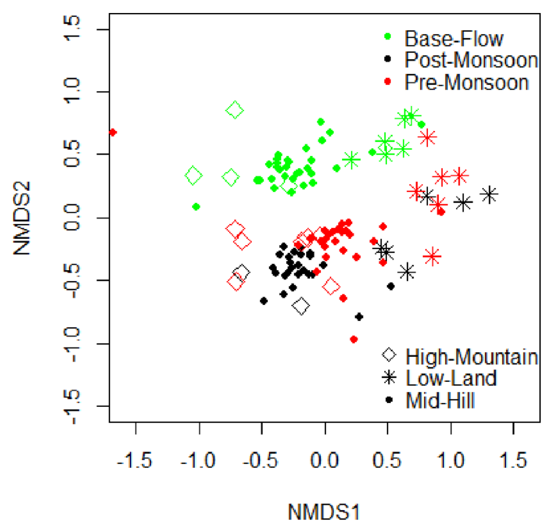


Fig. 4. Distribution of sites in NMDS ordination plot revealing groups of sites per seasons and eco-regions.

The sampling sites of the baseflow season (see Fig. 4) were located in the upper portion of the ordination map, while the sites of the post-monsoon and pre-monsoon seasons were located at the bottom of the ordination map. Despite abstraction intensity, sites were clustered by eco-region revealing similar community structure in sites of an eco-region. PERMANOVA revealed that there were significant differences in benthic macroinvertebrates assemblages across seasons ($F = 15.059$, $df = 2$, $p < 0.001$) and eco-regions ($F = 9.2149$, $df = 2$, $p < 0.001$). High mountain values are clumped to the left in the ordination map while Mid-Hill symbols and Lowland sites spread in the middle and to the right respectively in the ordination map, revealing spatial differences in benthic macroinvertebrate assemblages across the three eco-regions. Abstractions of river water were difficult to record in Lowland sites, and clustered with dam sites in Mid-Hill sites. Therefore, a second NMDS plot was created only for sites of High-Mountain and Mid-Hills to visualize clustering of sampling sites across different water abstraction categories (Fig. 5). PERMANOVA indicated differences among 3 water abstraction categories i.e., none to slight abstraction (< 30%), moderate abstraction (> 30 – < 80%) and heavy abstraction (> 80%) ($p = 0.047$).

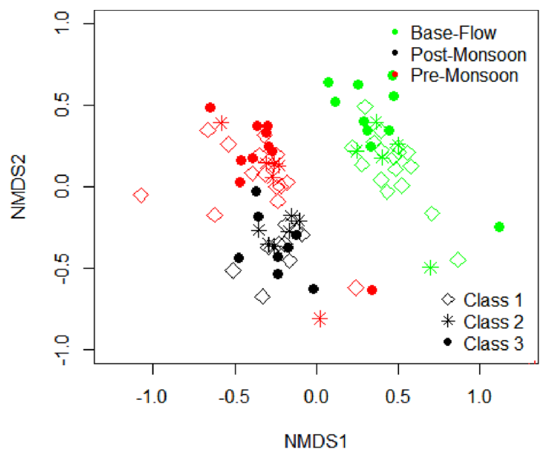


Fig. 5. Clustering of seasonal sites across 3 water abstraction classes. Significant clusters of sites as per water abstraction classes are presented in polygons for baseflow season (green points).

3.2. RDA analysis

The first two axes, roughly associated with velocity and water temperature, explain 66% of the taxonomic variance, with eigenvalue of $\lambda 1 = 0.050$ and $\lambda 2 = 0.028$, respectively. Three RDA axes were found highly significant (RDA1, $F = 10.6279$, $df = 1$, $p = 0.001$; RDA2, $F = 6.7487$, $df = 1$, $p = 0.001$, RDA3, $F = 3.184$, $df = 1$, $p = 0.006$). The sum of canonical eigenvalues was 0.2326. The RDA biplot (Fig. 6) illustrates the correlations of environmental variables and computed axes. The highest R^2 of regression with the first two axes were water velocity (32%) and temperature (18%), with velocity associated with the second axis and temperature mostly with the first. A strong negative correlation existed between the first axis and water temperature (r = -0.50), while oxygen saturation (DO%) correlated positively (r = 0.27). The second axis correlated strongly with velocity ($r = -0.68$), riffle ($r = -0.43$) and water depth ($r = -0.34$).

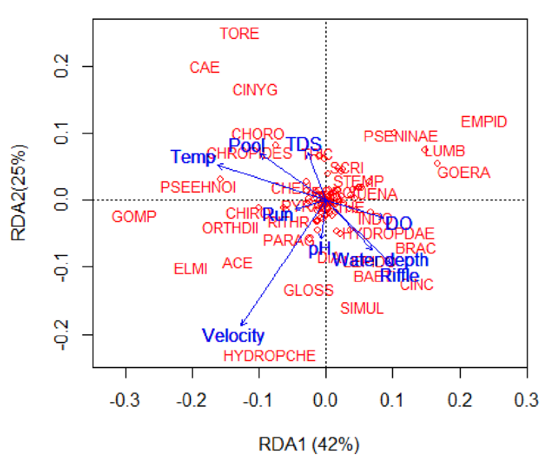


Fig. 6. RDA biplot of exploring environmental variables explaining variance in benthic macroinvertebrate communities. Taxa abbreviations are TORE = *Torleya* sp., CAE = *Caenis* sp., CINYG = *Cinygmina* sp., CHORO = *Choroterpes* sp., CHOROPIDES = *Choroterpides* sp., PSEEHNOI = Psephenoidinae, CHET = *Chematopsyche* sp., GOMP = Gomphidae, CHIRO = Chironominae, RITHRO = *Rithrogena* sp., ORTHDII = Orthocladiinae, ELMI = Elmidae, ACE = *Acentrella* sp., PARAG = *Paragnetina sp.*, GLOSS = Glossosomatinae, HYDROPSCHE = *Hydropsyche* sp., SIMUL = Simullidae, CINC = *Cincticostella* sp., BAETI = *Baetiella* sp., BRAC = *Brachycentrus* sp., INDO = *Indonemoura* sp., GOERA = *Goera* sp., LUMB = Lumbriciidae, EMPID = Empididae, PSENINAE = Psepheninae (anticlockwise). Significant environmental parameters are Temp = Temperature, Pool, Riffle and Velocity.

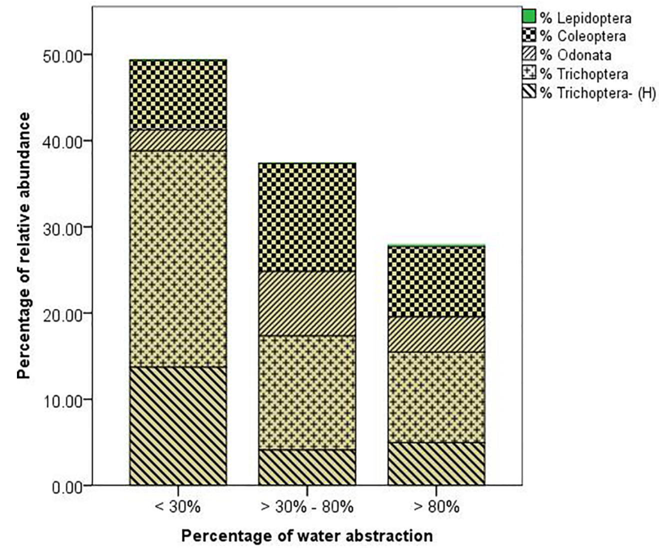


Fig. 7. Significant indicator taxonomic orders for water abstraction class.

3.3. Indicator species analysis

Indicator species analysis identified four indicators, namely, relative Trichoptera abundance for “None to Slight water abstraction”, relative Coleoptera and Odonata abundance for “Moderate water abstraction” and relative Lepidoptera abundance for “Heavy water abstraction” for all seasons (Fig. 7). For pre-monsoon season, relative Trichoptera and total abundance were identified as indicator groups for “None to Slight water abstraction” and Heavy water abstraction”, respectively from their high relative abundances.

3.4. Seasonal variation in water abstractions

The results of the ANOVA indicated significant seasonal variations in water abstractions (Wilk’s Lambda = 0.697, $F_{(2, \ 28)} = 4.215$, $p = 0.025$, $n^2 = 0.23$). Follow up comparison tests indicated that water abstractions were significantly different during baseflow ($p < 0.04$) and pre-monsoon season ($p < 0.02$) compared to post-monsoon season, while no significant difference was observed between baseflow and pre-monsoon seasons ($p = 0.21$).

4. Discussion

The present study suggests that temporal change in river discharge accompanied by consistent water abstraction is a strong driver of benthic macroinvertebrate assemblage structure, including trait composition. Significant variations in abundance of benthic macroinvertebrates in sites across the seasons (R-squared = 0.1192, $F_{(5,96)} = 3.734$, p-value = 0.003) indicate that reduced stream flow alters benthic macroinvertebrates composition. Reduction in flow regimes affects macroinvertebrate abundance and composition due to alterations in food availability, nutrient flow and dispersal mechanisms (Dewson et al., 2007b, Kennedy and Turner, 2011). However, richness was found less affected across seasons, between natural and abstracted classes, or even among abstraction classes which might be due to replacement of lotic taxa by lentic taxa between early seasons (*sensu* Bogan and Lytle, 2012). In this study, we found that some of the sensitive trichopteran in baseflow and pre-monsoon seasons were replaced by lentic taxa such as Depapoda, Hirudinea and Hydrachnidia. Our results highly supports the general findings that increase water diversions reduces river discharge in downstream river stretches affecting biological community (Anderson et al., 2015, Castella et al., 1995, Dewson et al., 2007b, McIntosh et al., 2002,). The altered

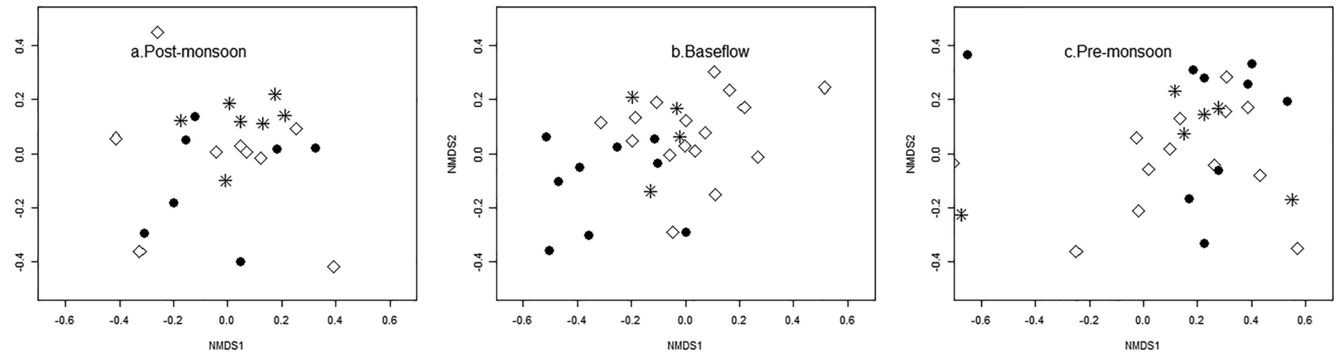


Fig. 8. NMDS plots for (a) post-monsoon, (b) baseflow and (c) pre-monsoon seasons. Symbols "Diamond" (◊), "Filled circle" (●) and strikes (✱) represent sites belonging to Class 1 (water abstraction < 30%), Class 2 (water abstraction > 30 – < 80%) and Class 3 (water abstraction > 80%).

macroinvertebrate community composition in the reduced flows in the regions is mainly dominated by sensitive taxa with tolerance scores above 4 which contradicts community composition in urban river reaches dominated by tolerant taxa of tolerance scores below 4 (Tachamo Shah and Shah, 2013). The river reaches in urban areas are stressed not only by water diversions but also influenced by organic pollutions and river bed mining. Water diversions that lead to river channelization can even cause serious impacts on diversity and density of aquatic organisms. A study conducted by Kennedy and Turner (2011) found 50% lower of benthic macroinvertebrates in channelized reaches.

Although it was difficult to disentangle macroinvertebrates variation across the three water abstraction categories in the NMDS plot (Fig. 5), distinct patterns of benthic macroinvertebrates across three water abstraction categories could be visualized in the season-specific NMDS plot for the baseflow season ($F = 2.087$, $R^2 = 0.126$, $p = 0.008$) (Fig. 8a–c). At sites of intensive water abstraction, a prolonged dry season can dry out downstream river segments making habitats unsuitable for colonization by organisms. Existing organisms may escape these habitats as well (e.g., Lytle et al., 2008) which was true in this study for heavily abstracted sites in particular Chipke River (Fig. 9a, b). Loss of longitudinal connectivity of river could influence long-term abundance of macroinvertebrates downstream due to failure of drifts of these organisms (*sensu* Brewin and Ormoerod, 1994b).

In general, EPT taxa are sensitive to flow alteration (Lenat, 1993) and abundance of EPT increases in high stream flows (Holt et al., 2014). Our results partly corroborate the findings of Holt et al. (2014) as abundance of Trichoptera (T) was lower at sites of increased water abstraction. Likewise, many of the EPT taxa were found positively associated with water velocity and riffles (Fig. 6). "Water Abstraction (Moderate) – Class 2" samples had increased abundance of Coleoptera and Odonata species indicating that river habitat alteration might have favored colonization of tolerant species (occurring in warm water and low flows) as opposed to more sensitive groups such as Trichoptera [occurring in adequate flows that provide clean, cool and oxygenated water (Brown et al., 1999, Timbol and Maciolek, 1978)]. Contrary to results from Castella et al. (1995) who assessed impacts of water abstractions for public water supply, energy production, fish farming and irrigations, our results did not demonstrate strong patterns of changes within many taxonomic groups. Sabater et al. (2018) have reported that that reduced flow regime due to irrigational water abstraction and channelization showed minor effects on river organisms, especially benthic macroinvertebrates, compared to when the flow was altered by dam operation but see Kennedy and Turner (2011). This is because dams completely (storage) or partially (fish ladders or release gates) block water flow, while irrigation water abstraction or channelization are run-of-river models allow where water continues to flow downstream of the intervention.

Since this study was conducted in rivers that were mainly affected by water diversions for irrigation, operations of micro-hydropower and water mills, changes in water quality parameters were not much distinguished in this study i.e., maintaining water quality parameters well above suitable to aquatic biodiversity. Reduced flows are known to affect physical and chemical characteristics of refugial waterbodies. In particular, the conductivity and diel temperature ranges usually increase, and dissolved oxygen concentrations usually decrease as waterbodies dry out (Boulton and Suter, 1986, Sheldon and Fellows, 2010). Increased water abstractions create unfavorable conditions for rheophilic macroinvertebrates (Castella et al., 1995, Fenoglio et al., 2007) such as the trichopterans. In abstracted sites, rheophiles are normally replaced by lentic or tolerant species (Death et al., 2009; Boix

Fig. 9. a) Chipke downstream during dry-period of sampling. Since, it was dried during pre-monsoon season, benthic samples did not collect for the season and collected only in post-monsoon and baseflow seasons and b) macroinvertebrates: Corydalidae belonging to Megaloptera found below the stone of recently dried river reach.

et al., 2010). Therefore, it is not surprising that abstracted sites in this study are favored by non-rheophilic groups such as Coleoptera, Odonata and Lepidoptera. We found many tolerant taxa such as *Caenis* sp., Chironominae, *Cheumatopsyche* sp., *Choroterpis* sp., Empididae, Lumbricidae etc. associated with high temperature, total dissolved solids and pool sites (Fig. 7). Elevated water temperature could enhance pupation frequency and emergence rate in macroinvertebrates (Verdonschot et al., 2015, Wooster et al., 2016). Similarly, Sabater et al. (2018) found a three-fold increase in downstream river metabolism as indicated by increased gross primary productivity and respiration as a response to accumulation of organic matter in low flow associated to damming and water abstraction.

In headwaters, availability and quality of food resources to benthic macroinvertebrates are depended on amount of allochthonous organic matters inputs from river banks (Vannote et al., 1980). Shredders and collector-gatherers make best foods out of the allochthonous inputs in the headwater reaches. But weak connection between river channel and riparian zone induced by low river discharges in the headwaters resulted decline numbers of shredders and collector-gatherers. These findings are corroborated with the results that hydrological modified sites have low diversity of collector-gatherers and shredders compared to natural sites (McKay and King, 2006; Dewson et al., 2007a). Changes in feeding groups might be due to reduction in trichopteran individuals in abstracted sites as they are sensitive to reduced flow regimes (McKay and King, 2006). On contrary, increased scrapers during low-flow seasons might be due to growth of algae which are enhanced with reduced flow and increased water temperature. Though our study illustrated small effects of water diversions on benthic macroinvertebrate community, the consequences of long term water diversion projects in river networks could have severe effects in water stress regions like in western Himalaya (*sensu* Boix et al., 2010; Boulton, 2003; Sabater et al., 2018).

In our study, some of the sampling sites, for example, Chipke River in the Karnali River basin and Ghatte River in the Mahakali River basin, were found dry during the pre-monsoon sampling season due to same quantity of water abstractions as in other seasons though there is naturally less flow in the season. Dewatering of stream reaches inhibits drifting of larvae downstream and upstream migration of juveniles of species (Brasher, 2003; Brewin and Ormerod, 1994a). The most important finding from this study was that macroinvertebrates richness did not significantly change even at > 80% of water abstraction. Similar results were recorded in an experimental flow-diversion study in New Zealand where a reduction in discharge by up to 90% caused relatively few effects on macroinvertebrate abundance and composition (James and Suren, 2009). With reduction in flow regimes, habitat and volume contract that in turn increases abundance and richness of macroinvertebrates and fishes in the short-term (Acuña et al., 2005; Stubbington et al., 2011).

Our study emphasized some of the effects of water diversion on headwaters of Western Himalaya, such as reduced abundance of rheophiles (Trichoptera taxa) and increased frequency and abundance of non-rheophilic taxa of Coleoptera, Odonata and Lepidoptera in disturbed sites. Our study provides evidence of abstraction effects on the phenology of sensitive species of macroinvertebrates which are the primary consumers, detritivores and prey in aquatic ecosystems.

In summary, the impact of water diversions in headwaters had little impact on benthic macroinvertebrates assemblages and river health in the Western Himalayas in Nepal. Water abstraction < 80% of the driest period (baseflow) of the year did not seem to influence benthic macroinvertebrates diversity and abundances in headwaters of the Himalaya under least hydro-morphological changes and pollution status in the rivers. It can be speculated that environmental flow atleast of 20% of river discharge for baseflow season should have minimum consequences on the benthic macroinvertebrate community composition in the headwaters of Western Himalaya. However, reduction in flow discharge in rivers coupled with increased water temperature and pollution due to waste discharge from the settlement into rivers and extraction of river beds is likely to impact benthic macroinvertebrate community and hence affect river health. This study demonstrates that run-of-river water diversions have little impact on river health and macroinvertebrate community composition in River Quality Classes (RQC) I and II (i.e., High and Good river quality status, respectively).

Acknowledgements

The project was made possible through funding from the United States Agency for International Development (USAID), U.S. Embassy, Kathmandu, Nepal. Grant Award Number: AID-367-IO-16-00002. Authors are thankful to Ms. Claire Swingle (IWMI – Princeton in Asia) for English editing of the manuscript. Authors are grateful to Dr. Kashmira Kakati and Netra Sharma (Sapkota USAID, Nepal) and anonymous reviewers for many helpful comments and constructive suggestions.

References

Acuña, V., Muñoz, I., Giorgi, A., Omella, M., Sabater, F., Sabater, S., 2005. Drought and postdrought recovery cycles in an intermittent Mediterranean stream: structural and functional aspects. J. North Am. Benthol. Soc. 24, 919–933.
Anderson, D., Moggridge, H., Shucksmith, J.D., Warren, P.H., 2015. Quantifying the Impact of water abstraction for low head 'run of the river' hydropower on localized river channel hydraulics and benthic macroinvertebrates. River Res. Appl. 33, 202–213.
Assess-HKH internal keys, 2006. Development of an assessment system to evaluate the ecological status of rivers in the Hindu Kush-Himalayan region. .
Balian, E.V., Segers, H., Lévèque, C., Martens, K., 2008. The Freshwater Animal Diversity Assessment-an overview of the results. Hydrobiologia 595, 627–637.
Barbour, M.T., Gerritsen, J., Snyder, B.D., Stribling, J.B., 1999. Rapid bioassessment protocols for use in streams and wadeable rivers: periphyton, benthic macroinvertebrates and fish. US Environmental Protection Agency, Office of Water, Washington, DC.
Bogan, M.T., Lytle, D.A., 2012. Severe drought drives novel community trajectories in desert stream pools. Freshw. Biol. 56, 2070–2081.
Boix, D., García-Berthou, E., Gascon, S., Benejam, L., Tornés, E., Sala, J., Benito, J., Munné, A., Solá, C., Sabater, S., 2010. Response of community structure to sustained drought in Mediterranean rivers. J. Hydrol. 383, 135–146.
Boulton, A.J., 2003. Parallels and contrasts in the effects of drought on stream macroinvertebrate assemblages. Freshw. Biol. 48, 1173–1185.
Boulton, A.J., Suter, P.J., 1986. Ecology of temporary streams—an Australian Perspective. In: De Deckker P., Williams W.D. (eds) Limnology in Australia. Monographiae Biologicae, vol 61. Springer, Dordrecht.
Brasher, A.M.D., 2003. Impacts of human disturbances on biotic communities in Hawaiian streams. Bioscience 5311, 1052–1060.
Brewin, P.A., Ormerod, S.J., 1994. Macroinvertebrate drift in streams of the Nepalese Himalaya. Freshw. Biol. 32, 573–584.
Brewin, P.A., Ormerod, S.J., 1994. The drift of macroinvertebrates in streams of the Nepalese Himalaya. Freshw. Biol. 32, 573–584.
Brown, L.R., Brasher, A.M., Harvey, B.C., Matthews, M., 1999. Success and failure of nonindigenous aquatic species in stream systems: Case studies from California and Hawaii. In: Claudi, R., Leach, J.H. (Eds.), Nonindigenous Freshwater Organisms: Vectors, Biology, and Impacts. Lewis Publishers, Boca Raton (FL), pp. 415–430.
Bunn, S.E., Arthington, A.H., 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. J. Environ. Manage. 30, 492–507. https://doi.org/10.1007/s00267-002-2737-0.
Caiola, N., Ibanez, C., Verdu, J., Munne, A., 2014. Effects of flow regulation on the establishment of alien fish species: a community structure approach to biological validation of environmental flows. Ecol. Ind. 45, 598–604.
Castella, E., Bickerton, M., Armitage, P.D., Petts, G.E., 1995. The effects of water abstractions on invertebrate communities in U.K. streams. Hydrobiologia 308, 167–182.
Clarke, K.R., 1993. Non-parametric multivariate analyses of changes in community structure. Aust. J. Ecol. 18, 117–143.
De Cáceres, M., 2013. How to use the indicspecies package (ver. 1.7.1). http://137.122.187.16/cran/web/packages/indicspecies/vignettes/indicspeciesTutorial.pdf.
Death, R.G., Dewson, Z.S., James, A.B., 2009. Is structure or function a better measure of the effects of water abstraction on ecosystem integrity? Freshw. Biol. 54, 2037–2050.
DePauw, N., Hawkes, H.A., 1993. Biological monitoring of river water quality. In: Walley, W.J., Judd, S. (Eds.), River Water quality monitoring and control. Aston University, Birmingham, pp. 87–112.
Dewson, Z.S., James, A.B.W., Death, R.G., 2007a. Invertebrate responses to short-term water abstraction in small New Zealand streams. Freshw. Biol. 52, 357–369.
Dewson, Z.S., James, A.B.W., Death, R.G., 2007b. A review of the consequences of decreased flow for instream habitat and macroinvertebrates. Journal of the North American Benthological Society 26, 401–415.
Dynesius, M., Nilsson, C., 1994. Fragmentation and flow regulation of the river systems in the northern third of the world. Sci. 266, 753–762.
Fenoglio, S., Bo, T., Cucco, M., Malacarne, G., 2007. Response of benthic invertebrate

assemblages to varying drought conditions in the Po river (NW Italy). Italian Journal of Zoology 74, 191–201.
Fox, F., Weisberg, S., 2019. An R Companion to Applied Regression, third ed. Sage, Thousand Oaks CA URL: https://socialsciences.mcmaster.ca/jfox/Books/Companion.
GoN (Government of Nepal), 2008. National Capacity Self-assessment for Global Environment Management, Government of Nepal/ Ministry of Environment. UNDP; and Global Environment Facility, Science and Technology.
Government of Nepal, Water and Energy Commission Secretariat (WECS), 2002. Available at: https://www.wecs.gov.np/uploaded/irrigation-policy-2060.pdf (Accessed on 14 September 2019).
Government of Nepal, Water and Energy Commission Secretariat (WECS), 2013. National Energy Strategy of Nepal. Available at: http://www.wecs.gov.np/uploaded/National-Energy-Strategy-of-Nepal-2013.pdf (accessed on 21 August 2018).
Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., Cheng, L., Crochetiere, H., Ehalt Macedo, H., Filgueiras, R., Goichot, M., Higgins, J., Hogan, Z., Lip, B., McClain, B.E., Meng, J., Mulligan, M., Nilsson, C., Olden, J.D., Opperman, J.J., Petry, P., Reidy Liermann, C., Saenz, L., Salinas-Rodriguez, S., Schelle, P., Schmitt, R.J.P., Snider, J., Tan, F., Tockner, K., Valdujo, P.H., van Soesbergen, A., Zarfl, C., 2019. Mapping the world's free-690flowing rivers. Nature 569 (7755), 215–221.
Hartmann, A., Moog, O., Stubauer, I., 2010. HKH screening: a field bio-assessment to evaluate the ecological status of streams in the Hindu Kush-Himalayan region. Hydrobiologia 651, 25–37.
Holt, C.R., Pfitzer, D., Scalley, C., Caldwell, B.A., Batzer, D.P., 2014. Macroinvertebrate community responses to annual flow variation from river regulation: an 11-year study. River Res. Appl. 31 (7), 798–807. https://doi.org/10.1002/rra.2782.
James, A., Suren, A., 2009. The response of invertebrates to a gradient of flow reduction – An instream channel study in a New Zealand lowland river. Freshw. Biol. 54, 2225–2242. https://doi.org/10.1111/j.1365-2427.2009.02254.x.
Kennedy, T.A., Turner, T.F., 2011. River channelization reduces nutrient flow and macroinvertebrate diversity at the aquatic terrestrial transition zone. part35. Ecosphere 2. https://doi.org/10.1890/ES11-00047.1.
Lenat, D.R., 1993. A biotic index for the southeastern United States: derivation and list of tolerance values, with criteria for assigning water-quality ratings. J. North Am. Benthol. Soc. 12, 279–290.
Lenat, D.R., 1993. A biotic index for the southeastern United States – derivation and list of tolerance values, with criteria for assigning water quality ratings. J. North Am. Benthol. Soc. 12, 279–290.
Lytle, D.A., Bogan, M.T., Finn, D.S., 2008. Evolution of aquatic insect behaviours across a gradient of disturbance predictability. Pro. Biol. Sci. 275 (1633), 453–462. https://doi.org/10.1098/rspb.2007.1157.
McIntosh, D., Benbow, M.E., Burky, A.J., 2002. Effects of stream diversion on riffle macroinvertebrate communities in a Maui, Hawaii, Stream. River Res. Appl. 18, 569–581 10.1002/rra.694.
McKay, S.F., King, A.J., 2006. Potential ecological effects of water extraction in small, unregulated streams. River Res. Appl. 22, 1023–1037.
Morse, J.C., Yang, L., Tian, L., 1994. Aquatic Insects of China Useful for Monitoring Water Quality. Hohai University Press, Nanjing pp XII + 570 ISBN 7–5630–0240–5.
Nesemann, H., Sharma, S., Sharma, G., Khanal, S.N., Pradhan, B., Shah, D.N., Tachamo, R. D., 2007. Aquatic Invertebrates of the Ganga River System (Mollusca, Annelida, Crustacea [in part]) vol. 1. Kathmandu.
Nesemann, H., Shah, R.D.T., Shah, D.N., 2011. Key to the larval stages of common Odonata of Hindu Kush Himalaya, with short notes on habitats and ecology. J. Threat. Taxa 3, 2045–2060.
Nilsson, C., Liermann, R., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the World's Large River Systems. Sci. 308, 405–408. https://doi.org/10.1126/science.1107887.
Papadaki, C., Soulis, K., Munoz-Mas, R., Martinez-Capel, F., Zogaris, S., Ntoanidis, L., Dimitriou, E., 2016. Potential impacts of climate change on flow regime and fish habitat in mountain rivers of the south-western Balkans. Sci. Total Environ. 540, 418–428.
Poff, N.L., Zimmerman, J.K.H., 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshw. Biol. 55, 194–205.
Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime. Bioscience 47, 769–784.
R Core Team, 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna https://www.R-project.org.
Sabater, S., Bregoli, F., Acũna, V., Barceló, D., Elosegi, A., Ginebreda, A., Marće, R., Mũnoz, I., Sabater-Liesa, L., Ferreira, V., 2018. Effects of human-driven water stress on river ecosystems: a meta-analysis. Sci. Rep. 8, 1–11. https://doi.org/10.1038/s41598-018-29807-7.
Schneider, S.C., Petrin, Z., 2017. Effects of flow regime on benthic algae and macroinvertebrates-A comparison between regulated and unregulated rivers. Sci. Total Environ. 579, 1059–1072.
Sheldon, F., Fellows, C.S., 2010. Water quality in two Australian dryland rivers: spatial and temporal variability and the role of flow. Mar. Freshw. Res. 61, 864–874.
Stubbington, R., Wood, P.J., Reid, I., Gunn, J., 2011. Benthic and hyporheic invertebrate community responses to seasonal flow recession in a groundwater-dominated stream. Ecohydrol 4, 500–511. https://doi.org/10.1002/eco.168.
Tachamo Shah, R.D., Shah, D.N., 2013. Evaluation of benthic macroinvertebrate assemblage for disturbance zonation in urban rivers using multivariate analysis: Implications for river management. J. Earth Syst. Sci. 122, 1125–1139.
Tachamo Shah, R.D., Sharma, S., Haase, P., Jähnig, S.C., Pauls, S.U., 2015. The climate sensitive zone along an altitudinal gradient in central Himalayan rivers: a useful concept to monitor climate change impacts in mountain regions. Clim Change 132, 265–278.
Ter Braak, C.J.F., Smilauer, P., 2002. CANOCO reference manual and user's guide to Canoco for Windows: Software for Canonical Community Ordination (version 4.5); Microcomputer Power, Thaca, NY, US.
Timbol, A.S., Maciolek, J.A., 1978. Stream Channel Modification in Hawaii, Part A: Statewide Inventory of Streams; Habitat Factors and Associated Biota Columbia (MO) US Fish and Wildlife Service. National Stream Alteration Team FWS/OBS-78/16.
Tonkin, J.D., Death, R.G., 2013. Macroinvertebrate drift-benthos trends in a regulated river. Fund. Appl. Limnol. 182, 231–245.
Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Gushing, E., 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37, 130–137.
Verdonschot, R., Oosten-Siedlecka, A.M., Braak, C.J., Verdonschot, P.F., 2015. Macroinvertebrate survival during cessation of flow and streambed drying in a lowland stream. Freshw. Biol. 60, 282–296.
Ward, J. V., Stanford, J. A., 1983. The serial discontinuity concept of lotic ecosystems. In: Fontaine, T.D., Bartell, S. M. (eds), Dynamics of Lotic Ecosystems. Ann. Arbor. Science: 29-42.
Wooster, D., Miller, S.W., DeBano, S.J., 2016. Impact of season-long water abstraction on invertebrate drift composition and concentration. Hydrobiologia 772, 15–30.
WSHP (West Seti Hydropower Project), 2007. Environmental Assessment Report of Nepal: West Seti Hydropower Project. Available at http://www.aecen.org/eia-documents/eia-west-seti-hydroelectric-project/nepal_eia_report_westsetihydroelectric_2007.pdf. Accessed on 15 June 2018.

Annex 7-1

ARTICLE IN PRESS

Water Resources and Economics xxx (xxxx) xxx

Contents lists available at ScienceDirect

Water Resources and Economics

journal homepage: http://www.elsevier.com/locate/wre

Balancing intersectoral demands in basin-scale planning: The case of Nepal's western river basins

Emily L. Pakhtigian [a], Marc Jeuland [b,*], Sanita Dhaubanjar [c], Vishnu Prasad Pandey [c]

[a] Sanford School of Public Policy, Duke University, 201 Science Drive, Durham, NC, 27708, USA
[b] Sanford School of Public Policy and Duke Global Health Institute, Duke University, 201 Science Drive, Durham, NC, 27708, USA and RWI Leibniz Institute for Economic Research, Essen, Germany
[c] International Water Management Institute (IWMI), Nepal Office, Lalitpur, Nepal

ARTICLE INFO

Keywords:
Ecosystem integrity
Economic optimization
Development priorities
Water resources planning
Hydropower
Irrigation

ABSTRACT

Basin-wide planning requires tools and strategies that allow comparison of alternative pathways and priorities at relevant spatial and temporal scales. In this paper, we apply a hydroeconomic model–the Western Nepal Energy Water Model–that better accounts for feedbacks between water and energy markets, to optimize water allocations across energy, agriculture, municipal, and environmental sectors. The model maximizes total economic benefits, accounting for trade-offs both within and across sectors. In Western Nepal, we find that surface water availability is generally sufficient to meet existing and growing demands in energy and agricultural sectors; however, expansion of water storage and irrigation infrastructure may limit environmental flows below levels needed to maintain the full integrity of important aquatic ecosystems. We also find substantial trade-offs between irrigation in Nepal and satisfaction of the institutional requirements implied by international water-use agreements with the downstream riparian India. Similar trade-offs do not exist with hydropower, however. Model results and allocations are sensitive to future domestic and international energy demands and valuations.

1. Introduction

In underdeveloped countries rich in water resources, the harnessing of water for productive uses creates opportunities for economic development. Water resources provide options for energy generation, agricultural production, industrial development, and navigation. Importantly, though, these various productive uses often entail complex and inter-sectoral trade-offs, including with nonmarket purposes such as support of basic livelihoods activities and environmental conservation. For example, water stored and released for steady electricity generation may conflict with release patterns desired by irrigators [1]; waterways preserved for navigation or ecosystem services may be ill-suited for infrastructure development [2,3]; export-focused production may discount or disregard local resource dependence [4]; and upstream abstractions may threaten the water security of downstream users [5,6]. Development of water resources has often been considered a threat to environmental quality, and many argue that environmental costs are too often ignored [7,8].

The possibility of acute resource use trade-offs highlights the need for careful consideration of competing water demands within a

* Corresponding author.
E-mail addresses: emily.pakhtigian@duke.edu (E.L. Pakhtigian), marc.jeuland@duke.edu (M. Jeuland), sdhauban@gmail.com (S. Dhaubanjar), v.pandey@cgiar.org (V.P. Pandey).

https://doi.org/10.1016/j.wre.2019.100152
Received 15 June 2019; Received in revised form 6 October 2019; Accepted 7 October 2019
Available online 18 October 2019

given river system, using appropriate tools. Without such tools, inefficient decision-making – in terms of infrastructure choices, institutional pressures, and sectoral prioritization – appears likely, for several reasons. First, water resources systems span diverse geographies and administrative boundaries and are physically complex, such that an intuitive or common understanding of their behavior and benefits, in both past and future, may diverge substantially from reality. Second, many water resources planning decisions, particularly those related to infrastructure investment, are irreversible except in the very long term, such that "mistakes" in planning may have significant negative consequences [9,10]. Third, political realities and exigencies imply that diverse stakeholders and perspectives will weigh in heavily on critical infrastructure and resource allocation decisions. Such dynamics complicate policymaking and implementation, and potentially lead to unequal weighting of water demands and infrastructure needs [6], particularly in transboundary rivers. Critically, it is often the needs of local, marginal communities or environmental considerations that receive lower priority in this decision-making process.

Coordinated and integrated river basin planning is just as essential from a national perspective, for both efficiency and equity reasons [11]. Considering first the efficiency lens, the free flow of rivers outside of typical administrative institutional boundaries such as districts or regions creates interdependence in water resource utilization across political zones [12]. Thus, productive water use may be constrained when water resources are misallocated in one region of a basin, due to its geographical or legal advantages over other regions. For example, a small, run-of-the-river hydropower plant may electrify a small locality and be preferred on financial or environmental grounds; however, a large, storage project in the same locality might more efficiently electrify the entire region and provide revenues from export of excess electricity. In the absence of basin-scale plans, resources may be allocated to small projects at the expense of more efficient and larger ones [13].

Looking next through an equity lens, consider, for example, an irrigation project that diverts water from one tributary to another. Such a diversion disrupts natural river flow and reduces water access to communities downstream of the diversion. These localities may then face food and water insecurity if insufficient water flows past the diversion to meet existing irrigation and municipal demands. Concerns over equity are particularly relevant in the presence of an unequal distribution of power; disadvantaged populations or small localities often bear the costs of development of water resources without enjoying its benefits. Equity issues can arise, for instance, due to locational asymmetries (upstream-downstream dynamics) [12], legal ambiguities [14], or differences in socio-economic or political power between different stakeholders [15]. Though trade-offs may be inevitable, a basin-wide perspective is again essential to evaluate the magnitude of such concerns and to adequately account for cross-sectoral interdependencies.

This paper implements a modular hydroeconomic model (HEM) to provide an integrated perspective on water resources development in the Karnali-Mohana and Mahakali River basins of western Nepal [16]. The modular approach incorporates energy, agricultural, domestic, and environmental perspectives around a core water balance model from which water control and allocations can be specified. The objective of the constrained optimization WNEWM (Western Nepal Energy Water Model) is to maximize total economic benefits within these river basins, accounting for trade-offs both within and across sectors. As western Nepal is on the cusp of economic development and the region's water endowments are often highlighted as a key asset to be leveraged for future growth, our multi-sector analysis approach provides information on potential benefits and their distribution across space, time, sectors, and populations, all of which are of interest to policy makers in Nepal. To frame the analysis, we work from scenarios oriented around three differentiated stakeholder visions–large-scale infrastructure development, limited infrastructure development, and environmentally sensitive development–the development of which was informed by detailed document reviews and stakeholder consultations, as described elsewhere [17].

We consider several specific questions in our analysis of these different water resources development visions for western Nepal. First, what are the economic benefits associated with various development pathways for western Nepal? Second, how does incorporation of environmental and municipal water demands constrain the benefits derived from energy generation and irrigation development? And third, how are these benefits distributed across space and sectors?

The remainder of the paper is as follows. Section 2 provides background on relevant HEM literature that helps to inform construction of the WNEWM model. Section 3 describes the context of our analysis, which covers the Karnali-Mohana and Mahakali River basins. Section 4 describes the key features and assumptions of the WNEWM, including details regarding model parameterization, data sources, and model simplifications required due to data limitations. Section 5 reports the overall results and highlights the trade-offs within and across regional development pathways. Section 6 concludes with a discussion of these results, limitations of the analysis, and implications for policy.

2. Background: hydroeconomic modeling

In providing an economic perspective on more efficient water use, HEMs represent an important tool for river basin planning. They offer a way to compare the economic benefits of potential competing water use allocation schemes or infrastructure choices within a flexible and customizable framework that accounts for system interdependencies [18]. Such models help to inform policy makers regarding the efficient use and distribution of water resources and benefits throughout a system, incorporating tools and principles from engineering, hydrology, and economics. A major strength of such models is their usefulness for analyzing the sectoral, spatial, and temporal trade-offs inherent in water resource use decisions.

HEMs have traditionally been grouped into simulation or optimization models [18,19], depending on the approach used for scenario analysis or generation of efficient water allocations. Wu et al. [6] note a blurring of these categorizations in their discussion of HEMs that compare optimal or near optimal solutions based on extensive analysis of potential scenarios. Pure optimization models are designed to generate the most efficient water allocation under specific conditions that are specified by the user, which may, however, not be optimal under even slightly modified conditions. Simulation methods, meanwhile, can more readily be used to explore a wide variety of situations, and their results can be analyzed to identify solutions that are both nearly optimal and more robust across assumptions about a system's future [19]. HEMs are also commonly used to calculate the marginal productivity of various water uses, rendering these tools valuable to analysis of alternative productive water uses, e.g., agriculture (irrigation) and energy (hydropower) [6].

Studies in the global south using HEMs have focused on optimization of water allocations and infrastructure development for expansion of productive usage of rivers–e.g., for hydropower generation and irrigation–while balancing existing needs and water rights. For example, previous studies have examined water allocation trade-offs in the Nile [20–22], Ganges [6,23], and Mekong [24,25], as well as across multiple basins in Nepal [26]. Indeed, these tools have been applied in major river basin systems in all global regions.

Prior applications have most often focused on specific policy or infrastructure proposals (i.e., the expansion of hydropower infrastructure or use of water storage to regulate river flows), or were developed to consider the implications of exogenous system changes (e.g., climate perturbations), as they percolate through complex and dynamic water resources systems. For example, in the Ganges basin, of which the Karnali-Mohana and Mahakali basins considered in this paper are a part, Wu et al. [6] found that upstream storage infrastructure would do little to reduce downstream flooding, which challenged standard assumptions about infrastructure development in the region at the time [27]. Jeuland et al. [23] used the same model to show that hydropower production from upstream storage projects could meanwhile deliver major benefits, despite sensitivity to uncertainties about future climate change. Considering these results in tandem points to the need to examine multiple water use options and drivers of change with these integrated modeling tools.

At the same time, recent reviews of HEMs have emphasized that some sectoral interactions remain weak or incompletely specified in most applications of these tools [18,19]. Water-energy nexus issues are often underspecified, since typical HEMs only model energy generation using water, ignoring feedbacks that drive water use (e.g., energy demand in agricultural production). Further, transmission systems for water and energy are often excluded. In addition, nonmarket or ecosystem values have only rarely or partially been included [28,29]. HEMs are also typically deficient in their representation of political constraints on behavior, which limits the relevance and accuracy of their predictions in many river basins that span multiple institutional boundaries.

In an effort to tackle some of these deficiencies, this paper implements a new HEM (the WNEWM) that spans two river basins and crosses provinces 6 and 7 in Nepal. By specifying the spatial scope of the model in this way, multiple sectors–agriculture, energy, municipal, and environmental–can be modeled and linked to hydrological and governance systems in parallel, with linkages between sectors (e.g., energy flows to agriculture) and between each sector and river hydrology (e.g., return flows from agriculture to water systems). We additionally incorporate political constraints based on existing water sharing agreements between India and Nepal, as well as linkages that allow for energy export from Nepal.

3. Application: water resources development in the Karnali-Mohana and Mahakali River Basins of western Nepal

The focal area for this study is the Karnali-Mohana and Mahakali River Basins, which together span nearly 55,500 square kilometers of the Karnali and Sudurpaschim provinces of Nepal (Fig. 1).

The region has three distinct ecological zones running north-to-south, the mountains, mid-hills, and Tarai. More than a third of the region is covered by forests, which reflects the underdeveloped nature of the region. Much of the region's land (14% of the Karnali-Mohana and 7% of the Mahakali Basin) is also classified as protected; such areas are key to meeting national conservation and biodiversity preservation goals. These protected areas include four national parks, one wildlife reserve, one hunting reserve, and two

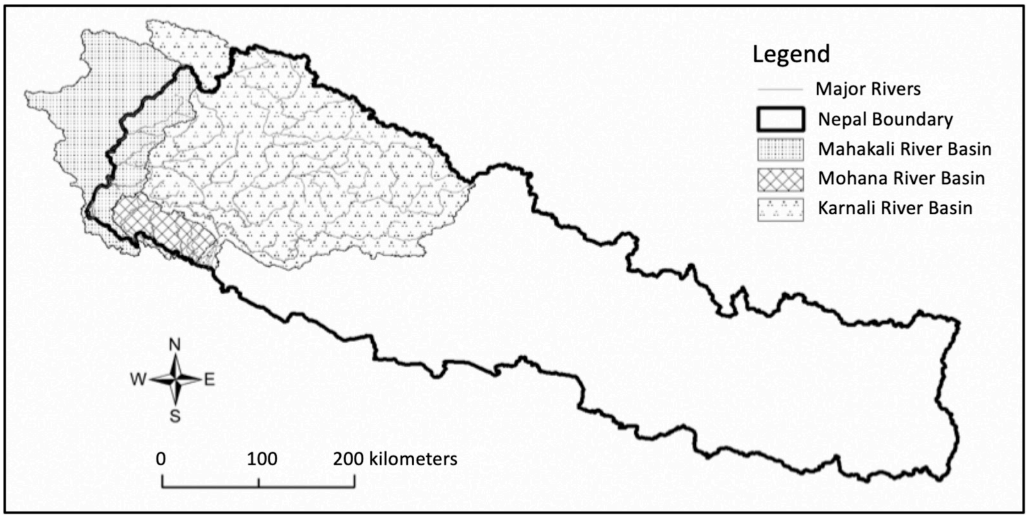


Fig. 1. Location map of the Karnali-Mohana and Mahakali River Basins in western Nepal.

buffer zones. Nevertheless, agriculture is the dominant economic activity throughout the region, but the most productive areas are in the flat plains of the southern Tarai [30]. In addition to agriculture, the region's economy is heavily dependent on remittance payments, with almost 40% of income in the region coming from migrants sending money home from abroad [17].

Nepal's monsoon climate is the dominant factor in determining water availability over time and space. Even though Nepal has ample water resources on average, nearly 80% of rainfall occurs during monsoon months (June–September), and water is especially scarce in the dry winter and pre-monsoon months. Irregular surface water flows challenge all water-dependent sectors. For example, run-of-the-river hydropower projects are less expensive and environmentally disruptive than storage infrastructure, but their power production is inefficient and unreliable in years or months with low flows. Lack of reliable power in turn constrains investment in energy-intensive industries that might drive economic growth, and limits household productivity gains from regular use of appliances or machinery [31]. Meanwhile, irrigators or fishers who depend on water for livelihood activities are typically unable to maintain steady income; in agriculture, this is exacerbated by a lack of energy for water pumping [32].

While rich in natural resources, and most notably water resources and biodiversity, the western regions lag in economic development, even in comparison to central and eastern Nepal [33]. A variety of factors besides water availability–both political and geographical–have constrained development of water resources in western Nepal. For example, while the Karnali-Mohana and Mahakali River Basins have a total hydropower generation potential of around 35,000 MW [34], installed capacity within these basins rests at just 8.5 MW, not including projects smaller than 1 MW (i.e., micro-hydro) for which the Government of Nepal does not issue licenses [35,36]. Similarly, only about 40% of cultivated land in western Nepal is irrigated [37]. While the lack of infrastructure in the region may be indicative of poverty, low investment or a lack of development-minded priorities, there is also considerable difference of opinion over the appropriate extent and scale of infrastructure for development [17]. This lack of consensus makes it difficult for policy-makers to both raise financial resources for projects and to implement them. As such, the region is a sort of training ground for analyzing (using hydro-economic modeling and other approaches) what conflicting development visions might mean at a regional scale–for food production, water utilization, energy generation, export- or locally-driven growth, and sustainable development.

4. Methods

4.1. The WNEWM framework

The objective of the WNEWM is to maximize the total economic benefit within the Karnali-Mohana and Mahakali River basins, from four water-related sectors: (i) energy, (ii) agriculture, (iii) municipal, and (iv) environmental. Each sector is included as a separate but interconnected module in the model. The general model structure is described in Bekchanov et al. [16].

The WNEWM solves a nonlinear, constrained optimization problem that has a monthly time step. It is solved using the CONOPT solver of the General Algebraic Modeling System (GAMS) software. It optimizes monthly water allocations over a flexible (user-specified) time horizon; we use a 12-year period for our analysis. The core of the model is based around a water system module whose structure is provided by a system of nodes and linkages consistent with the surface flow structure of the Karnali-Mohana and Mahakali River Basins, as depicted in the schematic shown in Fig. 2. The basin hydrology is obtained from historical data or flows that are generated outside the model. The basin runoff then runs through a system of 151 nodes; 112 of which are in the Karnali-Mohana River Basin, and 39 of which are part of the Mahakali River Basin. Some of these nodes accommodate storage or run-of-river hydropower facilities, and some include diversions for specific (agricultural, or municipal) uses. The outlet node from each river basin captures water flows that cross the border into India. Accordingly, the model can accommodate inclusion of water distribution agreements surrounding transboundary rivers (i.e., the Mahakali Treaty, or project-specific treaties such as the Grandhi Mallikarjuna Rao Treaty).

While the model core maintains the integrity of the hydrology of the system, each of the four sectors (i.e., energy, agriculture, municipal, environmental) can be activated in the modular structure, allowing each water system node to communicate with energy and agricultural production nodes, municipal/industrial and environmental water demands, and energy and food markets. The parameters of each of these are specified based on population, hydrological, and/or infrastructure development data. The WNEWM model includes 55 energy production nodes; of these nodes, 1 is an existing run-of-the-river scheme, 19 are proposed storage projects (with reservoirs), and 35 are proposed run-of-the-river schemes, as documented in basin master plans, other planning reports [38,39], and lists of licenses granted by the Department of Electricity Development. Additionally, the model includes 37 agricultural nodes; 25 are existing projects and 12 are proposed or currently under construction (these are similarly specified based on irrigation database reports from the Department of Irrigation, project summaries, and Master Plans). Municipal demand and energy demand constraints are estimated using a population-based approach applied to the 2011 national census data. In our application, municipal demands are included at each river node, while three energy markets represent domestic demand in western Nepal, domestic demand in Kathmandu, and export demand in North India. Similarly, one agricultural market exists to represent domestic demand in western Nepal because we only model major crops, and all of these are consumed locally in the region, which is a net importer of food [40]. Finally, environmental constraints maintain minimum flows according to specific rules as described further below.

We include several simplifications to the basic model to allow its application to western Nepal, accommodating the context of the region and in accordance with data availability, as described below. Energy and agriculture benefits are calculated based on the value of hydropower produced and the net benefits from crops grown using basin water, with productive revenues and costs calculated based on location-specific parameters related to marginal benefits, yields, and marginal production costs. Municipal and environmental water demands, for which valuation parameters are not readily available in Nepal, nonetheless constrain water allocations according to location and time-varying demand requirements; the shadow values on these allocations thus indicate the opportunity costs associated with these guarantees. Importantly, the model flexibly allows for examination of various development pathways,

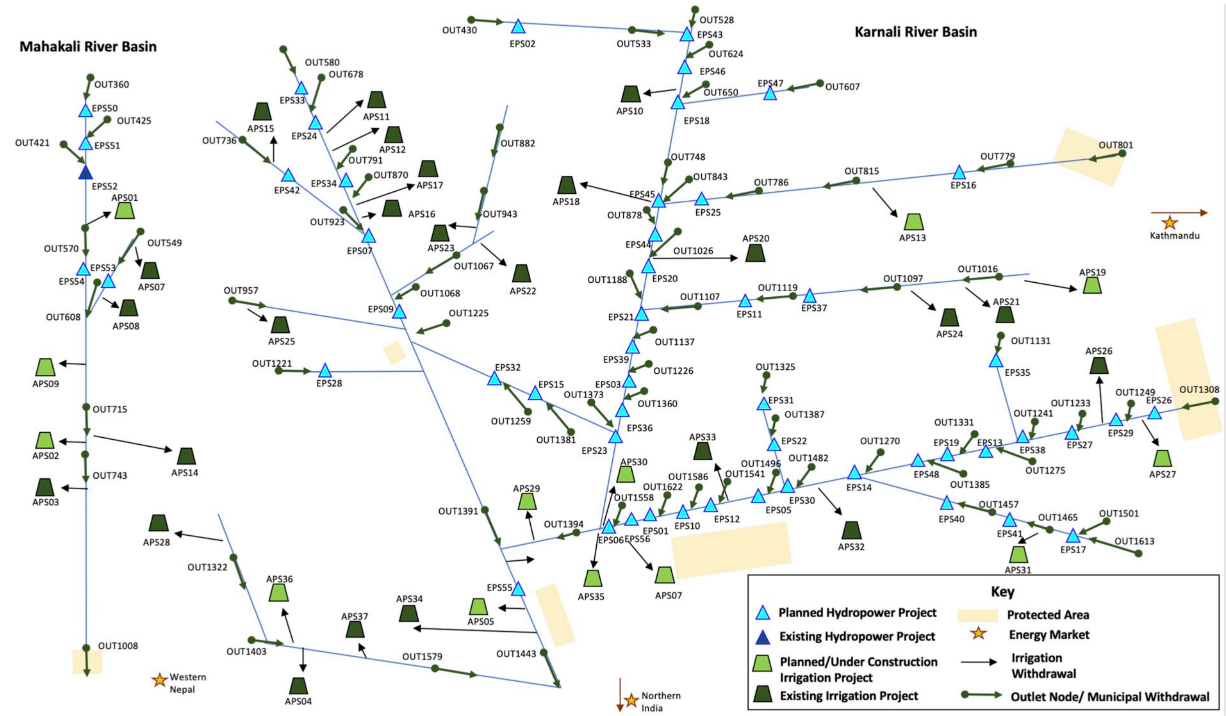


Fig. 2. Schematic of the Karnali-Mohana and Mahakali River Basins based on WNEWM node structure. Outlet nodes near energy and agricultural sites are included for reference; others are omitted to simplify the schematic. All outlet nodes (those included and omitted from schematic) allow for municipal surface water withdrawals based on population estimates.

facilitating analysis of trade-offs that occur across them. For example, model scenarios that focus exclusively on storage-based hydropower expansion can be compared to those that include reduced control (e.g., run-of-the-river schemes). Furthermore, both of these can be analyzed under current and increased energy demand conditions including those that account for energy export opportunities in India.

While the WNEWM HEM approach attempts to incorporate benefits from productive water use while also maintaining municipal and environmental water demands, the objective of benefit maximization may not directly align with stakeholders' and policy makers' goals. In particular, policy makers may be concerned about risks associated with various projects and development pathways; accordingly, they may seek to implement policy decisions that minimize risk, even if potential payoffs of such conservative strategies are limited [10]. Furthermore, data limitations can affect the accuracy of predictions from the model [6]. As such, our WNEWM analyses provide only one of many necessary inputs to planners and are not well suited for generating advice on detailed operations.

4.2. Key equations

The objective function solved by the WNEWM is expressed as:

$$\max B = \sum_{n} \sum_{s \in NSLINK} NB_{n,s} \tag{1}$$

where B is the total economic benefit (US$), calculated as the sum of the net benefits ($NB_{n,s}$) accruing to each sector (s) associated with each river node (n).[1] Within each sector, the net benefits are calculated according to the productivity of the sector as given by the optimal water allocations, which depend on region-specific price and cost parameters, as illustrated for the energy (E) and agricultural (A) sectors by Equations (1a) and (1b), respectively.

$$NB_{n,E} = \sum_{t} \sum_{e \in NELINK} P_e \cdot \left(EP^{ROR}_{e,t} + EP^{HP}_{e,t} \right) - C_{e,t} - T_{e,t} \tag{1a}$$

Here, the net benefits in the energy sector that accrue at each node ($NB_{n,E}$) are calculated by summing the difference between the price of electricity (P_e) multiplied by total energy produced from ROR and storage projects ($EP^{ROR}_{e,t}$ and $EP^{HP}_{e,t}$, respectively) and the costs

[1] Here, and throughout, nodes are connected by linking across sets. For example, in Equation 4.2, $s \in NSLINK$ provides the link between sector and river node.

of producing ($C_{e,t}$) and transmitting ($T_{e,t}$) energy across time (t) and energy production sites (e).

$$NB_{n,A} = \sum_{a \in NALINK} \sum_{cr} P_{a,cr} \cdot Q_{a,cr} - C_{a,cr} \tag{1b}$$

Similarly, the net benefits in the agriculture sector accrued at each node ($NB_{n,A}$) are calculated by summing the differences between the price of each crop ($P_{a,cr}$) multiplied by the quantity of each crop produced ($Q_{a,cr}$) and the costs of production ($C_{a,cr}$) across agricultural production sites (a) and crops (cr).

The core module maintains the water balance at each river node (n) at time (t), while the other modules track flows of energy and water as inputs to production or for use in final demand. Accordingly, the following water balance equation is maintained at each node:

$$\begin{aligned} &\sum_{nu \in NNULINK} WF_{nu,t} + WSRC_{n,t} + \sum_{g \in NGLINK} GWS_{g,t} + \sum_{s \in NSLINK} RF_{s,t} = \\ &\sum_{r \in NRLINK} (EV_{r,t} + \Delta VR_{r,t}) + \sum_{g \in NGLINK} GWC_{g,t} + \sum_{s \in NSLINK} DIV_{s,t} + \sum_{nd \in NNDLINK} WF_{nd,t} \end{aligned} \tag{2}$$

The left-hand side of Equation (2) captures the totality of hydrological inflows, summing across (i) water flowing from upstream nodes ($WF_{nu,t}$), (ii) water generated within the node catchment itself ($WSRC_{n,t}$), (iii) groundwater seepage ($GWS_{g,t}$), and (iv) return flow from productive sectors ($RF_{s,t}$). The right-hand side of Equation 4 captures all hydrological outflows, summing across (i) reservoir evaporation ($EV_{r,t}$), (ii) change in reservoir storage ($\Delta VR_{r,t}$), (iii) surface water lost to groundwater ($GWC_{g,t}$), (iv) water diverted to productive sectors ($DIV_{s,t}$), and (v) water flowing downstream ($WF_{nd,t}$).

