Hydro-economic modeling for more efficient water resources management

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Overview

1. Brief overview of hydro-economic modeling
   - What is it and why is it useful?
   - Traditional approach
   - Brief overview of more recent conceptual advances

2. Examples

3. Basic overview of model structure for Western Nepal
What is hydro-economic modeling?

“Hydroeconomic models represent regional scale hydrologic, engineering, environmental and economic aspects of water resources systems within a coherent framework” (Harou et al., 2009)

• Solution-oriented tools for discovering strategies to advance efficiency in water use
• Shift away from quantity-based, or physical, “targets”
• Reliance on a single metric to guide decisions – economic value (rather than multiple objectives)
Why is hydro-economic modeling useful?

- Can answer questions about the value of new development (which hydropower, irrigation projects generate highest value, relative to costs?)
- Can be used to improve basin coordination (should dam storage be increased during some periods to better allow dry season irrigation?)
- Can help identify tradeoffs between uses (do we lose irrigation potential if we increase hydropower production?)
- Can help expand solution set (can changes in water management solve shortages?)
- Can help quantify economic losses or gains due to changes in other factors (how does climate or land use change affect economic outcomes?)
Common applications of these models

- From a recent review (Bekchanov et al. 2017), much work on:
  - Economic sensitivities (to climate change, value of energy, etc.)
  - Tradeoffs between uses, especially irrigation vs. hydropower
  - Water efficiency investments (drip irrigation, lining of canals, etc.)
  - Water pricing (which makes water use more efficient)
  - Water trade (where users can trade water rights to those willing to pay)

- Relatively less on:
  - Ecosystem values
  - Complex feedbacks (water-energy-food nexus)
Our ambition: Better capturing this complexity

Environmental System

Energy System
- Extracting resources
- Harnessing hydro, wind, solar, biomass energy
- Generating and transmitting electricity
- Production, refinement and distribution of transport fuels
- Storing, buffering

Food/Land Use System
- Preparing land
- Growing crops
- Raising livestock
- Harvesting produce
- Drying, processing
- Storing food products
- Transport, distribution
- Preparing food

Water System
- Manage renewable surface- and groundwater resources
- Distribute water supply for human consumption
- Collect sewage
- Treat wastewater to protect human and ecological health
- Transfer between basins
- Desalination

Water pumping, delivery, water treatment, energy for desalination

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Traditional hydro-economic approach

- **Optimization** model that helps planner choose “best” infrastructure (e.g. where, how big)
  - Economics enter the objective function, which is in $.
  - Typical objectives include maximizing the value of market outputs and/or minimizing penalty functions for undesirable impacts (like floods).

- Reliance on historical flows (stationarity).

- Exploration of future changes by:
  - Specifying changes as decision variables controlled by planner; or
  - Creating scenarios of development for factors outside planner’s control (e.g., assumed changes in hydrology, or population).

- Typical misconception: Hydro-economic modeling is usually for planning purposes, not for operations.
Problems with the traditional approach

- Planners do not have **perfect foresight**
  - Models that solve for “optimal” allocation are perhaps unconvincing
  - Operations may be quite different

- Water planners are **risk averse**
  - They may not care much about average results, but want to reduce risk
  - They tend to think in terms of ‘satisficing’, not maximizing $\$

- Water planning challenges **optimization**
  - Many-dimensional uncertainty, ‘deep’ uncertainty
  - Near optimality (flatness of objective), or non-dominance of solutions
  - Political economy of water
  - Valuation difficulties

- But various methodological advances allow improvements over the traditional approach (stochastic, robust optimization, fuzzy mathematical programming)
## Basic design choices in hydro-economic models

<table>
<thead>
<tr>
<th>Options</th>
<th>Description</th>
<th>Comments</th>
</tr>
</thead>
</table>
| **Model type:** Optimization | -What strategy is best?  
-Simulation -How does strategy perform if...? | -Flexible solution space, but may be unconvincing or challenge solvers  
-Computational advantages, realistic rule representation, but may underperform |
| **Flows:** Historic | -Measured series | -Intuitive comparisons for managers / decision makers, but future may not be like the past  
-Sampling from stochastic series’ |
| Stochastic    | -Best-worst / ranges  
-Scenarios -Well-specified prob. distributions  
-Risk-based -No or partial prob. distributions | -Deterministic and simple, but limited  
-Other -Amenable to standard methods in decision analysis, assume away “deep” uncertainty  
-Uncertainty -Perhaps most relevant, but challenge for decision-making |
| **Integration:** Modular | -Linked models run separately | -Well adapted to limited expertise, but can be clunky to use  
-Holistic -Single integrated platform | -Allow modeling of feedbacks; but may be difficult to run |
Choosing a particular architecture

- Need to know objective: Inform policy, promote uptake, or work at the cutting edge of methods?

