Hydroeconomic modelling of water use trade-offs in Western Nepal

Brief for Stakeholders

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Introduction

With its vast water resources, Western Nepal is a region with substantial development potential. In light of the opportunities and challenges in the region, the Digo Jal Bikas (DJB) project set out to promote water resources development in Western Nepal that is sustainable, just, and productive. To do so, DJB has studied the ecological, economic, political, and social characteristics of the Mahakali and Karnali River Basins and engaged local and national stakeholders in policy discussions about enhanced water management. In this report, we outline the main activities of one arm of the DJB project—Work Package 3—which focused on the development and analysis of basin-scale scenarios in the Karnali and Mahakali River Basins of Western Nepal and discuss results of the trade-off analysis conducted using hydroeconomic modelling (HEM).

To guide the basin-scale analysis, WP3 outlined a series of objectives including: (i) examination of the effects and value of new water infrastructure, (ii) examination of trade-offs in water use, across sectors, space and time, and (iii) consideration of institution constraints to water resources development and allocations.

Objective one relates to the potential for infrastructure development in Western Nepal. Many plans and licenses for new hydropower projects exist in the region, as do blueprints for new and expanded irrigation projects. These investments are indicative of certain priorities for the basin—expansion of the energy and agriculture sectors—that figure into the broader development plans for Western Nepal. Objective two reflects the reality that while Wester Nepal is endowed with extensive water resources, there nevertheless exist trade-offs in water use and management. These trade-offs exist both between sectors and across space and time. For example, storage infrastructure for energy generation or irrigation alter natural river flows and may change water availability to meet downstream demands. Careful consideration of these trade-offs is important for effective planning. Finally, objective three recognizes that strictly productive water uses (i.e., energy generation and agricultural production) are not the only relevant factors in determining optimal water use and management. Specifically, municipal and ecological water demands and flows across institutional borders must be incorporated into basin-scale analysis.

Using hydroeconomic modelling (HEM) to analyze basin-scale scenarios

To help meet these objectives, we developed a modular hydroeconomic model that provides an integrated perspective on water resources development in the Karnali and Mahakali River Basins of Western Nepal (Bekchanov et al., 2018). This approach – which provides an economic perspective on efficient water use within a flexible and customizable framework that accounts for system interdependencies (Harou et al., 2009) – incorporates energy, agricultural, domestic, and environmental perspectives around a core water balance model from which water control and water allocations can be specified.[1] The WNEWM (Western Nepal Energy Water Model) solves for the maximum total economic benefits within these river basins, accounting for trade-offs both within and across sectors. Furthermore, by adjusting model parameters to reflect possible system changes in the future, we can obtain insights that can enhance future planning.

Applying the WNEWM to Western Nepal

The objective of the WNEWM is to maximize the total economic benefit within the Karnali and Mahakali River Basin systems across (i) energy, (ii) agriculture, (iii) municipal, and (iv) environmental sectors. This HEM, with its modular structure, allows for interdependencies across sectors; for example, energy demands in agricultural production are fulfilled via allocations from the energy module. Energy and agriculture benefits are calculated based on the value of hydropower produced and the net benefits from crops grown using basin water, with 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; these allocations have implicit value that is equal to the opportunity cost associated with satisfying these constraints.

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 1). The WNEWM comprises 151 river nodes.[2] 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.

[1] Hydroeconomic models inform policy makers about the efficient use and distribution of water resources throughout a system, incorporating tools and principles from engineering, hydrology, and economics. While we refrain from detailing the literature on HEM applications in this report, we point the interested reader to analyses in the Nile (Arjoon et al., 2014; Jeuland, 2010; Whittington, Wu, and Sadoff, 2005), Ganges (Jeuland et al., 2013; Wu et al., 2013), and Mekong (Lacombe et al., 2014; Lauri et al., 2012).

[2] The hydrological inputs used in the HEM were generated outside of the model using ArcSWAT as described in Pandey et al. (2019).