Notably, productive use of water in one sector may enhance productivity in another. A clear example of this is electricity generation. Water may be utilized in energy production (primarily through hydropower in western Nepal); this electricity may then be used as an input in agricultural or municipal sectors. In the agriculture sector, mechanization may increase agricultural productivity or electric water pumps may improve irrigation efficiency. In a dynamic system, then, these linkages between sectors must be included. The energy balance is expressed in Equation (3):

$$\sum_{de \in MDELINK} PRD_{de,t} = \sum_{n \in MNLINK} \sum_{s \in NSLINK} EDIV_{s,t} + TB_{m,t} \tag{3}$$

Here the energy produced across all energy nodes ($PRD_{de,t}$) associated with market m must be equal to the sum of the energy diverted to each sector ($EDIV_{s,t}$) and the energy available at market m ($TB_{m,t}$) across all nodes n associated with market m and sector s.

There are additional inter-sectoral linkages in the WNEWM as well. Some of these linkages span the entire set of sectors, similar to the energy balance expressed in Equation (3); others may only link two sectors. Fig. 3 depicts these many interlinkages between the hydrological core of the nexus-based HEM and productive water use sectors and also illustrates schematically the linkages between water use sectors.

4.3. Model assumptions, simplifications, and parameterization

While the WNEWM endeavors to flexibly represent river basin systems for planning purposes, specific applications of the model require additional assumptions and simplifications based on the application context and data availability. This section details these model assumptions and simplifications for each module, along with the data used in model parameterization. Table 1 then summarizes general parameters that are specified, although many project-specific parameters are omitted for the sake of brevity. A database of project-specific parameters used in this specific application is available in Appendix A.

4.3.1. Hydrology core

Hydrological data used as inputs for the WNEWM were generated from a Soil Water Assessment Tool (SWAT) model set up and calibrated using historical observed flows for the Karnali-Mohana and Mahakali River Basins, as described elsewhere [47,48]. SWAT is a rainfall-runoff model that incorporates physical characteristics of rivers and forcing climate datasets to simulate their flows and water availability over time [49]. Reflecting the limited good quality data availability for rivers in the region, the model provides a daily streamflow time series covering a recent but limited period of 12 years (1996–2007), that nonetheless includes some high and low flow periods. These daily time series were aggregated to a monthly level for use in the hydrology core.

4.3.2. Energy

Given that over 99% of Nepal's electricity is from hydropower [50], the current version of the WNEWM limits domestic energy production sites to hydropower. Accordingly, energy production is assigned to nodes that are directly downstream of existing, planned, or proposed projects. As much of this energy production infrastructure does not yet exist, there is variation in the extent of project plans available. For example, while the productive capacity of every project is known, specific project parameters–particularly related to storage dam heights and reservoir capacities–are often lacking. We made two specific assumptions related to reservoir parameters whenever data were insufficient: (i) linear parameterization of volume-height relationships and (ii) transfer of similar parameters (such as tail-end levels and minimum and maximum reservoir heights and volumes) from nearby projects for which plans were available. We note here that linear volume-height reservoir relationships dictate that reservoir height (key in energy production) is lost at a faster rate than it would be in a non-linear relationship that is more typical of reservoir sites. As such, hydropower production that is calculated in the model may be underestimated.

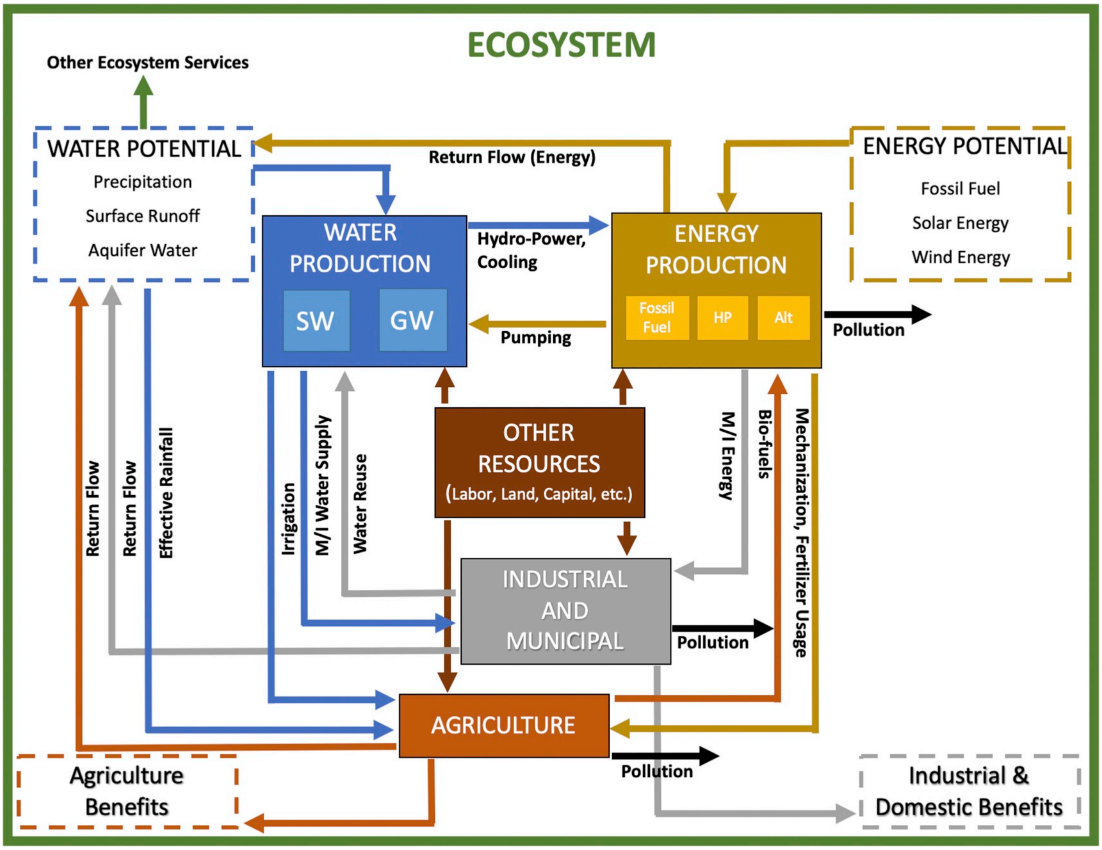


Fig. 3. Linkages between sectors in WNEWM approach.

Table 1
WNEWM parameters.

Parameter Description	Units	Status quo scenario Current conditions	Source
Panel A: Energy			
Electricity price (domestic)	US$/kWh	0.09	[41]
Electricity price (export)	US$/kWh	0.06	[42]
Production cost	US$/kWh	0.024–0.1	[41]
Installed capacity	MW	5–6720	Planning reports
Generation efficiency	none	0.65	[41]
Transmission cost	US$/km	0.001	[41]
Panel B: Agriculture			
Irrigation efficiency	percent	60	[43]
Return flow	percent	20	[43]
Crop prices	US$/MT	vary	[44]
Potential yields	MT/units	vary	[44]
Panel C: Municipal			
Water demand	Lpcd	40	[45]
Water from river	percent	10	DJB survey
Electricity demand	per capita kW-hr/yr	139	[46]
Panel D: Environment			
Minimum flow	MCM	10% of base flow	[36]

The value of electricity was obtained from the official price for energy; it and the cost of electricity production were parameterized using data from recent annual reports from the Nepal Electricity Authority (NEA) [41]. The use of this electricity price likely understates the marginal benefits of energy consumption, since the economy has historically been energy-constrained. The model also incorporates transmission costs and inefficiencies within the system, calculated based on linear distances between energy production sites and the Tarai, as this region is the most populous in western Nepal and represents the major market for electricity in the region. For distribution to other parts of Nepal, transmission costs and losses were calculated based on linear distances to the national capital of Kathmandu. Finally, for distribution to India, these parameters were calculated based on linear distances to the edge of a single potential nearby market in Uttar Pradesh in northern India.

4.3.3. Agriculture

The agricultural sector already uses substantial water resources but also has potential for expanded use. In the agricultural module, water demand was calculated for irrigable areas by differencing crop water requirements (calculated using the CROPWAT and CLIMWAT tools developed by the Food and Agricultural Organization (FAO)) and effective rainfall. Irrigation requirements were then increased to account for inefficiencies in conveyance and application, which together were assumed to be 60% throughout the region, consistent with regions that use similar flood-based irrigation systems. Cropping patterns and cultivable land areas were specified based on district-specific data from the Statistical Information on Nepalese Agriculture reports, which are released annually by the Ministry of Agricultural Development [44]. Crop yields were then determined based on historical agricultural productivity and constrained to avoid water shortages in the most water-constrained month of the growing period. Finally, costs associated with agricultural production, energy demand in agriculture, and farmgate prices were parameterized using region-specific data from governmental reports [44,51–53] and primary sources (survey data as described in [30]). Based on this parameterization and constraints, the model determines the allocation of land to both irrigated and rainfed agriculture, maintaining current cropping patterns at each agricultural site. We note that fisheries and livestock, typically considered to be part of the agriculture sector in Nepal, have not been represented here owing to lack of data on costs and water usage for these categories.

4.3.4. Municipal

Municipal constraints are included for both domestic water and electricity demand. To represent water demand in the model, each Village Development Committee (VDC) was matched to the nearest hydrology node, and demand was approximated by assigning that VDC's population as reported in the 2011 census to the node.[2] A daily per capita water requirement was assumed to be 40 L; furthermore, it was assumed based on data from a representative survey from the basin [30], that 10% of domestic water needs come from surface water sources.[3] Electricity demands were calculated similarly. Annual electricity demand was assumed to be 139 kWh per capita [46]; this demand was disaggregated to the monthly level (assuming uniform distribution across months) and combined with VDC population estimates from the 2011 census to obtain overall demand. Energy import from outside the basin is allowed, without penalty to the objective function, for scenarios where production is insufficient to meet this demand.

4.3.5. Environmental

Environmental constraints were included to reflect the environmental levels considered to be necessary for maintaining basic ecological functions in Nepalese rivers. The Hydropower Development Policy, 2001 [54] requires that disruptions to river systems caused by hydropower development ensure maintenance of a minimum of 10% of undisturbed flow across the river system. Using this guide, in our base analysis, an environmental constraint that maintains 10% of monthly flow was incorporated into the WNEWM.

In working with basin stakeholders to consider environmental objectives, however, we found that there is substantial variation in opinion regarding the appropriate level of environmental flows. Accordingly, we run the HEM with more stringent environmental flow requirements that are motivated by a desire to maintain the natural hydrological regime in certain key river stretches or tributaries. We also opt for more stringent requirements to indirectly represent water requirements that would maintain fish population in the Karnali-Mohana basin where fisheries are an important source of livelihood for many marginalized communities. These more stringent environmental flows were calculated using the Western Nepal Environmental Flow Calculator and follow the hydrological method for natural or slightly modified river basins outlined in Smakhtin and Anputhas [55].

While all environmental constraints maintain minimum flows within each sub-basin catchment, they do so at a monthly time step. That is, while ten percent of natural flows must be maintained at the beginning and end of each month, the model cannot guarantee that these minima would be continuous.

4.4. Scenario analysis

The WNEWM was used to model water allocations and economic benefits in the Karnali-Mohana and Mahakali River Basins under baseline conditions and for three scenarios that reflect different conceptions of how development should proceed. All runs used the hydrological time series from 1996 to 2007, and the 10% minimum environmental flow constraint was imposed in the base analysis. Model scenarios were specified to be consistent with development visions elicited from key water resources stakeholders representing both national and local perspectives, described in detail in Pakhtigian et al. [17]. In brief, priorities represented in national planning documents and policies for the region as well as a rich collection of local water use reports were combined with development perspectives elicited from stakeholders representing both local and national interests in workshop discussions. From these sources, three development pathways were developed for comparison with the status quo, which we model here as status quo, infrastructure

[2] At the time of model construction, these Village Development Committees were the lowest administrative unit in Nepal, but this unit no longer exists under the new federal system in Nepal. Nonetheless, data on local demands largely comes from VDC-level reports.

[3] According to household survey data, the other 90% of water for domestic needs come from groundwater, specifically from shallow tubewells. Households report using river water for some drinking and cooking water needs, but in general river water is used by inhabitants in the river for bathing, washing, and fishing.

development, limited infrastructure development, and environmentally-sensitive development.[4] All four sector modules (energy, agriculture, municipal, and environment) were included in these scenarios, but their parameterization was modified to reflect differences in priorities and project designs.

The 4 scenarios (Fig. 4) modeled using the WNEWM are thus:

1. Status quo: Current irrigation and hydropower infrastructure; supply to domestic municipal energy and water demands.
2. Infrastructure development: Development of all planned and proposed hydropower and irrigation projects; supply to domestic municipal energy and water demands and excess energy export.
3. Limited infrastructure development: Development of all planned projects, and proposed run-of-the-river hydropower and irrigation projects; supply to domestic municipal energy and water demands and limited energy export.
4. Environmentally-sensitive development: Development of all planned projects, and proposed run-of-the-river hydropower and irrigation projects outside of two ecologically significant tributaries (near Bardia National Park and Shey Phoksundo National Parks, respectively), supply to domestic municipal energy and water demands.

4.5. Sensitivity analysis

Sensitivity analysis was conducted to provide greater insight on the importance of specific modeling assumptions. Three types of sensitivity analysis altered: (i) environmental flow constraints, (ii) downstream flow requirements (into India), and (iii) alternative depictions of energy demand and export markets. The deviations from the base model for each sensitivity analysis are reported in Table 2 and summarized here. As there is not unified agreement that a 10% minimum flow requirement is sufficient to maintain aquatic ecosystems, the first sensitivity analysis provides understanding of how more stringent e-flow definitions may lead to forgone benefits from the water uses that are monetized in the model's objective function. These more stringent environmental flows are calculated using the Western Nepal Environmental Flow calculator, which yields flow calculations in accordance with the Environmental Management Classes outlined in Smakhtin and Anputhas [55]. In particular, we utilize environmental flows calculated to correspond with the "slightly modified" Environmental Management Class, in which infrastructure development is permitted, yet water diversions are limited to maintain aquatic ecosystems.[5] Varying downstream flow requirements incorporates the political dimension of water resources management in this region, specifically as it relates to water user agreements between India and Nepal. Finally, by modeling variation in energy demands and prices in both domestic markets, we examine trade-offs in energy distribution and access.

5. Results

Comparisons between the results of alternative development scenarios provide insights on the economic trade-offs inherent in different potential development pathways for the western Nepal region. We also consider the spatial and sectoral distribution of benefits and examine the effects of inclusion of different environmental, cross-border, and energy demand constraints as described above.

5.1. Trade-off analysis

Across the 12-year time horizon for which flow data are available, the expansion of western Nepal's agricultural and energy sectors through irrigation and hydropower infrastructure would yield between 9.1 and 28.4 billion US$, depending on the extent of infrastructure development (Table 3). Any of the development visions would lead to substantial increases in benefits over those produced with existing infrastructure (scenario 1), which are just above 1 billion US$ over the 12-year period. The upper bound of this range of economic benefits corresponds to the large infrastructure vision, in which all proposed hydropower and irrigation projects would be developed (scenario 2). Of course, these economic benefits would require establishment of an export energy market between Nepal and India, as the annual electricity generation in scenario 2 eclipses current demand in western Nepal by approximately 69 TWh. Unsurprisingly, the economic benefits generated from this high-infrastructure scenario are not distributed evenly across the energy and agricultural sectors: About 80% is generated by the energy sector.

Scenarios with more conservative infrastructure development (scenarios 3 and 4) provide lower economic benefits, yet still each generate over 9 billion US$ in productive benefits over the 12-year period. The decreased economic benefit in these scenarios is driven entirely by the energy sector, with these scenarios generating only 15–17% of the electricity that would be generated under the high-infrastructure storage-backed hydropower scenario modeled in scenario 2. The distribution of economic benefits across sectors is thus more evenly distributed, with just over 40% of monetized benefits coming from the energy sector and the rest of the benefits originating in the agricultural sector.

[4] In Pakhtigian et al. [17]; the development pathways are defined as state-led development, demand-driven development and preservation of ecosystem integrity. These pathways correspond with our model scenarios as infrastructure development, limited infrastructure development, and environmentally-sensitive development, respectively.

[5] Smakhtin and Anputhas [55] describe the "slightly modified" Environmental Management Class as "largely intact biodiversity and habitats despite water resources development and/or basin modifications".

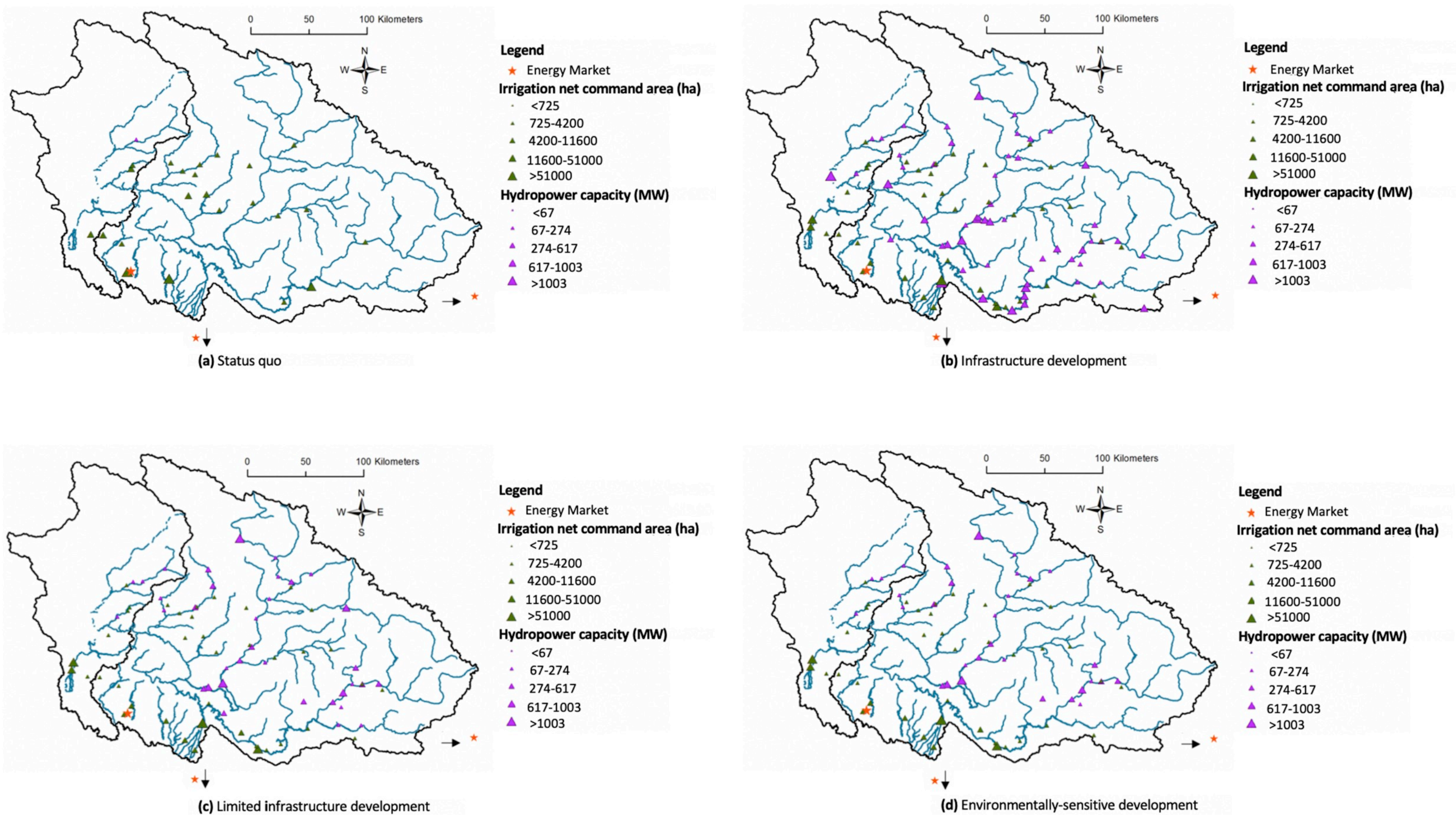


Fig. 4. Location of infrastucture projects in scenarios modeled using the WNEWM.

Table 2
Sensitivity analysis assumptions.

Sensitivity analysis	Deviations from base model
Environmental flows	•E-flow constraints calculated using the Western Nepal Environmental Flow Calculator •Flows correspond with the "slightly modified" Environmental Management Class [55]
Institutional constraints	•Water withdrawals constrained in Karnali and Mahakali River Basins according to allowances in the Mahakali River Treaty •Mahakali allowances: 4.25 m^3/s (dry season) and 28.35 m^3/s (wet season) • Karnali allowances: 12.8 m^3/s (dry season) and 48.14 m^3/s (wet season)
Projecting energy demand	•Per capita energy demand in western Nepal set at 139 kWh/year at a price of 9 NRs/kWh •Price of electricity varies linearly from 9 NRs/kWh to 0 NRs/kWh for per capita demand in western Nepal between 139 kWh/year and 278 kWh/year •Export demand assumed constant for energy priced at 6 NRs/kWh

Table 3
HEM energy and agriculture results, base case analysis.

	Status quo	Infrastructure development	Limited infrastructure development	Environmental development
Panel A: Hydropower				
Production (GWh)	603	835,171	172,519	159,971
Power to western Nepal (GWh)	603	13,329	13,329	13,329
Power exported (GWh)	0.21	821,842	159,190	146,643
Value (billion US$)	0.03	22.9	3.88	3.63
Panel B: Irrigation				
Irrigated land (km^2)	7,612	126,543	126,543	126,543
Production (million MT)	7.12	37.1	37.1	37.1
Value (billion US$)	1.05	5.51	5.51	5.51
Panel C: Objective function				
Value (billion US$)	1.07	28.4	9.40	9.14

Notes: Authors' calculations. All parameters take their base model values. Values reported are results from the GAMS model solved for optimal solutions using the CONOPT solver. For the infrastructure development scenario, the objective function is quite flat near the optimal solution, suggesting there are many near optimal solutions when a large number of projects is used in the model.

Further sensitivity analyses reveal that more stringent e-flow constraints and limits to water diversion for use in Nepal as per treaties with India would entail economic trade-offs. With more stringent e-flows (Table 4), overall economic benefits decline between 2 and 6%, with the greatest declines coming in scenarios with moderate development and limited water storage. The majority of these declines come from reductions in agricultural output–due to reduced water availability for irrigation–though there are minimal reductions in energy generation as well.

Table 5 reports results from the sensitivity analysis that limits water withdrawals for both basins in Nepal in accordance with those implied in the Mahakali River Treaty. We find that these constrained withdrawals lead to a reduction in productive benefits by 7–24%, depending on the scenario. Again, in percentage terms, the largest losses are among scenarios that include less water storage infrastructure. The cost of the trade-off between water use in Nepal and water flowing downstream is entirely borne by the agricultural sector, where agricultural output is reduced by 45%. The energy sector does not bear any burden; if anything, generation increases slightly within the scenario that contains storage infrastructure, as storage-backed water releases increase dry season flow in the river.

Our final sensitivity analysis addresses the uncertainty associated with future electricity demand and relative values from energy

Table 4
HEM energy and agriculture results, e-flows sensitivity.

	Status quo	Infrastructure development	Limited infrastructure development	Environmental development
Panel A: Hydropower				
Production (GWh)	603	833,742	172,531	159,983
Power to western Nepal (GWh)	603	13,329	13,329	13,329
Power exported (GWh)	0.18	820,413	159,202	146,655
Value (billion US$)	0.03	22.9	3.88	3.63
Panel B: Irrigation				
Irrigated land (km^2)	6,169	112,019	112,104	112,104
Production (million MT)	6.84	34.2	33.2	33.2
Value (billion US$)	1.00	5.08	4.94	4.94
Panel C: Objective function				
Value (billion US$)	1.03	27.9	8.82	8.57

Notes: Authors' calculations. Environmental flows are specified according to the flows to preserve aquatic ecosystems as calculated by the Western Nepal Environmental Flow Calculator. Values reported are results from the GAMS model solved for optimal solutions using the CONOPT solver. For the infrastructure development scenario, the objective function is quite flat near the optimal solution, suggesting there are many near optimal solutions when a large number of projects is used in the model.

Table 5
HEM energy and agriculture results, downstream flows sensitivity.

	Status quo	Infrastructure development	Limited infrastructure development	Environmental development
Panel A: Hydropower				
Production (GWh)	603	842,194	172,519	159,972
Power to western Nepal (GWh)	603	13,329	13,329	13,329
Power exported (GWh)	0.21	828,865	159,190	146,643
Value (billion US$)	0.03	23.1	3.88	3.63
Panel B: Irrigation				
Irrigated land (km^2)	7,612	69,234	69,234	69,234
Production (million MT)	7.12	22.2	22.2	22.2
Value (billion US$)	1.05	3.27	3.27	3.27
Panel C: Objective function				
Value (billion US$)	1.07	26.4	7.16	6.91

Notes: Authors' calculations. Withdrawal constraints are set according to the Mahakali River Treaty, signed between Nepal and India in 1996, which allots Nepal 28.35 m^3/s of water from the Mahakali River during the wet season and 4.25 m^3/s of water during the dry season. These values, as percentages of overall river flow, were also used to constrain withdrawals from the Karnali River at 48.14 m^3/s of water during the wet season and 12.8 m^3/s of water during the dry season. Values reported are results from the GAMS model solved for optimal solutions using the CONOPT solver. For the infrastructure development scenario, the objective function is quite flat near the optimal solution, suggesting there are many near optimal solutions when a large number of projects is used in the model.

use in the different markets of this broader region. If western Nepal were to build up its energy generating infrastructure, in accordance with the development scenarios presented here, it would generate excess electricity in the short to medium term. Our base model assumes that electricity demand could double in western Nepal without generating declines in the value of electricity. Given that demand may not increase in this way, the analysis presented in Table 6 sets prices in Nepal at current levels (0.09 US$/kWh) and then lets this value vary linearly to zero once current, domestic demand has been met. This means that, at some point, it becomes more beneficial for Nepal to export energy to India markets (for which the value is set at 0.06 US$/kWh, based on current tariffs for imported energy in India, power trade agreements between India and its neighbors, and power generation costs in Nepal [41,42]), leading to a different distribution of energy. Overall, this lower local demand scenario reduces energy generation benefits by 2–3%. The agricultural sector remains unaffected by these changes in energy demand and pricing.

5.2. *Benefit distribution*

Just as there exist sectoral trade-offs from optimizing water use allocations across the Karnali-Mohana and Mahakali River Basins from an economic perspective, so too are there spatial trade-offs. We consider these spatial trade-offs from the perspective of generation, recognizing that the true distribution of benefits from productive water use may not occur at the location of generation. Maps of total economic benefits from generation demonstrate the spatial variation across development scenarios (Fig. 5). In the status quo (scenario 1), we find economic productivity concentrated primarily across several districts in the southern Tarai and one district in the north-western portion of the basins. These are locations that currently have irrigation and hydropower infrastructure, respectively. Transitioning to an infrastructure development scenario (scenario 2), we find an intensification of this pattern, with high levels of productivity in the Tarai. The higher levels of productivity in the mountains and hills meanwhile reflect the distribution of hydropower production that dominates in this scenario.

The scenarios representing limited infrastructure development and environmentally-sensitive development, 3 and 4 respectively, also show a concentration of economic productivity from agriculture in the Tarai. Notably, these scenarios generate fewer productive

Table 6
HEM energy and agriculture results, energy market sensitivity.

	Status quo	Infrastructure development	Limited infrastructure development	Environmental development
Panel A: Hydropower				
Production (GWh)	603	833,847	172,519	159,971
Power to western Nepal (GWh)	603	6,837	6,837	6,837
Power exported (GWh)	0.21	827,011	165,683	153,135
Value (billion US$)	0.03	22.6	3.69	3.44
Panel B: Irrigation				
Irrigated land (km^2)	7,612	126,543	126,543	126,543
Production (million MT)	7.12	37.1	37.1	37.1
Value (billion US$)	1.05	5.51	5.51	5.51
Panel C: Objective function				
Value (billion US$)	1.07	28.1	9.21	8.96

Notes: Authors' calculations. Domestic energy is valued at 0.09 US$/kWh until current regional demands are met; afterwards, the value varies linearly to a value of zero. Exported energy keeps its base parameter value of 0.06 US$/kWh. Values reported are results from the GAMS model solved for optimal solutions using the CONOPT solver. For the infrastructure development scenario, the objective function is quite flat near the optimal solution, suggesting there are many near optimal solutions when a large number of projects is used in the model.

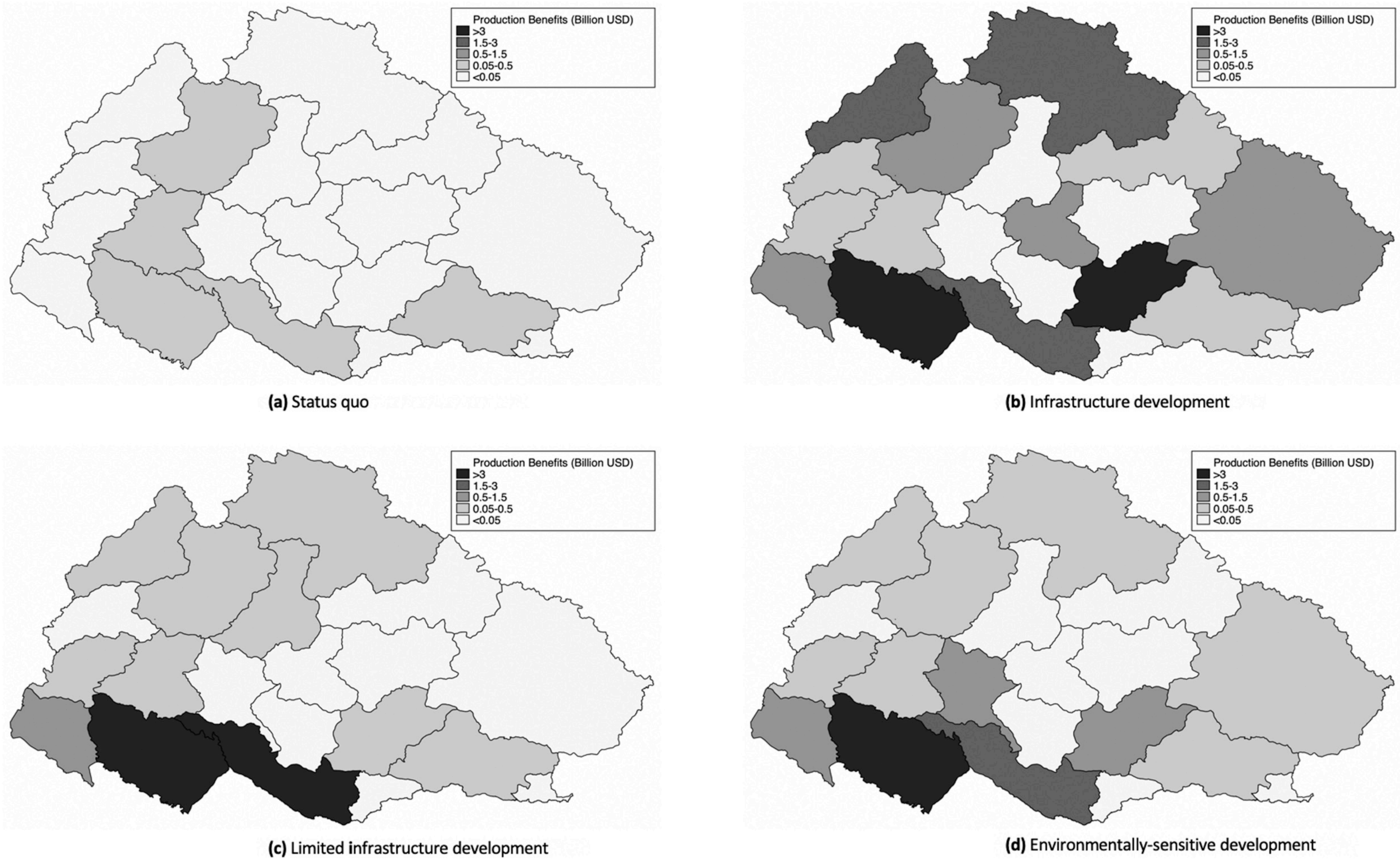


Fig. 5. Distribution of economic productivity throughout districts of the Karnali-Mohana and Mahakali River Basins.

benefits from hydropower. Additionally, scenario 4 preserves tributaries near conservation areas and reduces production in those locations; these efforts are most apparent in the central Tarai region, near Bardia National Park.

5.3. Infrastructure cost considerations

While development through investment in hydropower and irrigation infrastructure appears to align with priorities of policy makers and stakeholders across sectors and institutional levels [17], the appropriate scale of infrastructure remains an open question. The HEM results presented in this paper indicate that substantial economic benefits–on the order of over 9% of Nepal's annual GDP–could be realized through infrastructure investment, particularly in hydropower. Yet these potential economic benefits would also be balanced by the costs of the infrastructure development needed to produce them.

Detailed cost information is not available for most of the projects included in the planning documents we used to parameterize the three development visions in this paper, but we nonetheless consider here three illustrative projects for which such information exists. These are (i) the Kalanga Gad hydroelectric project, a 15.3 MW run-of-the-river project proposed in the Bajhang district; (ii) the West Seti hydropower project, a 750 MW storage project proposed in the Doti/Dadeldhura districts; and (iii) the Bheri Babai Multipurpose project, a 51,000 ha irrigation and 48 MW run-of-the-river project under construction in the Banke and Bardia districts.

The Kalanga Gad project is a small run-of-the-river scheme that might be taken as an example of one of the more than 30 other projects that are interspersed throughout the basin and considered in our analysis. The estimated cost of this project is just under 24 million US$ [60], demonstrating that even for small projects, substantial financial capital is required to develop the infrastructure necessary for electricity generation. The West Seti project is a massive storage reservoir, which has substantial electricity generation potential. While this project is one of the larger proposed reservoirs, there are 19 additional storage projects considered in the WNEWN. The estimated project cost is $1.2 billion US$ [56].[6] Finally, the Bheri Babai Multipurpose project is an irrigation project currently under construction, which exemplifies large-scale irrigation infrastructure, rather than smaller schemes. The project's estimated cost is 136 million US$ [61]. In addition to the comparison of annual benefits and costs of these projects, it must be recognized that the full set of infrastructure projects we consider in our analysis would entail substantial capital needs in a country like Nepal and would require a flow of both foreign and domestic investment maintained over a long period.

We report basic cost-benefit comparisons for these three projects in Table 7. Here, we estimate the annualized infrastructure costs for each project assuming a 30-year lifespan and using discount rates of 5 and 10% as well as the annualized, project-specific benefits from the WNEWM. We find that, comparing annualized benefits and infrastructure costs, Kalanga Gad and the Bheri Babai Multipurpose project have positive net benefits, while the West Seti project faces costs that exceed benefits. Specifically, comparing the Kalanga Gad costs and benefits, we find that annualized benefits exceed annualized infrastructure costs by 0.1–1.1 million US$, depending on the discount rate applied (see the notes in Table 7 for additional details pertaining to the calculation). The Bheri Babi Multipurpose project has an even more favorable benefit-cost comparison, with benefits exceeding costs by 63.8–69.4 million US$, depending on the discount rate applied. Finally, the West Seti project has costs that exceed its annual estimated benefits by 10.9–60.2 million US$, depending on the discount rate applied. Nepal has faced challenges in constructing the West Seti project, most recently with the Chinese power company China Three Gorges International pulling out of the $1.2 billion agreement citing financial infeasibility in 2018 [56]. These back-of-the-envelope cost-benefit calculations thus appear to confirm financial concerns related to this project.

In addition, infrastructure costs of the projects themselves are not the only relevant ones. For large hydropower projects to be economically viable for the region, establishing energy trade with India would be paramount, which would entail investment in greater transmission capacity needed to facilitate energy trade, as well as negotiation costs. Furthermore, the risk of environmental degradation and relocation costs would increase with the extent and scale of infrastructure development, and these should be carefully studied on a project-by-project basis. Pakhtigian and Jeuland [30] find that residents in western Nepal ascribe non-trivial values to environmental conservation (about one percent of household income), which suggests that environmental costs could be substantial, especially if regional economic growth proceeds.

6. Discussion and conclusion

Western Nepal is a region that in on the cusp of economic development, and enhanced management of its vast water resource wealth provides a rich set of options for investment to advance economic growth objectives. This paper considered pathways that put differential priority on various productive uses that aimed to consider agricultural productivity enhancements through irrigation, electricity generation via hydropower investment, and preservation of ecosystem functioning. We analyzed scenarios spanning investment in large-scale irrigation and energy infrastructure development, smaller locally-managed investments, and avoidance of projects in more environmentally-sensitive locations.

While more intensive infrastructure leads to economic benefits that are nearly three times those entailed by smaller-scale and environmentally-sensitive development trajectories, the realization of these benefits would depend on favorable energy trading terms, the availability of capital, and may also come with substantial environmental and social costs. Nonetheless, imposing more stringent environmental flow constraints (relative to the 10% rule-of-thumb currently used by the Nepali government) would only decrease

[6] Other sources estimate project costs up to $1.8 billion US$, but we utilize the 1.2 billion figure in our analysis [59].

Table 7
HEM energy and agriculture results, energy market sensitivity.

	Annualized cost	Annualized benefit
Kalanga Gad	1.6 [2.6]	2.7
West Seti	78.1 [127.3]	67.1
Bheri Babai	8.9 [14.4]	78.4

Notes: Authors' calculations. All values in million US$. Annualized costs reported assuming a 30-year lifespan and using a discount rate of 5% [annualized costs using a discount rate of 10%]. Annualized benefits are calculated as 1/12 of the project's benefits over the 12-year time horizon modeled in the HEM base model.

productive benefits by 0.5 billion US$ in our model, suggesting that infrastructure could be managed to balance environmental needs without severely compromising other benefits. Alternatively, these results suggest that more stringent environmental flows would be optimal from an economic perspective so long as they yielded benefits greater than 0.5 billion US$ (through ecotourism, harvesting of medicinal herbs, non-use benefits, etc.). With more comprehensive data on the value of these environmental benefits, environmental preservation could enter the WNEWM framework through productive benefits rather than as a set of constraints.

The results produced by the WNEWM and others like it provide policymakers with one perspective on enhanced basin-level water resources planning. Of course, there are key limitations to the implementation of any HEM, to which this tool is not immune. First, we rely on existing data to parameterize the model and, in the case of western Nepal, several data limitations deserve mention. Perhaps most critical is the lack of inclusion of groundwater in the model, which limited our focus to surface water demands and expansion of infrastructure related to surface water. In the agricultural sector there is growing interest in turning to groundwater for irrigation expansion; as these data become available, they would provide meaningful extensions to the surface water analysis presented in this paper.

In addition, our sensitivity analyses shed light on environmental concerns, institutional constraints, and future energy demand; however, limited data are available to support these analyses. First, we lack valuation data regarding different levels of e-flows, which guided our choice to include environmental constraints rather than value environmental services in the objective function. Thus, we are able to speak to the benefits forgone in agriculture or energy production due to the imposition of more stringent e-flow constraints, yet we are unable to compare these to benefits stemming from their inclusion. Second, while our efforts to incorporate more stringent environmental flow constraints and maintain municipal water access speak to livelihood concerns related to infrastructure development, we have little data on which to base the calculation of costs and benefits associated with local livelihoods such as fisheries destruction or preservation. Third, we conduct analysis at the basin-scale for Nepal, without analyzing the downstream system and trade-offs induced in India. By including institutional constraints, we consider the geopolitical realities of maintaining transboundary rivers, but we do not value benefits in India outside of these constraints and energy export markets. Relatedly, we do not consider flood control implications–for Nepal or downstream India–of built infrastructure in the Karnali-Mohana and Mahakali River basins. While flood control can be a vital benefit of water resources infrastructure, existing models of the full Ganges basin suggest that storage infrastructure in Nepal would not significantly curtail flooding in downstream countries (India and Bangladesh) due to the spatial distribution of rainfall and flooding, failures in embankment protection, and limited storage capacity relative to the flows in downstream rivers (even under high infrastructure scenarios) [23]. Dams in Nepal might, however, reduce the severity of some types of local riverine flooding events, especially in the flatter portions of the Tarai. Future analyses of flooding implications, though beyond the scope of this research, could provide insight on the value of more local flood control and on the institutional agreements needed to realize such benefits. Finally, we have little data on which to base our projections of future energy demand and value, both in Nepal and in export markets. Our baseline models and sensitivity analysis provide estimates for different energy demand scenarios; however, with more precise projections of demand and value, the model could expand to consider alternative energy scenarios.

All in all, the analysis suggests that there are considerable benefits in Nepal to water resources development, but that the value of specific projects should be evaluated carefully. Our simple benefit-cost assessments of three example projects, for example, indicate that one project (Bheri Babi) is highly attractive, a second (Kalanga Gad) modestly so, while a third (West Seti) looks to have costs that exceed benefits. This confirms the wide variation associated with infrastructure projects that has been observed in other syntheses and reviews [57,58]. Water resources in western Nepal can play an instrumental role in fostering regional economic development; however, prioritizing water resources for one sector is not without trade-offs. The WNEWM generates insights into these trade-offs at the basin level, and demonstrates both the compatibilities and divergences between priorities in energy generation, agricultural production, environmental conservation, and municipal demands. It also clarifies the influence of institutional constraints, providing a much needed comparative analyses for evaluating plans and policies for water resources management in western Nepal.

Funding

This study was made possible by the generous support of the American people through the United States Agency for International Development (USAID) under Digo Jal Bikas (DJB) project.

Disclaimer

The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government.

Declaration of competing interest

None.

Acknowledgements

We are grateful to Luna Bharati, Nishadi Eriyagama, and David Wiberg for their contributions related to hydrological inputs, to Emma Karki for her assistance with data collection and stakeholder meetings, to Maksud Bekchanov and Aditya Sood for their initial contributions to the model framework, and to two anonymous reviewers for their comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wre.2019.100152.

Appendix A

Table A1
Complete parameter database.

Parameter Description	Units	Status quo scenario (current conditions)	Sensitivity analysis	Source
Panel A: Hydrology				
Hydrological inflows	MCM	vary		SWAT model
Precipitation	mm	vary		SWAT model
Institutional withdrawal allowances	m^3/s		Mahakali: 4.25 (dry) and 28.35 (wet) Karnali: 12.8 (dry) and 48.14 (wet)	Mahakali River Treaty
Reservoir volume	MCM	vary		Project documentation
Reservoir surface area	million km^2	vary		Project documentation
Reservoir minimum capacity	MCM	vary		Project documentation
Reservoir maximum capacity	MCM	vary		Project documentation
Reservoir minimum water level	m	vary		Project documentation
Reservoir maximum water level	m	vary		Project documentation
Height-volume relationship		Linear relationship		
Area-volume relationship		Linear relationship		
Panel B: Energy				
Electricity price (domestic)	US$/kWh	0.09	0–0.09	[41]
Electricity price (export)	US$/kWh	0.06	0.06	[42]
Production cost	US$/kWh	0.024–0.1		[41]
Installed capacity	MW	5–6,720		Planning reports
Generation efficiency	percent	65		[41]
Transmission cost	US$/km	0.001		[41]
Transmission distance	km	vary		ArcGIS
Gravity acceleration	m/s^2	9.81		
Water density	kg/m^3	998		
Panel C: Agriculture				
Irrigation efficiency	percent	60		[43]
Return flow	percent	20		[43]
Potential yields	MT/units	vary		[44]
Effective rainfall	mm	vary		CROPWAT
PET	mm	vary		CROPWAT
Water stress		vary		CROPWAT
Crop coefficients		vary		CROPWAT
Potential rainfed area	km^2	vary		Project documentation
Potential irrigated area	km^2	vary		Project documentation
Production costs	$US\$/km^2$	vary		[52] [53] [44]
Yield of rainfed crops	MT/km^2	vary		[44]
Yield of irrigated crops	MT/km^2	vary		[44]
Crop prices	US$/MT	vary		[52] [53] [44]

(continued on next page)

Table A1 (*continued*)

Parameter Description	Units	Status quo scenario (current conditions)	Sensitivity analysis	Source
Energy demands	kWh	vary		DJB survey
District-wise cropping patterns	unitless	vary		Aquastat Project documentation
Panel D: Municipal				
Water demand	Lpcd	40		[45]
Water from river	percent	10		DJB survey
Electricity demand	per capita kWh/year	139		[46]
Panel E: Environment				
Minimum flow	MCM	10% of base flow		[36]
"Slightly modified" e-flow	MCM		"Slightly modified" Environmental Class	Western Nepal Environmental Flow Calculator

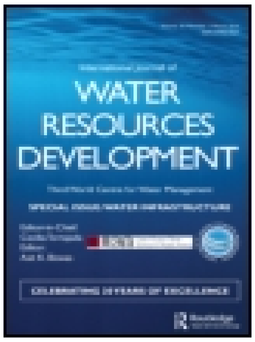
Notes: Values provided if there is a concise presentation; otherwise, only source material or methods are indicated. Values for sensitivity analysis assumed to equal status quo conditions unless otherwise specified.

References

[1] M. Bekchanov, C. Ringler, A. Bhaduri, M. Jeuland, How would the Rogun Dam affect water and energy scarcity in Central Asia? Water Int. 40 (5–6) (2015) 856–876.
[2] M. Arias, T. Piman, H. Lauri, T. Cochrane, M. Kummu, Dams on Mekong tributaries as significant contributors of hydrological alterations to the Tonle Sap Floodplain in Cambodia, Hydrol. Earth Syst. Sci. 18 (12) (2014) 5303–5315.
[3] M.A. Palmer, Water resources: beyond infrastructure, Nature 467 (7315) (2010) 534.
[4] S. Pokharel, Hydropower for energy in Nepal, Mt. Res. Dev. 21 (1) (2001) 4–10.
[5] J. Waterbury, D. Whittington, Playing chicken on the Nile? The implications of microdam development in the Ethiopian highlands and Egypt's New Valley Project, Nat. Resour. Forum 22 (1998) 155–163.
[6] X. Wu, M. Jeuland, C. Sadoff, D. Whittington, Interdependence in water resource development in the Ganges: an economic analysis, Water Policy 15 (S1) (2013) 89–108.
[7] A. Ansar, B. Flyvbjerg, A. Budzier, D. Lunn, Should we build more large dams? The actual costs of hydropower megaproject development, Energy Policy 69 (2014) 43–56.
[8] B.D. Richter, S. Postel, C. Revenga, T. Scudder, B. Lehner, A. Churchill, M. Chow, Lost in development's shadow: the downstream human consequences of dams, Water Altern. (WaA) 3 (2) (2010) 14–42.
[9] S. Hallegatte, A. Shah, R. Lempert, C. Brown, S. Gill, Investment Decision Making under Deep Uncertainty-Application to Climate Change, The World Bank, 2012.
[10] M. Jeuland, D. Whittington, Water resources planning under climate change: assessing the robustness of real options for the Blue Nile, Water Resour. Res. 50 (3) (2014) 2086–2107.
[11] F.A. Ward, M. Pulido-Velazquez, Efficiency, equity, and sustainability in a water quantity–quality optimization model in the Rio Grande basin, Ecol. Econ. 66 (1) (2008) 23–37.
[12] S. Islam, L.E. Susskind, Water Diplomacy: A Negotiated Approach to Managing Complex Water Networks, Routledge, 2012.
[13] M.T. Kahil, F.A. Ward, J. Albiac, J. Eggleston, D. Sanz, Hydro-economic modeling with aquifer–river interactions to guide sustainable basin management, J. Hydrol. 539 (2016) 510–524.
[14] P. Van der Zaag, Asymmetry and equity in water resources management; critical institutional issues for Southern Africa, Water Resour. Manag. 21 (12) (2007) 1993–2004.
[15] M. Zeitoun, J. Warner, Hydro-hegemony–a framework for analysis of trans-boundary water conflicts, Water Policy 8 (5) (2006) 435–460.
[16] M. Bekchanov, E.L. Pakhtigian, A. Sood, M. Jeuland, Hydro-economic Modeling Framework to Address Water-Energy-Environment-Food Nexus Questions at the River Basin Scale, Working paper, 2019. https://sites.globalhealth.duke.edu/jeulandresearch/wp-content/uploads/sites/5/2019/10/HEM_Framework.pdf.
[17] E.L. Pakhtigian, M. Jeuland, L. Bharati, V.P. Pandey, The role of hydropower in visions of water resources development for rivers of western Nepal, Int. J. Water Resour. Dev. (2019) 1–28.
[18] J.J. Harou, M. Pulido-Velazquez, D.E. Rosenberg, J. Medellín-Azuara, J.R. Lund, R.E. Howitt, Hydro-economic models: concepts, design, applications, and future prospects, J. Hydrol. 375 (3–4) (2009) 627–643.
[19] M. Bekchanov, A. Sood, A. Pinto, M. Jeuland, Systematic review of water-economy modeling applications, J. Water Resour. Plan. Manag. 143 (8) (2017), 04017037.
[20] D. Arjoon, Y. Mohamed, Q. Goor, A. Tilmant, Hydro-economic risk assessment in the eastern Nile River basin, Water Resour. Econ. 8 (2014) 16–31.
[21] M. Jeuland, Economic implications of climate change for infrastructure planning in transboundary water systems: an example from the Blue Nile, Water Resour. Res. 46 (11) (2010).
[22] D. Whittington, X. Wu, C. Sadoff, Water resources management in the Nile basin: the economic value of cooperation, Water Policy 7 (3) (2005) 227–252.
[23] M. Jeuland, N. Harshadeep, J. Escurra, D. Blackmore, C. Sadoff, Implications of climate change for water resources development in the Ganges basin, Water Policy 15 (S1) (2013) 26–50.
[24] G. Lacombe, S. Douangsavanh, J. Baker, C.T. Hoanh, R. Bartlett, M. Jeuland, C. Phongpachith, Are hydropower and irrigation development complements or substitutes? The example of the Nam Ngum River in the Mekong Basin, Water Int. 39 (5) (2014) 649–670.
[25] H. Lauri, H.d. Moel, P. Ward, T. Räsänen, M. Keskinen, M. Kummu, et al., Future changes in Mekong River hydrology: impact of climate change and reservoir operation on discharge, Hydrol. Earth Syst. Sci. 16 (2012) 4603–4619.
[26] S. Dhaubanjar, C. Davidsen, P. Bauer-Gottwein, Multi-objective optimization for analysis of changing trade-offs in the Nepalese water–energy–food nexus with hydropower development, Water 9 (3) (2017) 162.
[27] C. Sadoff, N.R. Harshadeep, D. Blackmore, X. Wu, A. O'Donnell, M. Jeuland, S. Lee, D. Whittington, Ten fundamental questions for water resources development in the Ganges: myths and realities, Water Policy 15 (S1) (2013) 147–164.
[28] A. Dinar, G.S. Nigatu, Distributional considerations of international water resources under externality: the case of Ethiopia, Sudan and Egypt on the Blue Nile, Water Resour. Econ. 2 (2013) 1–16.
[29] C. Ringler, X. Cai, Valuing fisheries and wetlands using integrated economic-hydrologic modeling–Mekong River Basin, J. Water Resour. Plan. Manag. 132 (6) (2006) 480–487.

[30] E.L. Pakhtigian, M. Jeuland, Valuing the environmental costs of local development: evidence from households in western Nepal, Ecol. Econ. 158 (2019) 158–167.
[31] V. Foster, J. Steinbuks, Paying the Price for Unreliable Power Supplies: In-House Generation of Electricity by Firms in Africa, The World Bank, 2009.
[32] R. Malik, Water-energy nexus in resource-poor economies: the Indian experience, Int. J. Water Resour. Dev. 18 (1) (2002) 47–58.
[33] B.N. Tiwari, S. Tropp, Nepal Human Development Report, 2009: State Transformation and Human Development, United Nations Development Programme, 2009.
[34] R.H. Sharma, R. Awal, Hydropower development in Nepal, Renew. Sustain. Energy Rev. 21 (2013) 684–693.
[35] API Power Company Limited, Naugarh Gad small hydroelectric project. http://apipower.com.np/home/pagesDisp/naugarh-gad-hydroelectric-project-8-5-mw, 2016.
[36] Government of Nepal, Hydropower development policy, 2058, http://www.lawcommission.gov.np/en/wp-content/uploads/2018/09/hydropower-development-policy-2058-2001.pdf, 2001.
[37] Central Bureau of Statistics, Agriculture monograph. http://cbs.gov.np/sectoral_statistics/agriculture/agriculture_monograph_preface_and_contents, 2006.
[38] Japan International Cooperation Agency, Master Plan Study for Water Resource Development of Upper Karnali and Mahakali River Basin, Nippon Koei Company, Tokyo, Japan, 1993.
[39] Japan International Cooperation Agency, Nationwide Master Plan Study on Storage-type Hydroelectric Power Development in Nepal, Electric Power Development Company, Tokyo, Japan, 2014.
[40] B. Pyakuryal, D. Roy, Y. Thapa, Trade liberalization and food security in Nepal, Food Policy 35 (1) (2010) 20–31.
[41] Nepal Electricity Authority, A year in review–fiscal year 2015-16. https://www.moen.gov.np/pdf_files/hydropower_development_policy_2001.pdf, 2016.
[42] PHD Research Bureau, An analysis of power tariffs across India. https://www.phdcci.in/wp-content/uploads/2018/11/4.-An-analysis-of-power-tariffs-across-India-feb-2013.pdf, 2013.
[43] Water and Energy Commission Secretariat, National water plan. http://www.moen.gov.np/pdf_files/national_water_plan.pdf, 2005.
[44] Ministry of Agricultural Development, Statistical Information on Nepalese Agriculture 2013/2014, 2014.
[45] World Health Organization, Minimum water quantity needed for domestic uses. http://ec.europa.eu/echo/files/evaluation/watsan2005/annex_files/WHO/WHO5%20-%20Minimum%20water%20quantity%20needed%20for%20domestic%20use.pdf, 2005.
[46] World Bank, Electric power consumption. https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC?locations=NP, 2014.
[47] V.P. Pandey, S. Dhaubanjar, L. Bharati, B.R. Thapa, Hydrological response of Chamelia watershed in Mahakali Basin to climate change, Sci. Total Environ. 650 (2019) 365–383.
[48] V.P. Pandey, S. Dhaubanjar, L. Bharati, B.R. Thapa, Spatio-temporal Distribution of Water Availability in Karnali-Mohana Basin, Western Nepal, under Current and Future Climates, 2019.
[49] S.L. Neitsch, J.G. Arnold, J.R. Kiniry, J.R. Williams, Soil and Water Assessment Tool Theoretical Documentation Version 2009, Texas Water Resources Institute, 2011. Technical report.
[50] World Bank, Electricity production from hydroelectric sources. https://data.worldbank.org/indicator/EG.ELC.HYRO.ZS?locations=NP, 2015.
[51] Asian Development Bank, Project Completion Report on the Rajapur Irrigation Rehabilitation Project, 2003.
[52] Market Research and Statistics Management Program, Average Production Cost and Profit Margin of Pulse, Oilseed, Spice and Commercial Crops 2071/2072, 2015, 2014/2015.
[53] Market Research and Statistics Management Program, Cost, Production and Price Spread of Cereal Crops in Nepal: A Time Series Analysis 2071/2072, 2015, 2014/2015.
[54] Ministry of Water Resources, The hydropower development policy, 2001, https://www.moen.gov.np/pdf_files/hydropower_development_policy_2001.pdf, 2001.
[55] V. Smakhtin, M. Anputhas, An Assessment of Environmental Flow Requirements of Indian River Basins, International Water Management Institute, Colombo, 2006. IWMI Research Report 107.
[56] D. Dhillon, August, China Pulling Out from a $1.2 Billion Project in Nepal Could Be an Opportunity for India, Business Insider, 2018.
[57] M. Jeuland, The economics of dams. Working paper, Oxf. Rev. Econ. Policy (2019).
[58] World Commission on Dams, Dams and development: a new framework for decision-making. https://www.internationalrivers.org/sites/default/files/attached-files/world_commission_on_dams_final_report.pdf, 2000.
[59] R.D. Sharma, November, NEA, CTGI Seal Deal on 750 MW West Seti Hydropower Project, 2018. The Kathmandu Post).
[60] Kalanga Group of Companies (KGC), Kalanga Gad Hydro-electric project, 2018. Retrieved from, http://www.kalanga.com.np/en/projects/kalanga-gad-hydro-electric-project-15-33mw/.
[61] Kathmandu Post Report, Bheri-Babai tunnel: Project completes 70 percent works. The Kathmandu Post, 2018, October 14. http://kathmandupost.ekantipur.com/news/2018-10-14/project-completes-70-percent-works.html.

Annex 7-2



Routledge
Taylor & Francis Group

International Journal of Water Resources Development

ISSN: 0790-0627 (Print) 1360-0648 (Online) Journal homepage: https://www.tandfonline.com/loi/cijw20

The role of hydropower in visions of water resources development for rivers of Western Nepal

Emily L. Pakhtigian, Marc Jeuland, Luna Bharati & Vishnu Prasad Pandey

To cite this article: Emily L. Pakhtigian, Marc Jeuland, Luna Bharati & Vishnu Prasad Pandey (2019): The role of hydropower in visions of water resources development for rivers of Western Nepal, International Journal of Water Resources Development

To link to this article: https://doi.org/10.1080/07900627.2019.1600474

INTERNATIONAL JOURNAL OF WATER RESOURCES DEVELOPMENT
https://doi.org/10.1080/07900627.2019.1600474

The role of hydropower in visions of water resources development for rivers of Western Nepal

Emily L. Pakhtigian [a], Marc Jeuland [b,c,d], Luna Bharati [e] and Vishnu Prasad Pandey [e]

[a]Sanford School of Public Policy, Duke University, Durham, NC, USA; [b]Sanford School of Public Policy and Duke Global Health Institute, Duke University, Durham, NC, USA; [c]Institute of Water Policy, National University of Singapore; [d]RWI Leibniz Institute for Economic Research, Essen, Germany; [e]International Water Management Institute, Lalitpur, Nepal

ABSTRACT

Water resources can play significant roles in development pathways for water-endowed, low-income countries like Nepal. This article describes three visions for water resource development in the Karnali and Mahakali Basins of Western Nepal: state-led development, demand-driven development and preservation of ecosystem integrity. The analysis calls attention to water use trade-offs, including those resulting from national priorities such as infrastructure-based hydropower and irrigation, from local drinking water demand, and from environmental conservation concerns. While these visions of water resources development do diverge, common trends appear, including acknowledgment of water management's role in expanding energy access and increasing agricultural productivity.