- Tension between promoting uptake and maintaining objectivity:
  - Users often impose assumptions to improve realism
  - These assumptions may reduce transparency
II. Brief overview and discussion of examples from the Nile (Why the Nile?)
## Hydro-economic examples from the Nile

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Model type</th>
<th>Flows</th>
<th>Uncertainty</th>
<th>Integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wu et al. (NEOM)</td>
<td>2005; 2006;</td>
<td>Optimization</td>
<td>Deterministic</td>
<td>Flow, dams, energy value</td>
<td>Holistic (Full basin)</td>
</tr>
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<td></td>
<td>2016; 2017</td>
<td></td>
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<td>Strzepek et al.</td>
<td>2007</td>
<td>Optimization (CGE)</td>
<td>Deterministic</td>
<td>Capital shocks</td>
<td>Holistic (Egypt)</td>
</tr>
<tr>
<td>Block (IMPEND)</td>
<td>2010</td>
<td>Optimization</td>
<td>Deterministic</td>
<td>Climate scenarios</td>
<td>Holistic (Eastern Nile)</td>
</tr>
<tr>
<td>Jeuland (3 linked models)</td>
<td>2010a, b; 2014</td>
<td>Simulation</td>
<td>Stochastic</td>
<td>Flow; development</td>
<td>Modular (Full basin)</td>
</tr>
<tr>
<td>Halleux; Goor; Arjoon et al.</td>
<td>2009; 2010; 2014</td>
<td>Optimization</td>
<td>Stochastic</td>
<td>Infrastructure</td>
<td>Holistic (East. Nile)</td>
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<tr>
<td>(Nile SDDP)</td>
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<tr>
<td>Dinar</td>
<td>2013; 2015</td>
<td>Optimization</td>
<td>Deterministic</td>
<td>Initial rights</td>
<td>Holistic (East. Nile)</td>
</tr>
<tr>
<td>Geressu et al.</td>
<td>2015</td>
<td>Optimization</td>
<td>Deterministic</td>
<td>Weights for decision vars.</td>
<td>Holistic (East. Nile)</td>
</tr>
<tr>
<td>Satti et al. (SHOM)</td>
<td>2015</td>
<td>Optimization</td>
<td>Deterministic</td>
<td>Flow; prices; development</td>
<td>Holistic (Nile in Sudan)</td>
</tr>
</tbody>
</table>

**Flows**: Irrigation; Hydropower; Flood control

**Uncertainty**: Siltation

**Integration**: Economy-wide
III. Interdependence and tradeoffs: Example from the Ganges
To achieve optimal outcomes, one needs to consider the complete water resource system.

Several reasons: dependencies across...

- Space; e.g. spillovers/externalities not considered by agents located upstream.
- Time; e.g. depleting water storage (in soils, surface or groundwater) could lead to permanent changes in land cover and hydrology.
- Outcomes; e.g. markets for goods and services, nonmarket values, environmental quality.

The need to consider the system resonates with ecologists / engineers / economists.
Where do we see these ideas reflected?

Two examples (among others):

- **Wide inclusion in national policy of Integrated Water Resource Management (IWRM)**: “A process which promotes the coordinated development and management of water, land & related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems”

- **Hydro-economic optimization models**: How should one choose where to build infrastructure, how to allocate water, etc., to maximize economic benefit?
Ganges Basin: One of very first international case studies for hydro-economic optimization

Objective: Maximize economic benefits (Hydropower + irrigation – flood damages)

More recent Ganges model
Insights from these models

- The largest dams in the Himalaya do not provide much storage compared to annual flow of Ganges
- Tributary flows can be reduced somewhat with storage, but ability to control floods is limited
- Dams would provide low flow augmentation, but these induce tradeoffs between:
  - Irrigation (mostly in India) and
  - Ecosystem and water quality benefits (mostly in Bangladesh)
- Few other tradeoffs, at least at large scale
- What about at smaller scale (in Western Nepal?)
More recent Ganges model
IV. Western Nepal model: Basic structure
Figure 8. Module interconnections for HEM model

From Vishnu’s SWAT model
Figure 2. Interactions between production domains included in the WEEF framework
Nodes and links

Figure 9. River Node network scheme
Model schematic

A water-secure world

www.iwmi.org
Objective is to maximize economic value (from hydropower, irrigation, what else?)

Nodal water balance (inflow, storage, diversion, outflow)

Production using water: Energy, food crops, industry, other services (including environmental)

Consumption by end users (households)

Use of energy by water sector (nexus!)

Institutional & other constraints (minimum flows, specific allocation rules)
Questions we hope to ask…

- What is the value of new water infrastructure? (storage/hydropower dams, expanded irrigation canals)
- Are there tradeoffs between uses? (e.g., irrigation vs. hydropower, ecosystem services vs. hydropower)
- Are there tradeoffs across space and time? (groundwater irrigation now vs. later; micro-irrigation in hills vs. irrigation in Terai)
- What is the effect of institutional constraints? (guaranteed flow to Terai irrigation, or power supply to India)
Thank you!