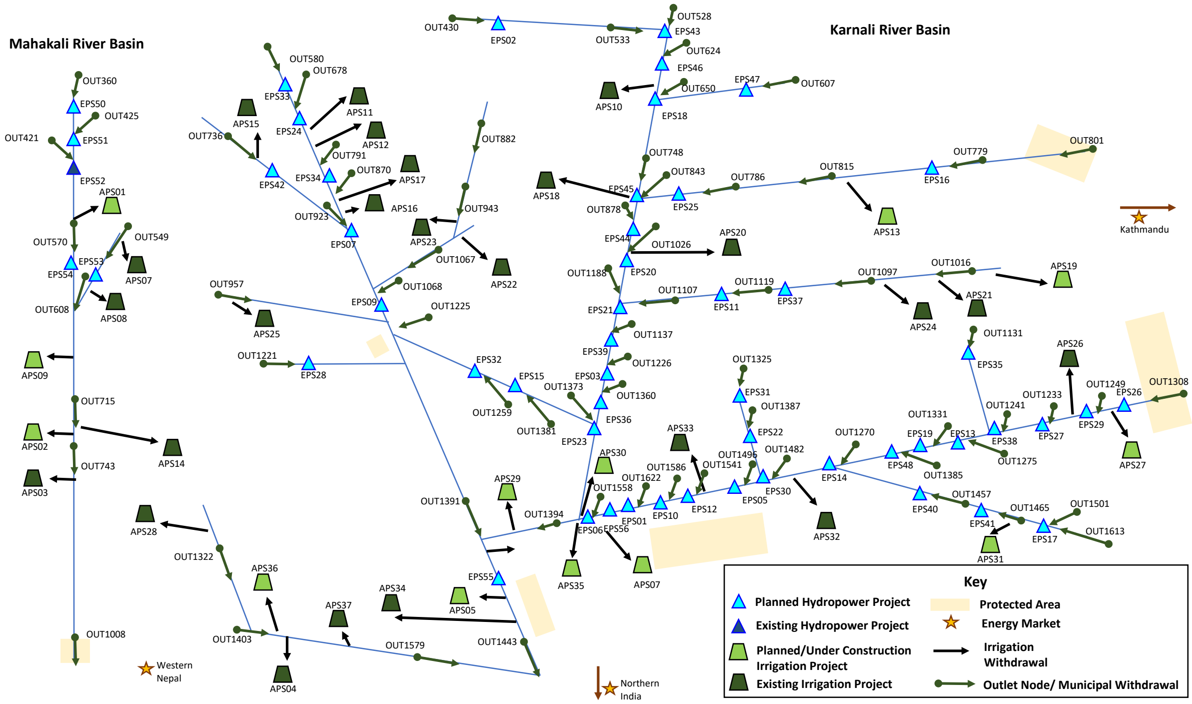

Figure 1: Node system for HEM of Karnali and Mahakali River Basins

Data

Hydroeconomic models are 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 WNEWM. All hydrological inputs were generated using ArcSWAT, while the CROPWAT and CLIMWAT tools developed by the Food and Agricultural Organization (FAO) were used to calculate crop water requirements, evapotranspiration, and crop coefficients. Other data sources included government department reports (annual reports from the Nepal Electricity Authority, Statistical Information on Nepalese Agriculture reports by the Ministry of Agricultural Development); government planning documents and policies (Hydropower Development Plan, Master Plan Study for Water Resource Development of Upper Karnali and Mahakali River Basin, Nationwide Master Plan Study on Storage-type Hydroelectric Power Development in Nepal, and the 2005 National Water Plan); hydropower or irrigation project-specific planning documents infrastructure planning information; local planning documents and data (Water User Master Plans, DJB basin-wide survey); and national level statistics. These sources, summarized in additional detail in Jeuland and Pakhtigian (2019), were used to obtain information on:

a) hydropower projects including installed capacity, reservoir volume, surface area, and height for storage projects, and operating and transmission costs;
b) municipal, agricultural, and export energy prices;
c) irrigation and rainfed agricultural areas, cropping patterns and crop yields, energy demands, production costs, and crop prices;

d) surface water demands, electricity usage, and populations; and
e) environmental flow requirements.

Model limitations

We highlight 3 major limitations before presenting the development scenarios and HEM results—conceptual, structural, and data limitations. **Conceptually**, we note that the productive benefit maximization objective 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 rather than expected economic benefit. Accordingly, they may seek to implement policies that minimize risk, even if potential payoffs of such conservative strategies are limited. **Structurally**, we take a conservative approach to benefit generation in cases where simplifications are necessary to decrease the complexity of the model. For energy generation from storage projects, we utilize linear height-volume relationships, which underestimate energy generation. For agricultural generation, we maintain existing cropping patterns for each agricultural site, even if alternative cropping patterns could yield increased output or production of more profitable crops. Finally, we confront several important **data limitations**. Our hydrological inputs are limited to surface water flows, and thus do not incorporate groundwater management. Second, we use uniform domestic energy and agriculture prices throughout the basin. Third, for many hydropower and irrigation projects, we do not have access to project-specific documentation and are therefore often forced to make assumptions about scale and biophysical relationships.

Scenarios for analysis

The WNEWM was developed to analyze different development scenarios for Western Nepal, which we compiled though interactions and input from two key interactions with national and local stakeholders representing diverse sectoral interests. Specifically, in August 2017, DJB held a Trade-off Arena Workshop with nearly 50 local and national stakeholders representing energy, agriculture, municipal, fisheries, and tourism sectors, among others. At this workshop, stakeholders engaged in a series of discussions and activities in which they shared their individual and collective visions for development in Western Nepal and identified development priorities. These were compiled into three development scenarios that were used in the initial modeling. Once initial results were generated, stakeholder opinion was elicited in a series of additional meetings, during which development scenarios and initial results and insights were presented to stakeholders and discussed. Here, we briefly outline the three WNEWM development scenarios (Figure 2), and their relation to the status quo:

1. <u>Status quo</u>: Current irrigation and hydropower infrastructure; domestic or exported energy; supply to municipal water demands and a 10% minimum flow constraint.