ARTICLE HISTORY
Received 15 October 2018
Accepted 21 March 2019

KEYWORDS
Development pathways; energy access; hydroelectricity; sustainable water management; trade-off analysis

Introduction

Natural resource management presents important opportunities and challenges for national governments and local communities. Effective balancing of domestic needs with international prospects, and economic growth with resource preservation, requires careful and consultative planning processes. Especially in low-income countries, the careful management of resource wealth can serve as the basis for local development – providing individuals and communities with inputs necessary for sustenance, livelihood or energy – or bring in needed foreign exchange from sales of energy or valuable commodities. Thus, investment in sustainable natural resource infrastructure development and management often entails important resource utilization trade-offs.

Of particular significance among shared resources is water. Water resources link upstream and downstream communities; there are numerous examples of efforts to develop shared water resources development policies and institutions (Song & Whittington, 2004; Wolf, 1998). Complicating such negotiations is a diversity of water use priorities, including, among others, flow maintenance, infrastructure development for power generation or irrigation, environmental concerns and ensuring equitable

CONTACT Emily L. Pakhtigian emily.pakhtigian@duke.edu
Supplemental data for this article can be accessed here.

access to domestic water. Furthermore, cross-border connectivity and disparities in resource access, socio-economic conditions and other factors challenge the regional balancing and sustainability aspects of these multiple water needs. For example, in the Ganges Basin in South Asia, negotiations between the riparian countries of China, Nepal, India and Bangladesh have attempted, with limited success, to advance cooperative management and infrastructure plans that would promote broad-based development, supply competing demands and meet energy needs (Rahaman, 2009). The challenge is not unique to South Asia: Riparian countries in other major transboundary basins (e.g., the Nile and Mekong) have similarly, for years, been trying to forge cooperative water use policies (Hensengerth, 2009; Whittington, 2004), yet have struggled to reach consensus on an equitable and appropriate approach (Suhardiman, Wichelns, Lebel, & Sellamuttu, 2014; Wu, Jeuland, & Whittington, 2016).

While international water resource planning and management is essential for addressing challenges in transboundary rivers, countries must also set internal priorities for water access and river maintenance. Nepal is endowed with ample river resources, with four major river basins and over 6000 minor rivers and tributaries (Pandey, Babel, Shrestha, & Kazama, 2010; Sharma & Awal, 2013). These vast resources offer substantial hydropower and irrigation potential, with around 43,000 megawatts (MW) of economically viable power, and annual surface runoff of over 200 billion cubic metres (BCM) plus 12 BCM of rechargeable groundwater potential (Asian Development Bank [ADB], 2013; Chalise, Kansakar, Rees, Croker, & Zaidman, 2003; Sharma & Awal, 2013). But Nepal today has only about 900 MW of installed hydropower capacity and very little surface water storage, and irrigates only 70% of its irrigable land, and much of that only partly (ADB, 2013; International Hydropower Association, 2018). Thus, water holds a pre-eminent position in the continuing development planning discourse in Nepal.

Water resources and hydropower planning is also particularly important in Nepal's western river basins, which comprise the lowest-income regions of the country. The Mid and Far West Development Regions of Nepal are home to the Karnali and Mahakali River basins, respectively (Figure 1). The Karnali is the largest basin and the longest river in the country, spanning 40,780 km^2 in Nepal and home to over 2.2 million people; it provides an average of 44.1 BCM of flow per year (Khatiwada, Panthi, Shrestha, & Nepal, 2016; Pandey et al., 2010; Water and Energy Commission Secretariat [WECS], 2005). Given Nepal's monsoon climate, the highest river flows occur near the peak of the rainy season, while minimum flows occur during the winter, when snow and glacier melt is low. Inhabitants in and around the Karnali River basin experience fluctuating water availability based on the timing and strength of the monsoon and other weather and climatological patterns.

The Mahakali River is the other major river system in Western Nepal; its main stem flows along the border between Nepal and India, and 34% of its basin lies in Nepal (WECS, 2005). Within Nepal, the basin covers just over 5000 km^2, has a population of 442,000 people and provides average water resources of about 18.1 BCM per year. The low population density in the Nepali portion of the basin means that per capita water resource availability is highest among all of the country's major basins (WECS, 2005; Pandey et al., 2010). As with the Karnali, water access is currently dependent entirely on rainfall and weather patterns; there is no storage infrastructure to regulate water flows in this basin in Nepal.

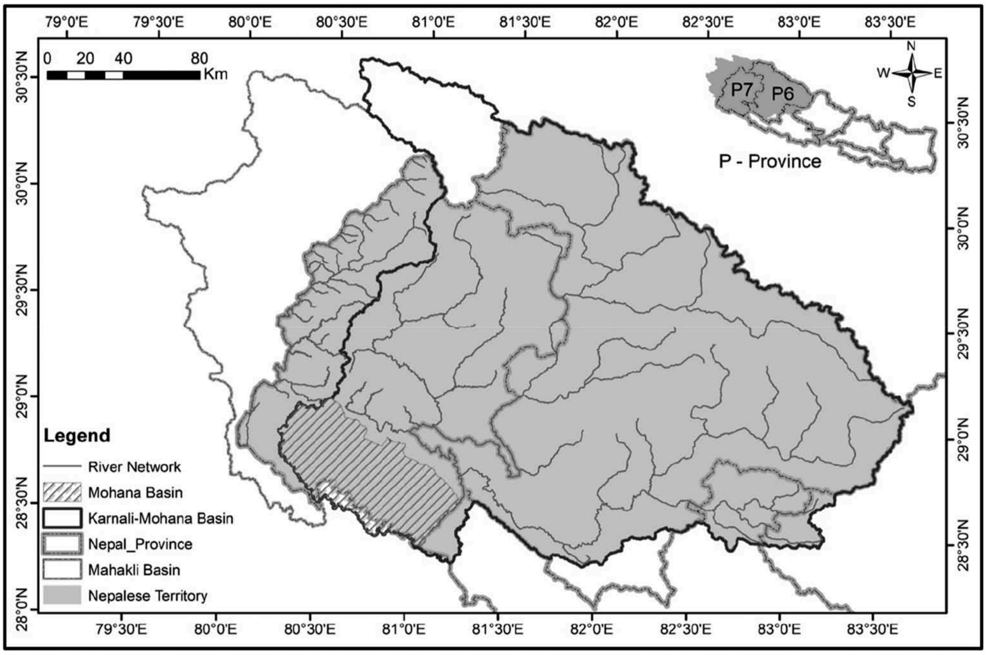


Figure 1. Locations of the Mahakali, Karnali and Mohana River basins in the Karnali and Sudurpaschim Provinces of Nepal.

These two river basins receive special attention from policy makers because they are seen as valuable assets in a poverty-stricken region. Western Nepal performs less well than other areas in Nepal on major development indicators such as per capita gross domestic product (GDP), literacy and life expectancy; has higher gender and social discrimination indices (Tiwari, Ghai, Levit-Shore, & Baral, 2009); and lags in access to electricity and energy generation (Parajuli, 2011). The region relies heavily on agriculture for both sustenance and livelihood, but a lack of economic opportunity has increased dependence on remittance payments from migrants (Bohra-Mishra, 2013; Maharjan, Bauer, & Knerr, 2013). While low development currently disadvantages Western Nepal, its relatively pristine ecosystems and high environmental quality enables consideration of development pathways that would not require large infrastructure. In particular, it enables proactive analysis of alternative trajectories that recognizes the opportunity costs of upstream water control or diversion (e.g. for hydropower generation or irrigation). On the other hand, hydropower generation and water storage potential in the Karnali River have attracted India's interest; therefore, energy export is a potential catalyst for development (Sharma & Awal, 2013).

With this context in mind, this article aims to synthesize different stakeholder perspectives into visions for water-related development in Western Nepal based on data from national and local planning documents; a stakeholder workshop and subsequent meetings, which included representation from different sectors and institutions; and a representative population of householders responding to basin surveys. The inclusion of views from stakeholders at the central, provincial and local levels provides insight on the competing and complementary regional water resources priorities. Because hydropower occupies such an important position in discussions of water-driven development for the region, special attention is devoted to perceptions of how this untapped potential fits into the visions, priorities, values, opportunities and challenges in the region. The synthesis, moreover, is timely because it provides a framework for considering alternative water resource opportunities in the context of a new era of governance in Nepal. The country's new constitution, which came into effect on 20 September 2015, established a federal structure aimed at enhancing the role of provincial and local governments, including in the water sector, under a new integrated ministry. Differences in the interests and objectives at national and local levels will now have to be confronted, and resolved, in new ways.

The rest of the article proceeds as follows. The next section describes the conceptual framework used for construction of the development visions and describes the data collection methods. The third section discusses the information available in existing policy documents, while the fourth describes the stakeholder views elicited during a visioning workshop held in Kathmandu, Nepal, in 2017. The fifth section summarizes the relevant data collected from a basin-wide survey. The sixth presents a set of potential development trajectories for Western Nepal that are consistent with these data, and identifies trade-offs, divergences and overlaps, all within a framework of broader economic development themes. The final section concludes with a discussion of the prioritization of these visions for development in the Karnali and Mahakali River basins.

Framework and methods for development vision construction

General framework

A backward iterative process (schematized for general resource management applications in Figure 2) was developed to build visions for development, and was subsequently applied to the water resources challenge in Western Nepal (Leigh & Blakely, 2016). The overarching goal of the process (top of Figure 2) is determination of the outcome or key objective of the development process, which may be sector-specific or general. In our application, it pertains to clarifying the position of water resources in development visions for Western Nepal. This goal needs to be measurable, and a feasible trajectory for its attainment should exist.

Getting to this ultimate goal requires identification of the means of achieving it, that is, specification of which resources – financial, knowledge, time, physical, or natural – can be brought to bear to attain it. Countries or communities have different endowments of these resources. For example, many societies are well endowed with specific natural resources and are effective in utilizing these as a means to catalyze development (Auty, 2000). Overreliance on a small set of resources can inhibit investments in other drivers of development, however, threatening sustainability (Mehlum, Moene, & Torvik, 2006; Sachs & Warner, 1995, 2001). Much research also links social capital and knowledge sharing to innovation (Putnam, 1993); acquisition of human capital is therefore an important factor in development (Gylfason, 2001).

The final aspect in this process involves identification of the priorities and trade-offs associated with meeting the development objective via the identified means and institutions required to realize it. Specific priorities may include energy access,

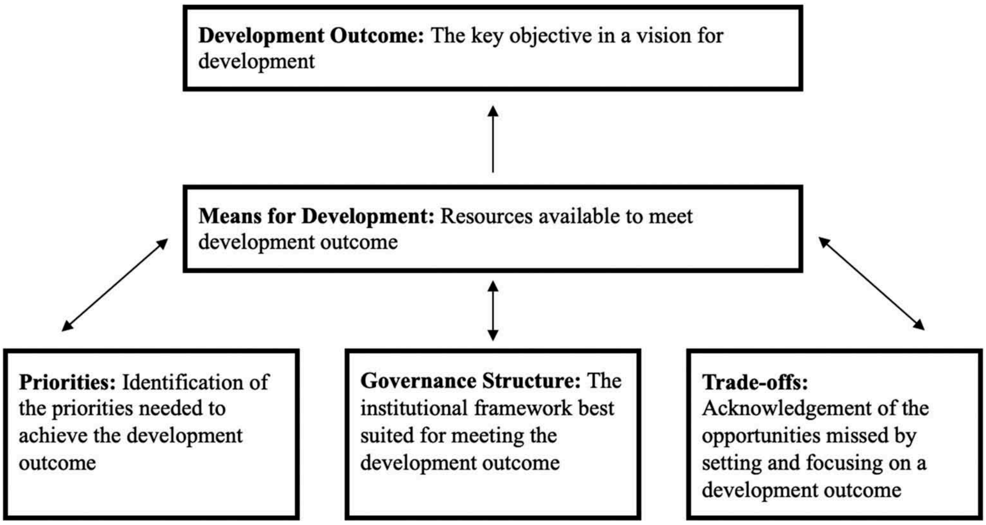


Figure 2. Schematic of the framework for development visions.

education, health, economic development, and environmental conservation, or a combination of several different priorities. Trade-offs highlight the opportunity costs associated with development objectives and priorities (North, 1994). Some objectives are best met under a strong, centralized institutional framework, whereas others flourish under decentralization (Bardhan, 2002; Davoodi & Zou, 1998; Iimi, 2005; Prud'Homme, 1995; Rondinelli, McCullough, & Johnson, 1989). As overarching analyses of the effectiveness of decentralization in fostering development have revealed divergent outcomes, Prud'Homme (1995) argues that choices should focus on how sectors or governmental functions decentralize, rather than on this reform as a stark, binary decision.[1]

Double arrows are used between the middle and bottom steps of Figure 2 to indicate the iterative process of determining the resources available for meeting the goal, and the priorities, trade-offs and governance structure implied by specific objectives. This iterative process provides opportunities to assess the feasibility and opportunity costs of specific choices, leading to refinement of the overarching development goal into one that is realistic.

Specific methods to generate visions for Western Nepal

Three primary sources are used to construct such development visions for Western Nepal: information in national and local planning documents; perspectives elicited during interactions – a workshop and subsequent meetings – with stakeholders; and data from a representative survey of householders in the Karnali and Mahakali basins. Below, each of these data sources is briefly described.

Review of planning documents

Central government planning documents related to the rivers of Western Nepal were collected. These documents include river basin and sectoral (e.g. irrigation, hydropower) master plans, natural resource policy documents and project-specific studies. To provide a local perspective, 62 Water User Master Plans (WUMPs), which discuss opportunities, priorities and constraints related to water at the village development committee (VDC) level, were also reviewed (Figure 3 shows the WUMP locations; a complete list of the WUMP reports is available in Table A1 in the supplementary online material). WUMPs were read in their original version (in either Nepali or English), and data detailing socio-demographic, economic, environmental, energy and water resource characteristics of their study areas were recorded using a standardized form.

Stakeholder interactions (visioning workshop and meetings)

To provide a richer understanding of different water resources development views, a multi-stakeholder visioning workshop was convened in Kathmandu in August 2017. Through this workshop, nearly 50 national and local stakeholders contributed perspectives on water-related sectoral priorities. The sectors represented included hydropower and energy, tourism, agriculture and irrigation, environment, municipal development, research and groundwater management, among others, and stakeholders represented both national and local priorities (Table 1).

The main workshop activities followed the basic framework outlined above and were centred on two primary questions: What are your visions and priorities for development in Western Nepal? And what challenges impede progress in attaining these goals and priorities? The process used to elicit responses to these questions involved time spent in sector-specific groups discussing key development objectives and challenges; and completion of individual surveys, followed by debriefing discussions to elicit ideas about alternative development pathways. Sample size constraints limit quantitative analysis of this survey data, but descriptive statistics provide insights on how various influential stakeholders might make decisions involving specific trade-offs.

Interactions with stakeholders continued after this visioning workshop. In particular, three meetings were held in June 2018 to gain additional stakeholder input on the development visions and priorities as they were beginning to coalesce. Two of these

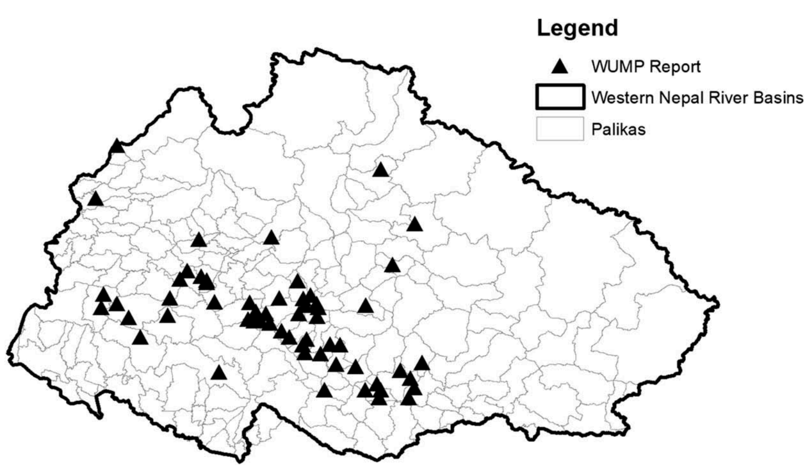


Figure 3. Location of Water User Master Plan reports included in the analysis.

Table 1. Sectors and institutional levels represented at the visioning workshop.

Sector/institutional level	Number of individuals	Percentage
Panel A: Sectoral representation		
Agriculture/irrigation	9	18.4
Donor	2	4.1
Drinking water	2	4.1
Energy	7	14.3
Environment	9	18.4
Finance	1	2.0
Fisheries	1	2.0
Gender/vulnerable groups	2	4.1
Municipal	9	18.4
Research	2	4.1
Tourism	1	2.0
Water	4	8.1
Panel B: Institutional representation		
Local/provincial	18	36.7
National	31	63.3

Source: Authors' calculations from preference ranking survey. Total participants: 49.

meetings were held in Kathmandu with officials from government ministries and departments, including energy, agriculture and watershed management, as well as non-governmental representatives from the environmental, conservation and fisheries sectors. The third meeting was held in Dhangadhi with local resource user groups, civil servants and regional project coordinators (Table 2). A key component of each meeting was a discussion of the visions for development in Western Nepal. The inputs and reactions from these approximately 40 participants in follow-up meetings help augment and expand the scope of analysis of stakeholder viewpoints.

Table 2. Sectors and institutional levels represented at stakeholder meetings.

Sector/institutional level	Number of individuals	Percentage
Panel A: Sectoral representation		
Agriculture/irrigation	13	32.5
Donor	1	2.5
Drinking water	2	5.0
Energy	4	10.0
Environment	4	10.0
Finance	1	2.5
Fisheries	1	2.5
Gender/vulnerable groups	6	15.0
Municipal	4	10.0
Research	2	5.0
Tourism	0	0.0
Water	2	5.0
Panel B: Institutional representation		
Local/provincial	16	40
National	24	60

Source: Authors' calculations from stakeholder meeting attendance. Total participants: 40.

Representative survey of households in the Karnali and Mahakali basins

Finally, a representative survey of 3660 households in the region was used to better characterize the existing water use situation among inhabitants of the Karnali and Mahakali River basins. These data cover aspects such as agricultural practices, resource reliance, livelihoods, environmental shocks, socio-economic and demographic characteristics, and networks and community participation. In an important exercise, respondents provided information on their priorities and preferences for development versus environmental conservation. These data provide the most comprehensive characterization of inhabitants of Western Nepal among our data sources, but they do not specifically address stakeholders' perspectives on what the future might entail. Thus, we incorporate relevant, descriptive statistics from this survey into our analysis to more accurately depict the situation and the challenges facing Western Nepal, even though the data are not directly suited to establishment of the development visions we discuss.

Priorities in water resource planning reports

Water resource planning, management and use are potentially contentious topics in Nepal given the diverse sector interests and governance levels represented in the policy-making and implementing process. The reviewed documents provide evidence of conflicting objectives. In the sections that follow, the evolution of trends in water use objectives and priorities is described, along with the divergence across various perspectives. Table 3 summarizes water utilization plans and demonstrates the differences found between the national and local levels; hydropower and irrigation demands dominate national perspectives, while domestic water use garners more local attention.

National-level perspectives

Over the years, the government of Nepal has developed numerous plans and policies related to natural resource management, spanning general river basin planning as well as covering specific sectors (Department of Irrigation & Groundwater Resources Development Project, 1994; Japan International Cooperation Agency [JICA], 1993, 2014; Ministry of Water Resources & Department of Irrigation, 1990; WECS, 2005). These documents characterize resource availability and present the central government's priorities (potential demands across sectors are summarized in Table 4). The Master Plan Study for Water Resource Development of Upper Karnali and Mahakali River Basin (JICA, 1993) was one of the first such reports. It details the geography, climate and land use patterns of the basins and identifies major opportunities in the energy (hydropower) and agricultural (irrigation) sectors, along with requirements to meet domestic water needs. The report provides useful insight on a two-decade-old planning vision that has been only partially implemented.

Indeed, the JICA report identified and assessed the economic viability and costs of 31 potential hydropower projects and 107 irrigation schemes.[2] This focus reflects a prioritization by the government of Nepal of energy and agriculture investments (JICA, 1993), which subsequent planning documents have continued to emphasize (JICA, 2014; WECS, 2005). Yet implementation of these priorities has been slow, and more recent documents (e.g. the National Water Plan) also reframe them in a context of evolving international norms for water resources development (WECS, 2005). Specifically, the National

Table 3. Water resource planning documents and policies.

Planning document	Level	Year	Key objectives and priorities
Master Plan for Irrigation Development in Nepal	National	1990	• Identifies potential sites and plans for irrigation projects based on geographical feasibility and economic efficiency • Prioritizes irrigation projects based on irrigation needs
Master Plan Study for Water Resources Development of Upper Karnali and Mahakali River Basin	National	1993	• Identifies energy, agriculture and domestic sectors as key water users • Develops list of feasible irrigation and hydropower projects • Prioritizes infrastructure for energy and irrigation
Nepal Agriculture Perspective Plan	National	1995	• Identifies opportunities for improvement in agriculture through technology, fertilizer, irrigation and energy • Develops short- and long-term priorities in agriculture • Prioritizes sustainable development of agricultural productivity
Water User Master Plans	Local	1998–2015	• Identifies drinking water, irrigation, hydropower and environmental water schemes at Village Development Committee level • Prioritizes domestic water use, farmer-managed irrigation, micro-hydro and environmental conservation
Hydropower Development Policy	National	2001	• Identifies energy demands and strategies to meet them • Prioritizes hydropower development as a path to reduce poverty
Water Resources Strategy	National	2002	• Identifies demands for water resource management, energy access, irrigation and domestic water use • Recognizes role of diverse stakeholders in water management planning • Prioritizes domestic water use and sustainable water management
National Irrigation Policy	National	2003	• Identifies irrigation projects and policies to increase access to year-round irrigation • Prioritizes water for irrigation to improve agricultural productivity
National Water Plan	National	2005	• Identifies domestic use, irrigation, hydropower and tourism as water-related sectors • Prioritizes integration, coordination, decentralization, popular participation and implementation of water-related programmes
Nationwide Master Plan Study on Storage-Type Hydroelectric Power Development in Nepal	National	2014	• Identifies sites and plans for storage hydropower development • Prioritizes water use in energy production

Table 4. Water demands.

A. National Plans and Policies

	Hydropower		Irrigation		Drinking water		Environmental	
	Projects	Capacity (MW) [a]	Projects	NCA (ha)	Projects	Population	Projects	Protected (km^2) [c]
Karnali								
Mount	55	R3,125	10	1,341			2	3,661
Hill	71	10,921	16	54,284			1	225
Terai	0	0	13	127,035			2	983
Mohana								
Hill	1	0.5	1	600			0	0
Terai	0	0	8	26,062			1	305
Mahakali								
Mountain	15	21	0	0			1	1,903
Hill	8	6,746	4	942			0	0
Terai	0	0	5	45,736			0	0
Total	150	20,813	57	141,000			7	7,077

B. Local Planning Documents (Water User Master Plans)[d]

	Hydropower		Irrigation		Drinking water		Environmental	
	Projects (% reporting)	Capacity (MW per household) (% reporting)	Projects (% reporting)	Net command area (ha) (% reporting)	Projects (% reporting)	Population (% reporting)	Projects (% reporting)	Households benefiting (% reporting)
Karnali								
Mount (n = 15)	23 (100)	0.4/2,059 (40)/(47)	452 (100)	5,675 (80)	411 (100)	62,178 (80)	192 (100)	2,172 (100)
Hill (n = 42)	81 (100)	2.3/5936 (55)/(67)	1,192 (98)	7,739 (98)	1,508 (100)	176,797 (95)	698 (74)	2,807 (7)
Mohana								
Hill (n = 2)	0 (100)	0/0 (100)/(100)	100 (100)	0 (0)	101 (100)	0 (0)	27 (50)	0 (0)
Mahakali								
Mount (n = 2)	4 (100)	0/567 (0)/(100)	55 (100)	196 (100)	55 (100)	1,308 (50)	35 (100)	0 (0)
Hill (n = 1)	0 (100)	0/0 (100)/(100)	35 (100)	75 (100)	39 (100)	1,019 (100)	25 (100)	0 (0)
Total	108	2.7/8562	1,834	13,685	2,114	214,302	977	4,979

Source: National planning documents and policies outlined above and Water User Master Plan reports compiled and summarized by authors.
[a]Projects with capacity over 1 MW and licensed as of June 2017 included. Projects less than 1 MW (which do not require a licence) planned as of June 2017 also included.
[b]For national plans, projects with net command area over 100 ha included.
[c]Includes national parks and conservation areas as designated by the Department of National Parks and Wildlife Conservation (http://www.dnpwc.gov.np/). Conservation areas that border the Karnali River basin from the east are included in the protected area calculation if part of the national park or conservation area lies within the basin.
[d]WUMP reports not evenly distributed throughout region (Figure 3). *n* refers to the number of WUMP reports in river basin / geographical region. Reporting is not completely standardized across reports; the percentage of reports providing the information is included to contextualize these demands.

Water Plan incorporates holistic and equitable concepts associated with Integrated Water Resources Management (IWRM) and River Basin Management (RBM), by seeking to balance the perspectives of diverse stakeholders and interests and applying a basin-scale approach to reduce water-related conflict. The more varied development objectives included in the National Water Plan are poverty reduction, access to quality drinking water and sanitation, energy demand and irrigation. 'Water sector purpose checks' are developed to gauge progress towards water management goals.

While this general water planning documentation provides insight into planning priorities, the government of Nepal has also been involved in sector-specific planning, most notably for irrigation and hydropower generation. The National Irrigation Policy (Government of Nepal, 2003–2004) provides an institutional framework for the development and maintenance of irrigation projects, with an expressed objective of increasing agricultural production via expansion of year-round irrigation. More specific project identification studies of note include the Nationwide Master Plan Study on Storage-type Hydroelectric Power Development in Nepal (JICA, 2014) and the Master Plan for Irrigation Development in Nepal (Ministry of Water Resources & Department of Irrigation, 1990). The latter details the status of large Department of Irrigation as well as farmer-managed irrigation projects, and described new options based on geographic feasibility, economic viability and irrigation needs. Two such potential projects, the Mahakali Irrigation and Bheri Babai Diversion Multipurpose Projects, are currently under construction. The JICA study, meanwhile, details the substantial energy potential in the region, and provides an inventory of potential new storage hydropower projects, highlighting which are viable based on financial, domestic and environmental criteria. Energy export continues to be a relevant factor in the energy development discussion for Western Nepal; in 2014, the governments of Nepal and India signed an agreement to facilitate future power trade from Nepal to India.

Local-level planning

Perhaps the most important water resource planning effort at the local level has been the development of water use master plans (WUMPs). The WUMP process allowed village development committees (VDCs) to engage in water resource planning. Despite no longer being applicable, the term 'VDC' is used throughout the forthcoming discussion as this was the relevant unit at the time that the WUMPs were written. Implemented by Helvetas and the Rural Village Water Resources Management project in many VDCs across Nepal starting in 1998, the WUMP process involved cataloguing existing schemes for domestic, agriculture, energy and environmental water use; assessing their functionality and also unmet water needs; identifying potential new schemes; and developing an implementation timeline for that infrastructure development. The WUMP reports also provide information on socio-economic conditions, available resources and economic activities (Rautanen, van Koppen, & Wagle, 2014; White, Badu, & Shrestha, 2015). Given this scope, the WUMPs improve understanding of different local-level priorities and collectively facilitate comparison with the centralized priorities discussed previously.

The WUMPs confirm the agrarian status of the surveyed communities, with over 77% of households engaged in agriculture as their main economic activity. The included VDCs vary in size from a population as large as 22,000 (over 4000 households) to a population as small as 1400 (214 households). They also vary along other dimensions: electricity access, cultivable land, market access, water source availability, existing water schemes, and water scheme updating and investment needs.

Through the details on proposed water schemes in each VDC (aggregated in Table 4), it is apparent that the projects are generally small and varied, including drinking water and source protection, micro-hydro, community and farmer managed irrigation, water milling and water for environmental purposes. This suite of projects is rarely catalogued in national plans, and discussion of micro-hydro projects in particular is oddly disconnected from consideration of grid extension. Across the WUMPs, the renovation and development of new drinking water and source protection schemes are given highest priority. Piped water access for drinking, cooking and washing is far from universal, with maximum coverage of around 70% of households in the best-covered VDC. Most VDCs hover between 10% and 40% coverage, with low coverage often resulting from dilapidated systems. In an analysis of community drinking water schemes examined in WUMP reports, White et al. (2015) found that nearly 40% of schemes were in need of repair, corroborating the above description of the data and pointing to a need for greater municipal water investment.

For households without piped water, the time and effort required to fetch water for domestic use is significant but variable. Households report spending an average of 15 to 60 minutes on one water collection trip; with several trips throughout the day, households may spend up to 3 hours on daily water collection. Given monsoonal fluctuations in rainfall, river flows and spring water levels vary throughout the year and sometimes dry out, leading to limited dry-season access. It is thus understandable that many communities express a desire to invest in drinking water infrastructure and to carefully and sustainably manage resources to achieve consistent flows throughout the year.

While improvements have occurred in the two decades since some of the early WUMPs, rural electrification lags in Western Nepal (ADB, 2013), and the reports generally show low rates of electricity access. Few VDCs have access to grid electricity; most electrified VDCs draw energy from small micro-hydro installations. Accordingly, most energy-based schemes incorporated into the development plans are similar small-scale facilities.

Agriculture is the dominant economic activity across all WUMP communities, which consistently report that most cultivated land is rainfed for the majority of the year. Furthermore, the WUMPs indicate that many irrigation schemes are in disrepair, functioning inefficiently if at all. The WUMPs commonly discuss needs for renovation and development of new farmer-managed projects. The variation in the types of irrigation projects proposed further suggests that communities seek to diversify their irrigation and agricultural practices. Farmers apparently view smaller-scale irrigation projects as superior to larger, centrally managed projects because the former enhance their control over water resource use.

While domestic water, irrigation and micro-hydro projects rank among the highest priorities in the WUMPs, communities also report high valuation and prioritization of environmental projects designed to limit erosion and conserve natural ecosystems. Many WUMPs note that the VDCs face a high risk of landslides and other environmental disturbances that result, in part, from development of forested lands, erosion, or other unsustainable practices. In many VDCs, communities express a desire for investments that would protect these assets and resources.

The WUMP reports highlight two additional important realities that relate to regional development (Rautanen et al., 2014). First, regardless of initial design, many community-managed water schemes are used for multiple purposes, suggesting that multipurpose design may be important in building infrastructure that meets community needs. Second, the WUMP process was highly participatory, empowering community members as well as strengthening local governance, providing a set of guidelines that could be followed or adapted for decentralized resource management and governance.

Convergence of river basin planning

The review of these central and local planning documents highlights several development challenges facing Western Nepal. First, while the government continues to engage in periodic updating of national-level planning documents, specific sectors and local plans have only recently been incorporated into planning processes. Second, the priorities found in the WUMPs – small hydro, irrigation, and especially domestic water supply security and convenience – contrast, and potentially conflict, with the large-infrastructure focus in government planning documents. This points to a potential tension between development visions held at different institutional levels. Current master plans in the agriculture and energy sectors are not reflective of the decentralized, multi-sectoral planning approach being favoured in Nepal (WECS, 2005). Furthermore, the growing recognition of local priorities for drinking water and environmental quality and the move towards local governance point to a need for coordination that carefully balances micro-level priorities with regional needs (Suhardiman, Bastakoti, Karki, & Bharati, 2018). Local elections were recently completed as one of the first steps towards the decentralization that is mandated by the new constitution. This new decentralization process, which transfers planning and implementation to the local level, will also impact future development, although it is too early to tell how the balance of power across levels of the government will play out, or how this will influence regional and trans-boundary outcomes, including energy trade.

Priorities from stakeholder interactions

Visioning workshop: development planning and challenges

In the stakeholder visioning workshop, participants were placed in sectorally homogeneous groups to discuss goals related to development in Western Nepal and challenges impeding progress towards those goals. These groups participated in the vision-building exercise described above and depicted in Figure 2 (and Figure 4 provides an example from one group that was largely composed of individuals involved in local-scale agriculture). Across the groups, visions of development revolved around improved living standards but differed in their approaches for reaching this objective. Several groups saw a strong need for planning at the central level, whereas others viewed a decentralized governance approach as more flexible and better able to adapt to location-specific needs and challenges. For most groups, however, the relative preference for one mode of governance over the other was nuanced. Many indicated that central planning was sometimes necessary but emphasized that local or provincial implementation could

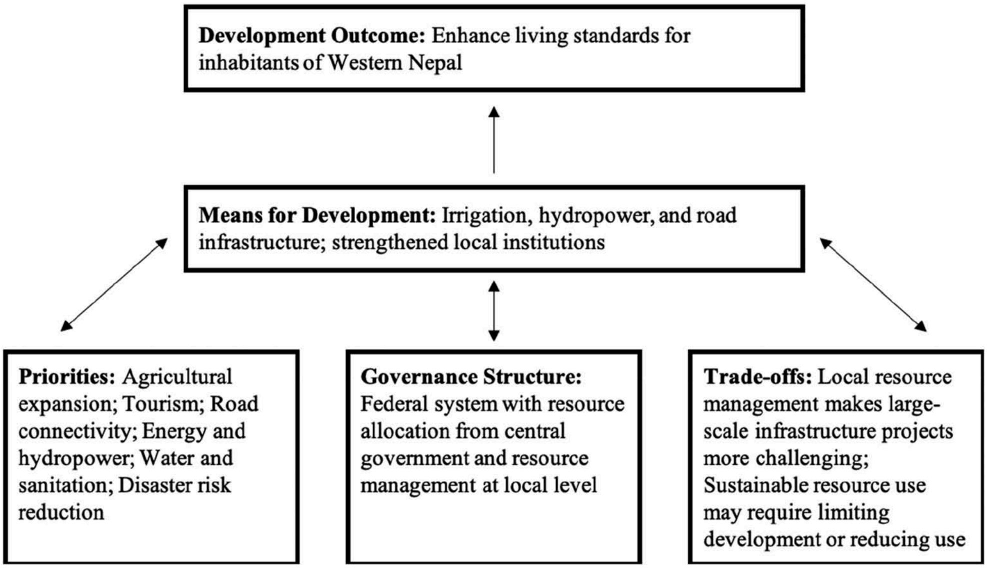


Figure 4. Schematic of the framework for development visions as imagined by stakeholders in the agriculture sector at the regional level.

be most efficient for achieving some objectives. There was divergence between groups on the appropriate level of environmental conservation, the correct scale and purpose of hydropower and irrigation projects and the importance of industry.

Summarizing across groups reveals that multipurpose development, integrated resource management (across governance levels and sectors), preservation of indigenous knowledge, tourism and environmental conservation were most often indicated as necessary means to achieve development in Western Nepal (for a complete summary of this exercise, see Table A2). These priorities recognize the need for a multi-sectoral approach. Priorities that appeared consistently across groups included investment in hydropower (though ranging from large storage for energy export to community-managed micro-hydro for rural electrification); irrigation (though sometimes centrally and other times farmer-managed); environmental conservation; transportation and communication infrastructure; education; health; and tourism.

In addition to identifying different visions for development, the groups also differed in their characterizations of the most pressing challenges in the region. Migration and limited livelihood opportunities, lack of political capacity and experience at district and sub-district levels, the realities of steep topography and wide population dispersion across mountainous terrain, and limited transportation infrastructure appeared as challenges across multiple groups. Other challenges such as limited access to health and educational facilities, social inequality, and insufficient data collection and sharing were also recognized.

All in all, groups agreed that equitable and sustainable development would only be possible with appropriate investments in health, education, environmental conservation and transportation networks. Some local stakeholders also emphasized the need for development of a local non-timber forest product industry (i.e. rare herbs with high market demand, such as *yartsa gunbu* [*Ophiocordyceps sinensis*]).

Preferences survey

Turning to the preference survey results, Table 5 reports average importance rankings of each sector. The mean importance for each governance level represented (national or local) is provided, as well as overall. This analysis is limited to trade-offs among stakeholders from sectors well represented at the workshop, so results may not fully reflect the priorities of under-represented sectors (fisheries and tourism). Confirming the heterogeneity in specific priorities at different governance levels, stakeholders representing a national perspective rated energy, health and transportation as most critical, whereas local stakeholders cited drinking water, transportation and agriculture. These rankings thus emphasize the potential tensions among development strategies, especially in light of Nepal's new federal governance system.

The preference ranking survey also posed hypothetical trade-offs regarding development initiatives and infrastructure projects. Figure 5 depicts responses to these questions. Respondents both indicated their preferences regarding each trade-off (on a scale from 1 to 5) and contextualized their choices with brief statements.[3] For several scenarios (*A*, energy vs. irrigation; *B*, road expansion vs. environmental conservation; *C*, storage for drought vs. flood control), respondents overwhelmingly favoured a middle-ground solution. Delving deeper, many respondents indicated that upstream hydropower would not necessarily inhibit downstream irrigation water availability; rather, this trade-off is surmountable with careful resource planning and use. Similarly, stakeholders noted in qualitative responses that reforestation programmes or alternative road placement could allow achievement of both priorities.

In other cases, there did appear preferences for one sector or option over another (Figure 5(d–g)). Most respondents indicated that projects threatening drinking water access in the region should be pursued only after substantial modification. Similarly, respondents indicated a preference for conservation of vulnerable ecosystems over disruptive hydropower infrastructure. Stakeholders suggested that run-of-the-river schemes would incur less environmental cost, and that maintenance of pristine ecosystems provide a development pathway through ecotourism and other environmentally

Table 5. Sectoral importance for development (1 = very unimportant, 5 = very important).

Sector	National	Local	Total
Agriculture/irrigation	4.3	4.5	4.4
Drinking water	4.3	4.7	4.4
Energy	4.4	4.3	4.4
Transportation	4.4	4.6	4.4
Health	4.4	4.4	4.3
Hydropower	4.0	4.4	4.2
Watershed	4.1	4.1	4.1
Environment	4.0	4.0	4.0
Tourism	3.8	4.2	4.0
Municipal	3.8	4.2	3.9
Forestry	3.7	3.6	3.6
Fisheries	3.1	2.9	3.0
Observations	23	16	40

Source: Authors' calculations from preference ranking survey conducted at visioning workshop.

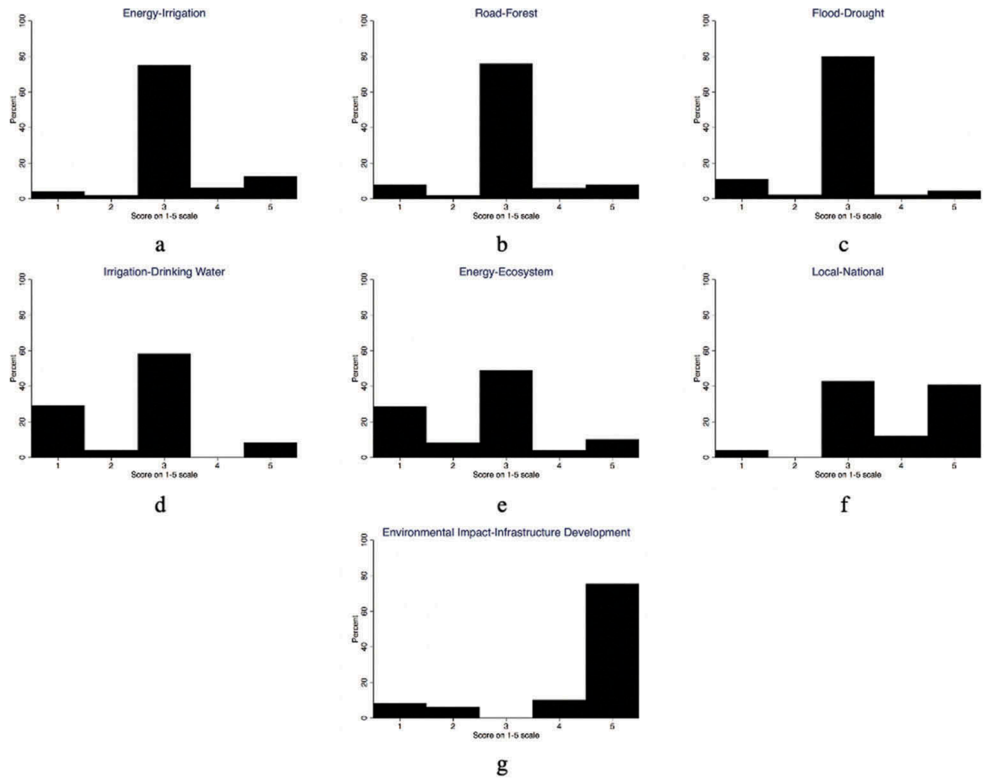


Figure 5. (a) Trade-off scenario between upstream run-of-river hydropower plant and downstream irrigation water availability. Sample size, 38. (b) Trade-off scenario between road network expansion and deforestation. Sample size, 41. (c) Trade-off scenario between storage project use as flood or drought control. Sample size, 36. (d) Trade-off scenario between groundwater irrigation and drinking water availability. Sample size, 39. (e) Trade-off scenario between storage project and ecosystem conservation. Sample size, 41. (f) Trade-off scenario between local and national water resource planning. Sample size, 40. (g) Trade-off scenario between environmental feasibility report requirements and a more streamlined infrastructure planning process. Sample size, 40.

sensitive industries. Finally, on average, stakeholders preferred local rather than national governance, though many also noted the need for coordinated planning.

The final section of the preference ranking survey elicited views on the greatest development challenges in the Karnali and Mahakali basins. While these questions were open-ended, a relatively cohesive view emerged from these responses. The most commonly cited challenges included lack of education; limited local capacity to develop and enforce policy; lack of coordination between interests; geopolitical challenges, including transboundary concerns, locationally scattered settlements and the incomplete road network; and the tendency to overlook environmental costs. All of these challenges point to the importance of integrated planning that considers all available resources. Furthermore, respondents indicated that fostering local human capacity would promote regional development and that environmental considerations must be included for holistic resource management.

While trade-offs are inherent to water resource use – water used in one sector or location is unavailable for use in another – important complementarities also exist. Most notably, increased hydropower generation could provide more electricity to households in Western Nepal, and could also be used to meet demands in the agricultural (e.g. for pumping or food processing), industrial and service (e.g. tourism) sectors. Despite its vast hydropower potential, Nepal is currently an electricity importer (Parikh et al., 2017); new generation could thus help meet domestic demand, and spur development in several benefitting sectors.

Stakeholder meetings: further visioning insight

Additional stakeholder meetings were held to solicit input on the development visions emerging from the visioning workshop through guided discussions and a brief survey. These subsequent meetings confirmed that stakeholders did indeed hold different priorities according to their sector and institutional perspectives; nonetheless, stakeholders consistently emphasized the need for multiple priorities to be pursued to foster sustained and effective economic development. Specifically, stakeholders did not believe that prioritizing one sector to the detriment of all others, or focusing exclusively on governance at one level, would be successful. Rather, they saw the need for combined investments, and pursuit of multi-pronged but coordinated development strategies.

Evidence from the basin-wide survey

In addition to views from specific sectoral and institutional stakeholders, insights relevant to development priorities and challenges can be gleaned from a parallel representative survey of basin inhabitants (for details on survey methodology and implementation, see Pakhtigian & Jeuland, 2019a). Table 6 reports descriptive statistics for the sample across three categories of natural resources – water, forest and biodiversity – spanning resource use for private consumption and income generation, as well as perceptions of environmental quality. Private water consumption accounts for most water resource reliance, with over 80% of households using water to care for livestock, over 50% for irrigation and over 40% for religious or ceremonial uses (Panel A). The latter are mostly non-consumptive, and stem from the Hindu need for holy water (*jal*) that is flowing, for ritual bathing that washes away impurities.[4] Households are less engaged in fishing or aquaculture, and respondents indicated low reliance on water for income generation other than livestock and agricultural production. Overall, respondents ranked the quality of natural resources as between fair and good; this ranking was generally consistent across uses.

Panel B describes reliance on forest resources, and Panel C presents rankings related to biodiversity. Ninety percent of households use firewood to satisfy at least some of their energy needs; nearly 70% use forest resources for livestock fodder; and over 30% use forest resources for religious or ceremonial purposes. As with water resources, use of forest resources for income generation is limited, with the most important such use being sale of medicinal or food products. Households find the quality of forest resources

Table 6. Natural resource reliance from basin inhabitants.

	Use for private consumption (%)[a]	Use for income generation (%)[a]	Resource quality[b] among users[c]
Panel A: Water Resources			
Aquaculture	0.3 (0.057)	0.2 (0.044)	1.62 (0.51) [13]
Wild fish	16.0 (0.367)	1.5 (0.122)	1.44 (0.66) [608]
Agriculture/irrigation	52.5 (0.499)	7.0 (0.256)	1.38 (0.72) [2020]
Livestock	80.3 (0.398)	8.1 (0.272)	1.45 (0.74) [3082]
Religious ceremony	44.5 (0.497)	n/a	1.53 (0.67) [1685]
Panel B: Forest Resources			
Firewood	90.7 (0.290)	2.3 (0.15)	1.23 (0.79) [3309]
Timber	14.4 (0.351)	0.2 (0.040)	0.96 (0.79) [519]
Raw materials	0.4 (0.060)	0.1 (0.023)	1.50 (0.86) [14]
Fodder/grazing	68.5 (0.465)	1.6 (0.126)	1.28 (0.73) [2497]
Medicinal/food products	12.1 (0.326)	3.3 (0.177)	1.24 (0.69) [460]
Religious ceremony	33.9 (0.473)	n/a	1.44 (0.69) [1231]
Panel C: Biodiversity			
Wildlife	n/a	n/a	1.19 (0.85) [2381]
Environment/ecosystem	n/a	n/a	1.53 (0.80) [3155]
Observations	3,660	3,660	

Source: Authors' calculations. Statistics reported as mean (standard deviation).
[a]Respondents can select multiple uses of water and forest resources for both private consumption and income generation.
[b]Quality ranges from 0 (below average) to 3 (excellent).
[c]As not all respondents use each resource, this statistic is calculated among users. Number of observations reported below mean in brackets [].

to be between fair and good. Finally, regarding biodiversity, respondents rank the quality of the natural environment to be slightly higher than that of wildlife.

Overall, these statistics indicate that households in the region derive diverse and important value from natural resources, especially for self-consumption. Resource patterns by river basin are further disaggregated in Table 7, and these complement the

Table 7. Household characteristics.

Variable	Karnali	Mahakali	Mohana	Entire sample
Use water resources (%)	94.5 (22.7)	98.3 (12.8)	86.7 (34.0)	93.4 (24.8)
Use forest resources (%)	96.8 (17.5)	92.0 (27.2)	83.2 (37.4)	93.0 (25.5)
Willing to pay for environmental conservation (%)	98.6 (11.8)	96.0 (19.6)	96.5 (18.3)	97.7 (15.0)
Migrant household member (%)	38.1 (48.6)	45.3 (49.8)	29.9 (45.8)	37.5 (48.4)
Electricity as main lighting source (%)	41.4 (49.3)	74.5 (43.6)	94.3 (23.2)	58.6 (49.3)
Observations	2,250	600	810	3,660

Source: Authors' calculations. Statistics reported as mean (standard deviation).

overall patterns: While use varies across river basins, most households rely on water and forest resources for either private consumption or income generation. Survey respondents place much importance on preserving environmental quality, which is required for households' subsistence and development needs.

Although the household survey did not specifically ask households about their development visions, a survey valuation exercise provides further insights on these environmental priorities. Respondents were asked about their willingness to pay for a hypothetical land conservation programme that would preserve undisturbed land in and around their villages. Nearly 98% of households indicated they were notionally in favour of such a programme. Furthermore, Pakhtigian and Jeuland (2019a) find that households are willing to pay an average of NPR 202 (US$ 1.96) each month for it, additional evidence that resource access and environmental conservation align with the basin inhabitants' priorities.

A noteworthy feature of livelihood support for the region relates to migration. Within the sample, nearly 40% of households have at least one temporary or permanent migrant member. These statistics are consistent with the high general levels of migration and remittance payments nationwide; households often seek options for income generation outside their home villages. Accordingly, increasing employment options in the region may provide another pathway to development in Western Nepal. Finally, there is evidence of intra-regional disparities in electricity access. While nearly 60% of households list electricity as their main lighting fuel, this aggregated figure obfuscates substantial variability across space. Electricity as a primary lighting source is lowest in the Karnali River basin, at just over 40%, and highest in the Mohana, at nearly 95%. Meanwhile, electricity use for non-lighting purposes is uniformly low throughout the basin, suggesting that there is scope for hydropower expansion to support domestic energy use.

Putting the pieces together: visions for the development of Western Nepal

Themes in development

These varied Western Nepal–specific development perspectives can be contextualized within broader themes in the development literature. The classical development theories of the early nineteenth century saw resource scarcity as an absolute constraint (Malthus, 1798; Mill, 1862; Ricardo, 1891), before dramatic advancements in trade and technology loosened them considerably. Still, classical concepts of resource-driven and resource-constrained development continue to feature in modern development theories, for example Rostow's (1959) piece-wise theory and the concept of a vicious cycle or poverty trap (Scully, 1988).

While many variations on these theories exist, two themes related to environmental quality and natural resources are highlighted here, due to their relevance for Western Nepal: the environmental Kuznets curve (EKC) and the resource curse. The EKC argues that a trade-off exists between environmental quality and economic development (Kuznets, 1955). At low levels of development, a region is largely untouched, and the natural environment is pristine. The advance of development then brings environmental degradation, reducing environmental quality. Finally, the natural environment begins to recover as development advances and social preferences evolve to prioritize environmental quality (Grossman & Krueger, 1995). Other development theories propose that effective use of natural resource endowments – for export, local sustenance, or tourism – can be a powerful means to foster growth. Thus, countries with ample resources possess at least some preconditions for economic development. Resource curse theory, however, argues that countries with plentiful natural resources often have slower economic growth than their less endowed counterparts, as a result of a number of negative institutional feedbacks (Mehlum et al., 2006; Sachs & Warner, 1995, 2001).

Development pathways in Western Nepal

In what follows, visions for the development of Western Nepal, as informed by the data discussed above, are related to these development theories. Three specific visions emerge, differing in governance, priority sectors and interests, and implications for trade and the growth of industry:

- State-led development: cohesive infrastructure investment
- Demand-driven development: local management
- Preservation of ecosystem integrity

Cohesive infrastructure investment makes large-scale infrastructure its main focus and implies export of excess energy and agricultural products. Local management is primarily aimed at satisfying local consumption and production needs. Finally, preservation of ecosystem integrity values environmental conservation and preservation of vulnerable and unique ecosystems. The following subsections provide additional explanation.

State-led development: cohesive infrastructure investment

Cohesive infrastructure investment rests on a premise of state-led development with streamlined planning and consistent implementation across potentially disparate regions. This vision, which incorporates large-scale infrastructure development, was imagined by several national-level and sector-focused stakeholder groups and is consistent with priorities found in national planning documents. Small localities lack the resources for implementation of this vision, corroborating its state-led character. While large hydropower and irrigation projects are among this strategy's priorities, the holistic vision includes investment in complementary transportation and communication systems to improve rural market access, and in health and education. This vision aligns with the theory of the EKC: It views degradation from infrastructure development as a necessary cost to incur along a development path that ascribes rising priority to the environment as economic growth proceeds.

While there are currently no major storage hydropower projects in Western Nepal, several licensed and planned dam projects, if constructed, would provide substantial energy-generation potential. The West Seti, Nalsing Gad, Pancheshwor and Karnali Chisapani storage projects are all large dams proposed in the region. Their economic viability rests on ties to an export market that can absorb excess electricity (Sharma &

Awal, 2013). Power trade and water use agreements (with India) are particularly important in the Mahakali basin, as it is a transboundary river, and Pancheshwor is a shared project.

Of course, large storage projects can also increase irrigation water availability by regulating river flows, ensuring year-round water supply in a monsoon climate. Projects like the three-phase Mahakali Irrigation Project and the Bheri Babai Diversion are under construction, indicating further progress towards a large-scale infrastructure vision, at least in irrigation. Furthermore, both stakeholders and planning documents mention the importance of integrated, multipurpose projects, designed to support simultaneous sectoral development. Among the most obvious examples is the Bheri Babai Diversion Project, which will increase water availability for irrigation and generate run-of-river electricity (Bhattarai, 2009; Karmacharya, 2008). What is more, increased electricity access can improve development in other sectors, meeting domestic electricity demands, increasing agricultural productivity and facilitating a growing tourism industry.

Besides irrigation and hydropower, this vision includes investments in transportation, health, education and communications. Stakeholders attending the visioning workshop especially noted the importance of roads for improving connectivity in Western Nepal. The most extreme version of this vision goes further, however, in endeavouring to reduce geographical dispersion by promoting 'urban centres' that would more cost-effectively deliver energy, education, healthcare and other services to large numbers of consumers. Clearly, this complete vision of state-led development would require highly organized and functional institutions to promote cohesive infrastructure investment, agglomeration and international trade.

Demand-driven development: local management

An alternative to the state-led vision is a local approach geared to demand-driven development. This vision was also developed by some stakeholder groups and corroborated by priorities identified in the WUMPs and the basin-wide survey. It identifies numerous challenges with large-scale infrastructure – high fixed costs, environmental degradation and destruction of unique ecosystems, and dependence on export agreements – and prioritizes water access for municipalities, small-scale hydro and farmer-managed irrigation. As with the first vision, this alternative development paradigm emphasizes access to education and healthcare. The vision thus aligns with an augmented EKC theory, in which small-scale infrastructure to improve energy, irrigation and transportation incurs lower environmental costs.

From an energy perspective, the demand-driven local management approach prioritizes generation for local consumption. New small-to-medium-scale run-of-the-river schemes, many of which are already licensed, therefore become more attractive. The construction of these licensed projects would add substantial energy-generating capacity, which could be used to expand electricity access throughout Western Nepal (Sharma & Awal, 2013). In addition to having lower fixed construction costs, run-of-the-river projects are less environmentally disruptive and do not require inundation of inhabited or natural areas. These projects rely on natural river flows, however, and therefore would deliver less reliable power and water supply to consumers and irrigators, absent investment in complementary generating capacity (e.g. solar) or storage.

This vision also includes farmer-managed irrigation and establishment of community user groups to sustainably manage resources. Such groups have been effective in

Western Nepal, where forest, irrigation and drinking-water user groups are common (Agrawal & Ostrom, 2001). The demand-driven development vision would therefore capitalize on existing knowledge and social capital. Enhancements to this approach would increase the capacity of local leaders and institutions (which stakeholders currently deem insufficient), improve access to high-quality educational and healthcare facilities and promote small-scale industry.

Stakeholders imagining this development pathway cited outmigration and a lack of non-agriculture livelihoods as major challenges to demand-driven development, trends verified by basin-wide survey data revealing that 30–40% of household income comes from remittances. While these payments sustain households in the short term, rural employment opportunities remain scarce, leading to permanent migration and loss of human capital. The promotion of both cottage industries to sell local produce and herbs and the tourism industry are potential responses to this livelihood challenge.

Preservation of ecosystem integrity

An environmentally minded vision of development surfaces as a third type of pathway. While conservation plays a role in the development visions outlined above insofar as environmental quality is incorporated into infrastructure planning, this vision considers it paramount. Stakeholders involved in tourism and representing national parks and conservation interests placed dual emphasis on environmental conservation and development, arguing that maintaining natural assets in Western Nepal is essential to sustainability. WUMP reports and basin inhabitants similarly cited the importance of environmental conservation. This vision thus leverages natural resource endowments. Yet unlike the examples from the resource curse literature that offer warnings about extraction (Mehlum et al., 2006; Sachs & Warner, 1995, 2001), this vision relies on preserving ecological wealth.

A pillar of this ecosystem-integrity vision is ecotourism. Protection of conservation areas and national parks offers wealthy tourists the opportunity to experience outdoor activities, and the region is home to some of the world's highest mountains and most unique trekking and rafting opportunities. Tourists have been eager to explore such opportunities in Western Nepal (Baral, Stern, & Bhattarai, 2008; Paudyal, 2012). The tourism sector also provides significant non-agricultural livelihood opportunities for local communities because it requires hospitality, food provision, tour services and souvenir industries, supported by transportation and communication investments (which have historically limited ecotourism in the region, relative to accessible areas in Central and Eastern Nepal). This vision enables such investments as long as they avoid disrupting vulnerable ecosystems containing valuable native plant and animal species, perhaps based on strategic locational trade-offs. For example, several stakeholders were strong proponents of developing some tributaries and land areas to ensure delivery of basic development needs such as food and energy, while committing to leaving others untouched.

A final tenet of this development vision pertains to resource use. Stakeholders promoting this vision recognized a need for interactions between humans and the natural environment; however, they suggested these should focus on sustainable management. Western Nepal is rich in water and forest resources, and many communities rely on medicinal herbs, fish, fodder and firewood obtained from natural areas. Under a vision of preservation of ecosystem integrity, communities could continue to use these resources, but the speed and scope of exploitation would be limited.

Promoting this vision would require national and local institutional support. Developing tourism policies and protecting conservation areas and national parks requires commitment from the central government and investment support for the tourism industry that extends beyond what local communities and institutions can normally provide. Local government would be tasked with policy implementation and enforcement, supported by investments in local capacity building; such efforts are already underway throughout Nepal (WECS, 2005).

Vision consistencies and divergences

The three development visions are not entirely inconsistent with one another. For example, transportation, communication and coordination are important components of development as envisioned by diverse stakeholders. As the rugged geography and dispersed settlements of Western Nepal present real challenges to development, none of the visions can really succeed without better road and communications networks. From an institutional perspective, some degree of coordination between sectors and/or governance levels appears in each vision. Finally, while diverging in the scope and scale of infrastructure investment, all development visions acknowledge the need for enhanced energy access and agricultural productivity, healthcare and educational access.

At the same time, major divergences across the visions highlight potential trade-offs. The visions differ substantially in the scope, scale and location of built infrastructure. From the cohesive infrastructure investment perspective, the built environment is essential to development. This infrastructure-heavy approach rests on the assumption that Western Nepal can enter into international trading arrangements for excess food and energy production, and that these macroeconomic activities will engender regional and local prosperity. Thus, investments in large-scale infrastructure benefit both Western Nepal and neighbouring regions, a premise that requires infrastructure to be placed in locations optimally suited to particular endeavours. In contrast, the locally managed vision of demand-driven development focuses primarily on local needs, placing resource use and management in their control. By promoting local management and smaller-scale infrastructure projects, this vision prioritizes community access to electricity and water. With the decentralized approach to resource management, however, comes the potential for conflicts among resource users, and for non-equitable growth and development. Finally, the sustainable development vision limits the scope and scale of the built environment by promoting careful selection of sites for environmentally friendly, and likely less efficient, infrastructure.

Conclusion

Understanding the visions for development of Western Nepal from the perspectives of stakeholders and basin inhabitants is a necessary first step towards sustainable planning. Voices from the basins provide the local knowledge required to develop feasible and actionable plans, while sectorally and institutionally diverse stakeholders identify the tension between priorities and trade-offs for water resources use and management.

Bringing together these different voices reveals there is no singular, cohesive vision of development and water resource management for Western Nepal; rather, three visions provide a more comprehensive representation of potential development pathways, with the region's development trajectory likely lying somewhere in the intersection. That is, while cohesive infrastructure development may prioritize the built environment; local management, the strengthening of local institutions; and preservation of ecosystem integrity, the opportunities of conservation and eco-tourism, there are unifying threads across these visions.

Most notable, of course, given Nepal's water resources, is the role that hydropower and electricity generation should occupy in development. Storage hydropower plays a dominant role in visions of infrastructure-led development to satisfy currently unmet electricity demand in Western Nepal, provide energy for export through trade agreements with India, and foster growth in sectors such as agriculture and tourism. A local management vision imagines a less dominant energy sector but one that still commits to meeting energy demands in Western Nepal through run-of-the-river and community-managed micro-hydro schemes. Finally, even environmentally focused development visions acknowledge the importance of electricity generation using Nepal's renewable resources. Thus, while agriculture remains the cornerstone of Nepal's economy, it is clear that Nepal's water resources, and particularly their use in power generation, have a key role to play in development in Western Nepal. This is largely because energy access is linked to so many other economic activities: agricultural production (through pumping and processing that add value to output), drinking water supply, small and large-scale industry, and tourism, to name a few (Cabraal, Barnes, & Agarwal, 2005; Fetter, Jeuland, Li, Pattanayak, & Usmani, 2019).

While different stakeholders offer varied visions for development in Western Nepal, political realities also factor importantly into regional development planning. The development visions presented in this article range in institutional preferences from mostly central-government management and decision making (cohesive infrastructure development) to predominance of local or provincial resource management (locally managed development), with the vision of preservation of ecosystem integrity relying on a mix of central and local governance. In all three visions, the central government is needed for coordination, but that role may be more or less emphasized. For example, for cohesive infrastructure development, optimization of project selection and operations would be centrally managed, whereas for the locally managed development vision, the central government would primarily be needed to avoid and mediate harmful spill-overs across sectors and locations. In this respect, the new federal system in Nepal incorporates three levels of governance – federal, provincial and local – as well as democratic elections, and provides a flexible governance structure that is theoretically compatible with pieces of each vision, although it is too early to judge its effectiveness at balancing particular perspectives. As the stakeholder interactions revealed, it is likely that combined governance, which allocates power over decision making to institutions at each level, will be necessary for the region's development.

In the end, missing from the discussions of development objectives and challenges in each of the three visions is a cohesive method for systematically weighing their advantages and disadvantages. While various interests prioritized different activities, it remains uncertain how to choose among very different pathways of investment. Offering insight into this question, Pakhtigian and Jeuland (2019b) use one tool, a hydro-economic model that integrates hydrological and economic and social systems dynamics into a consistent framework, to highlight differences in the production and distribution of benefits across sectors and regions, under development pathways that are consistent with each of the three visions discussed in this article. Future work should use other approaches – multi-objective analysis, cost-benefit analysis, etc. – to improve planning associated with different development opportunities, and must propose and apply criteria based on empirical data to evaluate progress. Such work should also look beyond the interests and agendas of particular sectoral ministries and instead take an integrated approach, to support and enhance development and management planning for Western Nepal.

Notes

1. Specifically, outcomes seem to depend on the baseline level of development in a country and vary depending on the research methodology (Davoodi & Zou, 1998; Iimi, 2005: Rondinelli et al., 1989). Oates's (1972) seminal work on financial federalism also posits that decentralization is most effective when spillovers between jurisdictions are minimal and preferences are heterogeneous. Finally, Bardhan (2002) argues that issues of political economy, particularly the accountability incentives at all levels of government, must be considered as a key component of the decentralization debate in low- and middle-income countries.
2. Six of the identified hydropower schemes were storage projects; 25 were run-of-the-river projects. While one run-of-the-river scheme (Nau Gad) was constructed in Darchula in 2015, no projects identified in the JICA report have been completed. Seven of the identified potential irrigation projects were large run-of-the-river or multipurpose projects, 82 were small schemes (less than 2,000 ha), and 18 were valley cultivation schemes. Several irrigation projects identified by the JICA report, including the large-scale Bheri Babai Multipurpose Project and the Mahakali Irrigation Project(s), are currently under construction.
3. The 1–5 scale followed the pattern that 1 indicated that the proposed project should not be pursued; 3, that the project should continue with some adjustments; and 5, that the project should continue as planned. Additional information regarding the specifics of the trade-offs presented, and the scale is given in the caption of each figure. Details of the scale for each figure are:*A*: 1, hydropower project should stop; 3, the project should continue with modification; 5, the project should continue without changes. *B*: 1, road project should stop; 3, the project should continue with modification; 5, the project should continue without changes. *C*: 1, the project should be used for drought control; 3, both are important; 5, the project should be used for flood control. *D*: 1, the irrigation project should stop; 3, the project should continue with modification; 5, the project should continue without changes. *E*: 1, the storage project should stop; 3, the project should continue with modification; 5, the project should continue without changes. *F*: 1, the national level should play the primary role; 3, equal roles; 5, the local level should play the primary role. *G*: 1, environmental feasibility reports substantially hinder the development process; 3, they are neutral; 5, they are essential to the planning process.
4. Many Hindu rituals and festivals require bathing or collection of holy river water in a container for pouring over one's head. Of particular note is the *dahasanskar* funeral ceremony, which carries away the ashes of the deceased, and the Maghesakranti, Shivaratri and Teej festivals, which encourage submersion in the river.

Acknowledgments

We acknowledge and appreciate the helpful comments from two anonymous reviewers.

Disclosure statement

None. All research conducted with permission of the Institutional Review Board of Duke University.

Funding

This study was made possible by the generous support of the American people through USAID's Digo Jal Bikas (DJB) project under Grant AID-367-IO-16-00002.

ORCID

Emily L. Pakhtigian http://orcid.org/0000-0003-3532-5596
Marc Jeuland http://orcid.org/0000-0001-8325-2622

Disclaimer

The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government.

References

Agrawal, A., & Ostrom, E. (2001). Collective action, property rights, and decentralization in resource use in India and Nepal. *Politics & Society*, *29*(4), 485–514. doi:10.1177/0032329201029004002

Asian Development Bank (ADB). (2013). Country environment note. *Country partnership strategy: Nepal*. Retrieved from https://www.adb.org/sites/default/files/linked-documents/cps-nep-2013-2017-sd-01.pdf

Auty, R. M. (2000). How natural resources affect economic development. *Development PolicyReview*, *18*(4), 347–364.

Baral, N., Stern, M. J., & Bhattarai, R. (2008). Contingent valuation of ecotourism in Annapurna conservation area, Nepal: Implications for sustainable park finance and local development. *Ecological Economics*, *66*(2–3), 218–227. doi:10.1016/j.ecolecon.2008.02.004

Bardhan, P. (2002). Decentralization of governance and development. *Journal of Economic Perspectives*, *16*(4), 185–205. doi:10.1257/089533002320951037

Bhattarai, D. (2009). Multi-purpose projects. In D.N. Dhungel & S.B. Pun (Eds.), *The Nepal–India water relationship: Challenges* (pp. 69–98). Dordrecht: Springer.

Bohra-Mishra, P. (2013). Labour migration and investments by remaining households in rural Nepal. *Journal of Population Research*, *30*, 171–192. doi:10.1007/s12546-012-9097-2

Cabraal, R. A., Barnes, D. F., & Agarwal, S. G. (2005). Productive uses of energy for rural development. *Annual Review of Environment and Resources*, *30*, 117–144. doi:10.1146/annurev.energy.30.050504.144228

Chalise, S. R., Kansakar, S. R., Rees, G., Croker, K., & Zaidman, M. (2003). Management of water resources and low flow estimation for the Himalayan basins of Nepal. *Journal of Hydrology*, *282*(1–4), 25–35. doi:10.1016/S0022-1694(03)00250-6

Davoodi, H., & Zou, H. (1998). Fiscal decentralization and economic growth: A cross-country study. *Journal of Urban Economics*, *43*, 244–257. doi:10.1006/juec.1997.2042

Department of Irrigation and Groundwater Resources Development Project. (1994). *Reassessment of groundwater development strategy for irrigation in the Terai*. Cambridge, UK: Groundwater Development Consultants, Ltd.

Fetter, T.R., Jeuland, M., Li, Y., Pattanayak, S.K., & Usmani, F. (2019). A systematic review of the literature on energy and development. Working paper. Durham, NC: Duke University.

Government of Nepal. (2003–2004). *Irrigation policy, 2060*. Kathmandu: Government of Nepal.

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *The Quarterly Journal of Economics*, *110*, 353–377. doi:10.2307/2118443

Gylfason, T. (2001). Natural resources, education, and economic development. *European Economic Review*, *45*(4–6), 847–859. doi:10.1016/S0014-2921(01)00127-1

Hensengerth, O. (2009). Transboundary river cooperation and the regional public good: The case of the Mekong River. *Contemporary Southeast Asia*, *31*(2), 326–349. doi:10.1355/cs31-2f

Iimi, A. (2005). Decentralization and economic growth revisited: An empirical note. *Journal of Urban Economics*, *57*(3), 449–461. doi:10.1016/j.jue.2004.12.007

International Hydropower Association. (2018). *Hydropower status report: Sector trends and insights 2018*. London: Author.

Japan International Cooperation Agency. (1993). *Master plan study for water resource development of Upper Karnali and Mahakali River Basin*. Tokyo, Japan: Nippon Koei Co.

Japan International Cooperation Agency. (2014). *Nationwide master plan study on storage-type hydroelectric power development in Nepal*. Tokyo, Japan: Electric Power Development Co.

Karmacharya, J. L. (2008). Maximizing benefits from hydropower: A Nepal case. *Hydro Nepal: Journal of Water, Energy and Environment*, *1*, 29–34. doi:10.3126/hn.v1i0.882

Khatiwada, K. R., Panthi, J., Shrestha, M. L., & Nepal, S. (2016). Hydro-climatic variability in the Karnali River Basin of Nepal Himalaya. *Climate*, *4*(2), 17. doi:10.3390/cli4020017

Kuznets, S. (1955). Economic growth and income inequality. *American Economic Review*, *45*(1), 1–28.

Leigh, N. G., & Blakely, E. J. (2016). *Planning local economic development: Theory and practice*. Washington DC: Sage Publications.

Maharjan, A., Bauer, S., & Knerr, B. (2013). International migration, remittances and subsistence farming: Evidence from Nepal. *International Migration*, *51*(1), e249–e263. doi:10.1111/imig.2013.51.issue-s1

Malthus, T. R. (1798). *An essay on the principle of population, as it affects the future improvement of society, with remarks on the speculations of Mr. Godwin, M. condorcet, and other writers*. London: The Lawbook Exchange, Ltd.

Mehlum, H., Moene, K., & Torvik, R. (2006). Institutions and the resource curse. *The Economic Journal*, *116*, 1–20. doi:10.1111/j.1468-0297.2006.01045.x

Mill, J. S. (1862). *Principles of political economy: With some of their applications to social philosophy; in two volumes. 2* (Vol. 2). New York: Longmans, Green, Reader and Dyer.

Ministry of Water Resources & Department of Irrigation. (1990). *Master plan for irrigation development in Nepal*. Kathmandu: Canadian International Water and Energy Consultants.

North, D. C. (1994). Economic performance through time. *American Economic Review*, *84*(3), 359–368.

Oates, W. (1972). *Fiscal federalism*. New York: Harcourt Brace Jovanovich.

Pakhtigian, E. L., & Jeuland, M. (2019a). Valuing the environmental costs of local development: evidence from households in Western Nepal. *Ecological Economics*, *158*, 158–167. doi:10.1016/j.ecolecon.2018.12.021

Pakhtigian, E.L, & Jeuland, M. (2019b). Hydroeconomic modelling of water use trade-offs in Western Nepal. Unpublished manuscript.

Pandey, V. P., Babel, M. S., Shrestha, S., & Kazama, F. (2010). Vulnerability of freshwater resources in large and medium Nepalese river basins to environmental change. *Water Science & Technology*, *61*(6), 1525–1534. doi:10.2166/wst.2010.751

Parajuli, R. (2011). Access to energy in Mid/Far west region-Nepal from the perspective of energy poverty. *Renewable Energy*, *36*(9), 2299–2304. doi:10.1016/j.renene.2011.01.014

Parikh, K., Parikh, J., Ghosh, P., Puri, R., Saini, V. K., Behera, A., & Das, A. D. (2017). *Economic benefits from Nepal-India electricity trade–South Asia regional initiative for energy integration*. New Delhi: Integrated Research and Action for Development (IRADe).

Paudyal, S. (2012). Does tourism really matter for economic growth? Evidence from Nepal. *NRB Economic Review*, *24*(1), 48–66.

Prud'Homme, R. (1995). The dangers of decentralization. *The World Bank Research Observer*, *10*(2), 201–220. doi:10.1093/wbro/10.2.201

Putnam, R. D. (1993). The prosperous community. *The American Prospect*, *4*(13), 35–42.

Rahaman, M. M. (2009). Principles of transboundary water resources management and ganges treaties: An analysis. *International Journal of Water Resources Development*, *25*(1), 159–173. doi:10.1080/07900620802517574

Rautanen, S. L., van Koppen, B., & Wagle, N. (2014). Community-driven multiple use water services: Lessons learned by the Rural Village Water Resources Management Project in Nepal. *Water Alternatives*, *7*(1), 160–177.

Ricardo, D. (1891). *Principles of political economy and taxation*. London: G. Bell.

Rondinelli, D. A., McCullough, J. S., & Johnson, R. W. (1989). Analysing decentralization policies in developing countries: A political-economy framework. *Development and Change*, *20*(1), 57–87. doi:10.1111/dech.1989.20.issue-1

Rostow, W. (1959). The stages of economic growth. *The Economic History Review*, *12*(1), 1–16. doi:10.1111/ehr.1959.12.issue-1

Sachs, J. D., & Warner, A. M. (1995). *Natural resource abundance and economic growth* (NBER Working Paper No. 5398).

Sachs, J. D., & Warner, A. M. (2001). The curse of natural resources. *European Economic Review*, *45*, 827–838. doi:10.1016/S0014-2921(01)00125-8

Scully, G. W. (1988). The institutional framework and economic development. *Journal of Political Economy*, *96*(3), 652–662. doi:10.1086/261555

Sharma, R. H., & Awal, R. (2013). Hydropower development in Nepal. *Renewable and Sustainable Energy Reviews*, *21*, 684–693. doi:10.1016/j.rser.2013.01.013

Song, J., & Whittington, D. (2004). Why have some countries on international rivers been successful negotiating treaties? A global perspective. *Water Resources Research*, *40*(5). doi:10.1029/2003WR002536

Suhardiman, D., Bastakoti, R. C., Karki, E., & Bharati, L. (2018). The politics of river basin planning and state transformation processes in Nepal. *Geoforum*, *96*, 70–76. doi:10.1016/j.geoforum.2018.07.019

Suhardiman, D., Wichelns, D., Lebel, L., & Sellamuttu, S. S. (2014). Benefit sharing in Mekong Region hydropower: Whose benefits count? *Water Resources and Rural Development*, *4*, 3–11. doi:10.1016/j.wrr.2014.10.008

Tiwari, B. N., Ghai, Y., Levit-Shore, S., & Baral, L. R. (2009). Nepal human development report 2009: State transformation and human development. *United nations development programme*. Retrieved from http://hdr.undp.org/sites/default/files/nepal_nhdr_2009.pdf/

Water and Energy Commission Secretariat (WECS). (2005). National Water Plan. *Government of Nepal*. Retrieved from http://www.moen.gov.np/pdf_files/national_water_plan.pdf

White, P., Badu, I. R., & Shrestha, P. (2015). Achieving sustainable water supply through better institutions, design innovations and water safety plans–An experience from Nepal. *Journal of Water Sanitation and Hygiene for Development*, washdev 2015002. doi:10.2166/washdev.2015.002.

Whittington, D. (2004). Visions of Nile basin development. *Water Policy*, *6*, 1–24. doi:10.2166/wp.2004.0001

Wolf, A. T. (1998). Conflict and cooperation along international waterways. *Water Policy*, *1*(2), 251–265. doi:10.1016/S1366-7017(98)00019-1

Wu, X., Jeuland, M., & Whittington, D. (2016). Does political uncertainty affect water resources development? The case of the Eastern Nile. *Policy and Society*, *35*(2), 151–163. doi:10.1016/j.polsoc.2016.07.001

Annex 7-3

Ecological Economics 158 (2019) 158–167

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Valuing the Environmental Costs of Local Development: Evidence From Households in Western Nepal

Emily L. Pakhtigian[a,*], Marc Jeuland[b,c,d]

[a] Sanford School of Public Policy, Duke University, 201 Science Drive, Durham, NC 27708, USA
[b] Sanford School of Public Policy and Duke Global Health Institute, Duke University, 201 Science Drive, Durham, NC 27708, USA
[c] Institute of Water Policy, National University of Singapore, Singapore
[d] RWI Leibniz Institute for Economic Research, Essen, Germany

ARTICLE INFO

Keywords:
Contingent valuation
Land conservation
Environmental quality
Willingness to pay
Ecosystem services

ABSTRACT

Environmental quality is rarely prioritized along the development pathways of developing countries, even though little is known about how individuals in these settings value intact environments. In 2017, we conducted a survey with a representative sample of 3660 households living throughout the Karnali and Mahakali River Basins in Western Nepal. As part of the survey, respondents were asked about how they use environmental services and participated in a double-bounded, dichotomous choice contingent valuation exercise designed to elicit their ability and willingness to pay (WTP) for a land conservation program that would prevent future development in and around their villages. We estimate the average monthly WTP for land conservation to be 202 NRs (US$1.96) and a lower bound of monthly household WTP to be 165 NRs (US$1.60). We find that households with higher levels of education exhibit higher willingness to pay; as do male respondents. We also find a significant negative relationship between household WTP and both migration and local NGO familiarity.

1. Introduction

Environmental quality is often considered a luxury good. The environmental Kuznets curve (EKC) provides a conceptual underpinning for this idea: At low levels of development, environmental quality is high; as development progresses, so too does environmental degradation up to a point where society deems environmental quality a priority and environmental conservation commences (Grossman and Krueger, 1995; Kuznets, 1955). The EKC does not provide the only potential relationship between environmental quality and economic development; rather, it describes a commonly-observed correlation. Between the increasingly evident consequences of global exploitation of natural resources and the continued reliance on these for subsistence and livelihood among individuals in developing countries, however, there surfaces the possibility that an EKC-like relationship between environmental quality and economic development may be–whether voluntarily or by necessity–shifting (Stern, 2004). Payment for ecosystem services schemes, conservation area designations, and initiatives taken by communities to sustainably manage natural resources all demonstrate efforts to reduce environmental degradation (Edmonds, 2002; Ferraro et al., 2012; Whittington and Pagiola, 2012). That we observe these initiatives in developing countries points to this potential recalibration of the relationship between environmental quality and economic development. They also suggest an important role for environmental quality valuation to support resource management decision-making, particularly in places where such valuation may be difficult to elicit or currently unknown.

In this context, a general lack of understanding of the value of environmental quality and intact, undisturbed lands contributes to the challenge of effectively implementing and enforcing effective conservation policies (Ferraro et al., 2012; Whittington and Pagiola, 2012). Nunes and van den Bergh (2001) argue that traditional stated preference valuation methodology may be ill-suited to ecosystem valuation in such contexts due to a lack of adequate information among respondents; Barkmann et al. (2008) demonstrate, however, that including contextual factors and social norms within stated preference valuation elicitation instruments can minimize information bias in value estimates. In this paper, we contribute to this debate by using the contingent valuation (CV) method to derive estimates of willingness to pay (WTP) for environmental conservation in Western Nepal.[1] Furthermore, the richness of our household-level data allows us to provide preliminary evidence on the correlations between environmental

* Corresponding author.
E-mail addresses: emily.pakhtigian@duke.edu (E.L. Pakhtigian), marc.jeuland@duke.edu (M. Jeuland).

[1] We characterize environmental conservation as efforts to promote forest conservation to prevent additional deforestation and development of undisturbed lands.

https://doi.org/10.1016/j.ecolecon.2018.12.021
Received 14 June 2018; Received in revised form 4 November 2018; Accepted 18 December 2018

quality valuations and household characteristics, focusing on property rights, community resource management, environmental shocks, and migration–all of which are highly relevant in Western Nepal. We rely on empirical evidence from a representative sample of households living in the Karnali and Mahakali River Basins in Western Nepal.

Several characteristics of Western Nepal make this location particularly relevant for expanding the literature on valuing environmental quality in developing countries. First, Nepal's water and forest endowments are among the country's most valuable resources, which establishes the relevance of the research questions in this setting (Edmonds, 2002; WECS, 2005). Second, Western Nepal is the least developed region of the country and development plans place high importance on utilizing its vast hydropower potential for both rural electrification and energy export (WECS, 2005). Thus, Western Nepal appears poised to embark on a development trajectory, the shape and consequences of which remain unclear. Without environmental quality valuation, the full costs of environmental degradation associated with infrastructure and other development initiatives are difficult to identify, leaving open the possibility of economic development pursuit without full consideration of its potential environmental consequences. In particular, the opportunity cost of land development is likely to be underestimated (Jeuland, 2010; Jeuland and Whittington, 2014).

The rest of the paper is structured as follows. Section 2 discusses relevant literature. Section 3 contextualizes the setting, outlines the structure of the survey instrument, and provides descriptive statistics for the sample. Section 4 presents the empirical methods applied in the analysis. Section 5 provides the results of the analysis. Finally, Section 6 concludes with a discussion of the results and their policy implications.

2. Existing Literature

While applications of nonmarket valuation techniques to elicit valuation for environmental quality in developed countries abound (Adamowicz et al., 1997; Bhat, 2003; Font, 2000; Hanley et al., 2003), a targeted review of stated preference techniques for environmental quality valuation in resource-constrained settings reveals a large gap in the literature.[2] Ferraro et al. (2012) and Whittington and Pagiola (2012) provide reviews of forest ecosystem valuation and watershed management and conservation, respectively, finding limited results relevant for policy application within the existing literature. Ferraro et al. (2012) argue that although ecosystem services have received significant research attention in the most recent decade, the failure to include valuation within the policy evaluation framework has led to disjointed analysis that communicates neither the value of environmental quality among individuals in developing countries nor the efficacy of conservation policies. Among the literature that does exist in developing country settings, valuation of environmental quality follows traditional nonmarket valuation patterns; that is, revealed preference applications use travel cost assessments or use values for national parks, conservation areas, and ecotourism as a means for valuation (Ellingson and Seidl, 2007; Navrud and Mungatana, 1994), while stated preference applications assess survey data for insight on non-use values (Barkmann et al., 2008). While evidence from both categories is limited, applications of stated preference methods in developed country contexts are particularly scarce.

There are several potential explanations for this lack of sufficient evidence on environmental quality valuation in developing countries. First, as Nunes and van den Bergh (2001) argue, the ecological mechanisms underpinning environmental quality can be challenging to understand even among the most well-informed of respondents. Thus, elicitation of valuations in resource constrained settings where environmental quality information is generally inaccessible can yield results that are of questionable relevance. Yet, assuming away indigenous knowledge about the environment seems problematic. Barkmann et al. (2008) empirically test the concerns of information and methodological misspecification biases using a choice experiment in rural Indonesia and find that respondents are highly attuned to their ecological surroundings. The authors conclude that careful valuation elicitation design informed by extensive *ex ante* study contextualization and field testing of stated preference survey instruments can overcome potential bias and yield more accurate estimates of the value of environmental quality in information-constrained settings. Second, standard concerns about yea-saying, hypothetical bias, strategic behavior, and framing yielding biased valuations from stated preference methods remain problematic within the context of environmental quality valuation (Diamond and Hausman, 1994; Hausman, 2012). These concerns notwithstanding, stated preference techniques remain the only option to elicit non-use values, which is particularly important for environmental quality valuation. Thus, there is considerable space in the literature for stated preference elicitation of the nonmarket value of environmental quality in a developing country context (Arrow et al., 1993; Carson, 2000; Whittington, 1998).

3. Reseach setting and data

3.1. The Karnali and Mahakali River Basins

Both geographical and man-made boundaries divide Nepal into a country of distinctive regions. North-to-south, Nepal has three geographic zones–the northernmost high Himalayas, the central mid-hills, and the southern Terai; east-to-west, Nepal has five development regions–the Eastern, Central, Western, Mid-Western, and Far-Western Development Regions. Along the north-to-south dimension, livelihood activities vary with terrain, with most agricultural production occurring in the fertile and irrigable flatlands of the Terai and small-scale agriculture dominating the hill and mountain zones. Although engagement in the agricultural sector dominates occupations and livelihoods, temporary and seasonal migration as well as a growing tourism industry supplement livelihoods, especially for those residing in less agriculturally-favorable terrain (Bohra-Misra, 2013; Mahajan et al., 2013; Massey et al., 2010).

The setting for the study, the Mid-West and Far-West Development Regions of Nepal, is an area rich in natural resources but poor in economic development. The Karnali and Mahakali Rivers flow through these regions and a variety of lands are deemed important for environmental and biodiversity reasons (Baral, 2007). Although ecosystem protection has risen in priority at both the central and regional levels (WECS, 2005), a lack of knowledge regarding the value of environmental quality among inhabitants of the region presents a challenge in the crafting, implementation, and enforcement of environmental policy. Given the region's high development potential and this increasing environmental prioritization, there is a uniquely relevant opportunity to implement stated preference environmental quality valuation techniques that would support current policy making.

The survey that yielded the valuation data analyzed in this paper took place during June and July of 2017 in the Karnali and Mahakali River Basins, the two westernmost river basins in Nepal. Fig. 1 provides a map of these river basins. The project area spans over 46,000 square kilometers (km^2) within Nepal and is home to over 2.6 million inhabitants (Khatiwada et al., 2016; Pandey et al., 2010; WECS, 2005).[3]

[2] Studies that consider WTP for environmental quality in developing countries among respondents (tourists) from developed countries also exist, see Baral et al. (2008).

[3] Neither the Karnali nor Mahakali River Basin falls entirely within Nepal's administrative boundaries. Six percent of the Karnali River Basin lies in Tibet; 66% of the Mahakali River Basin in India (WECS, 2005). The portions of these river basins outside of Nepal's administrative boundaries were not included in the survey.

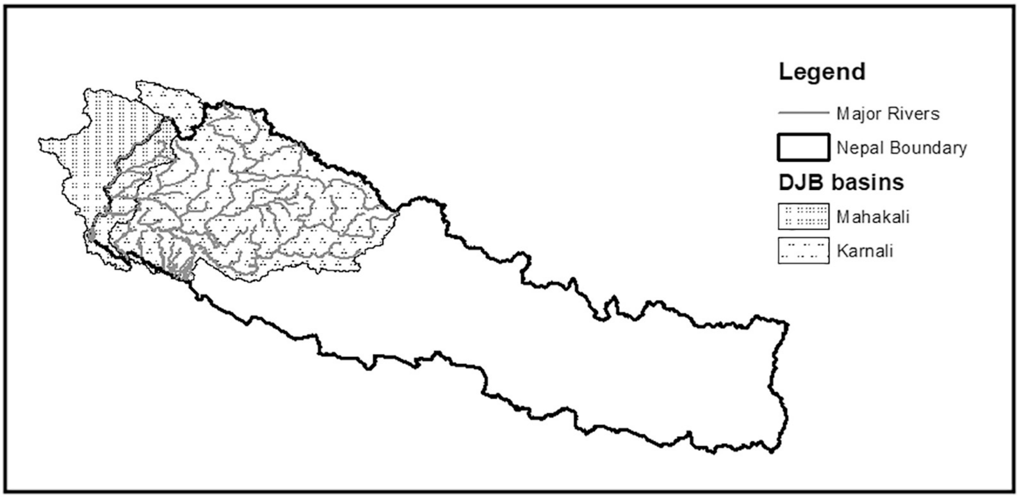


Fig. 1. Map of Karnali and Mahakali River Basins, Western Nepal.

The region is predominately rural and agrarian, with cultivation of paddy, maize, barley, millet, potatoes, and other vegetables among the most important contributions to local economies, livelihoods, and food security. In addition to agriculture, reliance on forest resources including fodder for livestock, firewood, medicinal herbs, and spices is common throughout the region. As both agriculture and natural resources contribute in vital ways to sustaining households and communities throughout Western Nepal, tradeoffs arise in land and resource use. Policies and initiatives at both central and local levels have addressed such tradeoffs; however, these remain controversial.[4] It is within this context that we seek to provide insight into how inhabitants of the Karnali and Mahakali River Basins value environmental quality.

3.2. Survey Instrument

The survey instrument was designed to collect information on livelihood practices, natural resource reliance, and economic activities from a representative sample of respondents residing in the region. The survey had ten sections. Section one collected locational data, obtained informed consent, and gathered demographic information about the respondent. Section two compiled a household roster containing demographic information about all individuals residing in the household.[5] Section three gathered information about land tenure, rental, and any land-related transactions in the previous ten years. Section four assessed living standards and asset ownership, spanning livestock, sanitation facilities, sources of drinking water, and fuel access, among others. Section five determined natural resource use and perceptions of natural resource quality and introduced the CV scenario used to assess WTP for environmental quality. Section six collected data on irrigation and other agricultural technologies. Section seven detailed crop production. Section eight gathered information about agricultural training and credit opportunities available to the household. Section nine outlined income and expenses. Finally, section ten recorded external shocks and household adaptation. The survey took between 45 and 60 minutes to complete, with the contingent valuation portion requiring about 15 minutes of this time.

3.2.1. Contingent Valuation Questionnaire

The CV portion of the questionnaire was designed to gauge interest in participation in local forest and land conservation efforts. We adhered to survey best practices for eliciting WTP from respondents, using a double-bounded, dichotomous choice questionnaire format (Arrow et al., 1993; Hanemann et al., 1991). After describing the relationship between limiting deforestation and environmental quality, enumerators asked respondents if they would vote to support establishment of an NGO-managed fund for maintaining forested areas in their community (i.e., avoiding future development of forest land), to which all community members would be required to contribute a fixed monthly amount.[6] Respondents received randomized initial bids for monthly fund contributions from a set of four different prices.[7] If respondents replied affirmatively to the initial bid, they received a follow up question with a payment option that was double the initial bid; if respondents replied negatively to the initial bid, they received a follow up question using a payment option that was half the initial bid.

The CV questionnaire contained several *ex ante* design elements and *ex post* checks intended to minimize potential bias. Before the initial bid question, respondents had multiple opportunities to ask questions about the presented scenario. Furthermore, we utilized a "cheap talk" script to remind respondents of the importance of accurate responses.[8] Finally, enumerators reminded respondents of their budget constraints several times and used visuals to convey and reinforce key elements of the valuation scenario. After the valuation questions, the script contained several debriefing questions to assess respondents' understandings of

[4] At the central level, irrigation infrastructure determines water resource availability in some areas and preservation and conservation area designations disallow the conversion of forest lands. At the local level, farmer managed irrigation schemes and irrigation, water, and forest user groups provide systems and enforcement mechanisms for communities to manage their own resources (WECS, 2005).

[5] Temporary and permanent migrants supporting the household through regular remittance payments were included in the household roster.

[6] The CV question reads: "Suppose a local NGO were to manage a special fund for natural land preservation. This would be funded by a required monthly contribution from each household in the community that would be collected and kept by the local NGO. The local NGO would use the money in this fund to preserve/protect areas of your community that have not yet been converted for agriculture. Your community would have the opportunity to work with the local NGO to decide which areas should be preserved under this fund. Specifically, this fund would be used to compensate people who want to and have the right to develop that land, so that they do not develop it. Keeping in mind your household budget and the potential impacts of this proposal, would you vote to support a household contribution of [80/150/250/350] rupees each month to fund this land preservation fund?".

[7] The initial bids were 80, 150, 250, and 350 Nepalese Rupees, which correspond to 0.78, 1.46, 2.43, and 3.40 US Dollars using the exchange rate prevailing at the time of approximately 103 NRs = 1 USD.

[8] "Cheap talk" scripts are intended to inform respondents of the consequences of stating a response that differs from their actual valuation. Cummings and Taylor (1999) demonstrate this strategy is effective in reducing some types of response bias.

the CV exercise. Respondents stated their certainty about their responses to each valuation question as well as answered an open-ended question to explain the rationale for their response.

Pilot testing of the CV script and broader survey during focus groups and enumerator training informed the design of the final survey instrument and selection of the payment vehicle-a community-mandated contribution to an NGO fund based on the results from a local vote.[9] Given the limited previous work in valuing environmental quality in a developing country context, this piloting was essential and informative in framing the CV scenario to make it relevant and appropriate for inhabitants of Western Nepal. Pilot testing strengthened the relevance of the initial bids, payment vehicle, visual aids, and scenario structure of the CV script for our sample population in Western Nepal.[10]

3.3. Survey Implementation

The representative sample of the Karnali and Mahakali River Basins was drawn based on a multi-step sampling procedure. First, the entire region was divided into five river basins, the Karnali Main, Bheri, Seti, Mahakali, and Mohana.[11] Each river basin was further divided according to Nepal's three geographical zones–mountain, mid-hill, and Terai–yielding twelve clusters.[12] Based on the population of each cluster, Village Development Committee (VDC) wards were randomly selected for fieldwork. The final sample included 122 such VDC wards.

Enumerators randomly selected thirty households from each VDC ward through a systematic procedure whereby a central landmark was selected and every *n*th household was selected for the survey.[13] Households were eligible for the sample if they were a permanent resident of the ward and if the chief wage earner or alternative knowledgeable household member was available and willing to participate.[14] Enumerators revisited households when respondents were available to maintain the sampling procedure; in cases where a household failed to meet the inclusion criteria or refused to participate, the next neighboring household was selected in its place. Enumerators received training in the sampling procedure and survey context and participated in pilot testing prior to the initiation of fieldwork.[15] The final sample of respondents comprised 3660 households living in the 122 selected VDCs.[16]

[9] We tested alternative payment vehicles, including local and regional taxes, during the pilot testing. At pilot sites, respondents were wary of the government's ability to enforce and maintain such a program, leading to the selection of the mandatory, monthly payment to a local NGO fund as the payment vehicle in the main study.

[10] For example, bids were determined by analyzing pilot test results (sample size $n = 100$) that included bids both higher and lower than the bids used in the study. Nearly 100% of respondents in the pilot survey responded affirmatively to a bid of 40 NRs; and only 13% responded affirmatively to a bid of 600 NRs. As the dichotomous choice format necessitated second round bids that doubled and halved the initial bids, we considered initial bids between 80 and 350 NRs to provide a reasonable range. Four bids were selected to maintain sufficient sample size at each initial bid for analysis.

[11] The Bheri, Seti, and Mohana are all sub-basins of the Karnali; given the population distribution we designated sub-basins for the sampling procedure.

[12] There are no Terai wards in the Bheri and Seti sub-basins and no mountain wards in the Mohana basin, leaving twelve clusters.

[13] Determination of n depended on the number of households in a given VDC ward: $n = (\textit{number of households})/30$.

[14] Respondents living in the ward for at least one year were considered permanent residents.

[15] The training contained specific emphasis on the CV script. Enumerators practiced with trainers, among themselves, and in pilot testing prior to participating in fieldwork.

[16] Given the sampling strategy and desired sample size of 3660 households, households that were approached and unwilling to participate were replaced by neighbors. There were few refusals reported by the survey team; however, as household refusal and replacement was not recorded in the final dataset, the refusal rate is unknown.

3.4. Descriptive Statistics

Table 1 reports descriptive statistics of the respondent and household characteristics of the sample; descriptive statistics are reported for each basin individually as well as the entire sample. Panel A provides the measures relating to survey respondents. Enumerators attempted to interview the chief wage owner, yielding a sample that was majority male and where the average respondent age was 40.

Panel B reports household-level descriptive statistics. We observe the highest educational level within households to be either some secondary education or completion of secondary education, demonstrating that many households have at least one member who has attended secondary school. Households have, on average, less than one member under the age of 5 and a total of about 6 members. Drinking water sources vary by river basin, with public and private taps dominating the Karnali and Mahakali Basins and tubewells more common in the Mohana Basin where groundwater is more easily accessible. Latrine access is high throughout the region, demonstrating the effectiveness of sanitation campaigns in Western Nepal. We also see variation in cookstove usage and access to electricity. Traditional cookstoves are particularly prevalent in the Karnali and Mahakali River Basins, where households also have lower access to electricity; liquid petroleum gas (LPG) and biogas cookstoves are more common in the Mohana River Basin.

Migration rates in the region reveal high levels of both temporary and permanent migration as important supplementary sources of employment and household income, which is consistent with the importance of remittances–by some estimates about 30%–in Nepal's GDP (World Bank, 2016). Migration rates are particularly high in the Mahakali River Basin with nearly half of households reporting having at least one migrant household member. Finally, the region is not immune to environmental or economic shocks, with households reporting experience of an average of two shocks in the past five years.[17]

Panel C displays descriptive statistics indicating a high reliance of households within the survey area on natural resources–particularly forest and water resources. Table 1 also reveals high reliance on natural resources within the sample as well as participation in community user groups to maintain and sustain forest and water resources. This reliance comes mainly in the form of subsistence. Over 90% of the sample reports using water and forest resources for consumption while only about 10% reports using these resources for income generation. Nearly 40% of sample households belong to a community user group for forest or water resource maintenance, and many households pay nominal fees for membership in these groups. Finally, households perceive ecosystem quality in their communities as ranging between “fair” and “good” on a scale from “below average” to “excellent”.

4. Empirical Methods

4.1. Analysis of Demand

We evaluate a household's demand for environmental quality through analysis of responses to the double bounded, dichotomous choice CV questionnaire. Demand for environmental quality (E_{ij}) depends on the cost of environmental quality preservation (B), and household characteristics, including both those unique to household i (X_{ij}) and those unique to the area j (Z_j). Thus, we characterize household demand for environmental quality

$$E_{ij} = f(B, X_{ij}, Z_j) \tag{1}$$

The household's WTP for environmental quality is represented by

[17] Shocks may include drought, untimely rains, irregular weather, hail, floods, animal disease, pest damage to crops, and market disruptions, among others.

Table 1
Descriptive statistics.

Variable	Karnali (N = 2250)	Mahakali (N = 600)	Mohana (N = 810)	All (N = 3660)
Panel A: Respondent characteristics				
% male	69.9	72.2	74.2	71.2
Age	42.1 (13.6)	44.1 (13.6)	42.3 (13.0)	42.5 (13.5)
Panel B: Household characteristics				
Highest education[a]	4.7 (1.3)	5.1 (1.4)	5.1 (1.4)	4.8 (1.4)
% children < 5	46.8	40.8	41.0	44.5
Household size	5.8 (2.4)	6.2 (2.6)	6.2 (2.7)	5.9 (2.5)
Drinking water source				
% private tap	14.8	22.7	6.9	14.3
% public tap	49.1	9.0	4.1	32.6
% tubewell	6.6	30.7	86.8	28.3
% river	11.9	4.0	3.2	8.7
% stone tap	18.6	33.3	0.9	17.1
Cookstove type				
% LPG	4.1	8.7	23.7	9.2
% biogas	2.6	11.5	24.4	8.9
% solar	0.2	0	0	0.1
% improved cookstove	13.8	1.2	1.1	8.9
% traditional cookstove	79.3	78.6	50.7	72.9
% Latrine	97.3	95.0	97.0	96.9
% electricity access	41.4	74.5	94.3	58.6
Reported monthly income[b]	19,185 (40,401)	20,620 (27,202)	36,738 (133,139)	23,305 (71,380)
% own land	98.2	96.5	98.4	98.0
% own motorbike	2.3	6.3	15.5	5.9
% own radio	34.7	37.5	17.2	31.3
% own cell phone	87.2	94.2	96.9	90.5
% migrant household member	38.1	45.3	29.9	37.5
Number of shocks	2.3 (1.5)	2.7 (1.8)	1.3 (1.5)	2.2 (1.6)
Panel C: Natural resource reliance				
% use water resources (personal)	90.3	96.7	83.5	89.8
% use water resources (income)	10.6	10.8	26.3	14.1
% use forest resources (personal)	96.8	92.0	83.2	93.0
% use forest resources (income)	7.2	3.7	8.5	6.9
Stated ecosystem quality[c]	0.5 (0.6)	0.1 (0.9)	0.3 (0.9)	0.4 (0.7)
% belong to user group[d]	44.4	23.7	57.5	37.5
User group fees[b,e]	4.8 (37.1)	12.7 (56.3)	6.7 (54.4)	6.5 (45.0)

Source: Authors' calculations.
Continuous variables displayed as mean (standard deviation) unless indicated otherwise.
[a] Refers to highest level of education reported in the household based on the scale: 1 = Illiterate, 2 = Just literate, 3 = Primary school, 4 = Secondary school, 5 = SLC complete, 6 = Intermediate, 7 = Bachelor's degree, 8 = Master's degree, 9 = PhD.
[b] Monetary values reported in Nepalese Rupees (2017 exchange rate of 103 NRs = 1 USD).
[c] Ecosystem quality measured on a scale of − 1 (below average) to 2 (excellent).
[d] Only includes user groups related to natural resources, that is drinking water, irrigation, or forest user groups.
[e] Only includes fees for natural resource-related user groups, zero fees included in calculation.

the area under the demand curve

$$WTP_{ij} = \int_0^\infty f(B, X_{ij}, Z_j)dP \tag{2}$$

We estimate the household's demand for environmental quality using a probit specification. This functional form assumes that

$$\mathbb{P}(E_{ij} = 1|\mu, B) = \Phi(\mu^T\beta + \gamma B) \tag{3}$$

where μ is a vector combining X and Z, and Φ is the cumulative distribution function of the standard normal distribution. Using the estimated parameters from the probit regression and assuming an exponential demand curve, we estimate household WTP for environmental quality as

$$WTP_{ij} = -(\alpha + \bar{\mu}^T\beta)/\gamma \tag{4}$$

where α is the regression constant, and $\bar{\mu}$ denotes the mean value of each component of vector μ.

As the WTP estimation in Eq. (4) does not take into account the double-bounded design of the CV questionnaire, we also use a maximum likelihood estimator that uses both the initial and follow up bid values to estimate WTP for comparison. We use the user-generated doubleb Stata command (Lopez-Feldman, 2010) for this calculation. Also for comparison we derive non-parametric estimates of WTP. We calculate the conservative Turnbull lower-bound estimates with 95% confidence intervals following the methods outlined in Haab and McConnell (2002) and the Kriström mid-point estimates with 95% confidence intervals following Kriström (1990) and Vaughan and Rodriguez (2001).

4.2. Linking Environmental Quality Valuation and Household Characteristics

In addition to eliciting WTP for environmental quality, we are also interested in the relationships between household characteristics and environmental valuations. To investigate this relationship, we use a fixed effects, OLS regression approach, estimating

$$PWTP_{ij} = \alpha + \beta A_{ij} + \lambda X_{ij} + \zeta_j + \varepsilon_{ij} \tag{5}$$

The left hand side, $PWTP_{ij}$, is the probability that a household responds affirmatively to the CV questionnaire based on the probit regression specified in Eq. (3). The right hand side includes the same household level (X_{ij}) covariates as included in the above WTP calculations as well as additional household characteristics (A_{ij}) including

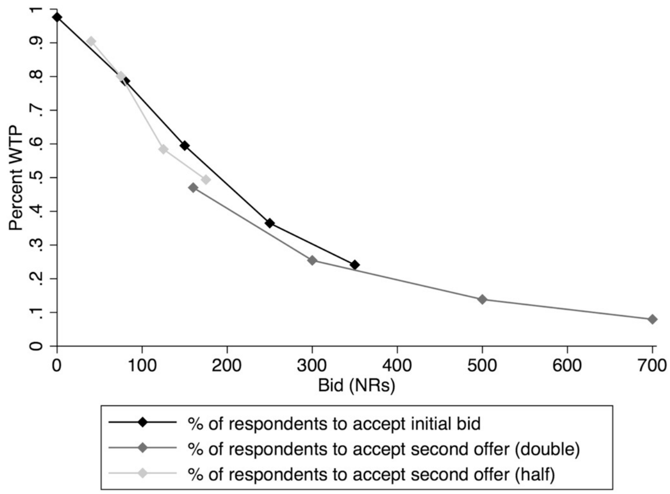


Fig. 2. Demand curve for environmental quality in Western Nepal based on initial and second round bids.

whether or not a household has at least one migrant member, land ownership, environmental shocks faced in the last 5 years, involvement in non-natural resource community user groups, familiarity with local NGOs, and participation in collective action. We also include a VDC-ward fixed effect, ζ_j, in our preferred specification to capture unobserved local factors that may affect the individual valuations within a location.

5. Results

5.1. Demand for Environmental Quality

Households in the Karnali and Mahakali River Basins in Western Nepal expressed their preferences for environmental conservation through their responses to the CV questionnaire. Fig. 2 shows the demand curve derived from responses to both the initial bid presented in the CV questionnaire as well as for the follow up half or double bid offers. Nearly 100% of respondents indicated their support of environmental conservation efforts at a price of zero. Given the tradeoff between environmental quality and development presented in the questionnaire scenario, this result suggests that environmental quality is a priority for respondents, even if it comes at the expense of development opportunities.[18] The derived demand curve demonstrates a mostly linear relationship between WTP for environmental quality and price among respondents in Western Nepal. Furthermore, demand at lower and higher bids, as reflected in the second round offers, largely extends this linear, downward sloping demand for environmental quality. Expanding the range of bids to a lower bound of 40 NRs (half of the lower bound 80 NRs initial bid) and upper bound of 700 NRs (double the upper bound 350 NRs initial bid) demonstrates nearly the entire range of WTP probabilities, from just over 90% of respondents willing to pay 40 NRs monthly for environmental conservation to less than 8% willing to pay 700 NRs.

Of course, Fig. 2 also demonstrates that while many respondents who were given low price bids indicated their willingness to pay for environmental conservation, it is clear that a large proportion of the sample was unwilling to pay the initial bid. While "no" responses can indicate that households' true valuations of environmental conservation are lower than the bid offered, they may also be protest responses (Meyerhoff and Liebe, 2006). To better understand the rationale behind these "no" responses, we consider respondents' specific reasons for being unwilling to pay the offered bid. Following Ramajo-Hernández and del Saz-Salazar (2012), Table 2 reports the reasons given for "no" responses, separated by rationales considered to indicate a true zero response and those considered to indicate a protest vote. Overwhelmingly, respondents cited budget constraints or distaste for monthly contributions as the reason for their "no" response, which we interpret as a true indication of a household's non-WTP at the offered bid. We also find, however, that respondents cite a lack of trust in local NGOs and a belief the proposal would be ineffective at relatively high rates. The latter two "no" responses could be considered protest votes. Importantly, however, respondents were permitted to indicate multiple reasons for their "no" responses. As panel B of Table 2 demonstrates, the prevalence of respondents giving only protest responses was low (only 3.9% of the sample). Furthermore, the near unanimity of respondents supporting the program at a price of zero suggests that many of these potential protests reflected beliefs that benefits would not be sufficient, or costs too high, to justify the bid offers they received. While there is precedent in the literature to omit protest votes from analysis of CV data (Ramajo-Hernández and del Saz-Salazar, 2012), we retain these respondents in our analysis to remove concerns about selection bias. Insofar as the 3.9% of the "no" response sample have actual valuations for environmental conservation, our WTP estimates will be biased downward, which would make them somewhat conservative (Calia and Strazzera, 2001).

Table 2
Reasons for an initial no WTP response.

Reasons	Number (%)
Panel A: Multiresponse rationale	
True zero response	
Land conservation is not a problem	132 (7.2)
Proposal is too expensive	1509 (83.2)
Do not want to contribute monthly	683 (37.7)
Benefits are not worth the cost	249 (13.7)
Protest response	
Do not trust local NGO	213 (11.8)
Proposal will not work	293 (16.2)
Would not benefit from proposal	41 (2.26)
Panel B: Distribution of response	
Only true zero response	1349 (73.6)
Only protest response	71 (3.9)
Both true zero and protest response	413 (22.5)
Total rejection	1834 (50.1)

Source: Authors' calculations.
Percentages calculated among the sub-sample that responded "no" to the initial WTP question. Multiple answers were permitted; distribution of multiple answers reported in Panel B.

Table 3
WTP estimates.

	Turnbull lower bound	Double-bounded MLE
Entire sample (N = 3660)	165.2 [155.0, 174.4]	201.8 [194.2, 209.4]
Karnali Basin (N = 2250)	162.2 [150.0, 174.5]	221.0 [208.7, 233.4]
Mahakali Basin (N = 600)	140.3 [115.3, 161.5]	157.4 [138.3, 176.5]
Mohana Basin (N = 810)	191.7 [169.8, 210.0]	252.1 [211.4, 293.6]
Mountains (N = 797)	210.6 [188.8, 228.4]	276.6 [255.2, 297.9]
Mid-hills (N = 1676)	142.1 [126.6, 157.3]	178.2 [161.0, 195.4]
Terai (N = 1187)	167.3 [150.8, 185.7]	240.8 [218.2, 263.4]

Source: Authors' calculations.
Results reported as mean [95% confidence interval]. Parametric estimates calculated with the following controls: respondent age, respondent gender, highest household education, household size, and presence of children under 5 in household, as well as controls for basin and geographic region, if applicable.

[18] The CV instrument reminded respondents that while the hypothetical conservation program would not alter current land use patterns, it would prevent additional development of forested land for agricultural purposes, roads, etc. As road access is a key factor in market access and economic development, this tradeoff was particularly salient for survey respondents.

Table 3 provides the willingness to pay estimates among the entire sample as well as divided by river basin and geographic region. Column 1 reports the non-parametric Turnbull lower-bound estimates; column 2 the double bounded dichotomous choice MLE estimates.[19] The confidence intervals of the Turnbull lower bounds were calculated using a bootstrapping method.

Among the entire sample, we find a lower bound on monthly WTP of 165 NRs (US$1.60) and an average monthly WTP of 202 NRs (US$1.96) for environmental conservation. Across the basins, these WTP values correspond to about 1% of a household's monthly income. Given the limited resources of many of the inhabitants of the Karnali and Mahakali River Basins, 1% of monthly income suggests a relatively high prioritization of environmental conservation. We see some variation in WTP estimates when dividing the sample by river basin. Valuation for environmental quality is highest in the Mohana River Basin and lowest in the Mahakali River Basin, regardless of the estimation method used. There is also variation in the WTP estimates across the Terai, hills, and mountain zones. Respondents in the mountain regions had the highest monthly WTP for environmental conservation, and respondents in the mid-hills had the lowest. While these results do demonstrate some variation in monthly WTP for environmental conservation based on location and terrain, they also reveal a consistently positive valuation for environmental quality among this representative sample of respondents.

While providing insight into conservation priorities in the Karnali and Mahakali River Basins, it should be noted that the valuation exercise indicates that value conditional on the mobilization of a community-wide conservation effort. Thus, considering the community-level WTP for environmental conservation is informative regarding the scale of conservation that could be feasible in the region. While 30 households from each of the 122 VDCs visited were included in the sample, VDCs vary considerably in both area and population; the smallest VDC has only 124 households, whereas the largest has over 34,000. Thus, comparisons of VDC-aggregated monthly WTP for environmental conservation are skewed based on population size and demonstrate substantial variation. Nevertheless, we find that the median VDC-aggregated WTP for environmental conservation is 32,707 NRs (US$318).[20] Of course, the natural land area available for conservation programs also varies by VDC; however, we can think of these aggregated values as the additional income that development would have to generate to fully compensate for loss of these preserved lands.

Fig. 3 depicts the spatial distribution of WTP for land conservation throughout the Karnali and Mahakali River Basins. Respondents in the mountainous regions of both the Karnali and Mahakali River Basins had higher WTP than those in the hill regions. Respondents in the Mahakali River Basin had lower WTP for land conservation efforts compared to those in the Karnali and Mohana River Basins. This locational variation in WTP demonstrates a need to consider regional heterogeneity in responses, as appropriate policy response may differ by region.

Analysis of the follow up questions included in the CV instrument to check for respondent understanding of the scenario presented reveals additional insight into demand for environmental quality. Over 80% of respondents reported being "very confident" in their responses to the initial bid, even at the maximum bid price of 350 NRs. Furthermore, less than 4% of the sample reported feeling only "somewhat confident". These confidence checks suggest that respondents understood the scenario and that the questions were salient and realistic. As such, we are fairly confident that hypothetical bias was limited in this context.[21]

We also considered the rationale respondents provided for why they would support the proposal presented in the CV questionnaire. The most common reason respondents supported the proposal, regardless of initial bid price, was to preserve access to forest resources, with nearly 50% of respondents citing this rationale after an affirmative response to the initial bid. Other rationales for an affirmative response included concerns about water scarcity, erosion, and biodiversity preservation.

5.2. Environmental Quality Valuation and Household Characteristics

In addition to locational heterogeneity in WTP among respondents throughout the Karnali and Mahakali River Basins, household characteristics may be related to WTP for land conservation. We consider both standard household correlates of demand–assets, education, and household size–as well as additional variables that we thought would be relevant in this setting–migration, land ownership, experience with environmental shocks, and various forms of community participation.[22]

Table 4 reports bivariate regression results of the probability of a household being willing to pay for land conservation as a function of household characteristics. Each regression is reported with and without VDC fixed effects. Households with at least one migrant household member demonstrate a lower probability of WTP for land conservation programs. This could indicate that such households are more mobile or view migrant family members as a source of income outside of the community and are thus less dependent on natural resources as a form of insurance or less willing to invest in their community.

We also find a positive, statistically significant relationship between the amount of land owned by a household and WTP for environmental conservation. Households owning higher amounts of land in a village may exhibit higher WTP because they are more invested in the village and its resources. Alternatively, these households may have higher wealth, and environmental quality may be a normal good. Similarly, we find a positive, significant relationship between household WTP for environmental conservation and experienced negative environmental shocks. This positive correlation could be indicative of a better understanding among these households of the relationship between environmental degradation and development of natural lands and incidence of environmental shocks (ex., landslides or erosion resulting from road building or deforestation). While these correlations are not significant in all specifications, they are precisely measured in our specification with VDC-ward fixed effects.

We also consider relationships between household WTP for environmental conservation and various measures of community participation. There is a positive and statistically significant relationship between a household's membership in community groups not related to natural resource use or conservation and WTP as well as between stated participation in community collective action and WTP. These relationships provide suggestive evidence that households that participate more in community activities also place a higher value on land conservation. As the benefits of such a program would be shared by the community, these relationships demonstrate consistency between reported behaviors and stated responses to the CV questionnaire. We find a negative, statistically significant relationship between WTP and familiarity with local NGOs, which may reflect a lack of confidence in NGO-implemented conservation programs or a belief that existing NGO

[19] The non-parametric Kriström mid-point estimates and probit results are available in Table A.1 in the Appendix.

[20] VDC-aggregated WTP calculated by multiplying the double-bound dichotomous choice WTP estimate for each basin and geographical region by the population of the VDC.

[21] The same WTP analysis was conducted on the subsample of survey respondents omitting those who reported they were "somewhat confident" (the lowest confidence level provided) as well as on the subsample of respondents who reported being "very confident" (the highest confidence level provided) in their answer. The results using these subsamples were statistically indistinguishable from those using the entire sample population.

[22] We use an asset score as a proxy for socio-economic status in the analysis, as asset ownership remains fairly stable over time, whereas some income measures collected vary throughout the year. The asset score was developed using principle components analysis using roof type, electricity access, and motorbike, livestock, radio, and cell phone ownership.

Fig. 3. WTP for land conservation in Western Nepal. Values calculated using double-bounded MLE parametric approach.