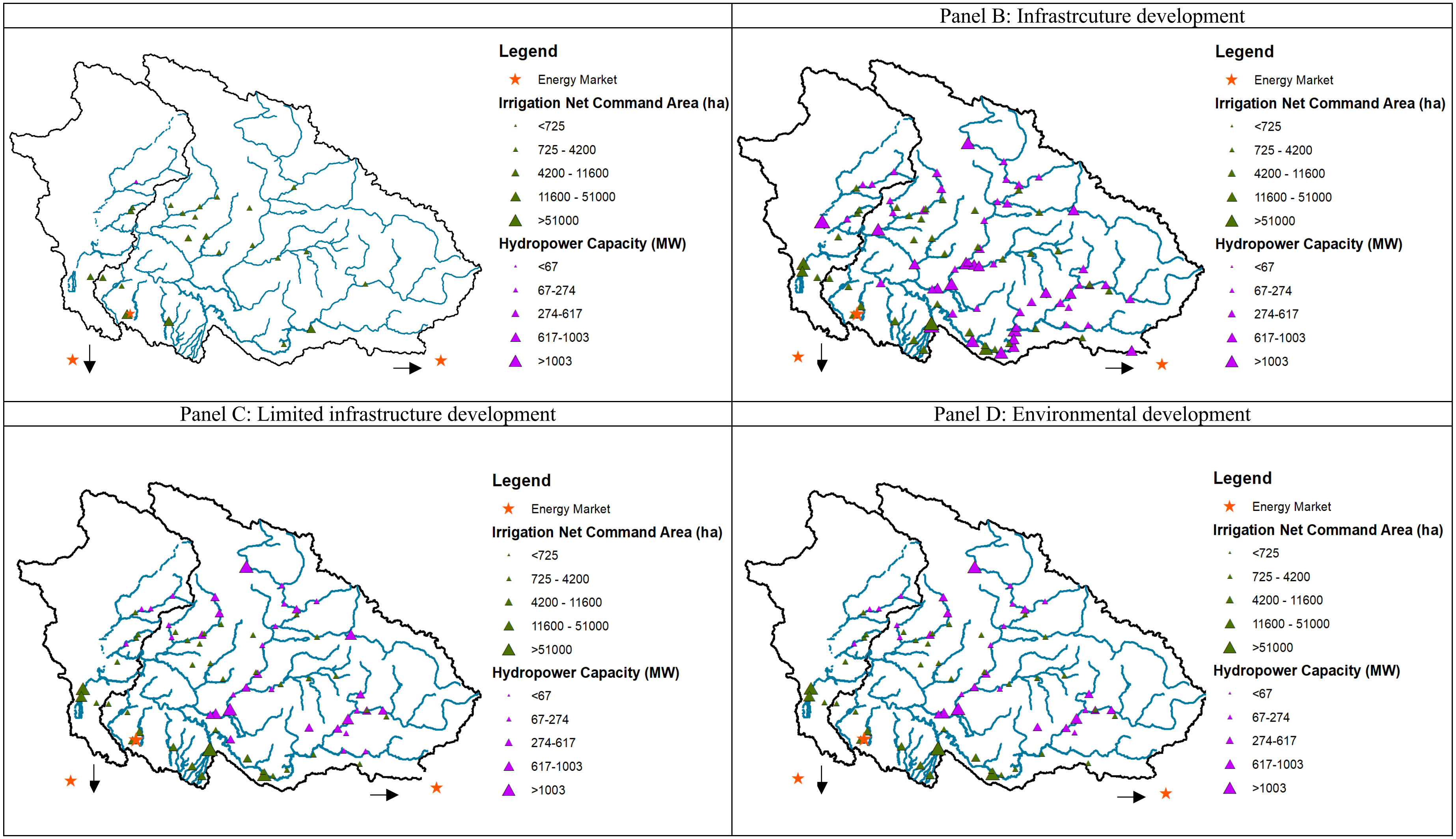

Figure 2: Maps depicting development scenarios used in HEM analysis

2. Full infrastructure development: Development of all planned and proposed hydropower and irrigation projects (with 55 energy production sites, and installed capacity of 20.3 GW, and 7136 km^2 of potential irrigation area); domestic or exported energy; supply to municipal water demands; and 10% minimum flow constraint.
3. Limited infrastructure development: Development of all planned projects, plus any proposed run-of-the-river hydropower and irrigation projects (with 36 energy sites, and installed capacity of 5.3 GW, and 7136 km^2 of potential irrigation area); domestic or exported energy; supply to municipal water demands; and 10% minimum flow constraint.
4. Environmental development: Development of all planned projects, plus any proposed run-of-the-river hydropower and irrigation projects outside of two ecologically significant tributaries near Bardiya and Shey Phoksundo National Parks, respectively (with 31 energy sites, and installed capacity of 4.6 GW, and 7136 km^2 potential irrigation area), domestic or exported energy; supply to municipal water demands; and 10% minimum flow constraint.

WNEWM results

Table 1 presents the main results of the WNEWM analysis, summarizing outcomes of electricity generation and agricultural production under the four scenarios, as well as the value of these benefits. Table 1, and all tables in the body of this report, provide values for a one-year model run in an average flow year. Tables for high and low flow years are provided in the appendix. While these values do take into account the costs of electricity and agricultural production, they do not incorporate infrastructure construction costs or the costs of filling new storage infrastructures.[3] We find that expanding the energy and agricultural sectors in Western Nepal could generate substantial value. Within this base model, we allow energy to be exported to the most profitable market, and we use differing electricity prices for domestic and exported energy, as described in the sensitivity analysis.