Table 4
Bivariate regression results: WTP probability.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Migrant HH member	−0.066***	−0.027***										
	(0.011)	(0.0092)										
Land owned (ha)			−0.0084	0.025**								
			(0.012)	(0.0099)								
No. of env. shocks					−0.0030	0.007**						
					(0.0045)	(0.0031)						
Community group membership[a]							0.015	0.034***				
							(0.013)	(0.0099)				
Local NGO familiarity									−0.016***	−0.0094**		
									(0.0061)	(0.0042)		
Collective action											0.053***	0.039***
											(0.015)	(0.013)
Constant	0.53***	0.51***	0.50***	0.49***	0.51***	0.49***	0.49***	0.48***	0.51***	0.51***	0.487***	0.49***
	(0.0099)	(0.0035)	(0.011)	(0.0036)	(0.013)	(0.0066)	(0.013)	(0.0059)	(0.011)	(0.0026)	(0.010)	(0.0033)
VDC-ward FE	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y
Observations	3649	3649	3659	3659	3659	3659	3640	3640	3651	3651	3659	3659
R^2	0.016	0.003	0.000	0.002	0.000	0.001	0.001	0.004	0.005	0.001	0.008	0.004

Source: Authors' calculations. Standard errors, clustered at VDC level, in parentheses.
[a] Only refers to user groups not related to natural resources such as savings groups and women's groups.
* $p < 0.10$.
** $p < 0.05$.
*** $p < 0.01$.

conservation programs already provide the necessary protection in their communities.

While the bivariate results provide insight into reduced form relationships between household characteristics and WTP for land conservation, these correlations are unable to account for the multiple correlated factors that may influence this relationship. Table 5 reports the results of multivariate regressions that control for a more complete set of observable household characteristics. Specifications 1 and 2 provide regression results including a basic set of household characteristics including asset ownership, education, gender, age, household size and composition, and the initial bid; we include VDC-ward fixed effects in the second specification. Households with more educated members and those with younger, male respondents reported higher willingness to pay. Asset ownership (as measured by the asset index) and the size and composition of households do not influence preferences for conservation. The relationships between household WTP for environmental conservation and asset ownership and household size and composition are not precisely measured.

Specifications 3 and 4 in Table 5 include the household characteristics from the bivariate regression analysis as well as some measures of household participation in ongoing conservation efforts. We include the basic set of household controls in both specifications and VDC-ward fixed effects in specification 4. The inclusion of these additional household characteristics does not alter the sign or significance of the relationships observed in specifications 1 and 2. Additionally, we find that payment of higher membership fees for natural resource-related user groups is associated with higher WTP and having a migrant household member, owning land, and familiarity with local NGOs are all negatively associated with WTP. This result demonstrates consistency between stated WTP for environmental conservation and reported conservation-related expenditures. While we do find statistically significant relationships in specification 3, the precision of the estimates is lost with the inclusion of VDC-ward fixed effects. The loss of statistical significance in these specifications is perhaps not surprising given that many of the relevant variables are highly correlated within communities rather than being individual or household-level factors; the fixed effects, therefore, likely absorb these relationships.

6. Discussion

The results of our analysis point to the importance of including environmental priorities in development planning for Western Nepal. While households and villages want access to roads and the economic activities afforded by markets, our results reveal that environmental

Table 5
Multivariate regression results: WTP probability.

	(1)	(2)	(3)	(4)
Asset score[a]	0.0011	0.00021	−0.0011	0.00025
	(0.0041)	(0.00047)	(0.0040)	(0.00048)
Highest HH education[b]	0.064***	0.064***	0.063***	0.064***
	(0.0025)	(0.00056)	(0.0025)	(0.00056)
Male respondent	0.11***	0.091***	0.099***	0.091***
	(0.0073)	(0.0014)	(0.0072)	(0.0015)
Respondent age	−0.0030***	−0.0028***	−0.0029***	−0.0028***
	(0.00018)	(0.000048)	(0.00017)	(0.000049)
Child < 5	−0.0014	−0.00090	0.0017	−0.00095
	(0.0049)	(0.0012)	(0.0047)	(0.0012)
HH size	−0.00016	−0.00016	0.0021*	−0.00010
	(0.0012)	(0.00025)	(0.0011)	(0.00027)
Initial bid	−0.0020***	−0.0020***	−0.0020***	−0.0020***
	(0.000010)	(0.0000079)	(0.000011)	(0.0000079)
Migrant HH member			−0.029***	−0.00077
			(0.0071)	(0.0013)
Land owned (ha)			−0.021**	−0.00078
			(0.0091)	(0.0011)
Number of environmental shocks			−0.0032	−0.000059
			(0.0039)	(0.00056)
Member of community group			−0.0057	−0.0013
			(0.0080)	(0.0013)
Familiarity with local NGO			−0.0080*	0.00079
			(0.0046)	(0.0011)
Collective action			0.018*	−0.00026
			(0.011)	(0.0014)
Natural resource user group membership			0.0021	−0.000028
			(0.012)	(0.0015)
Natural resource user group fees			0.000038	0.0000099
			(0.000060)	(0.0000081)
Constant	0.67***	0.67***	0.68***	0.67***
	(0.016)	(0.0029)	(0.019)	(0.0036)
VDC-ward FE	N	Y	N	Y
Observations	3655	3655	3607	3607
R^2	0.85	0.98	0.86	0.98

Source: Authors' calculations. Standard errors, clustered at VDC level, in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.001$.

[a] Asset score developed using principle components analysis using roof type, electricity access, and motorbike, livestock, radio, and cell phone ownership.

[b] Refers to highest level of education reported in the household based on the scale: 1 = Illiterate, 2 = Just literate, 3 = Primary school, 4 = Secondary school, 5 = SLC complete, 6 = Intermediate, 7 = Bachelor's degree, 8 = Master's degree, 9 = PhD.

conservation is a priority among inhabitants of the Karnali and Mahakali River Basins. We estimate that households are willing to pay an average of 202 NRs (US$1.96) per month to retain the natural state of undeveloped lands in and surrounding their villages, although variation in this WTP does exist based on river basin and geographical region. While this WTP appears low, it represents about 1% of monthly income, which is comparable to other estimates in the literature.[23] Furthermore, aggregation of WTP values at the VDC level demonstrates that inhabitants of the Karnali and Mahakali River basins attribute a high opportunity cost to environmental degradation. In the median VDC, development projects would need to generate over 32,000 NRs monthly to fully compensate for degradation to intact, undisturbed ecosystems.[24]

Households in the Karnali and Mohanna River Basins exhibit higher WTP for environmental conservation than those living in the Mahakali River Basin; households in the mountain and Terai regions similarly have higher WTP than those in the mid-hills. Additionally, we find that certain household and village characteristics are significantly related to WTP for environmental conservation. Households with higher levels of education and younger, male respondents report consistently higher WTP; additionally, those already participating in and paying for natural resource user groups report higher WTP. Households with migrant households members, high land ownership, and familiarity with local NGOs report lower WTP. These relationships are not consistent across all analyses: In particular, inclusion of VDC-ward fixed effects leads to less precisely estimated relationships, suggesting that village characteristics may also play a role in household WTP to pay for environmental conservation. This is consistent with a village level perspective on collective action for environmental preservation, whereby entire communities may be more or less willing to participate in conservation efforts.

From a policy perspective, the prioritization of environmental conservation over other development opportunities among respondents suggests that environmental concerns should continue to be an important factor in development planning in Western Nepal. Households rely on natural resources for household consumption and to maintain agricultural productivity and income, as well as for preserving ecosystem balance and reducing the instance and severity of hazards such as landslides. Infrastructure building and other development initiatives must take into account their potential environmental costs, if such livelihoods were to be displaced. Informed benefit-cost analysis of such projects would account for the nonmarket values associated with environmental impacts, as well as their distributional implications for local populations.

Importantly, we also found that WTP varies both spatially and according to household and regional characteristics. A single uniform conservation policy response for the region is thus unlikely to satisfy all inhabitants in all locations. Western Nepal remains a region poised to embark on a development trajectory that may include large scale development of water resources for energy generation or irrigation, smaller community-managed natural resource management, or ecotourism and industry based pathways. The economic net benefits of these various opportunities should be carefully considered alongside local inhabitants' willingness to pay for environmental conservation. Moreover, broad-based development should balance both vertical and horizontal equity concerns, supporting opportunities for locals with initiatives to protect those bearing higher costs, and especially protecting livelihoods needs among the poor who may have the lowest access to benefits from large infrastructure.

Supplementary material to this article can be found online at https://doi.org/10.1016/j.ecolecon.2018.12.021.

Acknowledgements

This study is made possible by the generous support of the American people through the United States Agency for International Development (USAID). The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government.

We acknowledge and appreciate the helpful comments from two anonymous reviewers.

Declarations of interest: none. All research conducted with permission of the Institutional Review Board (IRB) of Duke University.

References

Adamowicz, W., Swait, J., Boxall, P., Louviere, J., Williams, M., 1997. Perceptions versus objective measures of environmental quality in combined revealed and stated preference models of environmental valuation. J. Environ. Econ. Manag. 32, 65–84.

Arrow, K., Solow, R., Portney, P., Leamer, E., Radner, R., Schuman, H., 1993. Report of the NOAA panel on contingent valuation. Fed. Regist. 58, 4601–4614.

Baral, N., 2007. Resources use, conservation attitudes, management intervention and park-people relations in the Western Terai landscape of Nepal. Environ. Conserv. 34, 64–72.

Baral, N., Stern, M.J., Bhattarai, R., 2008. Contingent valuation of ecotourism in Annapurna conservation area, Nepal: implications for sustainable park finance and

[23] Barkmann et al. (2008) estimate WTP for hydrological ecosystem preservation in rural Indonesia to be 1% of monthly income.

[24] This estimate is calculated as the product of the regional basin WTP and the estimated number of households in the region.

local development. Ecol. Econ. 66 (2), 218–227.
Barkmann, J., Glenk, K., Keil, A., Leemhuis, C., Dietrich, N., Gerold, G., Marggraf, R., 2008. Confronting unfamiliarity with ecosystem functions: the case for an ecosystem service approach to environmental valuation with stated preference methods. Ecol. Econ. 65 (1), 48–62.
Bhat, M.G., 2003. Application of non-market valuation to the Florida Keys marine reserve management. J. Environ. Manag. 67 (4), 315–325.
Bohra-Misra, P., 2013. Labour migration and investments by remaining households in rural Nepal. J. Popul. Res. 30, 171–192 378.
Calia, P., Strazzera, E., 2001. A sample selection model for protest responses in contingent valuation analysis. Statistica 61, 473–485.
Carson, R.T., 2000. Contingent valuation: a user's guide. Environ. Sci. Technol. 34 (8), 1413–1418.
Cummings, R., Taylor, L., 1999. Unbiased value estimates for environmental goods: a cheap talk design for the contingent valuation method. Am. Econ. Rev. 89 (3), 649–665.
Diamond, P.A., Hausman, J.A., 1994. Contingent valuation: is some number better than no number? J. Econ. Perspect. 8 (4), 45–64.
Edmonds, E.V., 2002. Government initiated community resource management and local resource extraction from Nepal's forests. J. Dev. Econ. 68 (1), 89–115.
Ellingson, L., Seidl, A., 2007. Comparative analysis of non-market valuation techniques for the Eduardo Avaroa Reserve, Bolivia. Ecol. Econ. 60 (3), 517–525.
Ferraro, P.J., Lawlor, K., Mullan, K.L., Pattanayak, S.K., 2012. Forest figures: ecosystem services valuation and policy evaluation in developing countries. Rev. Environ. Econ. Policy 6 (1), 20–44.
Font, A.R., 2000. Mass tourism and the demand for protected natural areas: a travel cost approach. J. Environ. Econ. Manag. 39, 97–116.
Grossman, G.M., Krueger, A.B., 1995. Economic growth and the environment. Q. J. Econ. 110, 353–378.
Haab, T.C., McConnell, K.E., 2002. Valuing Environmental and Natural Resources: The Econometrics of Non-Market Valuation. Edward Elgar Publishing Limited, Northampton, MA.
Hanemann, M., Loomis, J., Kanninen, B., 1991. Statistical efficiency of double-bounded dichotomous choice contingent valuation. Am. J. Agric. Econ. 73 (4), 1255–1263.
Hanley, N., Bell, D., Alvarez-Farizo, B., 2003. Valuing the benefits of costal water quality improvements using contingent and real behaviour. Environ. Resour. Econ. 24 (3), 273–285.
Hausman, J., 2012. Contingent valuation: from dubious to hopeless. J. Econ. Perspect. 26 (4), 43–56.
Jeuland, M., 2010. Economic implications of climate change for infrastructure planning in transboundary water systems: an example from the Blue Nile. Water Resour. Res. 46, W11556.
Jeuland, M., Whittington, D., 2014. Water resources planning under climate change: assessing the robustness of real options for the Blue Nile. Water Resour. Res. 50 (3), 2086–2107.
Khatiwada, K.R., Panthi, J., Shrestha, M.L., Nepal, S., 2016. Hydro-climatic variability in the Karnali River Basin of Nepal Himalaya. Climate 4 (2), 17.
Kriström, B., 1990. A non-parametric approach to the estimation of welfare measures in discrete response valuation studies. Land Econ. 22 (2), 135–139.
Kuznets, S., 1955. Economic growth and income inequality. Am. Econ. Rev. 45 (1), 1–28.
Lopez-Feldman, A., 2010. doubleb: Stata module to estimate contingent valuation using double-bounded dichotomous choice model. Available at http://ideas.repec.org/c/boc/bocode/s457168.html. .
Mahajan, A., Bauer, S., Knerr, B., 2013. International migration, remittances and subsistence farming: Evidence from Nepal. Int. Migr. 51 (1), e249–e263.
Massey, D.S., Axinn, W.G., Ghimire, D.J., 2010. Environmental change and out-migration: evidence from Nepal. Int. Migr. 32 (2), 109–136.
Meyerhoff, J., Liebe, U., 2006. Protest beliefs in contingent valuation: explaining their motivation. Ecol. Econ. 57 (4), 583–594.
Navrud, S., Mungatana, E., 1994. Environmental valuation in developing countries: the recreational value of wildlife viewing. Ecol. Econ. 11 (2), 135–151.
Nunes, P.A.L.D., van den Bergh, J.C.J.M., 2001. Economic valuation of biodiversity: sense or nonsense? Ecol. Econ. 39 (2), 203–222.
Pandey, V.P., Babel, M.S., Shrestha, S., Kazama, F., 2010. Vulnerability of freshwater resources in large and medium Nepalese river basins to environmental change. Water Sci. Technol. 61 (6), 1525–1534.
Ramajo-Hernández, J., del Saz-Salazar, S., 2012. Estimating the non-market benefits of water quality improvement for a case study in Spain: a contingent valuation approach. Environ. Sci. Pol. 22, 47–59.
Stern, D., 2004. The rise and fall of the environmental Kuznets curve. World Dev. 32 (8), 1419–1439.
Vaughan, W.J., Rodriguez, D.J., 2001. Obtaining welfare bounds in discrete-response valuation studies: comment. Land Econ. 77 (3), 457–465.
Water and Energy Commission Secretariat, 2005. National water plan. http://www.moen.gov.np/pdf_files/national_water_plan.pdf.
Whittington, D., 1998. Administering contingent valuation surveys in developing countries. World Dev. 26 (1), 21–30 261.
Whittington, D., Pagiola, S., 2012. Using contingent valuation in the design of payments for environmental services mechanisms: a review and assessment. World Bank Res. Obs. 27 (2), 261–287.
World Bank, 2016. Migration and remittances factbook 2016. https://siteresources.worldbank.org/INTPROSPECTS/Resources/334934-1199807908806/4549025-1450455807487/Factbookpart1.pdf.

Annex 7-4

Hydro-Economic Modeling Framework to Address Water-Energy-Environment-Food Nexus Questions at River Basin Scale

Aditya Sood[1], Emily L. Pakhtigian[2], Maksud Bekchanov[3], and Marc Jeuland[4]

[1]The Nature Conservancy in India
[2]Sanford School of Public Policy, Duke University
[3]Center for Development Research, Bonn University
[4]Sanford School of Public Policy and Duke Global Health Institute, Duke University, and RWI Leibniz Institute for Economic Research

June 10, 2019

Executive Summary

Increasing competition for water resources among multiple economic and social sectors calls for efficient allocation of water and intelligent trade-offs among sectors. To support such an integrated planning approach, there is a need for tools that better account for the complex dynamics underlying water systems. Hydro-economic modeling is one such tool: It is typically used to understand how the economic benefits from water allocation can be improved or optimized or to assess the economic benefits of policy or infrastructure responses to current and changing conditions. Many hydro-economic models (HEMs) exist to study such problems, but a recent review of these tools points to areas where progress and innovation would improve their relevance. These include improvements in the representation and analysis of feedbacks between water and other systems in the economy (energy and industry, for example), more sophisticated accounting of ecosystem services, as well as analysis of the distributional implications of alternative management institutions (Bekchanov et al., 2017).

The underlying structure of HEMs is node-based, with flow continuity equations describing water movements (natural flows as well as human-controlled supply, storage, and distribution to demand locations) throughout a river system (Harou et al., 2009). This organization is useful for its detailed spatial and temporal representation of water resources systems. Such models are widely used in forecasting and scenario analyses to compare the economic consequences of environmental (e.g. water supply availability), technological (e.g., introducing drip irrigation), infrastructural (e.g., dam/reservoir development), and institutional (e.g., water markets, water pricing, or market liberalization) changes. The HEM framework suggested in this report is largely based on this structure, but places additional emphasis on interlinkages across the Water-Energy-Environment-Food nexus, which increasingly challenges the decisions of water and energy systems managers (McCornick et al., 2008). Nonetheless, it is important to acknowledge that HEMs have often included and considered trade-offs across the production and consumption needs of the energy and agricultural sectors, so our work should be considered an extension, rather than a re-invention, of such models.

The water, energy, and food components in this nexus HEM are controlled by the social system, which itself falls within a larger environmental ecosystem. The social system is comprised of individuals and communities that use water and other resources (e.g., land, energy) as well as the institutions that manage them. Each system also generates externalities, for example pollution, that affect inhabitants of the ecosystem in complex ways. Pollution externalities in particular have an adverse effect on the ecosystem's ability to provide services to the broader system. One central theme of the nexus approach is security, here defined in terms of water, food and energy security. These various notions of security are closely related to the concept of availability, access, and affordability (3As) of essential goods and services (Flatin and Nagothu, 2014). The availability of resources and final services depends upon biophysical conditions, domestic production, and regional trade. Production processes require built and social infrastructure and capacity. Accessibility and affordability, therefore, depends upon existing societal structures such as markets and allocative institutions and upon technological and economic opportunities. To address issues related to 3As, biophysical, economic, and institutional conditions are crucial.

Our HEM Nexus framework depicts interactions between five specific sectors or modules. The first core module is the water system; it is based on the typical node-link structure of most similar HEMs and necessarily contains linkages between surface and groundwater resources. Three other modules that are linked to this core are principally human production systems: energy, municipal and industrial, and agricultural production systems. A fifth module describes the broader ecosystem or environment; this component provides a variety of market and nonmarket goods and services (ecosystem services) to the other systems and is also the recipient of ?externalities? from them. These externalities, beyond certain levels, may lead to a reduction in the ability of ecosystem to provide services to other systems and to the environment.

The structure of the HEM Nexus framework is based on three concepts: scalability, i.e. the HEM should be able to represent basins or regions of different scales; transferability, i.e. the model should be transferable across river basins without substantial effort to change its underlying structure; and modularity, i.e. each module that is connected to the core water system should be able to function independently. The four connected modules are linked to the core via decision variables that enter the model objective function. This objective function aims for maximization of benefits across sectors and uses given both physical and social water and energy system relationships and constraints.

As an optimization model, the HEM Nexus tool is well-adapted to identifying solutions that most efficiently allocate water and other resources, which is especially useful for planning purposes. As with all similar models, it works from a standardized and simplified representation of a very complex system that is developed to be both sufficiently realistic and computationally tractable. Such models are sometimes criticized for the assumptions inherent in their structure. Optimization frameworks for example may not be well-suited to understanding real world outcomes because the institutions governing allocations rarely come close to resembling an omniscient social planner or a well-functioning water market. In addition, the model is not meant to be used for operational purposes, which typically require greater spatial and temporal resolution. A basin scale, node-based HEM framework, as suggested in this paper, works well at basin level and is best suited to answering questions related to investments and policies, water use optimization across sectors, trade-offs across sectors, and connections with ecosystem services. Such an HEM may need to be linked with more detailed economy-wide models to better understand the issues of affordability and accessibility. Finally, the HEM Nexus described here is new and needs to be applied to a variety of problems and contexts to improve its usability and relevance to real world situations.

1 Introduction

Future projections of water supply and demand suggest a trend towards increasing global and regional water scarcity (Rosegrant et al., 2002; Alcamo et al., 2007; Arnell et al., 2011; Hanasaki et al., 2013; Schewe et al., 2014). Reflecting this increased scarcity, analyses of likely future climate and socio-economic change point towards greater competition for water among various sectors of economy as well as the environment (Rijsberman, 2006; Chartres and Sood, 2013; Mancosu et al., 2015). Given this trend towards increased water competition, it will become increasingly crucial for society to efficiently and effectively manage allocations among competing uses. Various institutions will play an important role in this management process; these institutions will need to understand and balance numerous and complex trade-offs across sectors including agriculture, municipal and industrial, hydropower and energy, and environmental and recreation.

A careful balancing of such diverse interests requires that water resource planning continue to evolve from an approach focused on analysis of isolated projects and solutions towards more integrated consideration of development trajectories and portfolios of management and investment solutions. The tools needed for such analysis must achieve increasing integration and flexibility of ideas and principles from both physical and social science disciplines. Much progress has already been made in establishing robust hydro-economic models for use in water resource planning applications (Harou et al., 2009; Bekchanov et al., 2017), but the dominant approach in the field continues to focus on isolated objectives, e.g., maximization of water use benefits in hydropower production and/or irrigation, minimization of municipal and environmental water delivery costs, or management of well-defined risks. A more integrated approach requires that water demands and benefits from multiple sectors and interlinkages among these sectors be considered simultaneously and that trade-offs across them be analyzed to better understand how to efficiently deliver benefits to society as a whole.

The integrated approach to water resource planning first became prominent with the launch of Water Resource System Analysis (WRSA), defined as ?study of water resources systems using mathematical representations of the component processes and interactions of the system to improve understanding or assist in decision making? (Brown et al., 2015). WRSA began with development of a systems approach to water resource planning that included multi-objective optimization of water infrastructure investments (Maass et al., 1962). Since then, it has evolved into a more collaborative analytical approach, whereby stakeholders are involved in defining the relevant systems and couplings between them. The building blocks of the models used for analysis and understanding of interactions and feedbacks consist of mathematical functions that link together hydrological and human components (Brown et al., 2015).

Hydro-economic modeling is one particular WRSA tool that aims to understand the economic implications of interactions between human and water resource systems. Hydro-economic models (HEMs) are typically developed to understand the optimal economic benefits from water allocation or to assess the economic benefits of policy or infrastructure responses to current and changing conditions. The central concept for describing economic value in such models is that of marginal benefit, which is differentiated according to the type of water use. Traditionally, economic analysis using HEMs has been conducted to understand how changes in the availability of water ? from infrastructure, altered management and/or operating rules, or changing flow conditions ? translate into changes in marginal and overall economic benefits (Bekchanov et al., 2017). Thus, water allocation is driven by the value of water with the goal of increasing or maximizing its overall benefit to human society. To achieve optimal economic efficiency, water is allocated among various users until the marginal net benefit across uses is one and the same.

HEMs include spatially and temporally-differentiated data and flow continuity (mass balance) relationships that describe movements of water using a node-link network structure (Brouwer and Hofkes, 2008; Cai, 2008; Harou et al., 2009). Water flows move naturally through the network but can also be modified using potential and existing water management infrastructures. Water is then consumed, subject to its availability, according to the spatial configuration of economic agents and their demands, with infrastructural operating rules and/or allocative institutions acting through a set of constraints or decision variables (Bekchanov et al., 2017). Hydrological flows can be provided as a time series of inputs based on historical conditions in a basin or can be obtained from rainfall-runoff models that allow for consideration of changing climatic conditions. Water management infrastructure includes natural and human-built infrastructure, the latter of which can lead to temporal smoothing of variability in water availability at a particular location. Economic water users are associated with demand functions that both link quantities of allocated water to marginal or total benefits and also encompass nonmarket uses. Finally, management costs include those related to infrastructure development, storage, pumping, transfer, and distribution of water resources.

HEMs are often also distinguished according to whether they are simulation or optimization models (Harou et al., 2009; Bekchanov et al., 2017). Network-based simulation models are widely used in forecasting and scenario analyses to compare the economic consequences of environmental (e.g. water supply availability), technological (e.g., introducing drip irrigation), infrastructural (e.g., dam/reservoir development), and institutional (e.g., water markets, water pricing, or market liberalization) changes. Optimization models on the other hand allow for determination of the most efficient water allocations within a system under varying conditions and subject to a variety of constraints.

When it comes to analysis of the interlinkages between water and economic systems, the usefulness of a particular model structure depends on the research question and objective at hand. A recent review of basin-scale HEMs and economy-wide water models identified a number of critical research gaps that would improve the usefulness of such tools (Bekchanov et al., 2017). One critical shortcoming concerns a lack of sufficiently realistic integration of water, energy, and food systems. A second major gap concerns the often poor representation (and therefore understanding) of the value and systems trade-offs surrounding nonmarket water-related ecosystem services. HEMs by definition include many ecosystem services since these tools describe use of a specific natural resource, water, by a range of sectors. Inclusion of nonmarket water-based provisioning and regulating services, however, is often challenging.[1] Finally, most HEM studies tend to gloss over or oversimplify the importance and consequences of institutional constraints for economic production. Indeed, water allocation decisions are rarely made based on some idealized optimal value of water but, rather, within a complicated context of political and social constraints. As such, institutions can act as facilitators of, or obstacles to, efficient water allocation.

[1]These services include aspects such as soil fertilization; maintenance of subsistence livelihoods, wetlands and ecological function; pollution and erosion control; and many recreational values.

This paper describes a new and general HEM structure that aims to allow researchers to address some of these gaps. The next section presents a conceptual framework based around the Water-Energy-Environment-Food (WEEF) Nexus concept that helps to organize ideas by illustrating the scope and scale of the challenges facing integrated models of this type. We then review the prior literature that is relevant for understanding the myriad linkages in the WEEF Nexus using HEMs and highlight some of the most critical gaps in this prior work. Section 4 explains how our new HEM structure aims to fill these gaps, using pictorial schematics to clarify which aspects and connections have been included in the model. Section 5 describes the mathematical structure of the model in full detail, beginning with a presentation of the principles that were applied in its creation–scalability, transferability, and modularity–and then proceeding with a listing of equations and definitions for model parameters and variables. Finally, the report concludes by highlighting the importance and shortcomings of this work, suggesting how the model may be usefully applied in future research, and summarizing the lessons learned through this effort.

2 Conceptual Framework

Before developing a conceptual framework for nexus-based hydro-economic modeling, it is important to develop a more precise definition of what we mean by the Water-Energy-Environment-Food (WEEF) nexus. The basic idea motivating use of this nexus concept is that each of these various systems are interlinked and that the interlinkages and feedbacks across them must be considered in holistic fashion if development planning is to be improved. The energy and food systems may be considered as human production systems that influence and are influenced by the constraints and opportunities of the wider social system, all of which also fall within the environmental system (Figure 1). The social system is made up of the individuals and communities that use resources to produce economic benefits as well as the institutions that manage them. It demands resources (e.g., land, water, timber) from the environment, labor inputs from society, and intermediate and final goods from the three human production systems. The quantities of inputs and outputs that are demanded by different stakeholders in the social system depend on demand functions that relate quantities to willingness to pay (or marginal benefits). These marginal benefits are not static; rather, they evolve as a function of technology, demographic and other changes, and societal preferences.

Production is supported by natural resources derived from the ecosystem (a subset of broader ecosystem services), and accessing these resources entails costs that vary over time and space. Each system also generates externalities, for example pollution, that affect the inhabitants and ecology of the ecosystem in complex ways. Pollution externalities in particular have an adverse effect on the ecosystem's ability to provide services within the broader nexus.

Substantial prior work has worked to elucidate the theoretical interdependencies between these WEEF sectors and has correspondingly argued for the importance of an integrated approach to management in these domains (see for example McCornick et al. (2008), Bazilian et al. (2011), Ringler et al. (2013), Arent et al. (2014), Weitz et al. (2014)). Traditionally, nexus discourse has also been driven by a debate over the interrelated components of resource security (Hoff, 2011; ADB, 2013; UNESCAP, 2013; Dubois et al., 2014). The notion of water security for example refers to safeguarding "sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability" (UN Water, 2013). Food security meanwhile is achieved by ensuring "physical and economic access to sufficient, safe and nutritious food that meets dietary needs and food preferences for an active and healthy life" (FAO). Similarly, energy security can be maintained through "uninterrupted availability of energy sources at an affordable price" (International Energy Agency, 2016).

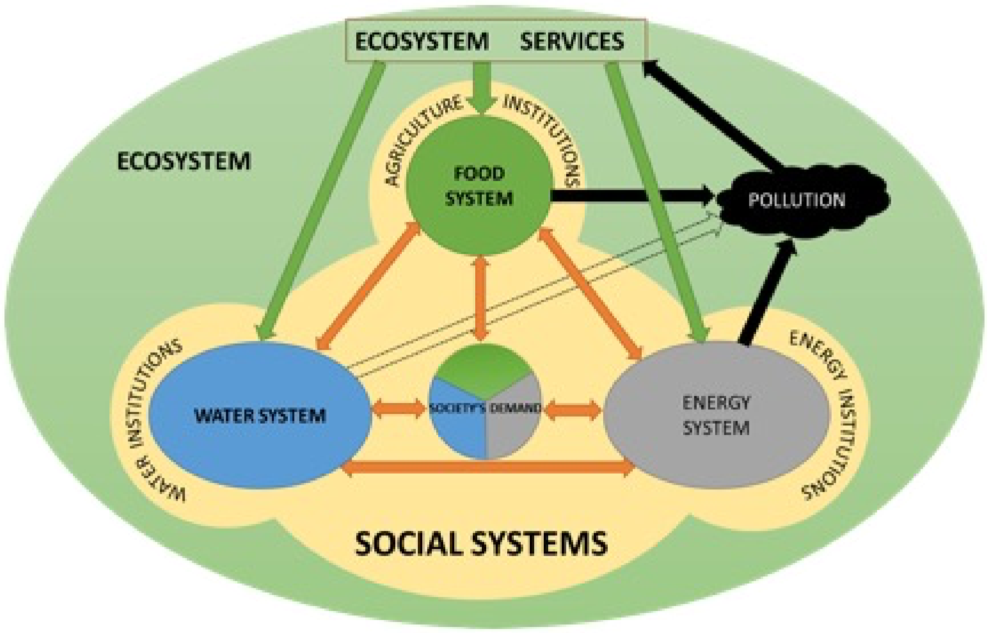


Figure 1: Water-Energy-Environment-Food (WEEF) Nexus framework

The unifying idea in each these definitions is that scarcity–of inputs and resources as well as capacities to use them–can lead to insecurity by threatening access to "sufficient" and "affordable" quantities of water, food, or energy to meet basic human needs. Uninterrupted availability of inputs and resources is thus necessary in securing the ability to achieve economic benefits derived from each of these systems. Nonetheless, resources need not be obtained or produced locally as they can also often be acquired from other regions through trade and migration.

The term ecosystem services then refers specifically to the set of provisioning and regulating features provided by natural resources, including those related to ecological function (Fisher et al., 2009). Many uses of natural resources and other inputs also require complementary inputs of investment or infrastructure development and social capital. Thus, there is often a divergence between potential and economically-relevant resource availability and between potential and actual resource use. When actual availability lies below potential availability due to lack of development, some label the situation as one of economic, rather than physical scarcity (Rijsberman, 2006). This conception of economic scarcity allows for the fact that pure physical availability of resources does not guarantee security. It also accommodates the idea that natural variation in the supply of resources may lead to temporary scarcity in the absence of sufficient investment in infrastructure. Finally, it covers the situation of scarcity that may arise during social disruptions such as economic crisis, famine, war, or sustained institutional failure. In all of these cases, additional investments and trade, better governance, or redistributive policies that help the poor may be required to achieve and maintain long-term security.

In sum, the availability of resources depends upon biophysical conditions, production by domestic or local systems, and regional trade. Use of resources in consumption and production processes require built and social infrastructure and capacity. A lack of security may be created if the cost of utilizing resources for societal needs is too high, either because of high levels of demand or because the cost of exploiting resources is prohibitive to those interests. Accessibility and affordability then depends upon the social structure of the society, stability of markets or allocative institutions, and on consumers' wealth and income. There are no clear boundaries that demarcate availability, access, and affordability (the 3As) (Clover, 2003; Cook and Bakker, 2012), but biophysical, institutional, economic conditions, and institutions clearly play crucial roles. Water can be available but not accessible because of mismanagement or institutional restrictions; it can be accessible but not affordable (such as in case of desalinated water) due to the high cost of technology.

A nexus-based HEM

A review of existing literature on the water-energy-environment-food nexus by UNESCAP (UNESCAP, 2013) shows that the primary issues of concern to researchers in this domain can be broadly grouped under three themes: i) describing the complex inter-relationships between water, energy, and food sectors, ii) the institutional and policy dimensions of these connections, and iii) their broader implications for resource security. As discussed above, one of the primary tools for understanding the physical and economic aspects of water resource systems has traditionally been the HEM. The strength of the HEM as a descriptive and planning tool is its ability to integrate mathematical descriptions of the hydrological (or biophysical) processes that describe water flow with economic production processes that require water inputs and infrastructure investment. Naturally, these production processes already often include energy and agricultural users. Thus, a more flexible, coupled WEEF model should be considered an extension, rather than a re-invention, of the standard HEM framework.

In fact, several systematic reviews of HEM tools indicate surprisingly limited integration–meaning little inclusion of feedbacks–across nexus domains (theme i) as well as a frequent lack of inclusion or realism with regards to institutional constraints (theme ii) (Harou et al., 2009; Bekchanov et al., 2017). This highlights the disconnect between theoretical discourses of the importance of nexus thinking, on the one hand, and the integration of such thinking into practicable and useful decision tools such as HEMs, on the other. These deficiencies hamper utilization of a systematic approach to analyze and understand the implications of nexus policies designed to enhance resource security (theme iii). A fully operational, nexus-based HEM would help in transforming the discourse on the nexus from one based on theoretical interconnections to one aimed at practical and holistic policy making.

A fully-operational nexus-based HEM would closely couple hydrology, energy, and agriculture biophysical models using water as a connecting thread and would enable linking of the biophysical components with economic and institutional realities. If linked to market wide models, such as computable general equilibrium (CGE) models, nexus-based HEMs could also help researchers understand final economic outcomes in terms of income and consumption at the sectoral, community, and/or household levels. The critical first step, however, it to consider the detailed connections and feedbacks between the various production WEEF systems.

Thus, we begin by depicting the interactions between five sectors or domains (Figure 2). Four of these represent human-centered use or production systems (water, energy, municipal and industrial, and agriculture), and the last corresponds to the broader ecosystem or environment. In this conception, the ecosystem domain provides a variety of market and nonmarket goods and services (i.e., ecosystem services) to the other systems and is also the recipient of pollution and other "externalities" from them. These externalities, beyond certain levels, may lead to a reduction in the ability of the ecosystem to provide services to other systems and to the broader environment.

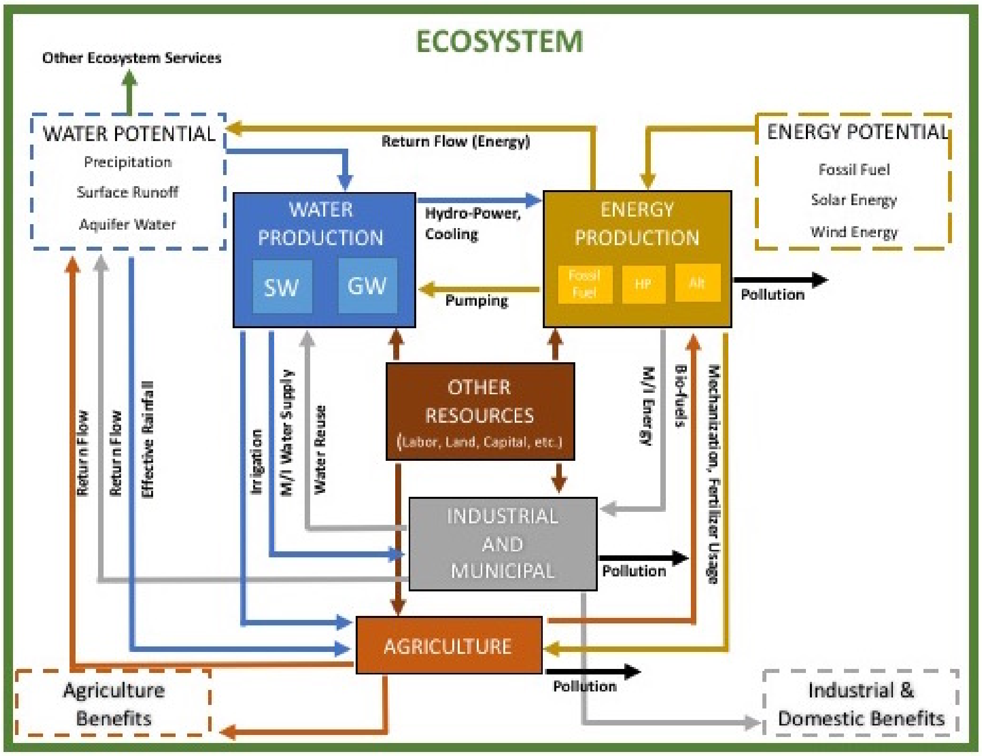


Figure 2: Interactions between production domains included in the WEEF framework

The first production domain represents the water system. Water is an essential natural resource for many economic and environmental functions, and is produced within the ecosystem. Rainfall and glacier or snow melt fills rivers, lakes, and reservoirs through surface runoff, infiltrates into the ground and storage aquifers, and contributes to soil moisture or storage in living plants and animals. Surface water and groundwater resource connections are influenced by physical properties of the local surface and subsurface. Water supply from this system is then allocated into one or more of the other three production systems (energy, industrial and domestic, and agriculture production), or remains in the natural environment, where it plays an essential role in a variety of other regulating and provisioning services. Utilization of these water resources by the three production sectors typically requires intervention and infrastructure. This infrastructure can include storage to cope with spatial and temporal variability in water availability, conveyance that moves water to the point of intended use, or pumping to bring water to the surface or to higher elevations. The flows of water towards human uses are termed water production (WP).

We provide a more detailed schematic of the connections between the WP system and the other 4 domains in Figure 3. The elements of WP can be categorized as being related to supply or demand. On the supply side, water potential is divided into surface and groundwater resources.

These ground and surface waters are connected by hydrological processes such as seepage and infiltration. The potential surface water available in a given location is the water that flows directly from upstream locations plus any surface return flow from other production sectors. The potential groundwater that is available consists of water stored in aquifers plus natural recharge and groundwater recharge from the production sectors.

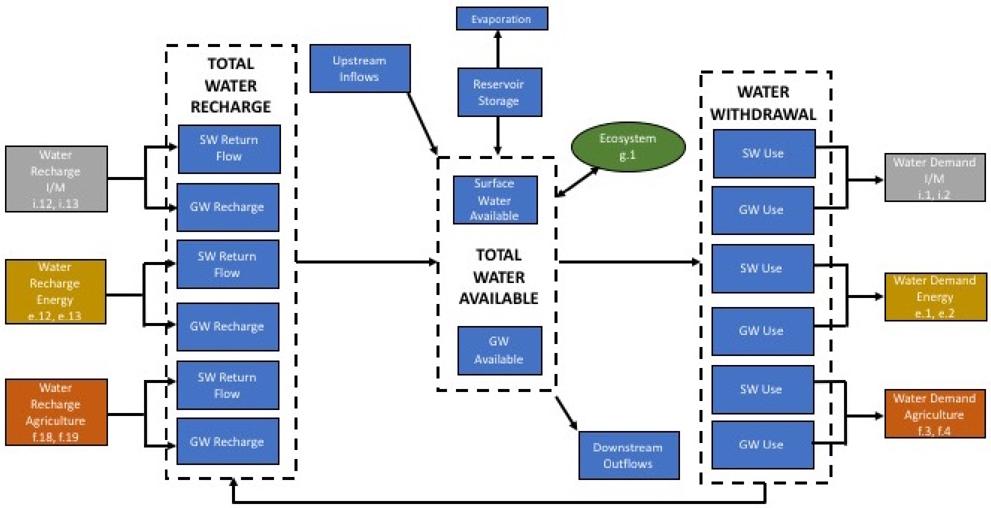


Figure 3: Schematic depiction of the Water Production (WP) system. Attributes or variables that are primarily related to the water system are shown in blue; energy in yellow; municipal/industrial in grey; and environmental in green. Model equations related to the interactions between the WP system and other production systems are included where applicable.

Water potential translates into water availability based on the location and capacity of existing storage, and connectivity of supplies to demand sites using conveyance infrastructure. Surface storage leads to loss of water from the system due to evaporation. Surface water not held in storage, and/or allocated to environmental flows, moves downstream. Actual availability of water for each of the other production systems may also depend on energy supply, which is needed to pump water to end users, especially for groundwater or for conveyance over long distances. The use or exploitation of the water potential will be determined by demand, from industrial/ municipal (I/M), agriculture, and energy sector users. Finally, the broader ecosystem both influences and is influence by the WP system.

Figure 3 relates this construct of the WP system to the HEM developed in Section 5 by including references to the equations that specify the links identified in this figure. Each additional production system (energy, agriculture, and industrial/municipal) links into the WP system through water demand and return flow. The approach is utilized in Figures 4-6 as well to illustrate the relationship between the conceptual construct of the inter-sectoral relationships with the modeling application.

Domain 2, Energy Production (EP), comprises the energy system (a detailed depiction of the connections within this domain and to the other domains is shown in Figure 4). As in the WP system, the ecosystem provides resources to the energy system, including fossil fuels such as oil, coal and gas and renewable energy potential from solar, wind, geothermal, or hydroelectric sources. Exploitation of these energy resources requires processing and infrastructure. Along with other investments, this exploitation necessitates water inputs. In particular, water is used for drilling, by refineries for oil and gas production, for dust suppression and washing in coal production, for irrigation of biofuel crops, for steam generation and cooling in thermal plants, for cooling in nuclear plants, and for hydropower generation. Conversely, energy production affects the quality (through pollution by chemicals or heat) and quantity (based on the balance of evaporation, embedding of water into products, and return flows) of water that can be used for other purposes (IEA, 2012).[2] For example, tapping groundwater resources and water supply conveyance require pumping, creating a potential trade-off between more energy intensive use of proximal and often higher quality resources (from aquifers), and more distant and lower quality sources (from surface water). Because of these connections between energy and water systems, economic water scarcity can arise from either insufficient energy or water supply infrastructure, or both.

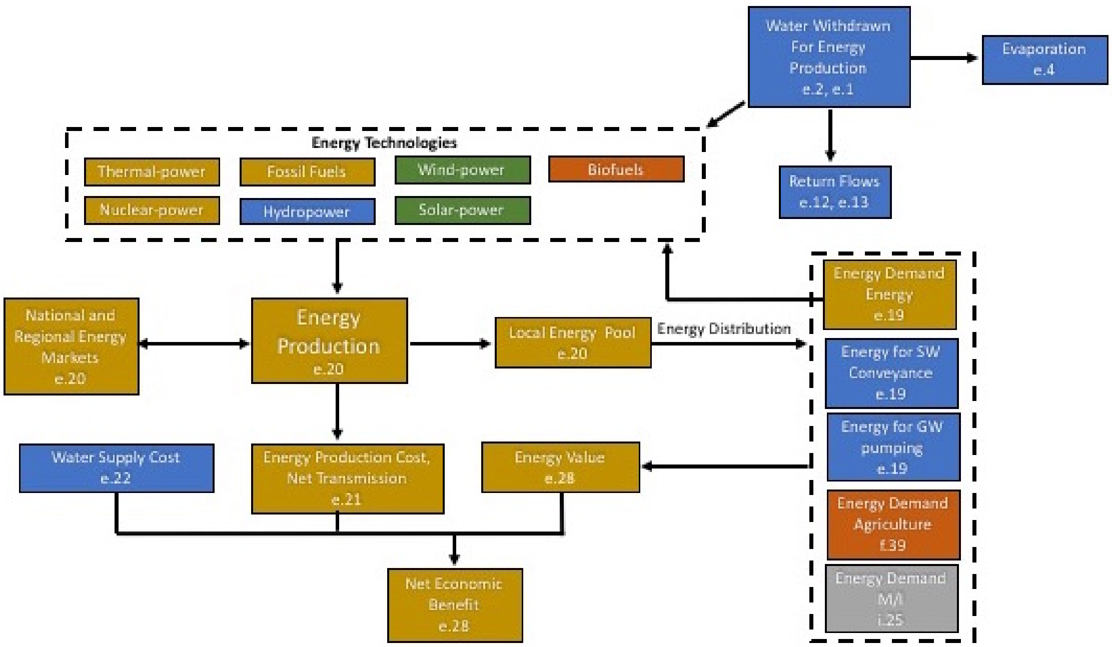


Figure 4: Schematic depiction of the Energy Production (EP) system. Attributes or variables that are primarily related to the water system are shown in blue; energy in yellow; municipal/industrial in grey; and environmental in green. Model equations related to the interactions between the EP system and other production systems are included where applicable.

Central to this domain is the idea of a "National/Regional Energy Pool", which may be considered as analogous to a storage reservoir in the WP domain. Whereas water storage pertains to a catchment, the regional energy pool, which contains locally produced energy as well as imported energy, lies within institutional boundaries. Linkages between the regional energy pool and national (or global) energy markets provide connections across political boundaries. The transmission lines that form these connections are especially important because of the particular challenge of storing energy.

The supply system for energy is broadly characterized into electricity and fuel. Each group can be further subdivided based on specific energy sources to better define the cost of energy within a given region. Electricity can be generated by thermal, nuclear, wind, solar or hydropower.

[2] In fact, according to IEA analysis, global water withdrawals for energy production in 2010 were 583 km^3, representing about 15% of total global water production, but only 11% of these withdrawals were consumed (i.e. not returned to the environment). Fossil fuel and nuclear power plants were the largest users of water due to the need for cooling water; this emphasizes the importance of return flows (and effects on quality) from this sector.

Fuel is made up of fossil fuels and biofuels. There also exists some overlap between the two; for example, thermal energy can be used in the production of fuels and fossil fuels themselves can generate electricity. The local pool of energy may be augmented by production of energy within municipalities (from waste) and industries (for their internal use), which is usually consumed locally by the M/I sector. In analyzing the true economic costs of different energy sectors, it is important to note that actual cost to users is frequently distorted by regional policies (price controls or subsidies) and that related adjustments are necessary to complete accurate analysis.

Water demand by local energy producers can be estimated as a function of energy generation, and is linked to the production systems in the WP domain. The flow balance that determines the balance of consumption, losses, and return flows to the WP system closes the loop. As in the case of WP domain, the energy available in the regional energy pool is distributed to the other domains (water, municipal/industrial, and agriculture) according to an economic objective (maximizing net benefits) or according to specific allocation rules and regulations.

The third domain, Agriculture Production (AG), concerns food production system (Figure 5 presents its schematic, again with connections to the other domains). Throughout the world, the agriculture sector is typically the largest user of water (representing around 70% of global water withdrawals), and it also often consumes significant energy resources (United Nations, 2016). The purpose of water allocation to this domain is to enable crop irrigation, which improves yields by enhancing control over essential water inputs, protects against droughts, provides production in areas with insufficient rainfall, and allows for higher cropping intensity than rainfed irrigation. Irrigation technology and techniques vary greatly, influenced by infrastructure investment on large (e.g., canals) and small (e.g., field technologies such as drip vs. spray) scales. This leads to different levels of water use efficiency across irrigated areas.

In low efficiency systems, less water is effectively used by crops, and more water evaporates and drains back into ground or surface water bodies, along with pollutants such as pesticides and fertilizers. In contrast, higher efficiency systems have higher rates of consumption, and lower return flows. These efficiency differences translate into varying patterns of energy consumption, due to differences in pumping requirements (which are usually higher for low efficiency systems because more water must be pumped) or technology. The agriculture sector, meanwhile, requires energy for other activities in addition to irrigation, including mechanization and fertilizer usage. Agriculture is not only a user of energy, however; an important feedback loop comes from its contribution to the energy system through biofuel production. Biofuels include a range of products (such as bio-alcohol, ethanol, bio-diesel etc.) that are made from crop-based sugar, starch, and vegetable oils.

The crops considered in the AG module are classified as rainfed and irrigated. Rainfed crops get their water only through precipitation (or effective rainfall, which refers to the fraction of rainfall used by crops). For irrigated crops, effective rainfall is augmented with allocations from surface or groundwater supplies. Each crop requires a specific amount of water to reach maximum yield in a particular region. Deviations from this requirement lead to water stress and crop-specific reductions in yield. The product of area under cultivation and yield then gives the total production of crops in the region. Energy is required for conveyance of surface water and pumping of groundwater; its cost depends upon distance conveyed, as well as depth and pumping technology (capacity and pump efficiency). This and other inputs in the agriculture sector (e.g., labor, fertilizer, etc.) also influence crop yields and production. Net profits for producers then come from the difference between revenues (or prices multiplied by production) and these various input costs.

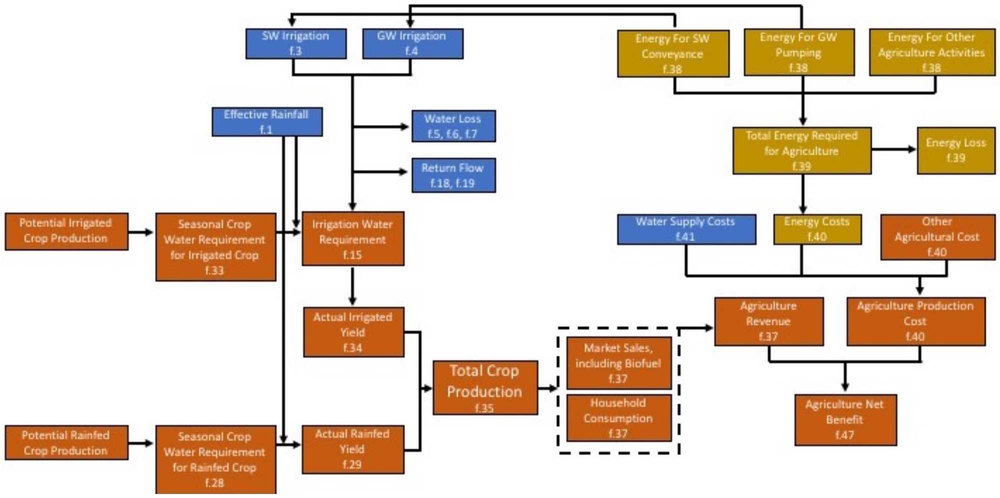


Figure 5: Schematic depiction of the Agricultural (AG) system. Attributes or variables that are primarily related to the water system are shown in blue; energy in yellow; municipal/industrial in grey; and environmental in green. Model equations related to the interactions between the AG system and other production systems are included where applicable.

The fourth domain, Municipal and Industrial (MI), represents consumption of water, food, and energy by humans for domestic purposes and for the production of industrial consumer goods (Figure 6). Households demand food and water to meet their dietary needs and maintain good health, demand water for other domestic purposes (cooking, hygiene, etc.), and demand energy for lighting, cooking, and heating. Yet there are wide disparities in water, food, and energy consumption across the globe, which are correlated with infrastructural and institutional capacities to tap water and energy resources, as well as with regional preferences and conditions and socio-economic factors. Production of water for domestic purposes also requires energy to enable effective drinking water treatment and distribution to users. In addition to domestic requirements, water and energy also factor into the production of intermediate and final consumer goods. In fact, the industrial sector is the second largest global consumer of water and the largest consumer of energy (United Nations, 2016; U.S. Energy Information Association, 2016). Water usage by households and industry also generates substantial amounts of polluted wastewater, which may or may not be treated prior to its discharge back into the environment depending on energy availability and infrastructure.

Water and energy demand depend on socio-economic factors such as population, per capita GDP, and urbanization. Furthermore, these demands provide the links between the MI domain and the WP and EP domains, and consumption of these inputs arises again from the profit maximizing behavior of firms in the sector and utility-maximizing behavior of consumers. Specifically, firms balance input costs for water pumping, treatment, and distribution along with the cost of energy purchases with the revenues derived from production of industrial goods. Usage of water and energy within this sector entails losses from evaporation during conveyance as well as in distribution and transmission of electricity. Some water may be reused after adequate treatment, and waste generated in the M/I sector may be used to generate energy for local consumption. Meanwhile, municipal distribution of water and energy services aims to satisfy consumer demand for energy and water, often by institutionalizing cost recovery pricing. Benefits in this domain thus arise from consumer surplus and the producer and consumer surplus produced by the industrial sector.

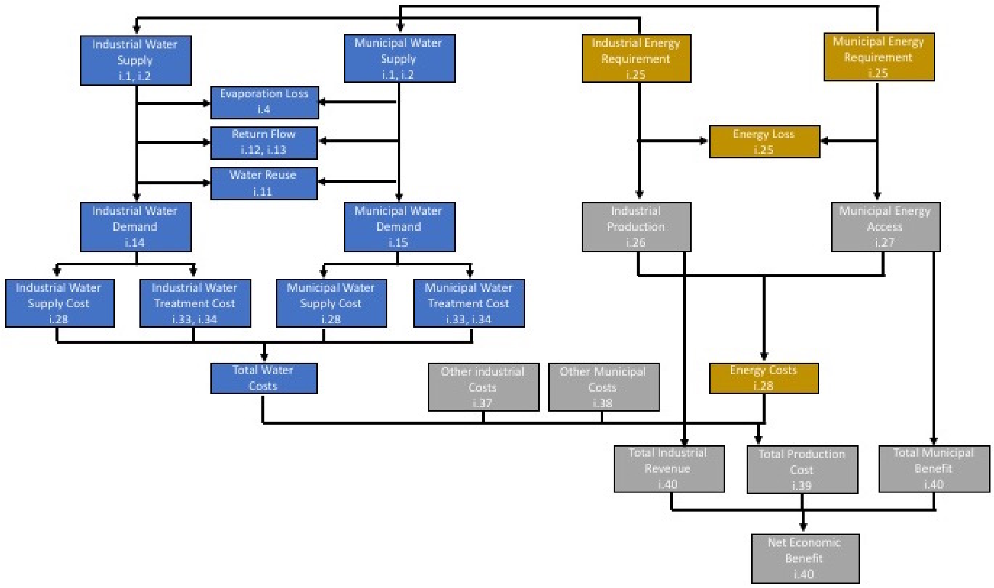


Figure 6: Schematic depiction of the Municipal/Industrial (MI) system. Attributes or variables that are primarily related to the water system are shown in blue; energy in yellow; municipal/industrial in grey; and environmental in green. Model equations related to the interactions between the MI system and other production systems are included where applicable.

All four domains discussed thus far connect back to the Ecosystem (ES) domain (Figure 7). The production of other services (not depicted in the systems described above) from the ES domain–such as fisheries, recreational values, disaster risk mitigation, existence values, etc.–depends on the temporal and spatial distribution of water availability and quality. Water quantity relates to hydrological variability and upstream consumptive uses by the four production systems. Quality, meanwhile, is influenced by utilization and return flows (which may or may not be subjected to treatment) from these production sectors and by the pollutants released from each sector. The economic benefits from ecosystem services then depend on market or nonmarket values for other provisioning and regulating ecosystem services.

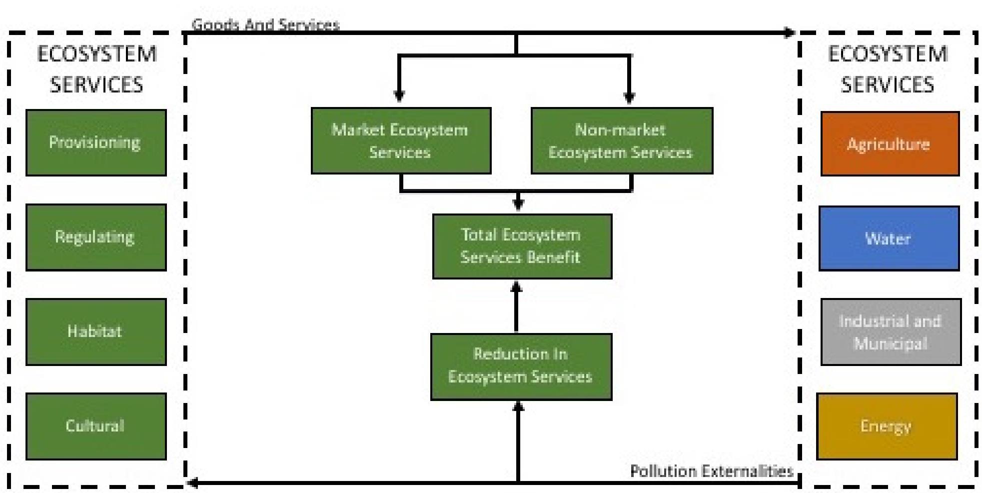


Figure 7: Schematic depiction of the Ecosystem (ES) system. Attributes or variables that are primarily related to the water system are shown in blue; energy in yellow; municipal/industrial in gray, and environmental in green.