Column 1 of Table 1 shows the results under the "Status Quo" scenario, including only currently existing irrigation and hydropower production infrastructure. Over the analyzed period, existing infrastructure generates 57 GWh of electricity, and the energy sector generates about 3 million US$. We see that all of this energy remains in Western Nepal, which is unsurprising as domestic prices are higher than export prices in the base model. We also find that the agricultural sector produces 0.7 million MT of output, generating 93 million US$. Thus, the overall value obtained under status quo conditions is just over 96 million US$ from the energy and agricultural sectors. Importantly, all environmental and municipal water demands are satisfied under these conditions, though we do not attempt to place value on these due to lack of valuation data. Here, environmental flows are constrained to maintain a minimum of 10 percent of natural flow, and municipal water demands are met according to population and surface water dependence. Thus,

[3] For a brief discussion of infrastructure construction costs in the context of the WNEWM, please see Jeuland and Pakhtigian (2019).

we might consider the total value estimate to be a lower bound for the benefits generated by optimal management and use of water resources in Western Nepal under existing conditions.

Columns 2-4 summarize the HEM results under the three development scenarios: "Infrastructure Development", "Limited Infrastructure Development", and "Environmental Development". Given the large expansion in hydropower infrastructure and irrigable land under each of these scenarios, it is unsurprising that output and benefits substantially increase. The energy sector now generates over 69, 14, and 13 TWh of electricity at a value of 1.9, 0.3, and 0.3 billion US$ across these scenarios, in one year alone. The agricultural sector meanwhile generates nearly 3 million MT of output at a value of 0.5 billion US$, in all three scenarios. The overall productive benefits therefore increase by 7-24 times over the total value generated under status quo conditions.

Table 1: HEM results, 1-year mean flows

	Status quo	**Infrastructure Development**	**Limited Infrastructure Development**	**Environmental Development**
1. Hydropower				
a. Production (GWh)	57.0	69575	14958	13833
b. Energy to Western Nepal (GWh)	57.0	1111	1111	1111
c. Energy to Kathmandu (GWh)	0	120	120	120
d. Energy to India (GWh)	0.012	68344	13727	12602
e. Value (billion US$)	0.003	1.90	0.34	0.31
2. Irrigation				
a. Irrigated land (km^2)	236	3112	3114	3114
b. Production (million MT)	0.64	2.95	2.95	2.95
c. Value (billion US$)	0.093	0.44	0.44	0.44
3. Objective function				
a. Value (billion US$)	0.096	2.34	0.77	0.75

We can interpret the difference between scenarios 3 and 4 as the opportunity cost of preserving pristine rivers around the National Parks mentioned above, which amounts to about $0.02 billion. Meanwhile, the difference between scenarios 2 and 3 ($1.6 billion) indicates the opportunity cost of not investing in additional storage-backed hydropower. While environmental flow conditions and municipal demands are met in the base-case for all scenarios, there could also be considerable environmental change and degradation with such substantial infrastructure investment, which is not penalized in the model. Accordingly, we consider more stringent environmental flows specifications in our sensitivity analysis.

Sensitivity analysis

Given the reliance of the WNEWM on the parameters of the model, we conducted several types of sensitivity analysis to provide a more comprehensive analysis of the trade-offs. The results from these analyses are presented in Tables 2-4. In Table 2, we consider a different set of environmental flow constraints. These environmental flow constraints are generated using the IWMI e-flows calculator and were generated for the DJB project by WP2.[4]

Table 2: HEM results, 1-year mean flows, more stringent environmental flows

	Status quo	**Infrastructure Development**	**Limited Infrastructure Development**	**Environmental Development**
1. Hydropower				
a. Production (GWh)	57.0	68282	14958	13833
b. Energy Western Nepal (GWh)	57.0	1111	1111	1111
c. Energy Kathmandu (GWh)	0	120	120	120
d. Energy India (GWh)	0.009	67051	13727	12602
e. Value (billion US$)	0.003	1.87	0.34	0.31
2. Irrigation				
a. Irrigated land (km^2)	166	2940	2942	2942
b. Production (million MT)	0.58	2.82	2.82	2.82
c. Value (billion US$)	0.085	0.42	0.42	0.42
3. Objective function				
a. Value (billion US$)	0.088	2.29	0.76	0.73

[4] Details of the e-flow calculator are available here: http://www.iwmi.cgiar.org/resources/models-and-software/environmental-flow-calculators/

These more stringent e-flow constraints were applied throughout the region; however, in some small tributaries they disallow for any water divergence and are, thus, incompatible with even municipal water demands. In these cases, a 10 percent e-flow was maintained rather than the more stringent flow. In examining these results, we find that more stringent flow constraints lead to a decline in irrigation, with a corresponding reduction in agricultural production. Furthermore, they lead to minor changes in energy generation, particularly from storage projects, due to required adjustments in the timing of releases to meet environmental requirements.

Table 3: HEM results, 1-year mean flows, flows to India

		Status quo	Infrastructure Development	Limited Infrastructure Development	Environmental Development
1. Hydropower					
a.	Production (GWh)	57.0	71586	14958	13833
b.	Energy Western Nepal (GWh)	57.0	1111	1111	1111
c.	Energy Kathmandu (GWh)	0	120	120	120
d.	Energy India (GWh)	0.012	70356	13727	12602
e.	Value (billion US$)	0.003	1.96	0.34	0.31
2. Irrigation					
a.	Irrigated land (km^2)	236	1488	1491	1491
b.	Production (million MT)	0.64	1.82	1.82	1.82
c.	Value (billion US$)	0.093	0.27	0.27	0.27
3. Objective function					
a.	Value (billion US$)	0.096	2.23	0.60	0.58

In Table 3, we consider the impact of downstream flow requirements to India, per the specifications in the Mahakali Treaty of 1996 with India. This treaty specifies that Nepal has a right to 28.35 m^3/s of water from the Mahakali during the wet season and 4.25 m^3/s during the dry season. As no such treaty exists for the Karnali, for illustrative purposes, we impose similar diversion constraints from the Karnali River based on average wet and dry season flow of 48.14 m^3/s during the wet season and 12.8 m^3/s during the dry season. Thus, for this sensitivity analysis, we constrained water diversions throughout both basins according to these allowances. As with the more stringent environmental flows, we find that these downstream flow requirements decrease irrigation, leading to substantially lower agricultural productivity across all three expansion scenarios. These declines lead to a decrease in productive value of about 0.17 billion US$.