3 Relevant Literature

Before presenting the details of the HEM model developed to span across these WEEF nexus domains, we provide a brief review of the literature related to prior hydro-economic modeling efforts to incorporate its different components. This helps to highlight some of the gaps that we aim to fill by developing a more complete integration across these domains and informs the eventual analytical approach we adopt.

In characterizing this literature, a recent and detailed systematic review of water-economy modeling applications that discusses HEMs is particularly helpful. Bekchanov et al. (2017) show that HEMs have been extensively used to analyze the linkages between water systems and the demand sectors described above (i.e., hydropower, agriculture, and municipal/industrial). Many of these prior studies face specific challenges, the most important of which are documented in existing reviews of hydro-economic modeling methods (Brouwer and Hofkes, 2008; Harou et al., 2009).[3] Focused attention on feedbacks to the water system and on cross-sectoral interactions poses perhaps an even greater challenge, in part because it is increasing in importance as population pressure and resource scarcity increase. Most existing multi-sectoral HEM studies consider trade-offs between sectors–predominantly comparing the benefits of irrigated agriculture versus hydropower production (Chatterjee et al., 1998; Barbier, 2003; Hurford and Harou, 2014; Bekchanov et al., 2015) or irrigated agriculture versus ecosystem preservation (Cai et al., 2003; Ward and Booker, 2003; Mainuddin et al., 2007; Blanco-Gutiérrez et al., 2013; Mullick et al., 2013). A small number of notable exceptions consider important system feedbacks such as the demand pressure on water systems that stems from energy use in surface water conveyance and groundwater pumping (Pulido-Velázquez et al., 2006; Harou and Lund, 2008; Kahil et al., 2016) or consumptive water use in biofuel production (Alcoforado de Moraes et al., 2009). A limited body of research examines temporal trade-offs between water use for hydropower production and for dilution of municipal and industrial pollution, usually on a very local scale (such as Yoon et al. (2015)). Out of a total of 160 applications reviewed in Bekchanov et al. (2017), only four focused primarily on trade-offs across WEEF sectors.

Reviews of existing literature also reveal that most nexus-based integrated models are purely bio-physical (Alcamo et al., 2007; Van Vliet et al., 2012; Hanasaki et al., 2013; Miara and Vörösmarty, 2013; Wada et al., 2013). These models typically start from hydrological models that link to sectoral water use models but allocations from them are usually not based on economic principles. Howells et al. (2013), in contrast, developed an integrated application linking climate, land, energy, and water use systems (CLEWS) in Mauritius. CLEWS is an energy focused simulation model that links off-the-shelf models–the Long-range Energy Alternatives Planning (LEAP) model for energy, the Water Evaluation and Planning System (WEAP) mode for water, and an Agro-Ecological Zones land production planning model (AEZ) for land, with climate models (Welsch et al., 2014). The integration of these models to consider sectoral interactions and feedbacks generated significant added value in the test application by highlighting the important effects of water stress on energy production, which led to overestimation of the benefits of ethanol-based energy generation in disaggregated models.

The inclusion of ecosystem services in HEMs remains a major challenge. Ecosystem services

[3] Prominent among these challenges are the following: a) the need for econometric analysis to evaluate marginal benefit, due to the price distortions that prevail in most water markets; b) the challenge of aggregating demands across different types of consumers or users; and c) the lack of volumetric consumption data in many uses (notably irrigation).

have been broadly grouped into four classes: provisioning, including food production and energy and water consumption; regulating, which deals with controlling climate and diseases as well as pollution control by dilution; supporting, such as nutrient cycling; and cultural, such as spiritual and recreational benefits (Millennium Ecosystem Assessment, 2005). Given the more straightforward connection between provisioning services and economic values, most HEM studies have focused on marketed provisioning services such as water allocation for irrigation or to municipal users. For nonmarket environmental services, the most common approach is to measure trade-offs between market benefits and environmental flow requirements (Bekchanov et al., 2017). Such studies optimize benefits subject to varying levels of environmental flow (or instream flow) constraints. Mainuddin et al. (2007) for example considered how optimized water use in irrigated agriculture changed subject to within- and cross-catchment water sharing constraints. Blanco-Gutiérrez et al. (2013) similarly used an HEM to analyze the loss to agriculture from maintaining environmental flows. Ward and Booker (2003) calculated the economic cost to the agriculture and the municipal and industrial sectors associated with increasing instream flows to meet the ecological needs of a particular fish species in a river system.

A different approach, utilized by Mullick et al. (2013), is the direct estimation the value of ecosystem service benefits. These authors used a hydrologic-economic optimization model to calculate the economic trade-offs between off stream water use (irrigation) and instream water use for fisheries and navigation, using marginal benefit functions that were created for off-stream and instream water use. Cai et al. (2003) include irrigation-induced soil salinization (a regulating ecosystem service) within an HEM analysis of the economic and environmental costs of various irrigation policy options. Ringler and Cai (2006) explicitly modelled water values for wetlands and fisheries in their Mekong River Basin HEM analysis. These direct valuation approaches more readily reveal trade-offs across sectors and uses but require careful derivation of nonmarket valuation estimates for marginal benefits. Nonetheless, a complete nexus approach that considers pollution and return flows must somehow address all such issues.

Finally, it is important to note that many WEEF nexus processes play out on a different and much longer time scale from that governing market processes that evolve via complex dynamics that may be highly nonlinear, emergent, context-specific, and uncertain (Liu et al., 2007). Ecosystems services production has been shown to have these types of features, which tend to challenge existing modeling efforts. The institutions that govern water allocations are similarly lumpy and discontinuous. For example, water sharing treaties with in-stream requirements, as included by Mainuddin et al. (2007), may specify complicated water sharing provisions or constraints on water withdrawals (Mullick et al., 2013; Blanco-Gutiérrez et al., 2013; Ringler and Cai, 2006). Analogous institutions in other sectors–such as energy and agriculture–are rarely if ever included. In a comprehensive nexus-based HEM, constraints in these other domains, such as bio-fuel regulations, renewable energy quotas, water-reuse standards, rainwater harvesting regulations, and cross-sector institutional interactions, need to be considered. This requires careful and detailed institutional mapping across nexus systems, highlighting a potential conflict between generalizability–which is enhanced by accuracy in the description of fundamental processes–and utility for policy making–which stems from well-calibrated and institutionally realistic descriptions that may not reflect fundamental socio-hydrological processes (Beck, 2014).

4 Model Analytical Framework

This section describes the analytical framework for an HEM developed to consider the interconnections in the WEEF nexus framework. We begin by describing the principles applied in the development of our model and then proceed with presentation of diagrams that show how the model relates to the schematics of the broader WEEF concept. This helps to clarify what is and is not included in our formulation. The model equations and definition of variables and parameters follows in Section 5.

4.1 Principles behind the model

The model is developed around three principles aimed at improving the versatility of the final HEM:

1. **Scalability:** The HEM should be able to represent basins or regions (and relevant subunits therein) of different scales and overlap. WEEF nexus issues vary according to the scale of the study area. For example, a small catchment may be dominated by rural populations engaged primarily in agriculture with little energy production or industrial activity or, alternatively, by a single urban setting that includes little to no agriculture. In contrast, a larger scale will likely require inclusion of both rural and urban areas. Also, a smaller area may be dominated by a single institution while larger systems may include multiple institutions. Finally, a scalable model should allow analysis at multiple time scales–for example a single year (as static) or across multiple years–or allow analysis over spatial units of different types such as catchment or geopolitical boundaries.
2. **Transferability:** The model should be easily transferable to any water resource system. This would require that the fundamental structure of the model need not change for different study areas. Differences and idiosyncratic characteristics of a study area instead would be reflected through differences in data.
3. **Modularity:** Outside of the core (which specifies the objective function, the water system, and indicates the other systems included), each module within the HEM framework should be able to function independently. This makes it easier to replace an existing module with an improved version or to "shut-off" modules that are not required to answer particular policy or research questions. It also allows testing of the sensitivity of results that do and do not include integration of multiple sectors, which is an interesting socio-hydrological research question in its own right.

4.2 Schematic presentation of the model

Each of the domains described in Section 2 is represented by a module. As alluded to above, the core is the Water System Module (WSM). This module handles the flow continuity equations that maintain the water balance throughout the system, describes storage in natural and built reservoirs as well as in groundwater aquifers, and specifies water flows in and out of the other production systems or sectors. This core, therefore, contains the objective function that drives water allocations in order to maximize net benefits across domains. The input data into the WSM consists of hydrological inputs (specifically partitioning of rainfall into runoff into surface water nodes and aquifer recharge). These data are best obtained from a separate hydrological rainfall-runoff model that is not directly connected to the HEM.[4] The four other modules that are connected to the core are the Energy, Agriculture, Municipal and Industrial, and Environmental Modules (Figure 8).

Equations pertaining to production processes in each of the other modules are then written within those modules. These are linked to the core via the decision variables that enter the model objective function, and via binary parameters that allow the user to switch the modules on and off. Various additional water and production system constraints appear in the WSM and in the production modules to reflect physical, technological, economic, or institutional realities.

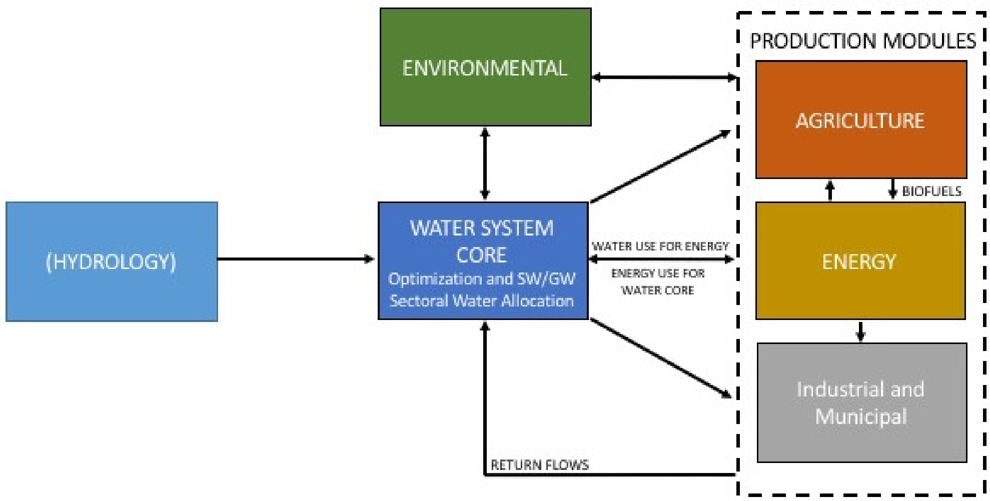


Figure 8: Module interconnections for HEM model

Considering the interdependence of users and the inherent directionality in water resource systems (Keller, 1996; Ringler et al., 2004), integrated WEEF system management is best considered at basin scale. The challenge is then to link basin scale hydrology to policy making in other sectors, given that those decisions are typically made according to a different set of administrative boundaries. Figure 9 shows an illustrative node structure that does not overlap cleanly with institutional (or administrative) boundaries. Reservoirs and/or water withdrawal are represented by "river or reservoir" nodes connected by the flow of a river (links) and into groundwater reservoir nodes. These nodes link to the outlets of the catchments in the hydrological model and represent the physical hydrology of the region. Each node has a surface water and a groundwater component. The surface water component represents the surface water flowing from upstream node as well as the surface water generated within the catchment of the node. The groundwater component represents the groundwater available within the node?s catchment. These are indexed according to institutional boundaries. Production sectors that fall within the institutional boundary but are outside the basin boundary are not considered (as shown by the blackened portion in the figure).

The WSM is then developed around the network of these nodes and links to specify water flow and distribution to users along the river. Economic sectors (or water users) along the river are represented by irrigation, industrial-municipal, and power generation sub-nodes, each of which are connected to parent river or reservoir nodes. Economic sectors also return a fraction of the

[4] The advantage of this approach is that it allows for the use of previously established and tested process-based hydrological models that incorporate catchment-level complexity and dynamics. Such models readily provide volumes of water stored as soil moisture, groundwater recharge, surface runoff, and water lost to evapotranspiration.

flows they receive to downstream nodes in the surface and groundwater systems through drainage or wastewater flows (return flows). Environmental sub-nodes represent the ecosystem services produced within the catchment represented by each node.

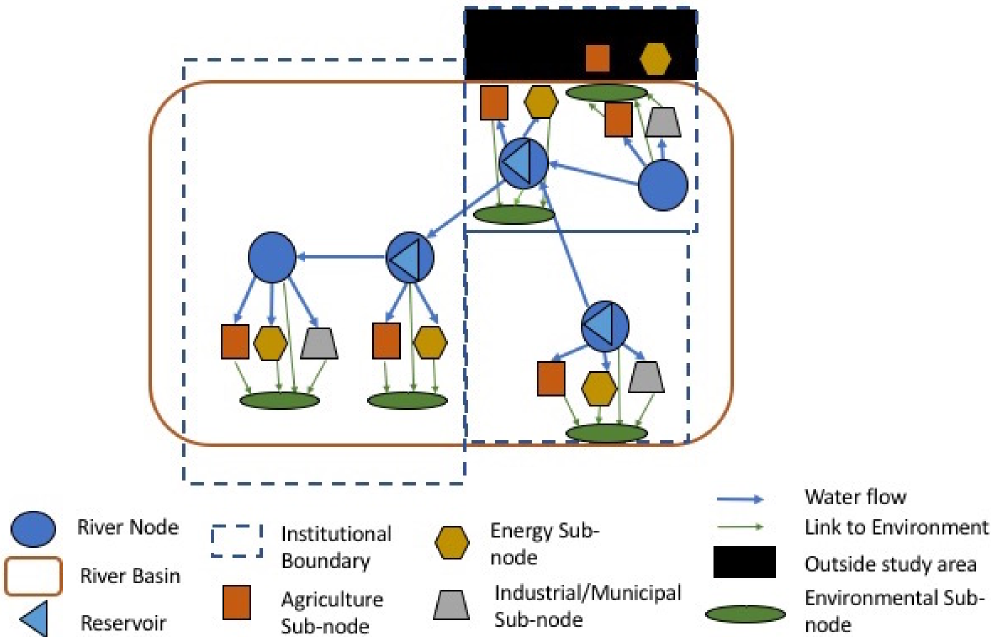


Figure 9: River node network scheme

5 Model Equations

This section presents the mathematical equations that comprise the model. We present these equations by module, and supplement them with diagrams insofar as the latter help to clarify complex relationships between variables.

5.1 Water system module (the core module)

5.1.1 Model objective function

Joint maximization of benefits (B^{OBJ}) across sites n and sectors s is formulated as:

$$B^{OBJ} = \sum_{n}(\sum_{s}\delta^{S}_{n,s}B^{PRD}_{n,s} + \delta^{ENV}_{n}B^{ENV}_{n}) \tag{w.1}$$

where $\delta^{S}_{n,s}$ is a binary parameter that takes a value of 1 if production related to sector s uses water from node n or a value of 0 otherwise;[5]
δ^{ENV}_{n} is a binary parameter that takes a value of 1 if environmental services rely on water from node n and takes a value of 0 otherwise;
$B^{PRD}_{n,s}$ represents the benefit in each production sector that withdraws water from node n; and

[5]In the GAMS code, such binary indicators are replaced by inclusion of sets that include only the subgroups of nodes pertaining to those sectors.

B_n^{ENV} is the benefit from environmental flows.

As described previously, the main sectors considered in the model are agriculture (A or $sa \subset s$), energy production (E or $se \subset s$), and the municipal and industrial sector (I or $si \subset s$). Separate sets are defined for agricultural (da), energy production (de), and municipal-industrial (di) sites. Thus, only a single sector can be referenced to one node but multiple production sites may belong to this sector according to the model formulation. This notation for sectors and production sites is introduced to make each module independent and to prevent errors in coding. If a particular module is not included in any given application, all binary indicators for that sector (or for environmental flows) can be set to zero using a single input command.

To represent optimization at the institutional level, an institution-specific grouping of nodes can be assigned a differential weighting (according to power or locational asymmetries), or the single global optimization procedure can be broken into sequential optimization problems that begin with the upstream groupings and then proceeds downstream, taking the upstream solution as given when solving the downstream optimization problem (Jeuland et al., 2014).

5.1.2 Surface water balance

Reservoir volume in period $t > 1$ depends on the volume in period $t-1$ as well as the change between periods:

$$V_{r,t}^{W\_RES} = V_{r,t-1}^{W\_RES} + \delta_{r,t}^{W\_V\_RES} \qquad \text{(w.2)}$$

where:
$V_{r,t}^{W\_RES}$ is the volume of reservoir r in time t;
$V_{r,t-1}^{W\_RES}$ is the volume of reservoir r in time $t-1$; and
$\delta_{r,t}^{W\_V\_RES}$ is the change in reservoir storage of reservoir r in time t.

Reservoir volume in period $t = 1$ ($RES_{r,IVL}^{B\_CHAR}$) is set to an initial reservoir level chosen by the user, and the final reservoir volume must also equal this initial volume (to prevent derivation of unsustainable solutions).

For reservoir nodes, the storage volume and surface area of the reservoir are related to each other using a polynomial relationship:

$$\begin{aligned} A_{r,t}^{W\_RES} = RES_{r,VB0}^{W\_CHAR} &+ RES_{r,VB1}^{W\_CHAR} V_{r,t}^{W\_RES} \\ &+ RES_{r,VB2}^{W\_CHAR} [V_{r,t}^{W\_RES}]^2 + RES_{r,VB3}^{W\_CHAR} [V_{r,t}^{W\_RES}]^3 \end{aligned} \qquad \text{(w.3)}$$

where:
$A_{r,t}^{W\_RES}$ is the surface area of reservoir r at time t; and
$RES_{r,VB0}^{W\_CHAR}$, $RES_{r,VB1}^{W\_CHAR}$, $RES_{r,VB2}^{W\_CHAR}$, and $RES_{r,VB3}^{W\_CHAR}$ are the parameters of the function that are obtained using regression techniques specific to reservoir r.

If data are missing for particular reservoir sites, a linear relationship between area and volume (and net head and volume, see below) should be assumed as a first-order approximation.

The reservoir net head also depends on the reservoir storage volume:

$$H_{r,t}^{W\_RES} = RES_{r,HT0}^{W\_CHAR} + RES_{r,VA0}^{W\_CHAR} + RES_{r,VA1}^{W\_CHAR} V_{n,t}^{W\_RES} + RES_{r,VA2}^{W\_CHAR} [V_{n,t}^{W\_RES}]^2 \quad \text{(w.4)}$$

where:
$RES_{r,VA0}^{W\_CHAR}$, $RES_{r,VA1}^{W\_CHAR}$, and $RES_{r,VA2}^{W\_CHAR}$ are parameters of a function as obtained using regression techniques for reservoir r;
$H_{r,t}^{W\_RES}$ is water level for reservoir r in time t; and
$RES_{r,HT0}^{W\_CHAR}$ is the tailwater level for the turbine discharge for reservoir r.

5.1.3 Node/reservoir water balance

The water balance at the river nodes of the model requires that all inflows to the node equal outflows from it (Figure 10). Water inflows are from upstream nodes, from surface runoff generated within the catchment of the node, from groundwater contribution into the surface water system, and from return flows from production sites. Water outflows are to downstream nodes, to irrigation and municipal and industrial users, water lost due to evaporation, and into groundwater systems. For reservoir nodes, changes in storage are also included.

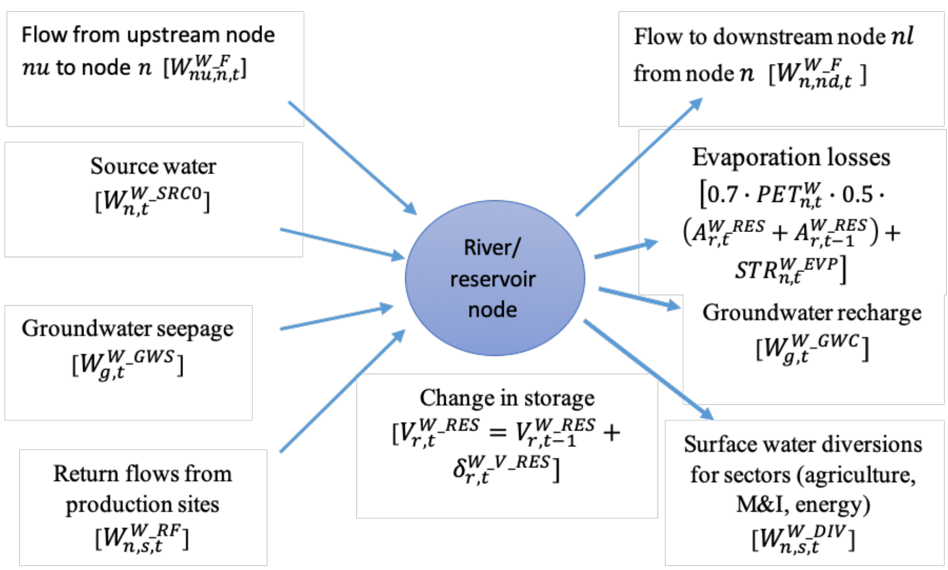


Figure 10: River node/reservoir water balance

Following this logic, the water balance at each river node is formulated as:

$$\begin{aligned}\sum_{nu \in NNULINK} (W^{W\_F}_{nu,n,t}) + W^{W\_SRC0}_{n,t} + \sum_{g \in NGLINK} (W^{W\_GWS}_{g,t}) + \sum_{s} (W^{W\_RF}_{n,s,t}) \\ = \sum_{r \in NRLINK} (0.7 \cdot PET^{W}_{n,t} \cdot 0.5 \cdot (A^{W\_RES}_{r,t} + A^{W\_RES}_{r,t-1})) \\ + STR^{W\_EVP}_{n,t} + \sum_{g \in NGLINK} (W^{W\_GWC}_{g,t}) + \sum_{s} (W^{W\_DIV}_{n,s,t}) \\ + \sum_{nd \in NNULINK} (W^{W\_F}_{n,nd,t}) + \sum_{r \in NRLINK} (\delta^{W\_V\_RES}_{r,t})\end{aligned} \tag{w.5}$$

where:
$W^{W\_F}_{nu,n,t}$ is the flow from upstream node nu to node n at time t (given a link $(nu, n) \in NNULINK$);
$W^{W\_SRC0}_{n,t}$ is the flow from source node (runoff into the river) at time t;
$W^{W\_GWS}_{g,t}$ is the groundwater seepage from groundwater aquifer g at time t (given a link $(g, n) \in NGLINK$);
$W^{W\_RF}_{n,s,t}$ is the return flow to node n, from sector s, at time t;
$PET^{W}_{n,t}$ is the potential evapotranspiration at node n at time t;
$STR^{W\_EVP}_{n,t}$ is evaporation from streams at node n at time t;[6]
$W^{W\_GWC}_{g,t}$ is the water lost to groundwater aquifer g from the river at time t;
$W^{W\_DIV}_{n,s,t}$ is the water diverted from node n, for sector s, at time t; and
$W^{W\_F}_{n,nd,t}$ is the flow from node n, to downstream node nd, at time t (given a link $(nu, n) \in NNULINK$).

5.1.4 Groundwater balance

Similar to the surface water balance in river and reservoir nodes, the groundwater balance requires equality of total inflows and outflows plus water volume change in the aquifer (Figure 11).

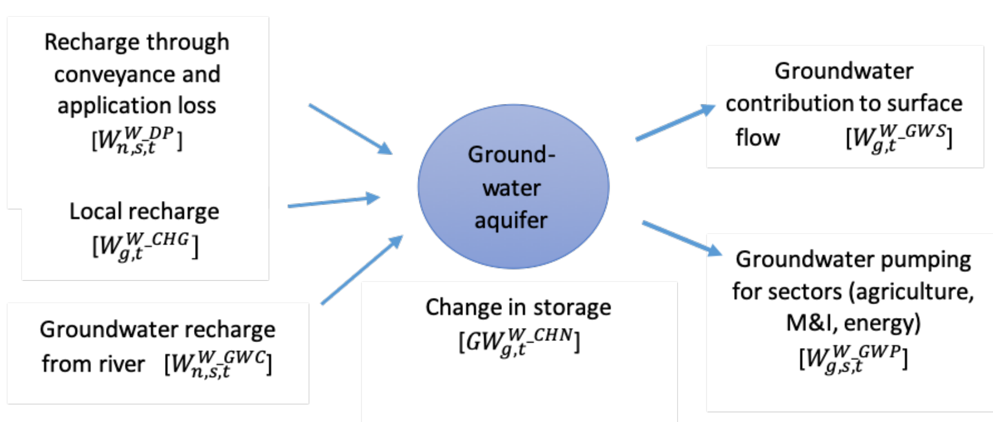


Figure 11: Groundwater aquifer water balance

Groundwater volumes change depending on water percolation from production sites, fields and irrigation canals, groundwater use and water seepage to (and from) the river.

[6] In the GAMS model, the hydrology input takes evaporation from streams into account, so this parameter is set to 0.

$$\sum_{g\in NGLINK}(W^{W\_CHG}_{g,t}) + \sum_{s}\sum_{g\in NGLINK}(W^{W\_DP}_{n,s,t}) + \sum_{g\in NGLINK}(W^{W\_GWC}_{g,t}) = \sum_{g\in NGLINK}(W^{W\_GWS}_{g,t}) + \sum_{g\in NGLINK}\sum_{s}(W^{W\_GWP}_{g,s,t}) + \sum_{g\in NGLINK}(GW^{W\_CHN}_{g,t}) \quad \text{(w.6)}$$

where:
$W^{W\_CHG}_{g,t}$ is the groundwater recharge from rainfall at groundwater aquifer g at time t;
$W^{W\_DP}_{n,s,t}$ is the recharge through conveyance at node n, from sector s, at time t (given a link $(n,g) \in GNLINK$);
$W^{W\_GWP}_{g,s,t}$ is the groundwater pumping at groundwater aquifer g, for sector s, at time t; and
$GW^{W\_CHN}_{g,t}$ is the change in aquifer storage for groundwater aquifer g ta time t.

The water table depth from ground surface in period $t > 1$ depends on the depth in period $t-1$ as well as the change in depth:

$$GW^{W\_D}_{g,t} = GW^{W\_D}_{g,t-1} + \frac{GW^{W\_CHN}_{g,t}}{AQ^{B\_CHAR}_{g,SPY} \cdot AQ^{B\_CHAR}_{g,EAR}} \quad \text{(w.7)}$$

where:
$GW^{W\_D}_{g,t}$ is the water table depth from ground surface at groundwater aquifer g at time t;
$GW^{W\_D}_{g,t-1}$ is the water table depth from ground surface at groundwater aquifer g at time $t-1$;
$AQ^{B\_CHAR}_{g,SPY}$ is the specific yield of groundwater aquifer g; and
$AQ^{B\_CHAR}_{g,EAR}$ is the effective aquifer area of groundwater aquifer g.

5.1.5 Constraints

Maximum and minimum water levels and storage volumes in reservoirs are imposed based on their capacity and minimum operating levels:

$$H^{W\_RES.lo}_{r,t} = RES^{B\_CHAR}_{r,HLO} \quad \text{(w.8a)}$$
$$H^{W\_RES.up}_{r,t} = RES^{B\_CHAR}_{r,HHI} \quad \text{(w.8b)}$$

where:
$H^{W\_RES.lo}_{r,t}$ is the lower bound of height of reservoir r at time t;
$RES^{B\_CHAR}_{r,HLO}$ is the minimum height of reservoir r;
$H^{W\_RES.up}_{r,t}$ is the upper bound of height of reservoir r at time t; and
$RES^{B\_CHAR}_{r,HHI}$ is the maximum height of reservoir r.

$$V^{W\_RES.lo}_{r,t} = RES^{B\_CHAR}_{r,VLO} \quad \text{(w.9a)}$$
$$V^{W\_RES.up}_{r,t} = RES^{B\_CHAR}_{r,VHI} \quad \text{(w.9b)}$$

where:
$V_{r,t}^{W\_RES.lo}$ is the lower bound of volume of reservoir r at time t;
$RES_{r,VLO}^{B\_CHAR}$ is the minimum volume of reservoir r;
$V_{r,t}^{W\_RES.up}$ is the upper bound of volume of reservoir r at time t; and
$RES_{r,VHI}^{B\_CHAR}$ is the maximum volume of reservoir r.

Maximum groundwater level constraints are included to constrain aquifer levels according to physical limits:

$$GW_{g,t}^{W\_D.lo} \leq AQ_{g,MXH}^{B\_CHAR} \quad \text{(w.10)}$$

where:
$GW_{g,t}^{W\_D.lo}$ is the water table depth from ground to surface of groundwater aquifer g at time t; and
$AQ_{g,MXH}^{B\_CHAR}$ is the maximum head of groundwater aquifer g.

Finally, the reservoir volume in the last period must equal the volume selected in period one:

$$V_{r,T}^{W\_RES} = RES_{r,IVL}^{B\_CHAR} \quad \text{(w.11)}$$

5.2 Energy module

5.2.1 A detailed scheme of energy generation and distribution interlinkages

Energy generation based on different technologies and distribution of this energy among different sectors are shown in Figure 12.

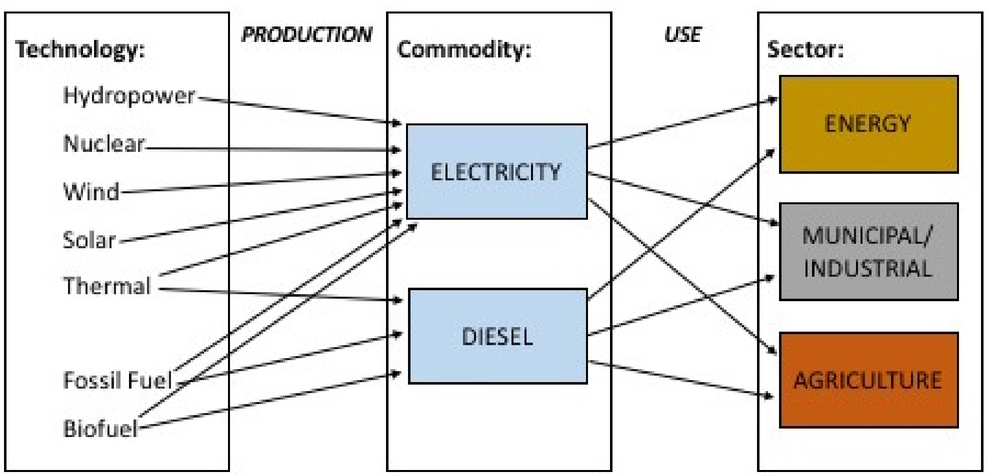


Figure 12: Energy generation and distribution system

5.2.2 Link to WSM core

The water balance at energy sites consists of inflows that come from surface and groundwater withdrawals. Some of that water is consumed or lost to evaporation, while the remainder flows back to the downstream system as drainage water, or returns to groundwater via seepage. The detailed water balance at an energy production site is depicted in Figure 13.

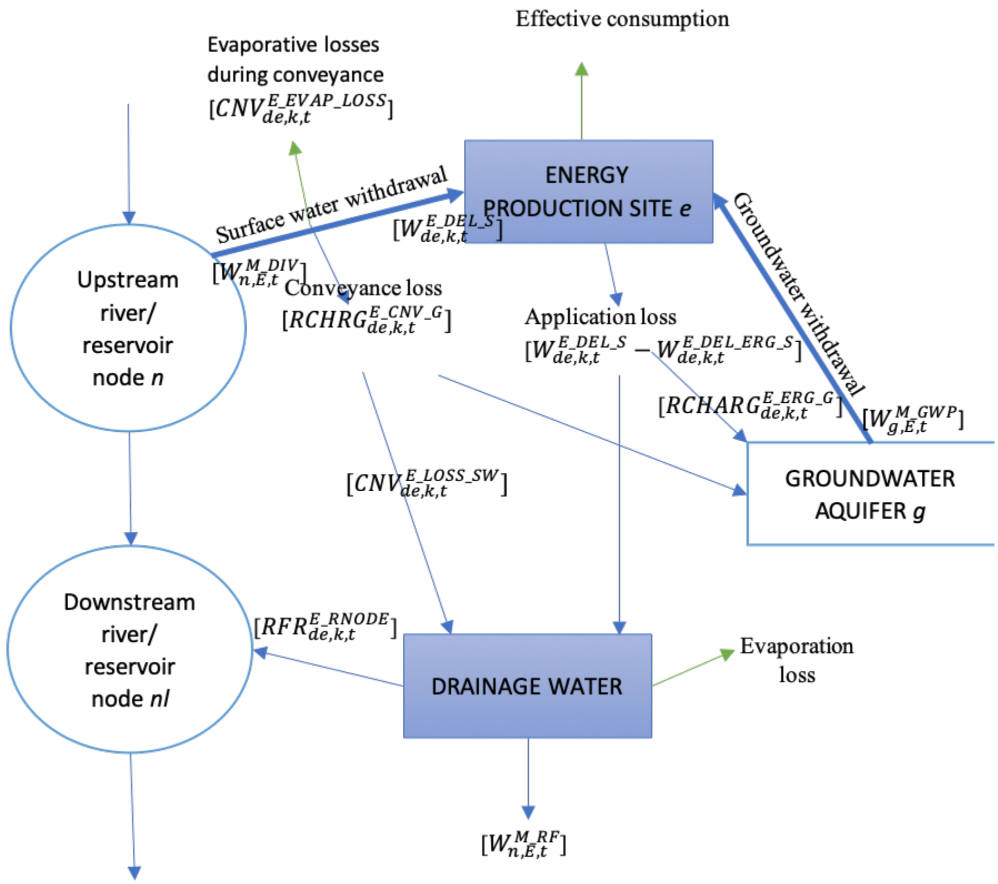


Figure 13: Water balance in an illustrative energy production site

Total surface water abstracted for energy at each site and technology depends on the surface water available:

$$W^{M\_DIV}_{n,E,t} = \sum_{de \in NDELINK} \sum_{k} \sum_{o \in KOLINK} W^{E\_ERG\_S}_{de,k,o,t} \tag{e.1}$$

where:
$W^{M\_DIV}_{n,E,t}$ is the surface water abstracted from node n at time t; and
$W^{E\_ERG\_S}_{de,k,o,t}$ is the surface water available at energy production site de (given a link $(de, n) \in NDELINK$) for technology k, to produce energy commodity o, (given a link $(o, k) \in KOLINK$) at time t.

Similarly, total groundwater abstracted for energy at each site depends on the groundwater available at each energy site and technology:

$$W^{M\_GWP}_{g,E,t} = \sum_{de \in GDELINK} \sum_{k} \sum_{o \in KOLINK} W^{E\_ERG\_G}_{de,k,o,t} \tag{e.2}$$

where:
$W^{M\_GWP}_{g,E,t}$ is the groundwater abstracted from aquifer g at time t for the energy sector; and
$W^{E\_ERG\_G}_{de,k,o,t}$ is the groundwater available at each energy production site de (given a link $(de, g) \in GDELINK$) for technology k, to produce energy commodity o, (given a link $(o, k) \in KOLINK$) at

time t.

5.2.3 Conveyance losses

Conveyance water lost to groundwater depends on the total water withdrawn and the conveyance efficiency, including efficiency gains:

$$RCHRG_{de,k,o,t}^{E\_CNV\_G} = W_{de,k,o,t}^{E\_ERG\_S} \cdot \left(1 - \left(E_{de,k}^{E\_CNV} \cdot \left(1 + \frac{E_{de,k}^{E\_CNV\_GN}}{100}\right)\right)\right) \tag{e.3}$$

where:
$RCHRG_{de,k,o,t}^{E\_CNV\_G}$ is the conveyance water lost to groundwater at energy production site de, for technology k, to produce energy commodity o, at time t;
$E_{de,k}^{E\_CNV}$ is conveyance efficiency at energy production site de for technology k; and
$E_{de,k}^{E\_CNV\_GN}$ is the gains to conveyance efficiency at energy production site de for technology k.

Conveyance water lost to evaporation further depends on evaporation:

$$CNV_{de,k,o,t}^{E\_EVAP\_LOSS} = (W_{de,k,o,t}^{E\_ERG\_S} - RCHRG_{de,k,o,t}^{E\_CNV\_G}) \cdot CNV_{de,k}^{E\_EVAP} \tag{e.4}$$

where:
$CNV_{de,k,o,t}^{E\_EVAP\_LOSS}$ is conveyance water lost to evaporation at energy production site de, for technology k, to produce energy commodity o, at time t; and
$CNV_{de,k}^{E\_EVAP}$ is evaporation at energy production site de for technology k.

Similarly, conveyance water lost to surface drainage further depends on drainage conveyance:

$$CNV_{de,k,o,t}^{E\_EVAP\_SW} = (W_{de,k,o,t}^{E\_ERG\_S} - RCHRG_{de,k,o,t}^{E\_CNV\_G} - CNV_{de,k,o,t}^{E\_EVAP\_LOSS}) \cdot CNV_{de,k}^{E\_DRNG} \tag{e.5}$$

where:
$CNV_{de,k,o,t}^{E\_EVAP\_SW}$ is conveyance water lost to surface drainage at energy production site de, for technology k, to produce energy commodity o, at time t; and
$CNV_{de,k}^{E\_DRNG}$ is drainage conveyance at energy production site de for technology k.

Finally, water returned to the river node is characterized by the fraction of water returned and the return flow:

$$RFR_{de,k,o,t}^{E\_RNODE} = RA_{de,k,o}^{E\_DIVRF} \cdot CNV_{de,k,o,t}^{E\_LOSS\_SW} \tag{e.6}$$

where:
$RFR_{de,k,o,t}^{E\_RNODE}$ is the water returned to the river node from energy production site de, using technology k, to produce energy commodity o, at time t; and
$RA_{de,k,o}^{E\_DIVRF}$ is the return flow from energy production site de, for technology k, to produce energy commodity o.

5.2.4 Total water available at energy site

The surface water delivered to an energy site to produce a given energy commodity depends on the total surface water withdrawn as well as the above outlined conveyance losses:

$$W_{de,k,o,t}^{E\_DEL\_S} = W_{de,k,o,t}^{E\_ERG\_S} - RCHRG_{de,k,o,t}^{E\_CNV\_G} - CNV_{de,k,o,t}^{E\_EVAP\_LOSS} - CNV_{de,k,o,t}^{E\_LOSS\_SW} \tag{e.7}$$

where:
$W_{de,k,o,t}^{E\_DEL\_S}$ is the total surface water delivered to energy production site de, for technology k, to produce energy commodity o, at time t.

The surface water actually available for the energy site is characterized by the application efficiency, including application efficiency gains:

$$W_{de,k,o,t}^{E\_DEL\_ERG\_S} = W_{de,k,o,t}^{E\_DEL\_S} \cdot APP_{de,o,k}^{E\_EFF} \left(1 + \frac{APP_{de,o,k}^{E\_EFF\_GN}}{100}\right) \tag{e.8}$$

where:
$W_{de,k,o,t}^{E\_DEL\_ERG\_S}$ is the surface water actually available at energy production site de, for technology k, to produce energy commodity o, at time t;
$APP_{de,o,k}^{E\_EFF}$ is the application efficiency at energy production site de, for technology k, to produce energy commodity o, at time t;
$APP_{de,o,k}^{E\_EFF\_GN}$ is the gains to application efficiency for energy production site de, for technology k, to produce energy commodity o.

Similarly the groundwater actually available to the energy site is characterized by:

$$W_{de,k,o,t}^{E\_DEL\_ERG\_G} = W_{de,k,o,t}^{E\_DEL\_G} \cdot APP_{de,o,k}^{E\_EFF} \left(1 + \frac{APP_{de,o,k}^{E\_EFF\_GN}}{100}\right) \tag{e.9}$$

where:
$W_{de,k,o,t}^{E\_DEL\_ERG\_G}$ is the groundwater actually available at energy production site de, for technology k, to produce energy commodity o, at time t; and
$W_{de,k,o,t}^{E\_DEL\_G}$ is the groundwater delivered to energy production site de, for technology k, to produce energy commodity o, at time t.

5.2.5 Total groundwater recharge

Groundwater recharge can be characterized by the total surface and groundwater delivered as well as application efficiency, including application efficiency gains:

$$RCHARGE_{de,k,o,t}^{E\_ERG\_G} = (W_{de,k,o,t}^{E\_DEL\_S} + W_{de,k,o,t}^{E\_DEL\_G}) \cdot \left(1 - \left(APP_{de,o,k}^{E\_EFF} \left(1 + \frac{APP_{de,o,k}^{E\_EFF\_GN}}{100}\right)\right)\right) \tag{e.10}$$

where:
$RCHARGE_{de,k,o,t}^{E\_ERG\_G}$ is the groundwater recharge at energy production site de, for technology k, to produce energy commodity o, at time t.

Total groundwater recharge for an energy technology and associated commodity depends on recharge from conveyance and recharge from energy site:

$$RCHARGE^{E\_TOT\_G}_{de,k,o,t} = RCHARGE^{E\_CNV\_G}_{de,k,o,t} + RCHARGE^{E\_ERG\_G}_{de,k,o,t} \tag{e.11}$$

where:
$RCHARGE^{E\_TOT\_G}_{de,k,o,t}$ is the total groundwater recharge at energy production site de, for technology k, to produce energy commodity o, at time t.

5.2.6 Return flows to WSM module

Given a link between energy production sites and nodes, $(de, n) \in NDELINK$, and a link between energy commodities and technologies $(o, k) \in KOLINK$ total return flows are characterized as:

$$W^{M\_RF}_{n,E,t} = \sum_{de \in NDELINK} \sum_{k} \sum_{o \in KOLINK} RFR^{E\_RNODE}_{de,k,o,t} \tag{e.12}$$

And total groundwater recharge from energy production sites is:

$$W^{E\_DP}_{n,E,t} = \sum_{de \in NDELINK} \sum_{k} \sum_{o \in KOLINK} RCHARG^{E\_TOT\_G}_{de,k,o,t} \tag{e.13}$$

where:
$W^{M\_RF}_{n,E,t}$ is total return flow for nodes n at time t; and $W^{E\_DP}_{n,E,t}$ is the total groundwater recharge for nodes n at time t.

5.2.7 Water demand

Water requirements at energy sites depend on requirements for energy production and the total energy produced at the site:

$$W^{E\_DEL\_ERG\_S}_{de,k,o,t} + W^{E\_DEL\_ERG\_G}_{de,k,o,t} = WATER^{E\_REQ}_{de,k,o,t} \cdot PRD^{E}_{de,k,o,t} \tag{e.14}$$

where:
$WATER^{E\_REQ}_{de,k,o,t}$: is the water required per unit of energy production at energy production site de, using technology k, to produce energy commodity o, at time t; and
$PRD^{E}_{de,k,o,t}$ is the energy produced at energy production site de, using technology k, of energy commodity type o, at time t.

5.2.8 Hydropower production

Given links between nodes and energy production sites, $(n, de) \in DENLINK$, and between nodes and reservoirs, $(n, r,) \in NRLINK$, hydropower production from reservoirs can be characterized:

$$PRD^{E}_{de,hyp,t} = \frac{1}{1000000} \cdot 24 \cdot d^{B}_{t} \cdot G \cdot D \cdot HP^{E\_CHAR}_{de,ehpp} \sum_{n \in DENLINK} \sum_{r \in NRLINK} \left(\frac{W^{W\_TURB}_{r,t} * 1000000}{60 \cdot 60 \cdot 24 \cdot d^{B}_{t}} \cdot \left(\frac{1}{2} H^{W\_RES}_{r,t} + \frac{1}{2} H^{W\_RES}_{r,t-1} - RES^{B\_CHAR}_{r,HT0} \right) \right) \tag{e.15}$$

where:
$PRD^{E}_{de,hyp,t}$ is hydropower production at energy production site *de* ,using reservoir systems, at time t;
d^{B}_{t} is the number of days in each month;
G is the gravitational constant $(9.81 \frac{m}{s^2})$;
D is the density of water $(998 \frac{kg}{m^3})$;
$HP^{E\_CHAR}_{de,ehpp}$ is the production efficiency of the reservoir hydropower generation facility at energy production site *de*;
$W^{W\_TURB}_{r,t}$ is river flow through the turbines in reservoir r at time t;
$H^{W\_RES}_{r,t}$ is the water level in reservoir r at time t; and
$RES^{B\_CHAR}_{r,HT0}$ is the tail water level for turbine discharge of reservoir r.

Similarly, hydropower production from rrun-of-the-river systems is charcterized by:

$$PRD^{E}_{de,ror,t} = \frac{1}{1000000} \cdot 24 \cdot d^{B}_{t} \cdot HP^{E\_CHAR}_{de,eror} \cdot HP^{E\_CHAR}_{de,grhp} \cdot \sum_{n \in DENLINK} \sum_{nd} \left(\frac{W^{W\_TURB\_ROR}_{de,t} * 1000000}{60 \cdot 60 \cdot 24 \cdot d^{B}_{t}} \right) \tag{e.16}$$

where:
$PRD^{E}_{de,ror,t}$ is hydropower production at energy production site *de* ,using run-of-the-river systems, at time t;
$HP^{E\_CHAR}_{de,eror}$ is the production efficiency of the run-of-the-river hydropower generation facility at energy production site *de*;
$HP^{E\_CHAR}_{de,grhp}$ is the electricity generated per unit of water at energy production site *de*; and
$W^{W\_TURB\_ROR}_{de,t}$ is river flow through the turbines of the run-of-the-river hydropower generation facility at energy production site *de* at time t.

5.2.9 Biofuel usage

Given links between nodes and energy production sites, $(n, de) \in DENLINK$, and between agricultural production sites and notes, $(da, n) \in NDALINK$, energy production from biofuels is characterized:

$$\sum_{t} PRD^{E}_{e,biof,t} = \sum_{bcr} \sum_{n \in DENLINK} \sum_{da \in NDALINK} BIO^{A\_YLD}_{da,bcr} \cdot E^{A\_BIO}_{da,bcr} \tag{e.17}$$

where:
$PRD^{E}_{e,biof,t}$ is the energy production at energy production site *de* from biofuels at time *t*;
$BIO^{A\_YLD}_{da,bcr}$ is the yield of biofuel crops (*bcr*) from agricultural production site *da*; and
$E^{A\_BIO}_{da,bcr}$ is the biofuel crop production at agricultural production site *da*.

5.2.10 Energy usage

Energy usage for water supply to energy sties depends on surface water availability and use and groundwater availability and use:

$$ENERGY^{E\_USE}_{de,o,k,o,t} = WTR^{E\_CHAR}_{de,o,k,o,SWER} \cdot WTR^{E\_CHAR}_{de,o,k,o,SWEF} \cdot W^{E\_ERG\_S}_{de,o,k,o,t} + \sum_{g \in GDELINK} L^{E\_GPMP}_{g,o,k,o,t} \cdot WTR^{E\_CHAR}_{de,o,k,o,GWEF} \cdot W^{E\_ERG\_G}_{de,o,k,o,t} \tag{e.18}$$

where:
$ENERGY^{E\_USE}_{de,o,k,o,t}$ is the energy usage for water supply to energy production site *de*, using energy commodity *o*, for technology *k*, to produce energy commodity *o*, at time *t*;
$WTR^{E\_CHAR}_{de,o,k,o,SWER}$ is the energy requirement per unit of surface water supply at energy production site *de*, using energy commodity *o*, for technology *k*, to produce energy commodity *o*;
$WTR^{E\_CHAR}_{de,o,k,o,SWEF}$ is the fraction of surface water pumped at energy production site *de*, using energy commodity *o*, for technology *k*, to produce energy commodity *o*;
$L^{E\_GPMP}_{g,o,k,o,t}$ is the energy requirement per unit of groundwater at groundwater aquifer *g*, using energy commodity *o*, for technology *k*, to produce energy commodity *o*, at time *t* (given link $(de, g) \in GDELINK$); and
$WTR^{E\_CHAR}_{de,o,k,o,GWEF}$ is the fraction of groundwater pumped at energy production site *de*, using energy commodity *o*, for technology *k*, to produce energy commodity *o*.

Total energy use in the sector depends on energy use at each site (given links $(de, n) \in NDELINK$), $(k, o) \in OKLINK$, and $(o, k) \in KOLINK$):

$$E^{M\_DIV}_{n,E,k,o,t} = \sum_{de \in NDELINK} \sum_{k \in OKLINK} \sum_{o \in KOLINK} ENERGY^{E\_USE}_{de,o,k,o,t} \cdot (1 + E^{E\_LOSS}_{de,o,k,o}) \tag{e.19}$$

where:
$E^{M\_DIV}_{n,E,k,o,t}$ is the energy withdrawn at node *n*, for the energy sector *E*, from technology *k*, to produce energy commodity *o*, at time *t*; and
$E^{E\_LOSS}_{de,o,k,o}$ is the energy lost at energy production site *de*, using energy commodity *o*, for technology *k*, to produce energy commodity *o*, at time *t*.

5.2.11 Energy balance

Given a link between energy markets and energy production sites, ($(de, m) \in MDELINK$), total energy produced must equal the sum of energy withdrawn for each sector and the energy trade balance:

$$\sum_{de \in MDELINK} PRD^{E}_{de,k,o,t} = \sum_{n \in MNLINK} \sum_{s} E^{E\_DIV}_{n,s,k,o,t} + TBAL^{E}_{m,k,o,t} \tag{e.20}$$

where:
$E_{n,s,k,o,t}^{E\_DIV}$ is the energy withdrawn at node n, for sector s, for technology k, used to produce energy commodity o, at time t; and
$TBAL_{m,k,o,t}^{E}$ is the energy trade balance in energy market m, for technology k, used to produce energy commodity o, at time t (given link between energy markets and nodes $(n, m) \in MNLINK$).

5.2.12 Energy production costs

Production costs depend on energy produced and the cost per unit:

$$C_{de}^{E\_PRD} = \sum_{k} \sum_{t} \sum_{o \in KOLINK} (PRD_{de,k,o,t}^{E} \cdot v_{de,k,o,t}^{E\_PROD}) \tag{e.21}$$

where:
$C_{de}^{E\_PRD}$ is the production cost at energy production site de; and
$v_{de,k,o,t}^{E\_PROD}$ is the cost per unit of energy production at energy production site de, using technology k, to produce energy commodity o, at time t.

Electricity transmission costs depend on the quantity of electricity transmitted and the distance from energy production site to market:

$$C_{de,t}^{E\_TRNS} = \sum_{m \in DEMLINK} pt_{de}^{E\_TRANS} \cdot et_{de,m}^{E\_TRANS} \cdot DIST_{de,m,t}^{E} \tag{e.22}$$

where:
$C_{de,t}^{E\_TRNS}$ is the transmission cost of electricity produced at energy production site de at time t;
$pt_{de,m}^{E\_TRANS}$ is the price of electricity transmission (in $\frac{Mwh}{m}$) from energy production site de;
$et_{de,m}^{E\_TRANS}$ is the distance (in m) from energy production site de to energy market m; and
$DIST_{de,m,t}^{E}$ is the electricity transmitted from energy production site de, to energy market m, (in Mwh) at time t.

Water supply costs depend on costs of surface and groundwater pumping, capacity expansion, and other costs:

$$\begin{aligned} C_{de}^{E\_WTR\_SUP} = & \sum_{k \in OKLINK} \sum_{t} \sum_{o \in KOLINK} (WTR_{de,k,o,SWGR}^{E\_CHAR} \cdot (1 - WTR_{de,o,k,o,SWEF}^{E\_CHAR}) \cdot W_{de,k,o,t}^{E\_ERG\_S} \\ & + P_{de,k,o,t}^{E} \cdot WTR_{de,o,k,o,SWER}^{E\_CHAR} \cdot WTR_{de,o,k,o,SWEF}^{E\_CHAR} + WTR_{de,k,o,SONC}^{E\_CHAR} \cdot W_{de,k,o,t}^{E\_ERG\_S} \\ & + P_{de,k,o,t}^{E} (\sum_{g \in DEGLINK} L_{g,o,k,o,t}^{E\_GPMP}) \cdot WTR_{de,o,k,o,GWEF}^{E\_CHAR} \\ & + WTR_{de,k,o,GONC}^{E\_CHAR} \cdot W_{de,k,o,t}^{E\_ERG\_G}) + C_{de}^{E\_PMXP\_S} + C_{de}^{E\_PMXP\_G} \end{aligned} \tag{e.23}$$

where: $C_{de}^{E\_WTR\_SUP}$ is water supply cost at energy production site de;
$WTR_{de,k,o,SWGR}^{E\_CHAR}$ is the fixed cost of water delivery by gravity to at energy production site de, for technology k, to produce energy commodity o;
$WTR_{de,k,o,SONC}^{E\_CHAR}$ is other non-energy costs of conveying surface water at energy production site de, for technology k, to produce energy commodity o;
$P_{de,k,o,t}^{E}$ is the energy price at energy production site de, for energy commodity o, produced using

technology k, at time t;
$WTR^{E\_CHAR}_{de,k,o,GONC}$ is other non-energy costs of conveying groundwater at energy production site de, for technology k, to produce energy commodity o;
$C^{E\_PMXP\_S}_{de}$ is the cost of expanding surface water pumping at energy production site de; and
$C^{E_PMXP_G}_{de}$is the cost of expanding groundwater pumping at energy production site de.

The cost of expanding surface pumping is calculated:

$$C^{E\_PMXP\_S}_{de} = \sum_{k} \sum_{o \in KOLINK} WTR^{E\_CHAR}_{de,k,o,SPAC} \cdot (WTR^{E\_CHAR}_{de,k,o,SPGC})^{WTR^{E\_CHAR}_{de,k,o,SPBC}} \tag{e.24}$$

where:
$WTR^{E\_CHAR}_{de,k,o,SPAC}$ and $WTR^{E\_CHAR}_{de,k,o,SPBC}$ are parameters of surface water pumping expansion at energy production site de, for technology k, to produce energy commodity o; and
$WTR^{E\_CHAR}_{de,k,o,SPGC}$ is surface water pumping capacity growth at energy production site de, for technology k, to produce energy commodity o.

Similarly, the cost of expanding groundwater pumping is calculated:

$$C^{E\_PMXP\_G}_{de} = \sum_{k} \sum_{o \in KOLINK} WTR^{E\_CHAR}_{de,k,o,GPAC} \cdot (WTR^{E\_CHAR}_{de,k,o,GPGC})^{WTR^{E\_CHAR}_{de,k,o,GPBC}} \tag{e.25}$$

where:
$WTR^{E\_CHAR}_{de,k,o,GPAC}$ and $WTR^{E\_CHAR}_{de,k,o,GPBC}$ are parameters of groundwater pumping expansion at energy production site de, for technology k, to produce energy commodity o; and
$WTR^{E\_CHAR}_{de,k,o,GPGC}$ is groundwater pumping capacity growth at energy production site de, for technology k, to produce energy commodity o.

5.2.13 Application and conveyance efficiency

The cost of improving water application efficiency depends on the cost of technology adoption and the quantity of water saved:

$$\begin{aligned} C^{E\_APP\_EFF}_{de} = &\sum_{k} \sum_{o \in KOLINK} \Bigg(V^{E\_IREF}_{de,k,o} \Bigg(\sum_{t} \Big(W^{E\_DEL\_ERG\_S}_{de,k,o,t} + W^{E\_DEL\_ERG\_G}_{de,k,o,t} \Big) \Bigg) \\ &\cdot APP^{E\_EFF}_{de,k,o} \cdot \frac{APP^{E\_EFF\_GN}_{de,k,o}}{100} \Bigg) \end{aligned} \tag{e.26}$$

where:
$C^{E\_APP\_EFF}_{de}$ is the cost of improving water application efficiency at energy production site de; and
$V^{E\_IREF}_{de,k,o}$ is the cost of technology adoption per unit of water at energy production site de, for technology k, used to produce energy commodity o.

The costs of expanding production capacity ($C^{E\_EXPK}_{de}$) are:

$$C^{E\_EXPK}_{de} = \sum_{k} \sum_{o \in KOLINK} \alpha^{E\_EXP}_{de,k,o} (PROD^{E\_POT\_EXP}_{de,k,o})^{\beta de,k,o^{E\_EXP}} \tag{e.27}$$

where:
$\alpha^{E\_EXP}_{de,k,o}$ and $\beta de, k, o^{E\_EXP}$ are the parameters of the power production capacity expansion function at energy production site de, for technology k, used to produce energy commodity o; and
$PROD^{E\_POT\_EXP}_{de,k,o}$ is the expansion gain at energy production site de, for technology k, used to produce energy commodity o.

5.2.14 Net benefits

Net benefits of energy production ($B^{M\_PRD}_{n,E}$) are calculated:

$$\begin{aligned} B^{M\_PRD}_{n,E} = \sum_{de \in NDELINK} \Bigg(&\sum_k \sum_t \sum_{o \in KOLINK} \left(P^E_{de,k,o,t} \cdot DIST^E_{de,m,t} + P^E_{de,agr} \cdot E^{E\_DIV\_A}_{n,k,o,t} \right) \\ &- C^{E\_PRD}_{de} - C^{E\_TRNS}_{de} - C^{E\_WTR\_SUP}_{de} - C^{E\_PMXP\_S}_{de} - C^{E\_PMXP\_G}_{de} - C^{E\_APP\_EFF}_{de} \\ &- C^{E\_CNV\_EFF}_{de} - C^{E\_EXPK}_{de} \Bigg) \end{aligned} \tag{e.28}$$

where:
$P^E_{de,agr}$ is the price of energy used in agriculture from energy production site de; and
$E^{E\_DIV\_A}_{n,k,o,t}$ is the energy diverted for agriculture at node n, of energy commodity o, produced by technology k, at time t.

5.2.15 Constraints

Water through turbine ($W^{E\_TURB}_{r,t}$) from reservoir r at time t cannot be more than water flowing downstream:

$$\sum_{r \in NRLINK} W^{E\_TURB}_{r,t} \leq \sum_{nd} W^{W\_F}_{n,nd,t} \tag{e.29}$$

Water through run-of-the-river turbine ($W^{E\_TURB\_ROR}_{de,t}$) at energy production site de at time t cannot be more than water flowing downstream:

$$\sum_{de \in NDELINK} W^{E\_TURB\_ROR}_{de,t} \leq \sum_{nd} W^{W\_F}_{n,nd,t} \tag{e.30}$$

Energy production cannot be greater than the capacity:

$$PRD^E_{de,k,o,t} \leq 24 \cdot d^B_t \cdot (PROD^{E\_POT}_{de,k,o} + PROD^{E\_POT\_EXP}_{de,k,o}) \tag{e.31}$$

Energy distribution cannot be greater than production:

$$\sum_{de} DIST^E_{de,m,t} \leq egreq^{UB}_{m,t} + egpop^{UB}_{m,t} \tag{e.32}$$

where:
$egreq^{UB}_{m,t}$ is the upper bound of per capita energy demand at market m and time t; and
$egpop^{UB}_{m,t}$ is the upper bound of the population getting electricity from market m at time t.

Finally, the following conditions should be fulfilled since water pumping is considered to occur either using electricity or diesel pumps:

$$\sum_{o} f^{E\_SP}_{de,o,k,o,t} = 1 \tag{e.33}$$

and

$$\sum_{o} f^{E\_GP}_{de,o,k,o,t} = 1 \tag{e.34}$$

where:
$f^{E\_SP}_{de,o,k,o,t}$ is the fraction of surface water pumped using electricity or diesel (o) for producing energy commodity o;
$f^{E\_GP}_{de,o,k,o,t}$ is the fraction of groundwater pumped using electricity or diesel (o) for producing energy commodity o.

5.3 Industry and municipality module

5.3.1 Water balance at industrial and municipal sites

The detailed water balance for an illustrative industrial production site is depicted in Figure 14. Similar to the energy module, municipal/industrial sites can draw water from groundwater and surface water sources. Some of that water is lost to evaporation and some is consumed in production or consumption processes. The remaining water returns through drainage to the surface water system or to groundwater through recharge. The water balance is presented in the equations that follow.

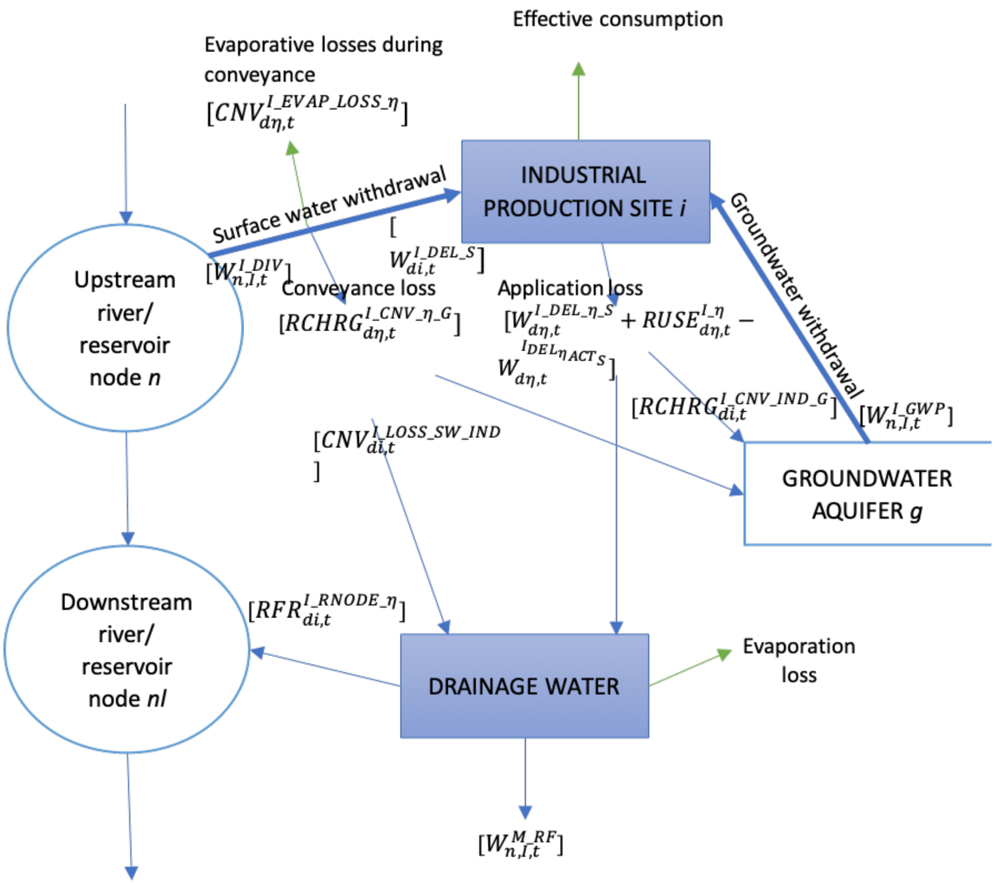


Figure 14: Water balance in an illustrative industrial production site

5.3.2 Linking to WSM module

The surface water abstracted for industrial and municipal use must be equal to the sum of the surface water available at each industry site and the surface water available at each municipal site:

$$W^{I\_DIV}_{n,I,t} = \sum_{di \in NDILINK} W^{I\_IND\_S}_{di,t} + \sum_{dm \in NDMLINK} W^{I\_MUN\_S}_{dm,t} \tag{i.1}$$

where:
$W^{I\_DIV}_{n,I,t}$ is the surface water abstracted for industrial and municipal use from node n in time t;
$W^{I\_IND\_S}_{di,t}$ is the surface water abstracted at industry site di in time t (given the link between industrial production sites and nodes $(di, n) \in NDILINK$); and
$W^{I\_MUN\_S}_{di,t}$ is the surface water abstracted at industry site dm in time t (given the link between industrial production sites and nodes $(dm, n) \in NDMLINK$).

Similarly, groundwater abstracted for industrial and municipal use must be equal to the sum of the groundwater available at each industry site and the groundwater available at each municipal site:

$$W^{I\_GWP}_{n,I,t} = \sum_{di \in NDILINK} W^{I\_IND\_G}_{di,t} + \sum_{dm \in NDMLINK} W^{I\_MUN\_G}_{dm,t} \tag{i.2}$$

where:
$W_{n,I,t}^{I\_GWP}$ is the groundwater abstracted for industrial and municipal use from node n in time t;
$W_{di,t}^{I\_IND\_G}$ is the groundwater abstracted at industry site di in time t; and
$W_{dm,t}^{I\_MUN\_G}$ is the groundwater abstracted at industry site dm in time t.

5.3.3 Conveyance losses

We consider the following characterization of conveyance losses for both the industrial and municipal sectors. For notational simplicity, we let $IND, MUN \in \eta$ to allow for these calculations in each sector. Conveyance water lost to groundwater for industrial sites depends on total surface water withdrawn and conveyance efficiency, including efficiency gains:

$$RCHRG_{d\eta,t}^{I\_CNV\_\eta\_G} = W_{d\eta,t}^{W\_\eta\_S} \cdot \left(1 - E_{d\eta}^{I\_CNV\_\eta} \cdot \left(1 + \frac{E_{d\eta}^{I\_CNV\_\eta\_GN}}{100}\right)\right) \quad \text{(i.3)}$$

where:
$RCHRG_{d\eta,t}^{I\_CNV\_\eta\_G}$ is the conveyance water lost to groundwater at industry site or municipality $d\eta$ in time g;
$E_{d\eta}^{I\_CNV\_\eta}$ is the conveyance efficiency at industry site or municipality $d\eta$; and
$E_{d\eta}^{I\_CNV\_\eta\_GN}$ is the conveyance efficiency improvement (in percentage) at industry site or municipality $d\eta$.

Conveyance water lost to evaporation depends on the total water withdraw, the water lost to groundwater, and the evaporation fraction:

$$CNV_{d\eta,t}^{I\_EVAP\_LOSS\_\eta} = (W_{d\eta,t}^{W\_\eta\_S} - RCHRG_{d\eta,t}^{I\_CNV\_\eta\_G}) \cdot CNV_{d\eta}^{I\_EVAP\_\eta} \quad \text{(i.4)}$$

where:
$CNV_{d\eta,t}^{I\_EVAP\_LOSS\_\eta}$ is the conveyance water lost to evaporation at industry site or municipality $d\eta$ and time t; and
$CNV_{d\eta}^{I_EVAP_\eta}$i s the conveyance evaporation loss fraction at industry site or municipality $d\eta$.

Total conveyance water lost to surface drainage at an industrial site or municipality depends on groundwater and evaporation loss as well as the fraction of water lost to surface drainage:

$$CNV_{d\eta,t}^{I\_LOSS\_SW\_\eta} = (W_{d\eta,t}^{W\_\eta\_S} - RCHRG_{d\eta,t}^{I\_CNV\_\eta\_G} - CNV_{d\eta,t}^{I\_EVAP\_LOSS\_\eta}) \cdot CNV_{d\eta}^{I\_DRNG\_\eta} \quad \text{(i.5)}$$

where:
$CNV_{d\eta,t}^{I\_LOSS\_SW\_\eta}$ is the conveyance water lost to surface drainage at industry site or municipality $d\eta$ and time t; and
$CNV_{d\eta}^{I\_DRNG\_\eta}$ is the conveyance lost to surface drainage fraction at industry site or municipality $d\eta$.

Finally, water returned to the river node from conveyance depends on the fraction of water returned and the return flow:

$$RFR_{d\eta,t}^{I\_RNODE\_\eta} = RA_{d\eta}^{I\_DIVRF\_\eta} \cdot CNV_{d\eta}^{I\_LOSS\_SW\_\eta} \tag{i.6}$$

where:
$RFR_{d\eta,t}^{I\_RNODE\_\eta}$ is water returned to the river node from conveyance at industry site or municipality $d\eta$ in time t; and
$RA_{d\eta}^{I\_DIVRF\_\eta}$ is the fraction of return flow returned to the river node at industry site or municipality $d\eta$.

5.3.4 Water reuse after wastewater treatment

Surface water delivered for industry site or municipality $d\eta$ depends on the total surface water withdrawn and conveyance groundwater, evaporation, and surface drainage loss:

$$W_{d\eta}^{I\_DEL\_\eta\_S} = W_{d\eta}^{I\_\eta\_S} - RCHRG_{d\eta,t}^{I\_CNV\_\eta\_G} - CNV_{d\eta,t}^{I\_EVAP\_LOSS\_\eta} - CNV_{d\eta,t}^{I\_LOSS\_SW\_\eta} \tag{i.7}$$

Surface water actually available depends on the water delivered and reused as well as application efficiency, including efficiency gains:

$$W_{d\eta}^{I\_DEL\_\eta\_ACT\_S} = (W_{d\eta,t}^{I\_DEL\_\eta\_S} + RUSE_{d\eta,t}^{I\_\eta}) \cdot APP_{d\eta}^{I\_EFF\_\eta}\left(1 + \frac{APP_{d\eta}^{I\_EFF\_\eta\_GN}}{100}\right) \tag{i.8}$$

where:
$W_{d\eta}^{I\_DEL\_\eta\_ACT\_S}$ is surface water actually available at industry site or municipality $d\eta$ and time t;
$RUSE_{d\eta,t}$ is reused water at industry site or municipality $d\eta$ and time t;
$APP_{d\eta}^{I\_EFF\_\eta}$ is application efficiency at industry site or municipality $d\eta$; and
$APP_{d\eta}^{I\_EFF\_\eta\_GN}$ is application efficiency at industry site or municipality $d\eta$.

Similarly, groundwater actually available can be calculated:

$$W_{d\eta,t}^{I\_DEL\_\eta\_G} = W_{d\eta,t}^{I\_\eta\_G} \cdot APP_{d\eta}^{I\_EFF\_\eta}\left(1 + \frac{APP_{d\eta}^{I\_EFF\_\eta\_GN}}{100}\right) \tag{i.9}$$

where:
$W_{d\eta,t}^{I\_DEL\_\eta\_G}$ is groundwater actually available at industry site or municipality $d\eta$ in time t.

Return flow from industrial site or municipality after application depends on total water availability (surface, ground, and reuse) and application efficiency including efficiency gains:

$$\begin{aligned} RTN_{d\eta,t}^{I\_\eta\_S} =& (W_{d\eta,t}^{I\_DEL\_\eta\_S} + RUSE_{d\eta,t}^{I\_\eta} + W_{d\eta,t}^{I\_\eta\_G}) \\ & \cdot \left(1 - APP_{d\eta}^{I\_EFF\_\eta} \cdot \left(1 + \frac{APP_{d\eta}^{I\_EFF\_\eta\_GN}}{100}\right)\right) \end{aligned} \tag{i.10}$$

where:
$RTN^{I\_\eta\_S}_{d\eta,t}$ is the return flow from industry site or municipality $d\eta$ and time t.

5.3.5 Water reuse after wastewater treatment

Total water reused is calculated from the return flow from industrial site or municipality after application and the fraction of reuse water:

$$RUSE^{I\_\eta}_{d\eta,t} = RTN^{I\_\eta\_S}_{d\eta,t} \cdot RUSE^{I\_FRC\_\eta}_{d\eta,t} \tag{i.11}$$

where:
$RUSE^{I\_FRC\_\eta}_{d\eta,t}$ is the fraction of reuse water at industry site or municipality $d\eta$ and time t.

5.3.6 Return flow back to WSM module

The return flow from industrial or municipal site in million cubic meters ($W^{M\_RF}_{n,I,t}$) depends on the return flow from each site:

$$\begin{aligned} W^{M\_RF}_{n,I,t} = & \sum_{di \in NDILINK} (RFR^{I\_RNODE\_IND}_{di,t} + RTN^{I\_IND\_S}_{di,t}) \\ & + \sum_{dm \in NDMLINK} (RFR^{I\_RNODE\_MUN}_{dm,t} + RTN^{I\_MUN\_S}_{dm,t}) \end{aligned} \tag{i.12}$$

Similarly, total groundwater recharge ($W^{M\_DP}_{n,I,t}$) is calculated as the sum of groundwater recharge from each industrial and municipal site:

$$W^{M\_DP}_{n,I,t} = \sum_{di \in NDILINK} RCHRG^{I\_CNV\_IND\_G}_{di,t} + \sum_{dm \in NDMLINK} RCHRG^{I\_CNV\_MUN\_G}_{dm,t} \tag{i.13}$$

5.3.7 Water demand

The industrial water requirement depends on the water requirement per unit of production as well as total production:

$$WATER^{I\_DMD\_IND}_{di,t} = WATER^{I\_IND\_REQ}_{di,t} \cdot \sum_{p} IND^{I\_PROD\_POT}_{di,t,p} \tag{i.14}$$

where: $WATER^{I\_DMD\_IND}_{di,t}$ is the industrial water requirement based on potential production at site di and time t;
$WATER^{I\_IND\_REQ}_{di,t}$ is the water required per unit of industrial production at site di and time t and $IND^{I\_PROD\_POT}_{di,t,p}$ is the potential industrial production of good p, at industrial site di, at time t.

Municipal water demand depends on the water requirement per person and the population of the municipality:

$$WATER^{I\_DMD\_MUN}_{dm,t} = WATER^{I\_MUN\_REQ}_{dm,t} \cdot POP^{I}_{dm,t} \tag{i.15}$$

where:
$WATER^{I\_DMD\_MUN}_{dm,t}$ is the municipal water requirement based on population at municipality dm and time t;
$WATER^{I\_MUN\_REQ}_{dm,t}$ is the water required per person (m^3/person) at municipality dm and time t; and
$POP^{I}_{dm,t}$ is the population of municipality dm at time t.

The reduction ratio in industrial production maintains the water constraint condition, taking into account the water demands and the sum of actual surface water and groundwater delivered. This is calculated:

$$IND^{I\_PROD\_RED\_RATIO\_WTR}_{di,t} = \frac{W^{I\_DEL\_IND\_ACT\_S}_{di,t} + W^{I\_DEL\_IND\_ACT\_G}_{di,t}}{WATER^{I\_DMD\_IND}_{di,t}} \tag{i.16}$$

Similarly, the reduction ratio in the municipal water requirement is calculated:

$$MUN^{I\_PROD\_RED\_RATIO\_WTR}_{dm,t} = \frac{W^{I\_DEL\_MUN\_ACT\_S}_{dm,t} + W^{I\_DEL\_MUN\_ACT\_G}_{dm,t}}{WATER^{I\_DMD\_MUN}_{dm,t}} \tag{i.17}$$

where:
$IND^{I\_PROD\_RED\_RATIO\_WTR}_{di,t}$ is the reduction ratio in industrial production at industrial site di at time t; and
$MUN^{I\_PROD\_RED\_RATIO\_WTR}_{dm,t}$ is the reduction ratio in the municipal requirement at municipality dm at time t.

5.3.8 Energy usage

Energy usage for water supply to industrial sites depends on the energy requirements for each type of water (surface, ground, reuse, and waste) the fraction of water pumped or treated, and the amount of each type of water used:

$$\begin{aligned} ENERGY^{I\_ENG\_CHAR\_\eta}_{d\eta,k,o,t} =& WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SWER} \cdot WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SWEF} \cdot W^{I\_\eta\_S}_{d\eta,t} \\ &+ \left(\sum_{g \in D\eta GLINK} L^{E\_GPMP}_{g,k,o,t} \right) \cdot WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,GWEF} \cdot W^{I\_\eta\_G}_{d\eta,t} \\ &+ WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,WUER} \cdot RUSE^{I\_\eta}_{d\eta,t} \\ &+ WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,WWTR} \cdot WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,WWFR} \cdot RTN^{I\_\eta\_S}_{d\eta,t} \end{aligned} \tag{i.18}$$

where:
$ENERGY^{I\_ENG\_CHAR\_\eta}_{d\eta,k,o,t}$ is the energy usage for water supply at industry site or municipality $d\eta$, using energy commodity o, produced by technology k, at time t;
$WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SWER}$ is the energy required to deliver a unit of surface water at industry site or municipality $d\eta$, using energy commodity o, produced by technology k;
$WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SWEF}$ is the fraction of surface water pumped at industry site or municipality $d\eta$,using energy commodity o, produced by technology k;

$L^{E\_GPMP}_{g,k,o,t}$ is the energy required to pump on unite of groundwater at site g, using energy commodity o, produced by technology k, at time t (given the link between groundwater aquifers and industrial production sites or municipalities $(g, d\eta) \in D\eta GLINK$);
$WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,GWEF}$ is the fraction of groundwater pumped at industry site or municipality $d\eta$, using energy commodity o, produced by technology k;
$WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,WUER}$ is the energy required to deliver a unit of reuse water to industry site or municipality $d\eta$ using energy commodity o, produced by technology k;
$WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,WWTR}$ is the energy required to deliver a unit of waste water at industry site or municipality $d\eta$ using energy commodity o, produced by technology k;
$WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,WWFR}$ is the fraction of waste water pumped industry site or municipality $d\eta$ using energy commodity o, produced by technology k.

Energy usage at industrial sites depends on the energy required per unit of industrial production as well as total production:

$$ENERGY^{I\_USE\_PROD\_IND}_{di,k,o,t} = ENERGY^{I\_IND\_REQ}_{di,k,o,t} \cdot \sum_p ACT^{I\_IND\_PROD}_{di,t,p} \tag{i.19}$$

where:
$ENERGY^{I\_USE\_PROD\_IND}_{di,k,o,t}$ is non-water energy usage at industrial site di, using energy commodity o, produced by technology k, at time t;
$ENERGY^{I\_IND\_REQ}_{di,k,o,t}$ is energy required per unit of industrial production at industrial site di, using energy commodity o, produced by technology k, at time t;
$ACT^{I\_IND\_PROD}_{di,t,p}$ is actual production of good p, at industrial site di, at time t.

And energy usage for municipalities depends on the energy requirement per capita and the population supported:

$$ENERGY^{I\_USE\_PROD\_MUN}_{dm,k,o,t} = ENERGY^{I\_MUN\_REQ}_{dm,k,o,t} \cdot ACT^{I\_POP\_WITH\_ERG}_{dm,t} \tag{i.20}$$

where:
$ENERGY^{I\_USE\_PROD\_MUN}_{dm,k,o,t}$ is non-water energy usage for municipality dm, using energy commodity o, produced by technology k, at time t;
$ENERGY^{I\_MUN\_REQ}_{dm,k,o,t}$ is energy required per capita for municipality dm, using energy commodity o, produced by technology k, at time t;
$ACT^{I\_POP\_WITH\_ERG}_{dm,t}$ is actual population supported at municipality dm at time t.

5.3.9 Energy demand

Industrial energy requirement is calculated as:

$$ERG^{I\_DMD\_IND}_{di,k,o,t} = ENERGY^{I\_IND\_REQ}_{di,k,o,t} \cdot f^{I\_PROD\_POT}_{di,t,p}(x_{di,t,p}, y_{di,t,p}) \tag{i.21}$$

where:
$ERG^{I\_DMD\_IND}_{di,k,o,t}$ is the industrial energy requirement at industrial site di, using energy commodity o, produced by technology k, at time t; and

$f_{di,t,p}^{I\_PROD\_POT}(x_{di,t,p}, y_{di,t,p})$ is the production function for industrial production for good p, at industrial site di, at time t, and $x_{di,t,p}$ and $y_{di,t,p}$ are the factors of production.

The municipal energy requirement is calculated similarly:

$$ERG_{dm,k,o,t}^{I\_DMD\_MUN} = ENERGY_{dm,k,o,t}^{I\_MUN\_REQ} \cdot IND_{dm,t}^{I\_POP} \tag{i.22}$$

where:
$ERG_{dm,k,o,t}^{I\_DMD\_MUN}$ is the municipal energy requirement for municipality dm, using energy commodity o, produced by technology k, at time t; and
$IND_{dm,t}^{I\_POP}$ is the total population of municipality dm at time t.

The reduction ratio in industrial production maintains the energy constraint condition, taking into account the energy demands and the sum of energy usage for water supply and non-water energy usage at the industrial site. This is calculated:

$$\begin{aligned} &IND_{di,t}^{I\_PROD\_RED\_RATIO\_ERG} = \\ &\sum_{k} \sum_{o \in KOLINK} \frac{ENERGY_{di,k,o,t}^{I\_USE\_WTR\_IND} + ENERGY_{di,k,o,t}^{I\_USE\_PROD\_IND}}{ERG_{di,k,o,t}^{I\_DMD\_IND}} \end{aligned} \tag{i.23}$$

Similarly, the reduction ratio in the municipal water requirement is calculated:

$$\begin{aligned} &MUN_{dm,t}^{I\_PROD\_RED\_RATIO\_ERG} = \\ &\sum_{k} \sum_{o \in KOLINK} \frac{ENERGY_{dm,k,o,t}^{I\_USE\_WTR\_MUN} + ENERGY_{dm,k,o,t}^{I\_USE\_PROD\_MUN}}{ERG_{dm,k,o,t}^{I\_DMD\_MUN}} \end{aligned} \tag{i.24}$$

where:
$IND_{di,t}^{I\_PROD\_RED\_RATIO\_ERG}$ is the reduction ration in industrial production at industrial site di at time t; and
$MUN_{dm,t}^{I\_PROD\_RED\_RATIO\_ERG}$ is the reduction ratio for municipality dm at time t.

5.3.10 Energy balance

Given the links between industrial production sties and nodes $(di, n) \in NDILINK$ and between municipal sites and nodes $(dm, n) \in NDMLINK$, total energy demand in the industrial and municipal sectors depends on the energy use and energy loss at each industrial or municipal site:

$$\begin{aligned} E_{n,I,k,o,t}^{M\_DIV} = &\sum_{di \in NDILINK} \big((ENERGY_{di,k,o,t}^{I\_USE\_WTR\_IND} + ENERGY_{di,k,o,t}^{I\_USE\_PROD\_IND}) \\ &\cdot (1 + E_{di,k,o}^{I\_LOSS\_IND})\big) + \sum_{dm \in NDMLINK} \big((ENERGY_{dm,k,o,t}^{I\_USE\_WTR\_MUN} \\ &+ ENERGY_{dm,k,o,t}^{I\_USE\_PROD\_MUN}) \cdot (1 + E_{dm,k,o}^{I\_LOSS\_MUN})\big) \end{aligned} \tag{i.25}$$

where:
$E_{di,k,o}^{I\_LOSS\_IND}$ is energy loss at industrial site di, using energy commodity o, produced by technology

k; and
$E^{I\_LOSS\_MUN}_{di,k,o}$ is energy loss at municipal site dm, using energy commodity o, produced by technology k.

5.3.11 Actual industry production and municipal population supported

The actual industrial production depends on the greatest production constraint (water or energy) and the potential industrial production. This is calculated for each technology k:

$$\begin{aligned} ACT^{I\_IND\_PROD}_{di,t,p} = & \min(IND^{I\_PROD\_RED\_RATIO\_WTR}_{di,t}, IND^{I\_PROD\_RED\_RATIO\_ERG}_{di,t}) \\ & \cdot f^{I\_PROD\_POT}_{di,t,p}(x_{di,t,p}, y_{di,t,p}) \end{aligned} \tag{i.26}$$

The actual population with access to energy from energy commodity o is calculated:

$$ACT^{I\_POP\_WITH\_ERG}_{dm,t} = MUN^{I\_RED\_RATIO\_ERG}_{dm,t} \cdot POP^{I}_{dm,t} \tag{i.27}$$

5.3.12 Industry and municipality production costs

Water supply costs depend on the fixed cost of water delivery by gravity, the energy costs of surface water conveyance and groundwater pumping, the costs of expanding pumping capacity, and other costs:

$$\begin{aligned} C^{I\_WTR\_SUP\_\eta}_{d\eta} = & \sum_t \Bigg(FXD^{I\_C\_WTR\_GRAVITY\_\eta}_{d\eta} \cdot \Big(1 - \sum_o WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SWEF}\Big) \cdot W^{I\_\eta\_S}_{d\eta,t} \\ & + \sum_k \sum_{o \in KOLINK} \Bigg(\Big(\sum_{e \in D\eta DELNK} P^{E}_{de,k,o,t} \Big) \cdot WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SWER} \\ & \cdot WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SWEF} + WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SONC} \Bigg) \cdot W^{I\_\eta\_S}_{d\eta,t} \\ & \sum_k \sum_{o \in KOLINK} \Bigg(\Big(\sum_{e \in D\eta DELINK} P^{E}_{de,k,o,t} \Big) \cdot \Big(\sum_{g \in D\eta GLINK} L^{E}_{g,o,t} \Big) \\ & \cdot WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,GWEF} + WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,GONC} \Bigg) \cdot W^{I\_\eta\_G}_{d\eta,t} \Bigg) + C^{I\_PMXP\_\eta\_S}_{d\eta} \\ & + C^{I\_PMXP\_\eta\_G}_{d\eta} \end{aligned} \tag{i.28}$$

where:
$C^{I\_WTR\_SUP\_\eta}_{d\eta}$ is the water supply cost at industry site or municipality $d\eta$;
$FXD^{I\_C\_WTR\_GRAVITY\_\eta}_{d\eta}$ is the fixed cost of water delivery by gravity at industry site or municipality $d\eta$;
$P^{E}_{de,k,o,t}$ is the energy price at site de, for energy commodity o, produced using technology k, at time t (given the link between industry site or municipality $d\eta$ and energy production sites $(de, d\eta) \in D\eta DELINK$);
$WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SONC}$ is other non-energy costs of conveying surface water at industry site or municipality $d\eta$;

$WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,GONC}$ is other non-energy costs of conveying groundwater at industry site or municipality $d\eta$;
$C^{I\_PMXP\_\eta\_S}_{d\eta}$ is the cost of expanding surface water pumping for industry site or municipality $d\eta$; and
$C^{I\_PMXP\_\eta\_G}_{d\eta}$ is the cost of expanding groundwater pumping for industry site or municipality $d\eta$.

The cost of expanding surface water pumping is calculated:

$$C^{I\_PMXP\_\eta\_S}_{d\eta} = \sum_{k} \sum_{o \in KOLINK} WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SPAC} \cdot (WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SPGC})^{WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SPBC}} \tag{i.29}$$

where:
$WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SPAC}$ and $WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SPBC}$ are parameters for expansion of surface water capacity at industry site or municipality $d\eta$, for energy commodity o, produced using technology k; and
$WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,SPGC}$ is surface water pumping capacity growth at industry site or municipality $d\eta$, for energy commodity o, produced using technology k.

Similarly, the cost of expanding groundwater pumping is calculated:

$$C^{I\_PMXP\_\eta\_G}_{d\eta} = \sum_{k} \sum_{o \in KOLINK} WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,GPAC} \cdot (WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,GPGC})^{WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,GPBC}} \tag{i.30}$$

where:
$WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,GPAC}$ and $WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,GPBC}$ are parameters for expansion of groundwater capacity at industry site or municipality $d\eta$, for energy commodity o, produced using technology k; and
$WTR^{I\_ERG\_CHAR\_\eta}_{d\eta,k,o,GPGC}$ is groundwater pumping capacity growth at industry site or municipality $d\eta$, for energy commodity o, produced using technology k.

The cost of improving water application efficiency depends on the cost of technology adoption and the quantity of water saved:

$$C^{I\_CNV\_EFF\_\eta}_{d\eta} = V^{I\_CNEF\_\eta}_{d\eta} \cdot \sum_{t} (W^{I\_DEL\_\eta\_S}_{d\eta,t}) \cdot E^{I\_CNV\_\eta}_{d\eta} \cdot \frac{APP^{I\_EFF\_\eta\_GN}_{d\eta}}{100} \tag{i.31}$$

where:
$C^{I\_CNV\_EFF\_\eta}_{d\eta}$ is the cost of improving water application efficiency for industry site or municipality $d\eta$; and
$V^{I\_CNEF\_\eta}_{d\eta}$ is the cost of technology adoption (per unit of water) for industry site or municipality $d\eta$.

Water treatment costs depend on the quantity of treated water. This is calculated for surface water:

$$C^{I\_WTR\_TREAT\_\eta\_S}_{d\eta} = \sum_{t} (V^{I\_TRT\_\eta\_S}_{d\eta} \cdot W^{I\_\eta\_S}_{n\eta,t}) \tag{i.32}$$

and for groundwater:

$$C^{I\_WTR\_TREAT\_\eta\_G}_{d\eta} = \sum_{t} (V^{I\_TRT\_\eta\_G}_{d\eta} \cdot W^{I\_\eta\_G}_{n\eta,t}) \tag{i.33}$$

where:
$C_{d\eta}^{I\_WTR\_TREAT\_\eta\_S}$ is the cost of surface water treatment at industry site or municipality $d\eta$;
$V_{d\eta}^{I\_TRT\_\eta\_S}$ is the treatment cost per unit of surface water at industry site or municipality $d\eta$;
$C_{d\eta}^{I\_WTR\_TREAT\_\eta\_G}$ is the cost of groundwater treatment at industry site or municipality $d\eta$; and
$V_{d\eta}^{I\_TRT\_\eta\_G}$ is the treatment cost per unit of groundwater at industry site or municipality $d\eta$.

Wastewater treatment cost for reuse depends on the quantity of water reused:

$$C_{d\eta}^{I\_WWTR\_RUSE\_TREAT\_\eta} = \sum_t (V_{d\eta}^{I\_RUSE\_WWTR\_TRT\_\eta} \cdot RUSE_{d\eta,t}^{I\_\eta}) \tag{i.34}$$

where:
$C_{d\eta}^{I\_WWTR\_RUSE\_TREAT\_\eta}$ is the cost of wastewater treatment for reuse at industry site or municipality $d\eta$; and
$V_{d\eta}^{I\_RUSE\_WWTR\_TRT\_\eta}$ is the wastewater treatment cost per unit of water reused at industry site or municipality $d\eta$.

Similarly, wastewater treatment cost for return flow depends on the treatment costs and the return flow, not counting reuse water:

$$C_{d\eta}^{I\_WWTR\_TREAT\_\eta} = \sum_t (V_{d\eta}^{I\_WWTR\_TRT\_\eta} \cdot (RTN_{d\eta,t}^{I\_\eta\_S} - RUSE_{d\eta,t}^{I\_\eta})) \tag{i.35}$$

where:
$C_{d\eta}^{I\_WWTR\_TREAT\_\eta}$ is the cost of wastewater treatment at industry site or municipality $d\eta$; and
$V_{d\eta}^{I\_WWTR\_TRT\_\eta}$ is the wastewater treatment cost per unit of water at industry site or municipality $d\eta$.

Other production costs are calculated based on total production for the industrial sector:

$$C_{di}^{I\_OTR\_PROD\_IND} = \sum_t \sum_p (V_{di,p}^{I\_OTR\_PROD\_IND} \cdot ACT_{di,t,p}^{I\_IND\_PROD}) \tag{i.36}$$

where:
$C_{di}^{I\_OTR\_PROD\_IND}$ is other production cost at industrial site di; and
$V_{di,p}^{I\_OTR\_PROD\_IND}$ is other production cost per unit of production of good p, at industrial site di, at time t.

This is calculated similarly for municipalities:

$$C_{di}^{I\_OTR\_PROD\_MUN} = \sum_t (V_{dm}^{I\_OTR\_PROD\_MUN} \cdot POP_{dm,t}^{I}) \tag{i.37}$$

where:
$C_{di}^{I\_OTR\_PROD\_MUN}$ is other production cost for municipality dm; and
$POP_{dm,t}^{I}$ is the population in municipality dm at time t.

Given the above calculations, total production costs for industrial sites or municipalities ($C_{d\eta}^{I\_TOT\_\eta}$)

are calculated:

$$
\begin{aligned}
C_{d\eta}^{I\_TOT\_\eta} = & C_{d\eta}^{I\_WTR\_SUP\_\eta} + C_{d\eta}^{I\_APP\_EFF\_\eta} + C_{d\eta}^{I\_CNV\_EFF\_\eta} + C_{d\eta}^{I\_WTR\_TREAT\_\eta\_S} \\
& + C_{d\eta}^{I\_WTR\_TREAT\_\eta\_G} + C_{d\eta}^{I\_WWTR\_RUSE\_TREAT\_\eta} + C_{d\eta}^{I\_WWTR\_TREAT\_\eta} \\
& + C_{d\eta}^{I\_OTR\_PROD\_\eta}
\end{aligned} \tag{i.38}
$$

5.3.13 Net benefits

The net benefits $(B_{n,I}^{M\_PRD})$ in this module depend on the total production value of industry as well as industrial and municipal costs:

$$
\begin{aligned}
B_{n,I}^{M\_PRD} = & \sum_{di \in NDILINK} \sum_{t} \sum_{p} R_{di,t,p}^{I} ACT_{di,t,p}^{I\_IND\_PROD} \\
& + \sum_{dm \in NDMLINK} \int_{0}^{WT_{dm}^{I}} A \cdot (WP_{dm}^{I})^{\alpha} dWP_{dm}^{I} - \sum_{di \in NDILINK} C_{di}^{I\_TOT\_IND} \\
& - \sum_{dm \in NDMLINK} C_{dm}^{I\_TOT\_MUN}
\end{aligned} \tag{i.39}
$$

where:
$R_{di,t,p}^{I}$ is the price of good p, at industrial site di, at time t;
WT_{dm}^{I} is the water tariff for municipality dm; and
$A \cdot (WP_{dm}^{I})^{\alpha}$ is the demand curve for water for municipality dm, with A being a constant, WP_{dm}^{I} the price of water, and α the price elasticity of demand.

5.3.14 Constraints

Surface and groundwater supply can occur using electricity pumps or diesel pumps:

$$
W_{d\eta,t}^{I\_\eta\_S} = \sum_{k} \sum_{o \in KOLINK} WTR_{d\eta,k,o,SWEF}^{I\_ERG\_CHAR\_\eta} \cdot W_{d\eta,t}^{I\_\eta\_S} \tag{i.40}
$$

$$
W_{d\eta,t}^{I\_\eta\_G} = \sum_{k} \sum_{o \in KOLINK} WTR_{d\eta,k,o,GWEF}^{I\_ERG\_CHAR\_\eta} \cdot W_{d\eta,t}^{I\_\eta\_G} \tag{i.41}
$$

Water treatment can occur using electricity or diesel pumps:

$$
RTN_{d\eta,t}^{I\_\eta\_S} = \sum_{k} \sum_{o \in KOLINK} TR_{d\eta,k,o,WWFR}^{I\_ERG\_CHAR\_\eta} \cdot RTN_{d\eta,t}^{I\_\eta\_S} \tag{i.42}
$$

5.4 Agriculture module

5.4.1 Water balance

The water balance at irrigation nodes includes conveyance, effective consumption, deep percolation and return flow relationships (Figure 15). Surface water withdrawn for irrigation needs is partially lost during conveyance. This conveyance loss is composed of non-productive evaporation losses, seepage to groundwater aquifers, and flow to the drainage system. Crop water demand can be met using surface water, pumping of groundwater, or through reuse of drainage water. Crops also consume water from precipitation. Finally, the water balance must account for the fact that only some of the water delivered to the field level is effectively used by crops, with the remaining water being lost through deep percolation back into groundwater. Return flows (drainage waters) are also split between the river, non-productive evaporation loss, and flows into other depressions located at the ends of irrigation canals. The equations below describe this water balance.

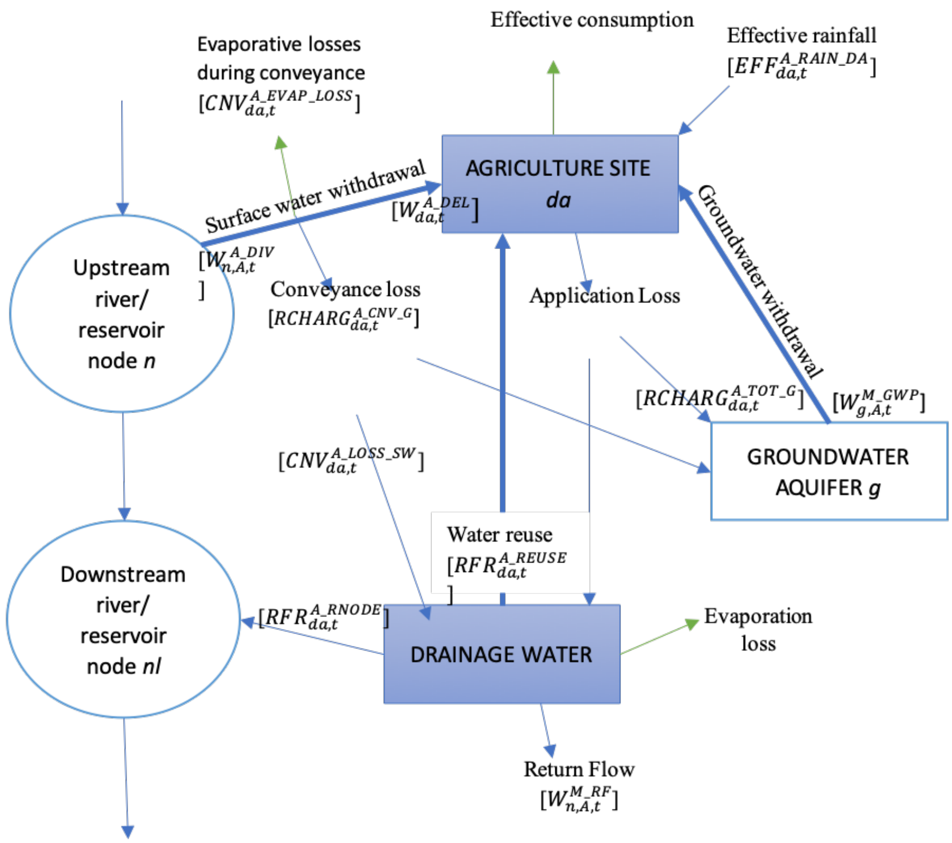


Figure 15: Water balance in an illustrative agricultural site

Total effective rainfall at a particular node is the sum of effective rainfall of all associated agricultural nodes[7]:

$$EFF_{da,t}^{A\_RAIN\_DA} = \sum_{n \in DANLINK} EFF_{n,t}^{A\_RAIN} \tag{f.1}$$

where:
$EFF_{da,t}^{A\_RAIN\_DA}$ is the total effective rainfall at agriculture production site da at time t; and $EFF_{n,t}^{A\_RAIN}$ is the effective rainfall at node n at time t (given the link between nodes and agriculture production sites $(n, da) \in DANLINK$).

Similarly, potential evapotranspiration $(PET_{da,t}^{A\_DA})$ is calculated:

$$PET_{da,t}^{A\_DA} = \sum_{n \in DANLINK} PET_{n,t}^{W} \tag{f.2}$$

[7]For effective rainfall calculation, see equations Af.1a-Af.1e in the Appendix.

where:
$PET^{W}_{n,t}$ is the potential evapotranspiration within the catchment at time t.

5.4.2 Linking to WSM module

Surface water abstracted for agriculture is calculated as:

$$W^{W\_DIV}_{n,A,t} = \sum_{da \in NDALINK} W^{A\_AGG\_S}_{da,t} \tag{f.3}$$

where:
$W^{W\_DIV}_{n,A,t}$ is water withdrawn for agriculture use from node n at time t; and
$W^{A\_AGG\_S}_{da,t}$ is the surface water abstracted for agriculture production site da at time t (given the link between agriculture production sites and nodes $(da, n) \in NDALINK$).

Similarly groundwater abstracted for agriculture is calculated:

$$W^{W\_GWP}_{n,A,t} = \sum_{da \in NDALINK} W^{A\_AGG\_G}_{da,t} \tag{f.4}$$

where:
$W^{W\_GWP}_{n,A,t}$ is groundwater pumping for agriculture use from groundwater aquifer g at time t; and
$W^{A\_AGG\_G}_{da,t}$ is the groundwater abstracted for agriculture production site da at time t (given the link between agriculture production sites and nodes $(da, g) \in GDALINK$).

5.4.3 Conveyance losses

Conveyance water lost to groundwater depends on the total water withdrawn and the conveyance efficiency, including efficiency gains:

$$RCHARG^{A\_CNV\_G}_{da,t} = W^{A\_AGG\_S}_{da,t} \cdot \left(1 - \left(E^{A\_CNV}_{da} \cdot \left(1 + \frac{E^{A\_CNV\_GN}_{da}}{100}\right)\right)\right) \tag{f.5}$$

where:
$RCHARG^{A\_CNV\_G}_{da,t}$ is the conveyance water lost to groundwater at agriculture production site da at time t;
$E^{A\_CNV}_{da}$ is the conveyance efficiency at agriculture production site da; and
$E^{A\_CNV\_GN}_{da}$ is the conveyance efficiency improvement over the original at agriculture production site da.

Conveyance water lost to evaporation depends on the total water withdraw, the water lost to groundwater, and the evaporation fraction:

$$CNV^{A\_EVAP\_LOSS}_{da,t} = (W^{A\_AGG\_S}_{da,t} - RCHARG^{A\_CNV\_G}_{da,t}) \cdot CNV^{A\_EVAP}_{da} \tag{f.6}$$

where:
$CNV^{A\_EVAP\_LOSS}_{da,t}$ is the conveyance water lost to evaporation at agriculture production site da at

time t; and
$CNV_{da}^{A\_EVAP}$ is the conveyance evaporation loss fraction at agriculture production site da.

Total conveyance water lost site to surface drainage at an agricultural site depends on groundwater and evaporation loss as well as the fraction of water lost to surface drainage:

$$CNV_{da,t}^{A\_LOSS\_SW} = (W_{da,t}^{A\_AGG\_S} - RCHARG_{da,t}^{A\_CNV\_G} - CNV_{da,t}^{A\_EVAP\_LOSS}) \cdot CNV_{da}^{A\_DRNG} \tag{f.7}$$

where:
$CNV_{da,t}^{A\_LOSS\_SW}$ is the conveyance water lost to surface drainage at agriculture production site da at time t; and
$CNV_{da}^{A\_DRNG}$ is the conveyance lost to surface drainage fraction at agriculture production site da.

Relatedly, water reused from the return flow depends on the fraction of reuse as well as the conveyance water lost to surface drainage:

$$RFR_{da,t}^{A\_RUSE} = RA_{da}^{A\_DRU} \cdot CNV_{da,t}^{A\_LOSS\_SW} \tag{f.8}$$

where:
$RFR_{da,t}^{A\_RUSE}$ is the water reused from return flow at agriculture production site da at time t; and
$RA_{da}^{A\_DRU}$ is the fraction of water reuse at agriculture production site da.

Finally, water returned to the river node depends on the fraction of water returned and the return flow:

$$RFR_{da,t}^{A\_RNODE} = RA_{da}^{A\_DIVRF} \cdot (CNV_{da,t}^{A\_LOSS\_SW} - RFR_{da,t}^{A\_RUSE}) \tag{f.9}$$

where:
$RFR_{da,t}^{A\_RNODE}$ is the water returned to the river node at agriculture production site da at time t; and
$RA_{da}^{A\_DIVRF}$ is the fraction of water returned at agriculture production site da.

5.4.4 Total water available at irrigation site

The surface water delivered to an irrigation site depends on the surface water withdrawn, water reuse, and all conveyance losses:

$$\begin{aligned} W_{da,t}^{A\_DEL\_S} =& W_{da,t}^{A\_AGG\_S} + RFR_{da,t}^{A\_RUSE} - RCHRG_{da,t}^{A\_CNV\_G} - CNV_{da,t}^{A\_EVAP\_LOSS} \\ & - CNV_{da,t}^{A\_LOSS\_SW} \end{aligned} \tag{f.10}$$

where:
$W_{da,t}^{A\_DEL\_S}$ is the total surface water delivered to agricultural production site da at time t.

And the surface water actually available to crops depends on the irrigation efficiency, including efficiency gains:

$$W_{da,t}^{A\_DEL\_CRPS\_S} = W_{da,t}^{A\_DEL\_S} \cdot IRR_{da}^{A\_EFF} \cdot \left(1 + \frac{IRR_{da}^{A\_EFF\_GN}}{100}\right) \tag{f.11}$$

where:
$W_{da,t}^{A\_DEL\_CRPS\_S}$ is the surface water available for crops at agriculture production site *da* at time *t*;
$IRR_{da}^{A\_EFF}$ is irrigation efficiency at agriculture production site *da*; and
$RR_{da}^{A\_EFF\_GN}$ is irrigation efficiency gain at agriculture production site *da*.

Similarly, the groundwater actually available to crops also depends on irrigation efficiency, including efficiency gains:

$$W_{da,t}^{A\_DEL\_CRPS\_G} = W_{da,t}^{A\_DEL\_G} \cdot IRR_{da}^{A\_EFF} \cdot \left(1 + \frac{IRR_{da}^{A\_EFF\_GN}}{100}\right) \qquad \text{(f.12)}$$

where:
$W_{da,t}^{A\_DEL\_CRPS\_G}$ is the groundwater available for crops at agriculture production site *da* at time *t*.

5.4.5 Total groundwater recharge

Groundwater recharge from irrigation depends on the surface and groundwater delivered as well as irrigation efficiency, including efficiency gains:

$$RCHARG_{da,t}^{A\_IRR\_G} = (W_{da,t}^{A\_DEL\_S} + W_{da,t}^{A\_AGG\_G}) \cdot \left(1 - \left(IRR_{da}^{A\_EFF} \cdot \left(1 + \frac{IRR_{da}^{A\_EFF\_GN}}{100}\right)\right)\right) \qquad \text{(f.13)}$$

where:
$RCHARG_{da,t}^{A\_IRR\_G}$ is the groundwater recharge from irrigation at agriculture production site *da* at time *t*.

Total groundwater recharge is the sum of recharge from conveyance and from irrigation:

$$RCHARG_{da,t}^{A\_TOT\_G} = RCHARG_{da,t}^{A\_CNV\_G} + RCHARG_{da,t}^{A\_IRR\_G} \qquad \text{(f.14)}$$

where:
$RCHARG_{da,t}^{A\_TOT\_G}$ is the total groundwater recharge at agriculture production site *da* at time *t*.

5.4.6 Return flows to WSM module

Return flow from irrigation is calculated:

$$W_{n,A,t}^{M\_RF} = \sum_{da \in NDALINK} RFR_{da,t}^{A\_RNODE} \qquad \text{(f.15)}$$

where:
$W_{n,A,t}^{M\_RF}$ is the return flow from irrigation (in million m^3) at node *n* and time *t*.

Groundwater recharge from irrigation is calculated:

$$W_{n,A,t}^{M\_DF} = \sum_{da \in NDALINK} RCHARG_{da,t}^{A\_TOT\_G} \qquad \text{(f.16)}$$

where:
$W_{n,A,t}^{M\_DF}$ is the groundwater recharge from irrigation (in million m^3) at node n and time t.

5.4.7 Irrigation water demand

We calculate irrigation water demand for each from using the crop coefficient, potential evapotranspiration, and taking into account effective rainfall:

$$W_{da,c,t}^{A\_DMD\_MM} = CRP_{da,c,t}^{A\_M\_COEFF} \cdot PET_{da,t}^{A\_DA} - EFF_{da,t}^{A\_RAIN\_DA} \tag{f.17}$$

where:
$W_{da,c,t}^{A\_DMD\_MM}$ is the irrigation water demand (in mm) for crop c, at agriculture production site da, at time t; and
$CRP_{da,c,t}^{A\_M\_COEFF}$ is the monthly crop coefficient for crop c, at agriculture production site da, at time t.

Then the total irrigation demand at each agriculture production site is calculated:

$$W_{da,t}^{A\_DMD\_SUM} = \sum_{c} W_{da,c,t}^{A\_DMD\_MM} \tag{f.18}$$

where:
$W_{da,t}^{A\_DMD\_SUM}$ is the total surface water irrigation demand (in million m^3) for all crops at agriculture production site da at time t.

5.4.8 Distribute water to crops

We calculate the total surface water distributed to all crops at each agricultural production site in the following way:

$$CWR_{da,t}^{A\_EXIST\_S} = \frac{W_{da,t}^{A\_DMD\_SUM}}{1000} \sum_{y \in TYLINK} AREA_{da,y}^{A\_IRR\_EXIST\_S} \tag{f.19}$$

where:
$CWR_{da,t}^{A\_EXIST\_S}$ is the total surface water irrigation distributed to crops on currently irrigated land at agriculture production site da at time t; and
$AREA_{da,y}^{A\_IRR\_EXIST\_S}$ is the total currently surface water irrigated land at agricultural production site da during year y (given the link between months and years $(y, t) \in TYLINK$) .

We allow for expansion of irrigated land in the following way:

$$CWR_{da,t}^{A\_EXPAND\_S} = \frac{W_{da,t}^{A\_DMD\_SUM\_S}}{1000} \sum_{y \in TYLINK} AREA_{da,y}^{A\_IRR\_EXPAND\_S} \tag{f.20}$$

where:
$CWR_{da,t}^{A\_EXPAND\_S}$ is the total surface water irrigation distributed to crops on potential expansion of irrigated land at agriculture production site da at time t; and
$AREA_{da,y}^{A\_IRR\_EXPAND\_S}$ is the total potentially surface water irrigable land at agricultural production

site da during year y (given the link between months and years $(y, t) \in TYLINK$) .

We calculate the total groundwater distributed to all crops at each agricultural production site in an identical way:

$$CWR_{da,t}^{A\_EXIST\_G} = \frac{W_{da,t}^{A\_DMD\_SUM}}{1000} \sum_{y \in TYLINK} AREA_{da,y}^{A\_IRR\_EXIST\_G} \tag{f.21}$$

where:
$CWR_{da,t}^{A\_EXIST\_G}$ is the total groundwater irrigation distributed to crops on currently irrigated land at agriculture production site da at time t; and
$AREA_{da,y}^{A\_IRR\_EXIST\_G}$ is the total currently groundwater irrigated land at agricultural production site da during year y (given the link between months and years $(y, t) \in TYLINK$) .

We allow for expansion of irrigated land in the following way:

$$CWR_{da,t}^{A\_EXPAND\_G} = \frac{W_{da,t}^{A\_DMD\_SUM\_S}}{1000} \sum_{y \in TYLINK} AREA_{da,y}^{A\_IRR\_EXPAND\_G} \tag{f.22}$$

where:
$CWR_{da,t}^{A\_EXPAND\_G}$ is the total groundwater irrigation distributed to crops on potential expansion of irrigated land at agriculture production site da at time t; and
$AREA_{da,y}^{A\_IRR\_EXPAND\_G}$ is the total potentially groundwater irrigable land at agricultural production site da during year y (given the link between months and years $(y, t) \in TYLINK$).

Then, the total surface water distributed to crops is calculated[8]:

$$W_{da,t,}^{A\_DEL\_CRPS\_S} = CWR_{da,t}^{A\_EXIST\_S} + CWR_{da,t}^{A\_EXPAND\_S} \tag{f.23}$$

and the total groundwater distributed to crops is calculated:

$$W_{da,t,}^{A\_DEL\_CRPS\_G} = CWR_{da,t}^{A\_EXIST\_G} + CWR_{da,t}^{A\_EXPAND\_G} \tag{f.24}$$

5.4.9 Agriculture production

Agriculture production from rainfed sites is calculated:

$$Q_{da}^{A\_RFD} = \sum_{y} (YLDACT_{da,y}^{A\_TOTAL\_RF} \cdot AREA_{da,y}^{A\_RFD}) \tag{f.25}$$

[8]This characterization of water demand aggregates crop production at each agricultural site and does not allow for irrigation trade-offs between crops. Accordingly, the distribution of crops throughout the year at each agricultural site and the total productive yield associated with that distribution are critical input to the model. For a characterization of a more flexible model that does allow for within site irrigation trade-offs, see the distribution of water to specific crops in Section A.4.3 and the calculation of water deficits in Section A.4.4 (rainfed) and Section A.4.5 (irrigated). These specifications constrain the total rainfed and irrigated areas, allowing the distribution of water to vary flexibly within the model; the specifications listed here allow the irrigated areas to vary but constrain the distribution of water to crops and the cropping pattern at each agriculture production site.

where:
$Q_{da}^{A\_RFD}$ is the agriculture production (in tons) of rainfed crops across all crops at agriculture production site da;
$YLDACT_{da,y}^{A\_TOTAL\_RF}$ is the actual yield (in $\frac{tons}{km^2}$) of rainfed crops at agriculture production site da in year y; and
$AREA_{da,y}^{A\_RFD}$ is the total area (in km^2) used for rainfed agriculture at agriculture production site da in year y.

Agriculture production from surface water irrigated sites is calculated:

$$\begin{aligned} Q_{da}^{A\_IRR\_S} = & \sum_{y}(YLDACT_{da,y}^{A\_TOTAL\_IRR_S} \cdot AREA_{da,y}^{A\_IRR\_EXIST\_S} \\ & + YLDACT_{da,y}^{A\_TOTAL\_EXP_S} \cdot AREA_{da,y}^{A\_IRR\_EXPAND\_S}) \end{aligned} \tag{f.26}$$

where:
$Q_{da}^{A\_IRR\_S}$ is the agriculture production (in tons) of surface water irrigated crops across all crops at agriculture production site da;
$YLDACT_{da,y}^{A\_TOTAL\_IRR\_S}$ is the actual yield (in $\frac{tons}{km^2}$) of surface water irrigated crops on currently irrigated land at agriculture production site da in year y; and
$YLDACT_{da,y}^{A\_TOTAL\_EXP\_S}$ is the actual yield (in $\frac{tons}{km^2}$) of surface water irrigated crops on potentially irrigable land at agriculture production site da in year y.

Similarly, agriculture production from groundwater irrigated sites is calculated:

$$\begin{aligned} Q_{da}^{A\_IRR\_G} = & \sum_{y}(YLDACT_{da,y}^{A\_TOTAL\_IRR_G} \cdot AREA_{da,y}^{A\_IRR\_EXIST\_G} \\ & + YLDACT_{da,y}^{A\_TOTAL\_EXP_G} \cdot AREA_{da,y}^{A\_IRR\_EXPAND\_G}) \end{aligned} \tag{f.27}$$

where:
$Q_{da}^{A\_IRR\_G}$ is the agriculture production (in tons) of groundwater irrigated crops across all crops at agriculture production site da;
$YLDACT_{da,y}^{A\_TOTAL\_IRR\_G}$ is the actual yield (in $\frac{tons}{km^2}$) of groundwater irrigated crops on currently irrigated land at agriculture production site da in year y; and
$YLDACT_{da,y}^{A\_TOTAL\_EXP\_G}$ is the actual yield (in $\frac{tons}{km^2}$) of groundwater irrigated crops on potentially irrigable land at agriculture production site da in year y. Then, total crop production from irrigated sites $(Q_{da}^{A\_IRR})$ is calculated:

$$Q_{da}^{A\_IRR} = Q_{da}^{A\_IRR\_S} + Q_{da}^{A\_IRR\_G} \tag{f.28}$$

and total crop production from rainfed and irrigated sites (Q_{da}^{A}) is calculated:

$$Q_{da}^{A} = Q_{da}^{A\_RFD} + Q_{da}^{A\_IRR} \tag{f.29}$$

Total benefits depend on total crop production and prices:

$$GR_{n}^{A\_BEN} = \sum_{da \in NDALINK} Q_{da}^{A} \cdot CR_{da}^{A\_P} \tag{f.30}$$

where:
$GR_n^{A\_BEN}$ is the total benefit at node n; and
$CR_{da}^{A\_P}$ is the aggregated price across all crops produced at agriculture production site da.