Table 4: HEM results, 1-year mean flows, energy distribution

	Status quo	Infrastructure Development	Limited Infrastructure Development	Environmental Development
1. Hydropower				
a. Production (GWh)	57.0	69740	14957	13833
b. Energy Western Nepal (GWh)	57.0	569.71	570	570
c. Energy Kathmandu (GWh)	0	120	120	120
d. Energy India (GWh)	0.012	69051	14268	13143
e. Value (billion US$)	0.003	1.89	0.32	0.30
2. Irrigation				
a. Irrigated land (km^2)	236	3112	3114	3114
b. Production (million MT)	0.64	2.95	2.95	2.95
c. Value (billion US$)	0.093	0.44	0.44	0.44
3. Objective function				
a. Value (billion US$)	0.096	2.32	0.76	0.74

Next, in Table 4 we consider the fact that accounts for more limited demand in local markets, relative to those in the rest of Nepal and especially India. In this sensitivity analysis, we allow the value of energy in Nepal to vary linearly to a value of zero beyond current per capita consumption levels, rather than assuming that unmet local demand would have the same value as current demand. Thus, once current local energy demands (valued at 9 NRs./kWh) are met, excess energy generated is mostly exported to India (valued at 6 NRs./kWh).

Finally, in the appendix, we present results for high and low flow years. As expected, for nearly all results, the benefits – of hydropower generation and irrigation – are somewhat reduced in low flow years, by 7-16% across infrastructure scenarios in the base case, and increased in high flow years, by 5-11%. This is intuitive because less water is available for production purposes in low flow years. The only exception to this pattern is for the status quo in the high flow year, for which no additional production occurs, due to lack of ability to store those flows.

In addition to examining the sectoral distribution of benefits across the scenarios modeled in the WNEWM, we also consider the distribution of production benefits across the Karnali and Mahakali River Basins (Figure 3). We note that the productive benefits depicted in these figures reflect where the benefits are generated, and not necessarily where they are consumed (given that agricultural production is sold in markets throughout the broader region, and that energy is similarly consumed in locations to which the power is transmitted). For example, if a storage hydropower project is built but most of the energy produced at this site is transmitted to Kathmandu or exported to India, then few of these benefits will actually be enjoyed by the surrounding population. In contrast, local populations typically bear many (but not all, since large numbers of water users also reside downstream especially in India) of the costs—changing water access, relocation, alternations to ecosystem services, etc.—from infrastructure development.

The maps illustrated in Figure 3 demonstrate more clearly the spatial patterns of benefits generation than the aggregate results presented in Table 1. As before, we observe that the full "Infrastructure Development" scenario generates the most value, and this is especially apparent in central-eastern parts of the basin. While levels of development vary across the scenarios, we observe that the distribution of benefits is mostly consistent. Across all scenarios, the most benefit is produced in the Terai and lower Mid-Hills regions. This is due to the fact that land in the Terai is better suited for the expansion of irrigated agriculture as well as the nearby location of some of the larger hydropower facilities (e.g., Chisapani). In scenarios 2, 3, and 4 (panels B, C, and D), we also see that energy and agriculture infrastructure expansion generates substantial benefits in the Western mountain region as well the Eastern Mid-Hills. Notably the reduction in energy expansion in panels C and D is most evident in the Western Mid-Hills and Northern Mountains, as well as the Eastern mountains in panel D.

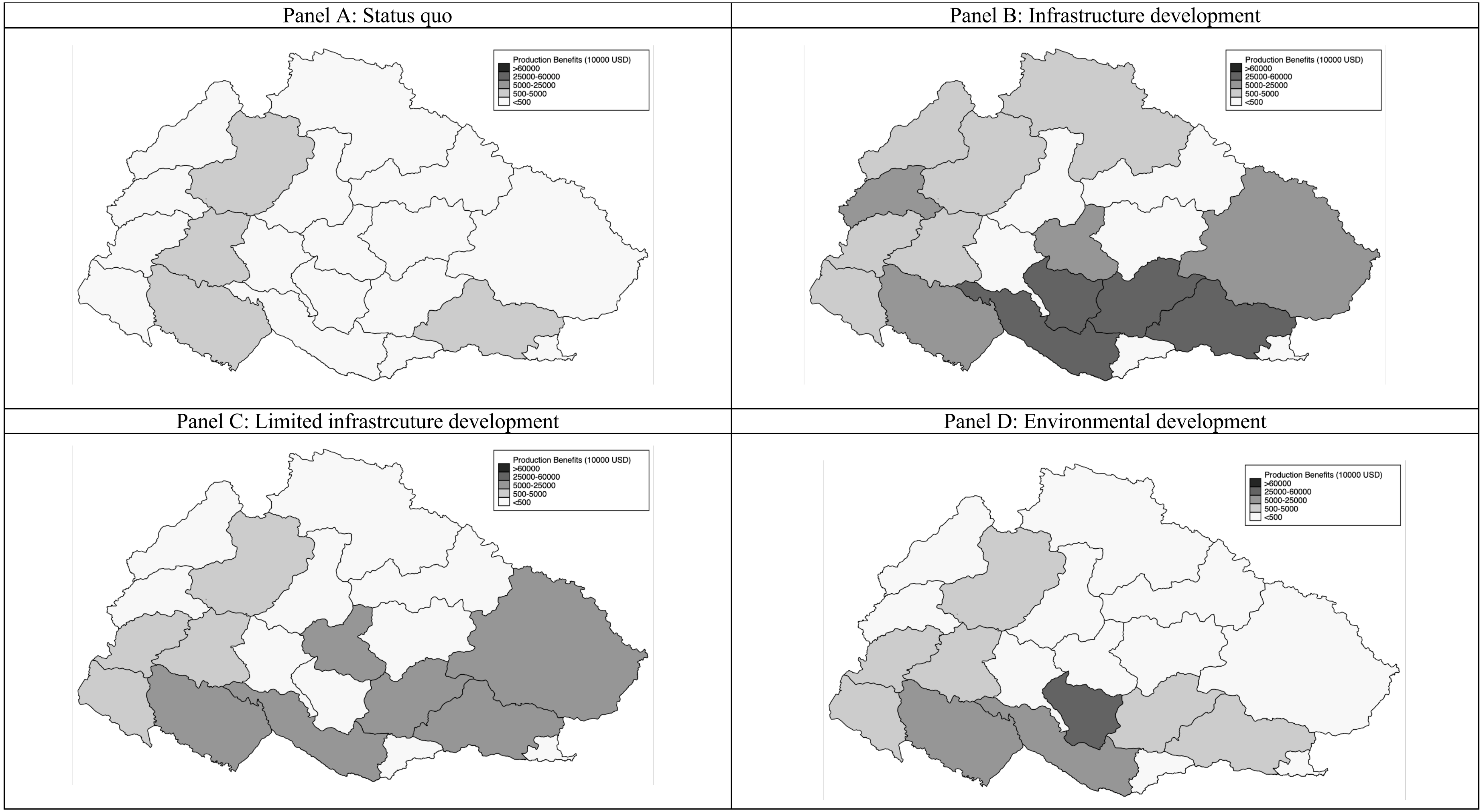

Figure 3: Distribution of origin of productive benefits throughout Western Nepal, base case

Conclusions

Hydroeconomic modeling of development scenarios provides important insights into planning for water management and use in the Karnali and Mahakali River Basins of Western Nepal. While the model cannot incorporate all of the intricacies of the actual hydrological and economic conditions of the region, the WNEWM does carefully analyze expansions in two sectors—energy and agriculture—that are essential to Nepal's current economy and future development prospects. Furthermore, the model expands on existing HEM methods by utilizing a module structure for sector incorporation, which allows for interdependencies both within and across sectors.

Our results demonstrate that irrigation and hydropower infrastructure offer high potential value as development priorities in Western Nepal. First, the economic value generated through large-scale infrastructure depends, in part, on power trade agreements between Nepal and its neighbors, most notably India. If electricity value in domestic markets is higher than export prices, electricity generated in the basin should be used to contribute to meeting the electricity demands in Western Nepal; however, once this value dips below export prices, excess potential exists in the region that can best be allocated to export markets. Second, we find substantial trade-offs between institutionally-mandated diversion constraints (i.e., the Mahakali River Treaty) and agricultural productivity. Third, we find that while the incorporation of more stringent environmental constraints (ex., Environmental Development) does induce financial costs; these costs could be reduced by careful determination of protected waterways. Additionally, ecotourism and recreational benefits, which we were unable to value in this work, may help to offset these costs. Finally, we find that more stringent e-flow constraints induce some trade-offs with both energy generation and agricultural production; however, in the absence of these constraints, flows are permitted to fall below levels that may be dangerous for preserving aquatic ecosystems.

Annotated bibliography: References for further reading

Arjoon, D., Mohamed, Y., Goor, Q., & Tilmant, A. (2014). Hydro-economic risk assessment in the eastern Nile River basin. *Water Resources and Economics*, *8*, 16-31.

This paper uses a stochastic, integrated hydroeconomic model to examine the implications for the entire eastern Nile River basin of building a hydroelectric dam with a storage reservoir with a capacity of 60 km^3 in Ethiopia. It identifies potential trade-offs between water storage and electricity production in Ethiopia and downstream flow disruptions, of particular concern to Egypt. The model is used to analyze different types of dam management and development and demonstrates that cooperative (multi-country) management of the dam could result in substantial gains throughout the region in terms of electricity access, flood management, and flow predictability.

Bekchanov, M., Pakhtigian, E. L., Sood, A. & Jeuland, M. (2018). Hydro-economic Modeling Framework to Address Water-Energy-Environment-Food Nexus Questions at the River Basin Scale.

This paper summarizes the literature of hydroeconomic modelling and its applications and develops a new, conceptual framework for a node-based, multi-sector hydroeconomic model. This is the model used for the WNEWM application described in this stakeholder brief. The paper outlines the general model equations, which have been adjusted to align with the data availability and context of the Karnali and Mahakali River Basins.