5.4.10 Energy usage

Energy requirement in agriculture depends on energy for pumping water, delivering water, the distribution of water types used (surface, ground, reused), and the area of cropland:

$$\begin{aligned} E_{da,k,o,t}^{A\_AGG} =& IRR_{da,k,o,SWER}^{A\_CHAR} \cdot IRR_{da,k,o,SWEF}^{A\_CHAR} \cdot W_{da,t}^{A\_AGG\_S} + IRR_{da,k,o,RUER}^{A\_CHAR} \cdot IRR_{da,k,o,RUEF}^{A\_CHAR} \\ & \cdot RFR_{da,t}^{A\_REUSE} + \left(\sum_{g \in GDALINK} L_{g,k,o,t}^{E\_GPMP} \right) \cdot IRR_{da,k,o,GWEF}^{A\_CHAR} \cdot W_{da,t}^{A\_AGG} \\ & + \sum_c (L_{da,k,o,c,t}^{A\_APRD} \cdot AREA_{da,c}^{A\_RFD} + AREA_{da,c}^{A\_IRRSW} + AREA_{da,c}^{A\_IRRGW}) \end{aligned} \tag{f.31}$$

where:
$E_{da,k,o,t}^{A\_AGG}$ is the energy requirement in agriculture at production site da, using energy commodity o, produced using technology k, at time t;
$IRR_{da,k,o,SWER}^{A\_CHAR}$ is the energy required to deliver a unit of surface water to agriculture at production site da, using energy commodity o, produced using technology k;
$IRR_{da,k,o,SWEF}^{A\_CHAR}$ is the fraction of surface water used at agriculture production site da, using energy commodity o, produced using technology k;
$IRR_{da,k,o,RUER}^{A\_CHAR}$ is the energy required to deliver a unit of reuse water to agriculture production site da, using energy commodity o, produced using technology k;
$IRR_{da,k,o,RUEF}^{A\_CHAR}$ is the fraction of reuse water used at agriculture production site da, using energy commodity o, produced using technology k;
$L_{g,o,k,o,t}^{E\_GPMP}$ is the energy required to pump one unit of groundwater (depends on depth) from groundwater aquifer g, using energy commodity o, produced using technology k, at time t;
$IRR_{da,k,o,GWEF}^{A\_CHAR}$ is the fraction of groundwater used at agriculture production site da, using energy commodity o, produced using technology k;
$L_{da,k,o,c,t}^{A\_APRD}$ is the energy required per hectare of crops at agriculture production site da, using energy commodity o, produced using technology k, at time t;
$AREA_{da,c}^{A\_RFD}$ is the rainfed area at agriculture production site da for crop c;
$AREA_{da,c}^{A\_IRRSW}$ is the surface water irrigated area at agriculture production site da for crop c;
$AREA_{da,c}^{A\_IRRGW}$ is the groumdwater irrigated area at agriculture production site da for crop c.

Total energy withdrawn for the agricultural sector is calculated:

$$E_{n,A,k,o,t}^{M\_DIV} = \sum_{da \in NDALINK} \left(E_{da,k,o,t}^{A\_AGG} \cdot (1 + E_{da,k,o}^{A\_LOSS}) \right) \tag{f.32}$$

where:
$E_{n,A,k,o,t}^{M\_DIV}$ is the energy withdrawn at node n, for the agricultural sector A, of energy commodity o, produced using technology k, at time t; and
$E_{da,k,o}^{A\_LOSS}$ is energy loss in agriculture at agriculture production site da, using energy commodity o, produced using technology k.

5.4.11 Costs

Production costs depend on the price of energy, energy use, and other production costs such as fertilizer, labor, capital, chemical production, seeds, etc.:

$$C_{da}^{A\_PRD} = \sum_{k}\sum_{c}\sum_{t}\sum_{o\in KOLINK}\left(\Big(\sum_{de\in DEDALINK}(P_{de,k,o,t}^{E}\cdot L_{da,k,o,c,t})\Big) + V_{da,c,t}^{A\_APRD}\right) \tag{f.33}$$

where:
$C_{da}^{A\_PRD}$ is production cost at agriculture production site da;
$P_{de,k,o,t}^{E}$ is the energy price at site de, for energy commodity o, produced using technology k, at time t (given the link between energy production sites and agriculture production sites $(da, de) \in DEDALINK$); and
$V_{da,c,t}^{A\_APRD}$ is other production cost at agriculture production site da, for crop c, at time t.

Water supply costs depend on the costs of water delivery by gravity, cost of surface water conveyance, costs of reuse water, costs of groundwater pumping, costs of expanding pumping capacity, and other costs:

$$\begin{aligned} C_{da}^{A\_SUP} = \sum_{k}\sum_{t}\sum_{o\in KOLINK}\Bigg(& IRR_{da,SWGR}^{A\_CHAR}\cdot(1 - IRR_{da,SWEF}^{A\_CHAR})\cdot W_{da,t}^{A\_AGG\_S} \\ & + \Big(\sum_{de\in DEDALINK} P_{de,k,o,t}^{E}\Big)\cdot IRR_{da,SWER}^{A\_CHAR}\cdot IRR_{da,SWEF}^{A\_CHAR} + IRR_{da,SONC}^{A\_CHAR} \\ & \cdot W_{da,t}^{A\_AGG\_S} + \Big(\sum_{de\in DEDALINK} P_{de,k,o,t}^{E}\Big)\cdot IRR_{da,RUER}^{A\_CHAR}\cdot IRR_{da,RUEF}^{A\_CHAR} \\ & + IRR_{da,RONC}^{A\_CHAR}\cdot RFR_{da,t}^{A\_REUSE} + \Big(\sum_{de\in DEDALINK} P_{de,k,o,t}^{E}\Big) \\ & \cdot\Big(\sum_{g\in GDALINK} E\_GPMP\Big)\cdot IRR_{da,GWEF}^{A\_CHAR} + IRR_{da,GONC}^{A\_CHAR}\cdot W_{da,t}^{A\_AGG\_S}\Bigg) \\ & + C_{da}^{A\_PXMP\_S} + C_{da}^{A\_PXMP\_G} + C_{da}^{A\_PXMP\_R} \end{aligned} \tag{f.34}$$

where:
$C_{da}^{A\_SUP}$ is the water supply cost at agriculture production site da;
$IRR_{da,SWGR}^{A\_CHAR}$ is the fixed cost of water delivered using gravity at agriculture production site da;
$IRR_{da,SONC}^{A\_CHAR}$ is the other non-energy cost of conveying surface water at agriculture production site da;
$IRR_{da,RONC}^{A\_CHAR}$ is the other non-energy cost of conveying reuse water at agriculture production site da;
$IRR_{da,GONC}^{A\_CHAR}$ is the other non-energy cost of conveying groundwater at agriculture production site da;
$C_{da}^{A\_PXMP\_S}$ is the cost of expanding surface water pumping at agriculture production site da;
$C_{da}^{A\_PXMP\_G}$ is the cost of expanding groundwater pumping at agriculture production site da; and
$C_{da}^{A\_PXMP\_R}$ is the cost of expanding reuse water pumping at agriculture production site da.

We further calculate the cost of expanding surface water pumping as:

$$C_{da}^{A\_PXMP\_S} = \sum_{k} \sum_{o \in KOLINK} \left(IRR_{da,k,o,SPAC}^{A\_CHAR} (IRR_{da,k,o,SPCG}^{A\_CHAR})^{IRR_{da,k,o,SPBC}^{A\_CHAR}} \right) \tag{f.35}$$

where:
$IRR_{da,k,o,SPCG}^{A\_CHAR}$ is the increased surface water pumping capacity at agriculture production site da, for energy commodity o, produced using technology k; and
$IRR_{da,k,o,SPAC}^{A\_CHAR}$ and $IRR_{da,k,o,SPBC}^{A\_CHAR}$ are the parameters of non-linear regression function for the relationship between the costs and level of the surface water pumping capacity expansion at agriculture production site da, for energy commodity o, produced using technology k.

Similarly, we calculate the cost of expanding groundwater pumping as:

$$C_{da}^{A\_PXMP\_G} = \sum_{k} \sum_{o \in KOLINK} \left(IRR_{da,k,o,GPAC}^{A\_CHAR} (IRR_{da,k,o,GPCG}^{A\_CHAR})^{IRR_{da,k,o,GPBC}^{A\_CHAR}} \right) \tag{f.36}$$

where:
$IRR_{da,k,o,GPCG}^{A\_CHAR}$ is the increased groundwater pumping capacity at agriculture production site da, for energy commodity o, produced using technology k; and
$IRR_{da,k,o,GPAC}^{A\_CHAR}$ and $IRR_{da,k,o,GPBC}^{A\_CHAR}$ are the parameters of non-linear regression function for the relationship between the costs and level of the groundwater pumping capacity expansion at agriculture production site da, for energy commodity o, produced using technology k.

Finally, we calculate the cost of expanding reuse water pumping as:

$$C_{da}^{A\_PXMP\_R} = \sum_{k} \sum_{o \in KOLINK} \left(IRR_{da,k,o,RPAC}^{A\_CHAR} (IRR_{da,k,o,RPCG}^{A\_CHAR})^{IRR_{da,k,o,RPBC}^{A\_CHAR}} \right) \tag{f.37}$$

where:
$IRR_{da,k,o,RPCG}^{A\_CHAR}$ is the increased reuse water pumping capacity at agriculture production site da, for energy commodity o, produced using technology k; and
$IRR_{da,k,o,RPAC}^{A\_CHAR}$ and $IRR_{da,k,o,RPBC}^{A\_CHAR}$ are the parameters of non-linear regression function for the relationship between the costs and level of the reuse water pumping capacity expansion at agriculture production site da, for energy commodity o, produced using technology k.

The cost of improving water application efficiency depends on the cost of irrigation technology adoption and the amount of water saved:

$$\begin{aligned} C_{da}^{A\_IRR\_EFF} = & V_{da}^{A\_IRR} \cdot \left(\sum_{t} (W_{da,t}^{W\_DEL\_CRPS\_S} + W_{da,t}^{W\_DEL\_CRPS\_G}) \right) \cdot IRR_{da}^{A\_EFF} \\ & \cdot \frac{IRR_{da}^{A\_EFF\_GN}}{100} \end{aligned} \tag{f.38}$$

where:
$C_{da}^{A\_IRR\_EFF}$ is the cost of irrigation improvement at agriculture production site da; and
$V_{da}^{A_IRR}$is the cost of irrigation technology adoption per unit of water at agriculture production site

da.

The cost of improving water conveyance efficiency depends on the cost of conveyance technology adoption and the amount of water saved:

$$C_{da}^{A\_CNV\_EFF} = V_{da}^{A\_CNEF} \cdot \left(\sum_{t} (W_{da,t}^{A\_AGG\_S}) \right) \cdot E_{da}^{A\_CNV} \cdot \frac{E_{da}^{A\_CNV\_GN}}{100} \tag{f.39}$$

where:
$C_{da}^{A\_CNV\_EFF}$ is the cost of conveyance efficiency improvement at agriculture production site *da*; and
$V_{da}^{A\_CNEF}$ is the cost of improving conveyance efficiency per unit of water agriculture production site *da*.

5.4.12 Net benefits

We calculate the net benefit of the agricultural sector as:

$$\begin{aligned} B_{n,A}^{M\_PRD} =& GR_{n}^{A\_BEN} - \sum_{a \in NDALINK} (C_{da}^{A\_PRD} + C_{da}^{A\_SUP} + C_{da}^{A\_PMXP\_S} + C_{da}^{A\_PMXP\_G} \\ &+ C_{da}^{A\_PMXP\_R} + C_{da}^{A\_IFF\_EFF} + C_{da}^{A\_CNV\_EFF} \end{aligned} \tag{f.40}$$

where:
$B_{n,A}^{M\_PRD}$ is the production benefit from the agricultural sector at node *n*; and
$GR_{n}^{A\_BEN}$ is the total gross benefit at node *n*.

5.4.13 Constraints

Surface water and reuse water pumping is constrained by the installed capacity:

$$\begin{aligned} \sum_{t} W_{da,t}^{A\_AGG\_S} \leq & \sum_{k} \sum_{o \in KOLIK} \Big((IRR_{da,k,o,SPCP}^{A\_CHAR} + IRR_{da,k,o,SPCG}^{A\_CHAR} + IRR_{da,k,o,RPCP}^{A\_CHAR} \\ &+ IRR_{da,k,o,RPCG}^{A\_CHAR}) \cdot 3600 \cdot 24 \cdot \frac{365}{12} \Big) \end{aligned} \tag{f.41}$$

where: $IRR_{da,k,o,SPCP}^{A\_CHAR}$ is surface water pumping capacity ($\frac{m^3}{s}$) at agriculture production site *da*, using energy commodity *o*, produced using technology *k*;
$IRR_{da,k,o,SPCG}^{A\_CHAR}$ is surface water pumping capacity growth ($\frac{m^3}{s}$) at agriculture production site *da*, using energy commodity *o*, produced using technology *k*;
$IRR_{da,k,o,RPCP}^{A\_CHAR}$ is reuse water pumping capacity ($\frac{m^3}{s}$) at agriculture production site *da*, using energy commodity *o*, produced using technology *k*; and
$IRR_{da,k,o,RPCG}^{A\_CHAR}$ is reuse water pumping capacity growth ($\frac{m^3}{s}$) at agriculture production site *da*, using energy commodity *o*, produced using technology *k*.

Similarly, groundwater pumping is constrained by the installed capacity:

$$\sum_t W_{da,t}^{A\_AGG\_G} \leq \sum_k \sum_{o \in KOLIK} \left(\left(IRR_{da,k,o,GPCP}^{A\_CHAR} + IRR_{da,k,o,GPCG}^{A\_CHAR} \right) \cdot 3600 \cdot 24 \cdot \frac{365}{12} \right) \tag{f.42}$$

where: $IRR_{da,k,o,GPCP}^{A\_CHAR}$ is groundwater pumping capacity ($\frac{m^3}{s}$) at agriculture production site da, using energy commodity o, produced using technology k; and
$IRR_{da,k,o,GPCG}^{A\_CHAR}$ is groundwater pumping capacity growth ($\frac{m^3}{s}$) at agriculture production site da, using energy commodity o, produced using technology k.

The upper bound of land for rainfed agriculture is defined as the land at each agriculture production site currently used for rainfed agriculture ($AREA_{da,y}^{A\_TOTAL\_RFD}$):

$$AREA_{da,y}^{A\_RFD\_.up} = AREA_{da,y}^{A\_TOTAL\_RFD} \tag{f.43}$$

The land for existing surface water and groundwater irrigated agriculture is constrained by the land at each agriculture production site currently irrigated ($AREA_{da,y}^{A\_TOTAL\_IRR}$):

$$AREA_{da,y}^{A\_TOTAL\_IRR} \geq AREA_{da,y}^{A\_IRR\_EXIST\_S} + AREA_{da,y}^{A\_IRR\_EXIST\_G} \tag{f.44}$$

Similarly, the land for surface water and groundwater irrigation expansion is constrained by the potentially irrigable land at each agriculture production site ($AREA_{da,y}^{A\_POTENTAIL\_IRR}$):

$$AREA_{da,y}^{A\_POTENTIAL\_IRR} \geq AREA_{da,y}^{A\_IRR\_EXPAND\_S} + AREA_{da,y}^{A\_IRR\_EXPAND\_G} \tag{f.45}$$

Finally, the area used for agriculture at any production site is constrained by the total cultivable land at that site ($AREA_{da,y}^{A\_TOTAL\_CUL}$):

$$\begin{aligned} AREA_{da,y}^{A\_TOTAL\_CUL} \geq & AREA_{da,y}^{A\_TOTAL\_RFD} + AREA_{da,y}^{A\_IRR\_EXIST\_S} + AREA_{da,y}^{A\_IRR\_EXIST\_G} \\ & + AREA_{da,y}^{A\_IRR\_EXPAND\_S} + AREA_{da,y}^{A\_IRR\_EXPAND\_G} \end{aligned} \tag{f.46}$$

5.5 Environmental module

5.5.1 Water balance

Water flow at a particular node n that is available for downstream flow is calculated as the sum of all associated upstream water flows:

$$FLOW_{n,t}^{G\_DS} = \sum_{nd \in NNDLINK} W_{n,nd,t}^{W\_F} \tag{g.1}$$

where:
$FLOW_{n,t}^{G\_DS}$ is the flow at node n and time t available for downstream flow;
$W_{n,nd,t}^{W\_F}$ is the flow from upstream at node N and time t (given the link between nodes $(n, nd) \in NNDLINK$).

5.5.2 Benefits

Ecosystem benefits $(GROSS_{n,es,t}^{G\_BEN})$ depend on a set of parameters used to calculate the benefits as well as the downstream flow:

$$\begin{aligned} GROSS_{n,es,t}^{G\_BEN} = & ESS_{n,es,A}^{G\_PARMS}(FLOW_{n,t}^{G\_DS})^{ESS_{n,es,B}^{G\_PARMS}} + ESS_{n,es,C}^{G\_PARMS}(FLOW_{n,t}^{G\_DS})^{ESS_{n,es,D}^{G\_PARMS}} \\ & + ESS_{n,es,E}^{G\_PARMS} \end{aligned} \tag{g.2}$$

where:
$ESS_{n,es,A}^{G\_PARMS}$, $ESS_{n,es,B}^{G\_PARMS}$, $ESS_{n,es,C}^{G\_PARMS}$, $ESS_{n,es,D}^{G\_PARMS}$, and $ESS_{n,es,E}^{G\_PARMS}$ are parameters used in ecosystem functions at node n for ecosystem service es.

The net benefits of ecosystem services $(B_{n,Env}^{M\_PRD})$ depend on the gross benefit and the cost $(ESS_{n,es}^{G\_COST})$:

$$B_{n,Env}^{M\_PRD} = \sum_{es}\sum_{t} GROSS_{n,es,t}^{G\_BEN} - \sum_{es} ESS_{n,es}^{G\_COST} \tag{g.3}$$

5.5.3 Constraints

Environment flows $(ENVFLOW_{n,t}^{G})$ are constrained according to:

$$FLOW_{n,t}^{G\_DS} \geq ENVFLOW_{n,t}^{G} \tag{g.4}$$

6 Application

This HEM was first applied to the Karnali and Mahakali River Basins (see Figure 16), which span nearly 47,000 square kilometers in Western Nepal (for more complete details of this application as well as the results, see Pakhtigian and Jeuland (2019a)). Like the rest of Nepal, the Karnali and Mahakali River Basins are characterized by river resources that are vast in terms of potential–particularly for hydropower generation–yet largely undisturbed.[9] Furthermore, the economy of Western Nepal is dominated by agriculture, and Nepal's unique and valuable natural ecosystems have brought environmental conservation to the forefront of development planning among some key stakeholders in water resource development (Pakhtigian et al., 2019). These characteristics make Western Nepal an ideal context for the application of a HEM based on the WEEF nexus, which seeks to capture the integration of water resource use across energy, agriculture, and environmental sectors.

The Western Nepal application follows the structure of the model outlined above to optimize water resource use across energy, agriculture, municipal, and environmental demands. While we focus primarily on water use within Nepal, we acknowledge that transboundary considerations, particularly in the Mahakali River Basin as the Mahakali River forms the boundary between Nepal and India, enter into the model in two distinctive ways–through downstream water requirements and through energy export. These and other considerations are also explored more thorough in sensitivity analyses (Pakhtigian and Jeuland, 2019a).

[9] The Karnali and Mahakali Rivers have an estimated hydropower generation potential of around 35,000 MW (Sharma and Awal, 2013), yet installed capacity remains around 10 MW with no storage infrastructure existing across the basins.

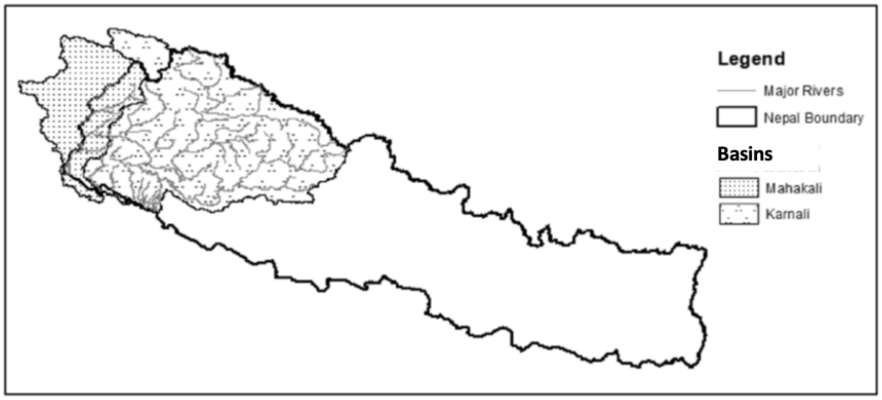


Figure 16: Map of the Karnali and Mahakali River Basins, Western Nepal.

The model structure is maintained by a set of nodes that are connected by flows links, which reflect the hydrology, municipal demands, energy production, and agricultural production throughout the system (see Figure 17). The model comprises 151 river nodes. Additionally, there are 55 energy production nodes, which identify existing, planned, or proposed run-of-the-river or storage hydropower projects, and 37 agricultural production nodes, which identify existing, planned, or under construction irrigation projects. Municipal surface water demands are satisfied at each of the 151 river nodes, as are environmental flow constraints. The model is run using hydrology that spans a period of 12 years, with different combinations of infrastructure. Specification of production, biophysical, and economic relationships relies on a variety of data sources.

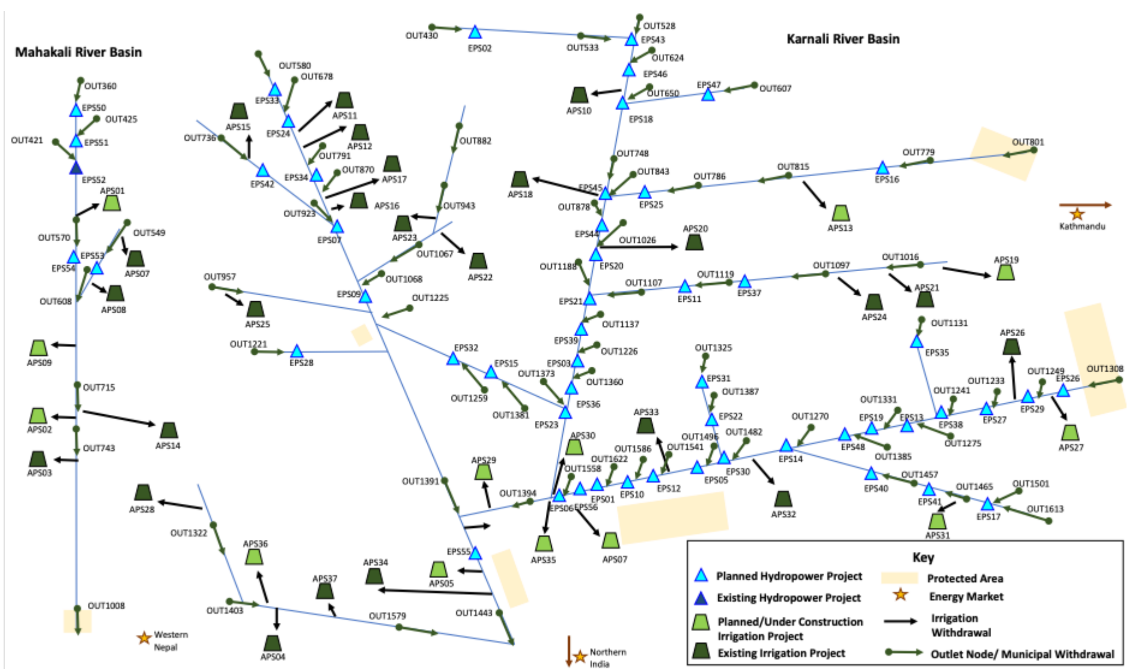


Figure 17: Schematic of the node system used in the Western Nepal application.

6.1 Data for model

The HEM is data intensive, as application-specific parameters are required to ensure that the model accurately reflects operations in the river basins under consideration. Here, we briefly outline the main data sources and tools used to parameterize the model; more details regarding each data source are provided in Pakhtigian and Jeuland (2019a). The hydrological data inputs are generated from a ArcSWAT model developed for the region and described in (Pandey et al., 2019). These data include source flow generated at each of the river nodes as well as precipitation and evaporation.

The energy module, which in this application focuses exclusively on electricity generated via hydropower, is parameterized using data from hydropower reports and, when available, project-specific documentation. In particular, energy production sites were determined based on existing licenses for projects above 1 MW granted by the Government of Nepal. The existence of a license does not guarantee that a project exists, is under construction, or has financing; rather, projects are separated into four categories: existing, under construction, planned, and proposed. Many of these project sites and capacities are mentioned or detailed in government-commissioned reports such as the Hydropower Development Plan, the Master Plan Study for Water Resource Development of Upper Karnali and Mahakali River Basin, and the Nationwide Master Plan Study on Storage-type Hydroelectric Power Development in Nepal. In addition, for projects under planning or construction phases, project-specific documents outlining more specific dimensions of the project, particularly reservoir characteristics for planned and proposed storage projects. Finally, reports from the Nepal Electricity Authority provided details about electricity prices, costs, transmission, and efficiency.

A combination of modeling and reports formed the basis for parameterization of the agriculture module. The set of agriculture production sites was established based on existing agriculture as well as existing, under construction, planned, or proposed irrigation infrastructure sites. These lists were available in documents such as the Nepal Department of Irrigation's Irrigation Master Plan, the National Irrigation Database, and communications with personnel at the the Department of Irrigation. The CROPWAT and CLIMWAT tools developed by the Food and Agricultural Organization (FAO) were used to calculate crop water requirements, evapotranspiration, and crop coefficients. In addition the annual Statistical Information on Nepalese Agriculture and other Ministry of Agriculture documents provided parameters regarding cropping patterns, crop prices and costs, and irrigation practices.

Municipal water and energy demands were calculated based on information from Water User Master Reports, national statistics, and data from a household-level survey (see Pakhtigian and Jeuland (2019b) for a description of the household-level survey data). Finally, environmental flows (e-flows) were calculated using an environmental flows calculator developed for Western Nepal. These e-flows also capture cultural demands on river resources.

6.2 Model simplifications and deviations

Data availability and context-specific characteristics of Western Nepal require certain model simplifications and deviations from the general model outlined in the previous section. In the next five subsections, we clarify and explain these deviations.

6.2.1 Hydrology core

Throughout the generalized model, both in the hydrology core and in other sector modules, water is separated into two categories based on source–surface water and groundwater. In our application, we model only surface water. The primary reason for this deviation is the lack of comprehensive groundwater data for Western Nepal, making it infeasible to incorporate groundwater access, demands, and use into the HEM application. There are two primary concerns associated with this omission. First, there is evidence of some trade-offs in municipal water use between surface and ground water which our model is unable to capture in this application. That is, households cannot supplement decreases in surface water access with groundwater (or vice versa) due to the lack of groundwater data. These trade-offs are likely concentrated in the Terai–the southern plain region–suggesting that the lack of groundwater to supplement surface water access in the model would provide a conservative estimate for overall productive benefits because the main trade-off region exists downstream. Second, we are unable to account for expansion of groundwater irrigation. While currently there are few large-scale groundwater irrigation schemes in the region, it is possible that expansion of groundwater irrigation would provide a viable water source for farmers in the Terai, and this is missing from our application.

Reservoir relationships, in our application used exclusively in conjunction with storage hydropower projects, are also calculated as part of the core hydrology module. In the Western Nepal application, we impose linear relationships between area and volume (and net head and volume) rather than the polynomial relationships specified in the general model. Again, data limitations regarding the exact site location of reservoirs, force this simplification. These linear relationships will also provide a conservative estimate of reservoir volume, and, subsequently, energy generation.

6.2.2 Energy

The main simplification in the energy module relates to the specific energy context in Western Nepal. Nepal has vast river resources and hydropower potential; with investments in storage infrastructure to regulate water availability, Nepal's hydropower potential could meet domestic electricity demands and form a basis of energy export trade with neighboring countries, particularly India. Accordingly, in this application we focus on just one energy generating technology–hydropower–and just one energy commodity–electricity. Given this technology, water requirements for energy generation are tied directly to water availability at a river node (for an energy production site with run-of-the-river infrastructure) or a reservoir node (for an energy production site with storage infrastructure). Furthermore, demands for energy commodities as inputs to energy generation via hydropower are minimal.

6.2.3 Industrial and Municipal

The Western Nepal application does not include industrial water demands. There is very limited industrial production in Western Nepal and, while eco-tourism and environmental conservation do provide one potential avenue of development in the region (Pakhtigian et al., 2019), recreational and hospitality demands on water resources are captured within municipal water demands and e-flow constraints. Thus, the context of this application is ill-suited to incorporate industrial water demands as part of the model. Relatedly, wastewater treatment are uncommon throughout Western Nepal, so this component is omitted from the application.

For the municipal sector, we apply municipal water constraints rather than incorporating values associated with provision of water to meet municipal demands. Water resource stakeholders at both national and local levels recognize the importance of surface water resources to meet municipal water demands and often prioritize municipal access over water uses for productive sectors like agriculture and energy if a proposed infrastructure project would incur such a trade-off (Pakhtigian et al., 2019). Accordingly, we constrain diversions to ensure some level of surface water access at each river node based on the population surrounding each river node and demands for surface water in each geographically distinct portion of the region (i.e., the demands for surface water to meet municipal needs are different in the mountains compared to the mid-hills or Terai). With regard to municipal energy demands, while in our main specification we allow energy to flow to markets where it is most beneficial from an economic perspective, we do calculate how much of municipal energy demand in met in each specification and conduct sensitivity analyses which constrain the distribution of energy across energy markets in alternative ways.

6.2.4 Agriculture

Within the agriculture model, our application follows closely to the equations specified in the section above. Importantly, as the model allows cultivated areas (both rainfed and irrigated) to vary as it solves, the cropping patterns, pricing, and cost data are aggregated to the agricultural production site-year level. Furthermore, while there is likely variation within-district regarding crop prices, agricultural costs, and other parameters within the agriculture module, district-level data was the finest resolution available; thus, the model does not incorporate intra-district variation across agricultural parameters. The main data limitations in agriculture include a lack of information on energy demands in agriculture, particularly those related to water pumping for irrigation. Finally, water reuse in agriculture in uncommon in Western Nepal, so water reuse is omitted from the model.

6.2.5 Environmental

As with the municipal module, we incorporate the environmental sector as a system of constraints rather than ascribing value to ecosystem-related water use. In particular, we incorporate a variety of e-flow constraints that allow for different levels of diversions from the river. These e-flows are calculated to maintain aquatic integrity in the rivers. Thus, the difference between model outcomes in the presence and absence of the e-flow constraints provides insight into the economic value the existence of aquatic ecosystems or maintenance of river flows for recreation, navigation, or other purposes would need to afford to promote the binding of these e-flow constraints.

7 Discussion and Summary

Increasing competition for water resources among multiple economic and social sectors calls for efficient allocation of water and intelligent trade-offs among sectors. These, in turn, require a planning approach that incorporates development trajectories and portfolios of management and investment solutions. To support such an integrated planning approach there is a need for tools that better account for the complex social and physical dynamics underlying water systems. This report described an HEM structure that is based around the concept of the Water-Energy-Environment-Food (WEEF) Nexus. The specific structure of the HEM has been developed to describe the integrated social-physical system with three core principles in mind: scalability, transferability, and modularity.

The first two principles allow the model to be implemented in any catchment or river basin with minimal changes. The third principle allows the model to be more effective in handling research questions by turning "on" and "off" relevant modules based on the research question at hand.

More specifically, our HEM Nexus framework depicts interactions between five specific sectors or modules. The first core module, which contains the model objective function, is the water system. It is based on the typical node-link structure of most similar HEMs. This module also includes surface and groundwater interlinkages as appropriate. This objective function aims for maximization of benefits across sectors and uses given both physical and social water and energy system relationships and constraints. Three other modules that are linked to this core are principally human production systems; these represent the energy, municipal and industrial, and agricultural production systems, organized around the representation of the water system core. A fifth module describes the broader ecosystem or environment; this component provides a variety of market and nonmarket goods and services (ecosystem services) to the other systems and is also the recipient of "externalities" from these systems. These externalities, beyond certain levels, may lead to a reduction in the ability of ecosystem to provide services to other systems and to the broader environment.

This model forms an important component for a Decision Support System (DSS). It must be linked to a database of parameters for use in the model equations. Following the model parameterization, users can explore efficient water allocations and specify scenarios or changes to the system that would affect those efficient solutions. Given the inherent complexity in integrated water resources systems, such scenario analyses can help provide more reliable, or data-driven, understanding of the potential costs and benefits of policy and investment changes across multiple sectors that are linked to a water resources system. They can also illuminate critical policy trade-offs and their implications for users or interests in different locations.

As an optimization model, the HEM Nexus tool is well-adapted to identifying solutions that most efficiently allocate water and other resources, which is especially useful for planning purposes at the basin level. As with all similar models, these work from a standardized and simplified representation of very complex system that is developed to be both sufficiently realistic and computationally tractable. Such models are sometimes criticized for the assumptions inherent in their structure. Optimization frameworks in particular may not be well-suited to understanding real world outcomes because the institutions governing allocations rarely come close to resembling an omniscient social planner or a well-functioning water market. In addition, the model is not meant to be used for operational purposes, which typically require greater spatial and temporal resolution. Finally, the HEM Nexus described here is new, and needs to be applied to a variety of problems and contexts to improve its usability and relevance to real world situations, and to better streamline the nature of its data requirements.

References

ADB (2013). *Thinking about Water Differently: Managing the Water-food-energy Nexus*. Asian Development Bank.

Alcamo, J., Flörke, M., and Märker, M. (2007). Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrological Sciences Journal*, 52(2):247–275.

Alcoforado de Moraes, M. M. G., Cai, X., Ringler, C., Albuquerque, B. E., Vieira da Rocha, S. P., and Amorim, C. A. (2009). Joint water quantity-quality management in a biofuel production area–integrated economic-hydrologic modeling analysis. *Journal of Water Resources Planning and Management*, 136(4):502–511.

Arent, D., Döll, P., Strzepek, K., Jiménez Cisneros, B., Reisinger, A., Tóth, F., and Oki, T. (2014). Cross-chapter box on the water-energy-food/feed/fiber nexus as linked to climate change. *Climate change*, pages 163–166.

Arnell, N. W., van Vuuren, D. P., and Isaac, M. (2011). The implications of climate policy for the impacts of climate change on global water resources. *Global Environmental Change*, 21(2):592–603.

Barbier, E. B. (2003). Upstream dams and downstream water allocation: The case of the Hadejia-Jama'are floodplain, northern Nigeria. *Water Resources Research*, 39(11).

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., and Tol, R. S. (2011). Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy policy*, 39(12):7896–7906.

Beck, B. (2014). Model evaluation and performance. *Wiley StatsRef: Statistics Reference Online*.

Bekchanov, M., Ringler, C., Bhaduri, A., and Jeuland, M. (2015). How would the rogun dam affect water and energy scarcity in Central Asia? *Water International*, 40(5-6):856–876.

Bekchanov, M., Sood, A., Pinto, A., and Jeuland, M. (2017). Hydro-economic models to address river basin management problems: Structure, applications, and research gaps. *Journal of Water Resources Planning and Management*, 143(8):04017037.

Blanco-Gutiérrez, I., Varela-Ortega, C., and Purkey, D. R. (2013). Integrated assessment of policy interventions for promoting sustainable irrigation in semi-arid environments: A hydro-economic modeling approach. *Journal of environmental management*, 128:144–160.

Brouwer, R. and Hofkes, M. (2008). Integrated hydro-economic modelling: Approaches, key issues and future research directions. *Ecological Economics*, 66(1):16–22.

Brown, C. M., Lund, J. R., Cai, X., Reed, P. M., Zagona, E. A., Ostfeld, A., Hall, J., Characklis, G. W., Yu, W., and Brekke, L. (2015). The future of water resources systems analysis: Toward a scientific framework for sustainable water management. *Water Resources Research*, 51(8):6110–6124.

Cai, X. (2008). Implementation of holistic water resources-economic optimization models for river basin management–reflective experiences. *Environmental Modelling & Software*, 23(1):2–18.

Cai, X., McKinney, D. C., and Rosegrant, M. W. (2003). Sustainability analysis for irrigation water management in the Aral Sea region. *Agricultural systems*, 76(3):1043–1066.

Chartres, C. and Sood, A. (2013). The water for food paradox. *Aquatic Procedia*, 1:3–19.

Chatterjee, B., Howitt, R. E., and Sexton, R. J. (1998). The optimal joint provision of water for irrigation and hydropower. *Journal of Environmental Economics and Management*, 36(3):295–313.

Clover, J. (2003). Food security in sub-saharan africa. *African Security Studies*, 12(1):5–15.

Cook, C. and Bakker, K. (2012). Water security: Debating an emerging paradigm. *Global Environmental Change*, 22(1):94–102.

Dubois, O., Faurès, J., Felix, E., Flammini, A., Hoogeveen, J., Pluschke, L., Puri, M., and Ünver, O. (2014). The water-energy-food nexus: A new approach in support of food security and sustainable agriculture. *Rome, Food and Agriculture Organization of the United Nations*.

FAO. World Food Summit 1996. http://www.fao.org/wfs/. Accessed April 2019.

Fisher, B., Turner, R. K., and Morling, P. (2009). Defining and classifying ecosystem services for decision making. *Ecological Economics*, 68(3):643–653.

Flatin, I. T. and Nagothu, U. S. (2014). *Food security in the context of global environmental and economic change*, pages 17–50. Routledge.

Hanasaki, N., Fujimori, S., Yamamoto, T., Yoshikawa, S., Masaki, Y., Hijioka, Y., Kainuma, M., Kanamori, Y., Masui, T., and Takahashi, K. (2013). A global water scarcity assessment under shared socio-economic pathways-part 1: Water use. *Hydrology and Earth System Sciences*, 17(7):2375–2391.

Harou, J. J. and Lund, J. R. (2008). Ending groundwater overdraft in hydrologic-economic systems. *Hydrogeology Journal*, 16(6):1039.

Harou, J. J., Pulido-Velazquez, M., Rosenberg, D. E., Medellín-Azuara, J., Lund, J. R., and Howitt, R. E. (2009). Hydro-economic models: Concepts, design, applications, and future prospects. *Journal of Hydrology*, 375(3-4):627–643.

Hoff, H. (2011). Understanding the nexus. background paper for the Bonn 2011 Conference: The water, energy and food security nexus. *Stockholm Environment Institute, Stockholm*.

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., Gielen, D., Rogner, H., Fischer, G., and Van Velthuizen, H. (2013). Integrated analysis of climate change, land-use, energy and water strategies. *Nature Climate Change*, 3(7):621.

Hurford, A. and Harou, J. (2014). Balancing ecosystem services with energy and food security-assessing trade-offs for reservoir operation and irrigation investment in kenya's tana basin. *Hydrology and Earth System Sciences*, 11(1):1343–1388.

International Energy Agency (2016). What is energy security? https://www.iea.org/topics/energysecurity/subtopics/whatisenergysecurity/. Retrieved March 2016.

Jeuland, M., Baker, J., Bartlett, R., and Lacombe, G. (2014). The costs of uncoordinated infrastructure management in multi-reservoir river basins. *Environmental Research Letters*, 9(10):105006.

Kahil, M. T., Ward, F. A., Albiac, J., Eggleston, J., and Sanz, D. (2016). Hydro-economic modeling with aquifer-river interactions to guide sustainable basin management. *Journal of Hydrology*, 539:510–524.

Keller, A. A. (1996). *Integrated water resource systems: Theory and policy implications*, volume 3. IWMI.

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., and Lubchenco, J. (2007). Complexity of coupled human and natural systems. *Science*, 317(5844):1513–1516.

Maass, A., Hufschmidt, M. M., Dorfman, R., Thomas, H. A., Marglin, S. A., Fair, G. M., Bower, B. T., Reedy, W. W., Manzer, D. F., and Barnett, M. P. (1962). Design of water-resource systems.

Mainuddin, M., Kirby, M., and Qureshi, M. E. (2007). Integrated hydrologic-economic modelling for analyzing water acquisition strategies in the murray river basin. *Agricultural Water Management*, 93(3):123–135.

Mancosu, N., Snyder, R., Kyriakakis, G., and Spano, D. (2015). Water scarcity and future challenges for food production. *Water*, 7(3):975–992.

McCornick, P. G., Awulachew, S. B., and Abebe, M. (2008). Water–food–energy–environment synergies and tradeoffs: major issues and case studies. *Water Policy*, 10(S1):23–36.

Miara, A. and Vörösmarty, C. J. (2013). A dynamic model to assess tradeoffs in power production and riverine ecosystem protection. *Environmental Science: Processes & Impacts*, 15(6):1113–1126.

Millennium Ecosystem Assessment, M. (2005). Ecosystems and human well-being. *Synthesis*.

Mullick, M., Akter, R., Babel, M. S., and Perret, S. R. (2013). Marginal benefit based optimal water allocation: case of Teesta River, Bangladesh. *Water Policy*, 15(S1):126–146.

Pakhtigian, E. and Jeuland, M. (2019a). Hydroeconomic modelling of water use trade-offs in Western Nepal. *Unpublished manuscript*.

Pakhtigian, E. and Jeuland, M. (2019b). Valuing the environmental costs of local development: Evidence from Western Nepal. *Ecological Economics*, 158:158–167.

Pakhtigian, E., Jeuland, M., Bharati, L., and Pandey, V. (2019). The role of hydropower in visions of water resources development for rivers of Western Nepal. *International Journal of Water Resources Research*.

Pandey, V., Dhaubanjar, S., Bharati, L., and Thapa, B. (2019). Spatio-temporal distribution of water availability in Karnali-Mohana basin, Western Nepal, under current and future climates.

Pulido-Velázquez, M., Andreu, J., and Sahuquillo, A. (2006). Economic optimization of conjunctive use of surface water and groundwater at the basin scale. *Journal of Water Resources Planning and Management*, 132(6):454–467.

Rijsberman, F. R. (2006). Water scarcity: fact or fiction? *Agricultural Water Management*, 80(1-3):5–22.

Ringler, C., Bhaduri, A., and Lawford, R. (2013). The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency. *Current Opinion in Environmental Sustainability*, 5(6):617–624.

Ringler, C. and Cai, X. (2006). Valuing fisheries and wetlands using integrated economic-hydrologic modeling–mekong river basin. *Journal of Water Resources Planning and Management*, 132(6):480–487.

Ringler, C., von Braun, J., and Rosegrant, M. W. (2004). Water policy analysis for the Mekong River Basin. *Water International*, 29(1):30–42.

Rosegrant, M. W., Cai, X., and Cline, S. A. (2002). *World water and food to 2025: dealing with scarcity*. Intl Food Policy Res Inst.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M., and Colón-González, F. J. (2014). Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences*, 111(9):3245–3250.

Sharma, R. and Awal, R. (2013). Hydropower development in Nepal. *Renewable and Sustainable Energy Reviews*, 21:684–693.

UN Water (2013). Water Security & the Global Water Agenda. United Nations University.

UNESCAP (2013). Water, Food and Energy Nexus in Asia and the Pacific. *Economic and Social Commission for the Asia and the Pacific*.

United Nations (2016). The United Nations World Water Development Report 2016. http://unesdoc.unesco.org/images/0024/002440/244041e.pdf. Retrieved July 2017.

U.S. Energy Information Association (2016). International Energy Outlook 2016. https://www.eia.gov/outlooks/ieo/. Retrieved July 2017.

Van Vliet, M. T., Yearsley, J. R., Ludwig, F., Vögele, S., Lettenmaier, D. P., and Kabat, P. (2012). Vulnerability of us and european electricity supply to climate change. *Nature Climate Change*, 2(9):676.

Wada, Y., Wisser, D., Eisner, S., Flörke, M., Gerten, D., Haddeland, I., Hanasaki, N., Masaki, Y., Portmann, F. T., and Stacke, T. (2013). Multimodel projections and uncertainties of irrigation water demand under climate change. *Geophysical Research Letters*, 40(17):4626–4632.

Ward, F. A. and Booker, J. F. (2003). Economic costs and benefits of instream flow protection for endangered species in an international basin. *JAWRA Journal of the American Water Resources Association*, 39(2):427–440.

Weitz, N., Nilsson, M., and Davis, M. (2014). A nexus approach to the post-2015 agenda: Formulating integrated water, energy, and food sdgs. *SAIS Review of International Affairs*, 34(2):37–50.

Welsch, M., Hermann, S., Howells, M., Rogner, H. H., Young, C., Ramma, I., Bazilian, M., Fischer, G., Alfstad, T., and Gielen, D. (2014). Adding value with clews?modelling the energy system and its interdependencies for mauritius. *Applied Energy*, 113:1434–1445.

Yoon, T., Rhodes, C., and Shah, F. A. (2015). Upstream water resource management to address downstream pollution concerns: A policy framework with application to the nakdong river basin in south korea. *Water Resources Research*, 51(2):787–805.

A Potential Future Extensions

Extensions to the contained modules are included as potential expansions of the model subject to appropriate data availability.

A.1 Water Module

A.1.1 Two-way surface and groundwater flows

For any particular node, there cannot be both seepage into groundwater (from the river) and seepage out of groundwater (into the river) in the same month.

$$W_{g,t}^{W\_GWS} \cdot W_{g,t}^{W\_GWC} = 0 \tag{Aw.1}$$

In the water module, the physical limitations of the aquifer are accounted for by the inclusion of a maximum groundwater level constraint (Equation w.10). Thus, the actual pumping head can be specified as:

$$Z_{g,t} = AQ_{g,MXH}^{B\_CHAR} - GW_{g,t}^{W\_D.lo} + ghd0_{g,t}^{W} \tag{Aw.2}$$

where:
$AQ_{g,MXH}^{B\_CHAR}$ is the height at the top of groundwater aquifer g;
$GW_{g,t}^{W\_D.lo}$ is the head of groundwater aquifer g at time t; and
$ghd0_{g,t}^{W}$ is the pump draw-down of groundwater aquifer g at time t.

Groundwater seepage into surface river flow depends on the water volume in the groundwater aquifer and the transitivity coefficient $(\varphi_{g,n})$

$$W_{g,t}^{W\_GWS} = 0.01 \cdot \varphi_{g,n} G_{g}^{W\_YGW0} A_{g}^{W\_GWA0} \left(\frac{H_{g,t}^{W\_GWA} + H_{g,t-1}^{W\_GWA}}{2} \right) \tag{Aw.3}$$

Aquifer recharge through river flows are considered through linear relationship between the amount of the recharge and river flow:

$$W_{d,t}^{W\_GWC} = \sum_{g \in NGLINK} \left(r_{n,t}^{W\_RGW} \sum_{nu \in NNULINK} W_{nu,n,t}^{W\_F} \right) \tag{Aw.4}$$

where:
$r_{n,t}^{W\_RGW}$ is the share of river flow to charge a groundwater aquifer g at node n and time t (given the link between groundwater aquifers and nodes $(g, n) \in NGLINK$).

A.2 Energy Module

A.2.1 Endogenous quantity adjustments

Given time-varying price data, energy supply in market m depends on the price of energy commodity o:

$$L_{m,o,t}^{E\_SUP} = \alpha_{m,o,t}^{E\_END} (P_{m,o,t}^{E\_M})^{\beta_{m,o,t}^{E\_END}} \tag{Ae.1}$$

where:
$\alpha^{E\_END}_{m,o,t}$ and $\beta^{E\_END}_{m,o,t}$ are the parameters of the exponential regression function; and
$P^{E\_M}_{m,o,t}$ is the price for energy commodity o at market m.

Energy prices for commodity o used at production site de and in its related regional energy market are the same:

$$P^{E}_{de,o,t} = \sum_{m \in MELINK} P^{E\_M}_{m,o,t} \tag{Ae.2}$$

A.3 Industrial/Municipal Module

A.3.1 Leontief production

The relationship between value added by industrial sector and uses of water and energy resources is considered to be a Leontief production process:

$$\frac{VA^{I}_{di}}{\bar{VA}^{I\_0}_{di}} \leq \left(\frac{\sum_t W^{I\_USE}_{di,t}}{\sum_t \bar{W}^{I\_USE0}_{di,t}} \right) \tag{Ai.1a}$$

$$\frac{VA^{I}_{di}}{\bar{VA}^{I\_0}_{di}} \leq \left(\frac{\sum_t \sum_o (f^{I\_O}_{di,o} L^{I\_PRD}_{di,o,k,t})}{\sum_t \sum_o (f^{I\_O}_{di,o} \bar{L}^{I\_PRD}_{di,o,k,t})} \right) \tag{Ai.1b}$$

where:
VA^{I}_{di} and $\bar{VA}^{I}_{di}$ are actual and baseline industrial value added at industrial site di;
$W^{I\_USE}_{di,t}$ and $\bar{W}^{I\_USE0}_{di,t}$ are actual and baseline water uses at industrial site di at time t;
$L^{I\_PRD}_{di,o,k,t}$ and $\bar{L}^{I\_PRD}_{di,o,k,t}$ are actual and baseline energy uses at industrial site di, using energy commodity o, produced by technology k, at time t; and
$f^{I\_O}_{di,o}$ is a weight factor used to make electricity and diesel use units comparable.

This production function is based on an assumption of no substitution between water and energy resources in industrial production but allows substitution between electricity and diesel.

A.4 Agriculture Module

A.4.1 Calculating effective rainfall

In the event that data on effective rainfall is unavailable, it can be calculated. To calculate effective rainfall, run the following loop over every node n:

$$EFF^{A\_RAIN}_{n,t} = 0 \text{ if } PPT^{W}_{n,t} \leq 10 \tag{Af.1a}$$

$$EFF^{A\_RAIN}_{n,t} = 0.2 \cdot (PPT^{W}_{n,t} - 10) \text{ if } 10 < PPT^{W}_{n,t} \leq 20 \tag{Af.1b}$$

$$EFF^{A\_RAIN}_{n,t} = 2 + 0.6 \cdot (PPT^{W}_{n,t} - 20) \text{ if } 20 < PPT^{W}_{n,t} \leq 70 \tag{Af.1c}$$

$$EFF^{A\_RAIN}_{n,t} = 32 + 0.7 \cdot (PPT^{W}_{n,t} - 70) \text{ if } 70 < PPT^{W}_{n,t} \leq 80 \tag{Af.1d}$$

$$EFF^{A\_RAIN}_{n,t} = 39 + 0.8 \cdot (PPT^{W}_{n,t} - 70) \text{ if } PPT^{W}_{n,t} > 80 \tag{Af.1e}$$

A.4.2 Endogenous quantity adjustments

The total amount of the crop produced in the basin depends on crop prices:

$$\sum_{da} Q^{A\_CRP}_{a,c} = \alpha^{A\_AGD}_{c} (P^{A}_{c})^{\beta^{A\_AGD}_{c}} \tag{Af.2}$$

where:
$\alpha^{A\_AGD}_{c}$ and $\beta^{A\_AGD}_{c}$ are the coefficients of the agricultural commodity demand function that relate crop price to the produced amount.

A.4.3 Distribute water to crops

We define $W^{A\_SUM\_P}_{da,t}$ in the following way as a placeholder for the product of water stress, area, and crop price:

$$W^{A\_SUM\_P}_{da,t} = \sum_{c} (CRP^{A\_WS\_COEFF}_{da,c,t} \cdot AREA^{A\_IRRSW}_{da,c} \cdot CR^{A\_P}_{c}) \tag{Af.3}$$

where:
$CRP^{A\_WS\_COEFF}_{da,c,t}$ is the water stress coefficient for agriculture production site da, crop c, at time t; and
$CR^{A\_P}_{c}$ is the crop price.

Then the surface water available for each crop $(CR^{A\_AVB\_VOL\_S}_{da,c,t,})$ (in million m^3) is calculated:

$$CR^{A\_AVB\_VOL\_S}_{da,c,t} = W^{A\_DEL\_CRPS\_S}_{da,t} \cdot \left(CRP^{A\_WS\_COEFF}_{da,c,t} \cdot AREA^{A\_IRRSW}_{da,c} \cdot \frac{CR^{A\_P}_{c}}{W^{A\_SUM\_P}_{da,t}} \right) \tag{Af.4}$$

Similarly, the groundwater available for each crop $(CR^{A\_AVB\_VOL\_G}_{da,c,t,})$ (in million m^3) is calculated:

$$CR^{A\_AVB\_VOL\_G}_{da,c,t} = W^{A\_DEL\_CRPS\_G}_{da,t} \cdot \left(CRP^{A\_WS\_COEFF}_{da,c,t} \cdot AREA^{A\_IRRSW}_{da,c} \cdot \frac{CR^{A\_P}_{c}}{W^{A\_SUM\_P}_{da,t}} \right) \tag{Af.5}$$

We convert these to surface water available in mm:

$$CR^{A\_AVB\_MM\_S}_{da,c,t} = \frac{CR^{A\_AVB\_VOL\_S}_{da,c,t}}{AREA^{A\_IRRSW}_{da,c}} \cdot 1000 \tag{Af.6}$$

And groundwater available to each crop in mm:

$$CR^{A\_AVB\_MM\_G}_{da,c,t} = \frac{CR^{A\_AVB\_VOL\_G}_{da,c,t}}{AREA^{A\_IRRGW}_{da,c}} \cdot 1000 \tag{Af.7}$$

A.4.4 Rainfed crops: Calculate deficit

The stage deficit for rainfed crops ($D^{A\_R}_{da,c,t}$) depends on the effective rainfall, water available through irrigation, the crop coefficient, and the potential evapotranspiration. Here, only crops with a positive crop coefficient, those exhibiting water demand, are included in the calculation. The stage deficit is calculated:

$$D^{A\_R}_{da,c,t} = 1 - \left(\frac{EFF^{A\_RAIN\_DA}_{da,t}}{CRP^{A\_M\_COEFF}_{da,c,t} \cdot PET^{A\_DA}_{da,t}} \right) \tag{Af.8}$$

The maximum stage deficit ($DMAX^{A\_R}_{da,c}$) is, in turn, estimated based on monthly stage deficits:

$$DMAX^{A\_R}_{da,c} = \max_t (D^{A\_R}_{da,c,t}) \tag{Af.9}$$

Next, we calculate seasonal relative yield for rainfed crops ($YLDS^{A\_REL\_R}_{da,c}$), which depends on effective rainfall, the seasonal crop coefficient, and potential evapotranspiration:

$$YLDS^{A\_REL\_R}_{da,c} = \frac{\sum_t EFF^{A\_RAIN\_DA}_{da,t}}{\sum_t (CRP^{A\_S\_COEFF}_{da,c,} \cdot PET^{A\_DA}_{da,t})} \tag{Af.10}$$

where:
$CRP^{A\_S\_COEFF}_{da,c,}$ is the seasonal crop coefficient at agriculture production site *da* specific to crop *c*.

The minimum relative yield for rainfed crops ($YLDREL^{A\_MIN\_R}_{da,c}$) is calculated:

$$YLDREL^{A\_MIN\_R}_{da,c} = \min(1 - DMAX^{A\_R}_{da.c}, YLDS^{A\_REL\_R}_{da,c}) \tag{Af.11}$$

Finally, the actual yields ($YLDACT^{A\_R}_{da,c}$) depend on relative and potential yields:

$$YLDACT^{A\_R}_{da,c} = YLDREL^{A\_MIN\_R}_{da,c} \cdot RFD^{A\_P\_YLD}_{da,c} \tag{Af.12}$$

where: $RFD^{A\_P\_YLD}_{da,c}$ is the potential rainfed yield of crop *c* at agriculture production site *da*.

A.4.5 Irrigated crops: Calculate deficit

In calculating the stage deficit for irrigated crops, we recognize two different water sources for irrigation–surface water and ground water. As the deficit is calculated the same way for both sources, we let $S, G \in \nu$. Then the stage deficit for irrigated crops ($D^{A\_I\_\nu}_{da,c,t}$), where ν indicates either surface or groundwater, depends on effective rainfall, water available for each crop, the monthly crop coefficient, and potential evapotranspiration. As with rainfed crops, only crops with a positive crop coefficient, those exhibiting water demand, are included in the calculation. The stage deficit is calculated:

$$D^{A\_I\_\nu}_{da,c,t} = 1 - \left(\frac{EFF^{A\_RAIN\_DA}_{da,t} + CR^{A\_AVB\_MM\_\nu}_{da,c,t}}{CRP^{A\_M\_COEFF}_{da,c,t} \cdot PET^{A\_DA}_{da,t}} \right) \tag{Af.13}$$

The maximum deficit among stages for irrigated crops $(DMAX_{da,c}^{A\_I\_v})$ is, in turn, estimated based on monthly stage deficits:

$$DMAX_{da,c}^{A\_I\_v} = \max_t(D_{da,c,t}^{A\_I\_v}) \tag{Af.14}$$

Next, we calculate seasonal relative yield for irrigated crops $(YLDS_{da,c}^{A\_REL\_I\_v})$, which depends on effective rainfall, available irrigation, the seasonal crop coefficient, and potential evapotranspiration:

$$YLDS_{da,c}^{A\_REL\_I\_v} = \frac{\sum_t(EFF_{da,t}^{A\_RAIN\_DA} + CR_{da,c,t}^{A\_AVB\_MM\_v})}{\sum_t(CRP_{da,c,}^{A\_S\_COEFF} \cdot PET_{da,t}^{A\_DA})} \tag{Af.15}$$

The minimum relative yield for irrigated crops $(YLDREL_{da,c}^{A\_MIN\_I\_v})$ is calculated:

$$YLDREL_{da,c}^{A\_MIN\_I\_v} = \min(1 - DMAX_{da,c}^{A\_I\_v}, YLDS_{da,c}^{A\_REL\_I\_v}) \tag{Af.16}$$

Finally, the actual yields for irrigated crops $(YLDACT_{da,c}^{A\_I\_v})$ depend on relative and potential yields:

$$YLDACT_{da,c}^{A\_I\_v} = YLDREL_{da,c}^{A\_MIN\_I\_v} \cdot IRR_{da,c}^{A\_P\_YLD} \tag{Af.17}$$

where:
$IRR_{da,c}^{A\_P\_YLD}$ is the potential irrigated yield of crop c at agriculture production site da.