Jeuland, M. (2010). Economic implications of climate change for infrastructure planning in transboundary water systems: An example from the Blue Nile. *Water Resources Research*, *46*(11), W11556.

This paper utilizes hydroeconomic modeling to examine alternative hydropower development schemes in the Blue Nile under uncertainty related to climate change and the need for water storage. It directly speaks to the uncertainties policymakers face in planning for water resources use and management when they plan for infrastructure development. Furthermore, it provides a framework for integrating hydrological, economic, and climate-related factors into tools for data analysts and policy makers.

Jeuland, M., Harshadeep, N., Escurra, J., Blackmore, D., & Sadoff, C. (2013). Implications of climate change for water resources development in the Ganges basin. *Water Policy*, *15*(S1), 26-50.

This paper examines the implications of climate changes for the Ganges basin in terms of hydrology and production. This research determines that different climate change projections have differential predictions for flow predictions; however, predicted mean flows in the main stem of the Ganges remain within the range of natural variability. Furthermore, it finds that predicated climate change-related variability in flows would not reduce hydropower potential in Nepal and that upstream storage could regulate flows throughout the basin.

Jeuland, M. and Pakhtigian, E.L. (2019). Hydroeconomic modelling of water use trade-offs in Western Nepal.

This paper provides the technical details of the HEM research presented in this stakeholder brief.

Lacombe, G., Douangsavanh, S., Baker, J., Hoanh, C. T., Bartlett, R., Jeuland, M., & Phongpachith, C. (2014). Are hydropower and irrigation development complements or substitutes? The example of the Nam Ngum River in the Mekong Basin. *Water International*, *39*(5), 649-670.

This paper examines the relationship between hydropower and irrigation in terms of the development of water use and management infrastructure. It uses an optimization model to analyze hydropower and irrigation potential under various development scenarios in the Nam Ngum sub-basin of the Mekong basin. The model finds complementarities between hydropower and irrigation; however, it is unable to generalize these sub-basin findings to the entire Mekong basin.

Lauri, H., de Moel, H., Ward, P. J., Räsänen, T. A., Keskinen, M., & Kummu, M. (2012). Future changes in Mekong River hydrology: Impact of climate change and reservoir operation on discharge. *Hydrology and Earth System Science*, 16, 4603–4619.

This paper examines the hydrology of the Mekong River, specifically comparing future development scenarios with predicted hydrological changes induced by climate change. The models demonstrate much larger hydrological changes due to planned storage in hydropower reservoirs; these changes are even more apparent during the dry season. The research also demonstrates that climate change could have large impacts on reservoir operations, suggesting that future climate uncertainty should be considered in plans for hydropower development in the Mekong. Furthermore, both climate-induced and hydropower, as well as their interaction, could significantly alter river ecology, implying potential damages to fisheries.

Pandey, V. P., Dhaubanjar, S., Bharati, L., & Thapa, B. R. (2019). Spatio-temporal distribution of water availability in Karnali-Mohana Basin, Western Nepal, under current and future climates.

This paper provides the technical details of the SWAT model used to generate the hydrological inputs for the HEM research presented in this stakeholder brief.

Whittington, D., Wu, X. & Sadoff, C. (200US5). Water resources management in the Nile Basin: the economic value of cooperation. *Water Policy, 7*, 227–252.

This paper presents an economic optimization model of water resource use throughout the Nile River Basin. It highlights the potential benefits associated with hydropower generation and irrigation, within a discussion of international cooperation over riparian resource management, access, and use. The authors argue that these economic dimensions are an essential piece of international negotiations over development in the Nile Basin and acknowledge that environmental, social, and cultural aspects also play a role.

Wu, X., Jeuland, M., Sadoff, C., & Whittington, D. (2013). Interdependence in water resource development in the Ganges: an economic analysis. *Water Policy*, *15*(S1), 89-108.

This paper seeks to understand the role of interdependence in water resource development given existing uncertainty in the literature regarding whether interdependence deserves more attention or is overvalued in its importance. Implementing an economic optimization model in the Ganges basin, this research identifies economic interdependence between existing and planned water storage infrastructure. The analysis reveals that upstream storage projects may not play a significant role in limiting downstream floods or regulating flows, suggesting that a full understanding of interdependences is essential to calculating the potential benefits under various development scenarios.

Appendix A: High and Low Flow Years

Table A1: HEM results, 1-year high flows

	Status quo	**Infrastructure Development**	**Limited Infrastructure Development**	**Environmental Development**
1. Hydropower				
a. Production (GWh)	50.1	76919	14824	13710
b. Energy to Western Nepal (GWh)	50.1	1111	1111	1111
c. Energy to Kathmandu (GWh)	0	120	120	120
d. Energy to India (GWh)	0.021	75689	13593	12479
e. Value (billion US$)	0.002	2.10	0.33	0.31
2. Irrigation				
a. Irrigated land (km^2)	385	4016	4016	4016
b. Production (million MT)	0.58	3.25	3.25	3.25
c. Value (billion US$)	0.085	0.48	0.48	0.48
3. Objective function				
a. Value (billion US$)	0.088	2.59	0.82	0.79

Table A2: HEM results, 1-year high flows, more stringent environmental flows

	Status quo	Infrastructure Development	Limited Infrastructure Development	Environmental Development
1. Hydropower				
a. Production (GWh)	50.1	76685	14824	13710
b. Energy to Western Nepal (GWh)	50.1	1111	1111	1111
c. Energy to Kathmandu (GWh)	0	120	120	120
d. Energy to India (GWh)	0.02	75454	13593	12479
e. Value (billion US$)	0.002	2.10	0.33	0.31
2. Irrigation				
a. Irrigated land (km^2)	355	3347	3350	3350
b. Production (million MT)	0.57	2.87	2.87	2.87
c. Value (billion US$)	0.084	0.43	0.43	0.43
3. Objective function				
a. Value (billion US$)	0.086	2.53	0.76	0.74

Table A3: HEM results, 1-year high flows, flows to India

	Status quo	Infrastructure Development	Limited Infrastructure Development	Environmental Development
1. Hydropower				
a. Production (GWh)	50.1	79004	14824	13710
b. Energy to Western Nepal (GWh)	50.1	1111	1111	1111
c. Energy to Kathmandu (GWh)	0	120	120	120
d. Energy to India (GWh)	0.021	77773	13593	12479
e. Value (billion US$)	0.002	2.16	0.33	0.31
2. Irrigation				
a. Irrigated land (km^2)	385	1852	1852	1852
b. Production (million MT)	0.58	1.77	1.77	1.77
c. Value (billion US$)	0.085	0.26	0.26	.026
3. Objective function				
a. Value (billion US$)	0.088	2.43	0.59	0.57

Table A4: HEM results, 1-year high flows, energy distribution

	Status quo	Infrastructure Development	Limited Infrastructure Development	Environmental Development
1. Hydropower				
a. Production (GWh)	50.1	77726	14824	13710
b. Energy to Western Nepal (GWh)	50.1	570	570	570
c. Energy to Kathmandu (GWh)	0	120	120	120
d. Energy to India (GWh)	0.021	77036	14134	13020
e. Value (billion US$)	0.002	2.11	0.32	0.29
2. Irrigation				
a. Irrigated land (km^2)	385	4016	4016	4016
b. Production (million MT)	0.58	3.25	3.25	3.25
c. Value (billion US$)	0.085	0.48	0.48	0.48
3. Objective function				
a. Value (billion US$)	0.088	2.59	0.80	0.78

Table A5: HEM results, 1-year low flows

	Status quo	Infrastructure Development	Limited Infrastructure Development	Environmental Development
1. Hydropower				
a. Production (GWh)	44.4	56414	12764	11759
b. Energy to Western Nepal (GWh)	44.4	1111	1111	1111
c. Energy to Kathmandu (GWh)	0	120	120	120
d. Energy to India (GWh)	0.019	55183	11534	10528
e. Value (billion US$)	0.002	1.54	0.29	0.27
2. Irrigation				
a. Irrigated land (km^2)	282	3466	3466	3466
b. Production (million MT)	0.46	2.86	2.86	2.86
c. Value (billion US$)	0.067	0.42	0.42	0.42
3. Objective function				
a. Value (billion US$)	0.070	1.97	0.72	0.70

Table A6: HEM results, 1-year low flows, more stringent environmental flows

	Status quo	Infrastructure Development	Limited Infrastructure Development	Environmental Development
1. Hydropower				
a. Production (GWh)	44.4	54697	12764	11759
b. Energy to Western Nepal (GWh)	44.4	1111	1111	1111
c. Energy to Kathmandu (GWh)	0	120	120	120
d. Energy to India (GWh)	0.017	53467	11534	10528
e. Value (billion US$)	0.002	1.50	0.29	0.27
2. Irrigation				
a. Irrigated land (km^2)	267	3168	2908	2908
b. Production (million MT)	0.46	2.69	2.50	2.50
c. Value (billion US$)	0.07	0.40	0.37	0.37
3. Objective function				
a. Value (billion US$)	0.07	1.89	0.66	0.64

Table A7: HEM results, 1-year low flows, flows to India

	Status quo	Infrastructure Development	Limited Infrastructure Development	Environmental Development
1. Hydropower				
a. Production (GWh)	44.4	57489	12764	11759
b. Energy to Western Nepal (GWh)	44.4	1111	1111	1111
c. Energy to Kathmandu (GWh)	0	120	120	120
d. Energy to India (GWh)	0.019	56258	11534	10528
e. Value (billion US$)	0.002	1.57	0.29	0.27
2. Irrigation				
a. Irrigated land (km^2)	282	1934	1934	1934
b. Production (million MT)	0.46	1.79	1.79	1.79
c. Value (billion US$)	0.067	0.26	0.26	0.26
3. Objective function				
a. Value (billion US$)	0.07	1.84	0.55	0.53

Table A8: HEM results, 1-year low flows, energy distribution

	Status quo	Infrastructure Development	Limited Infrastructure Development	Environmental Development
1. Hydropower				
a. Production (GWh)	44.4	59135	12764	11759
b. Energy to Western Nepal (GWh)	44.4	570	570	570
c. Energy to Kathmandu (GWh)	0	120	120	120
d. Energy to India (GWh)	0	58445	12075	11069
e. Value (billion US$)	0.002	1.60	0.28	0.26
2. Irrigation				
a. Irrigated land (km^2)	282	3466	3466	3466
b. Production (million MT)	0.46	2.86	2.86	2.86
c. Value (billion US$)	0.07	0.42	0.42	.42
3. Objective function				
a. Value (billion US$)	.07	2.03	0.70	0.68