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Balancing intersectoral demands in basin-scale planning: The case of Nepal's western river basins

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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

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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

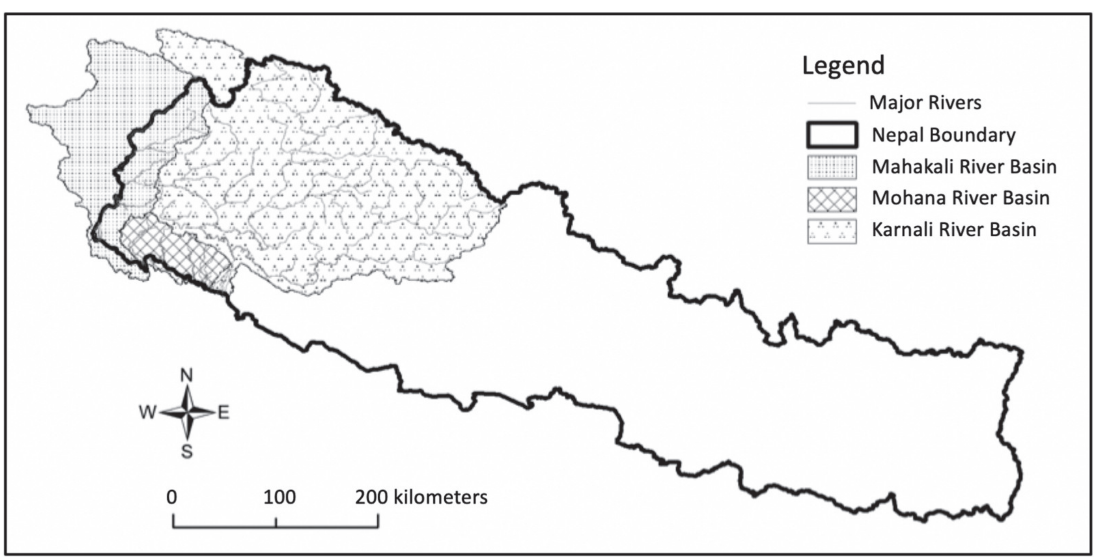

Fig. 1. Location map of the Karnali-Mohana and Mahakali River Basins in western Nepal.

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,

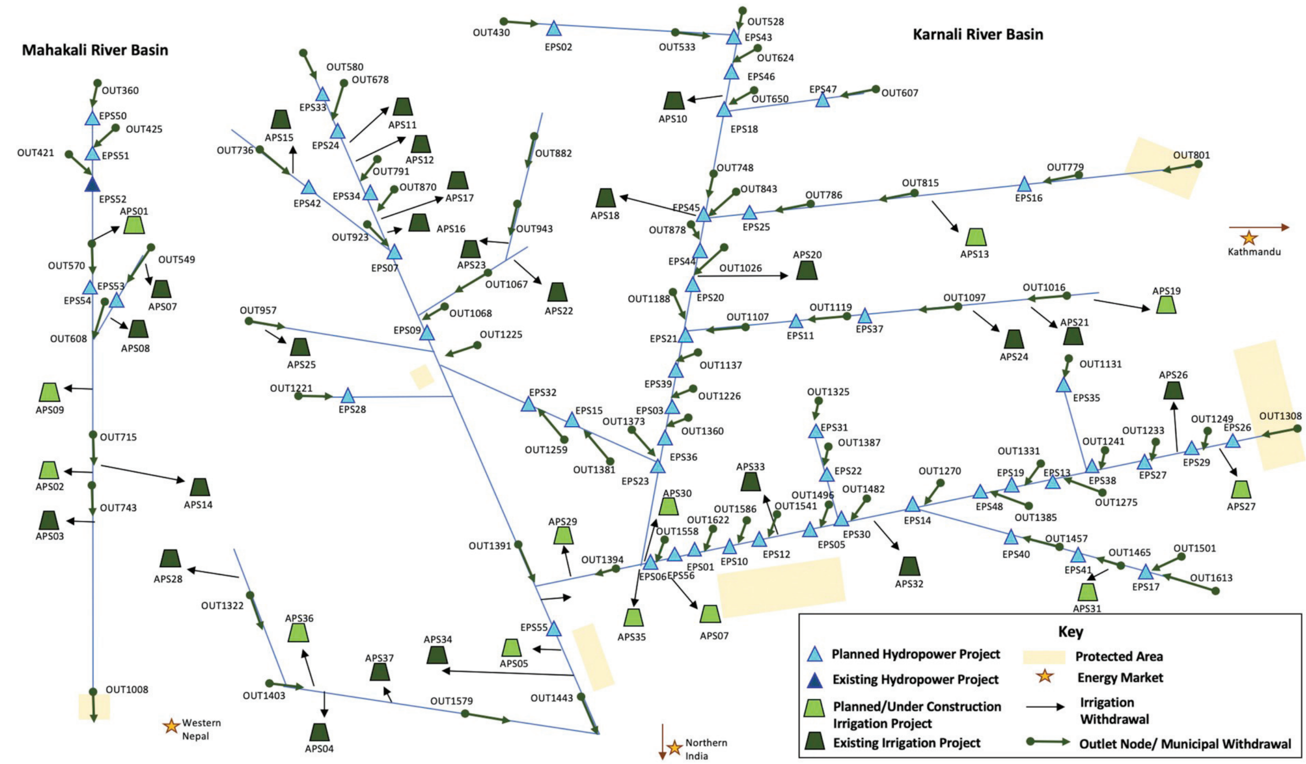

Fig. 2. Schematic of the Karnali-Mohana and Mahakali River Basins based on WNEWM node structure. Outlet nodes near energy and agricultural sites are included for reference; others are omitted to simplify the schematic. All outlet nodes (those included and omitted from schematic) allow for municipal surface 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.

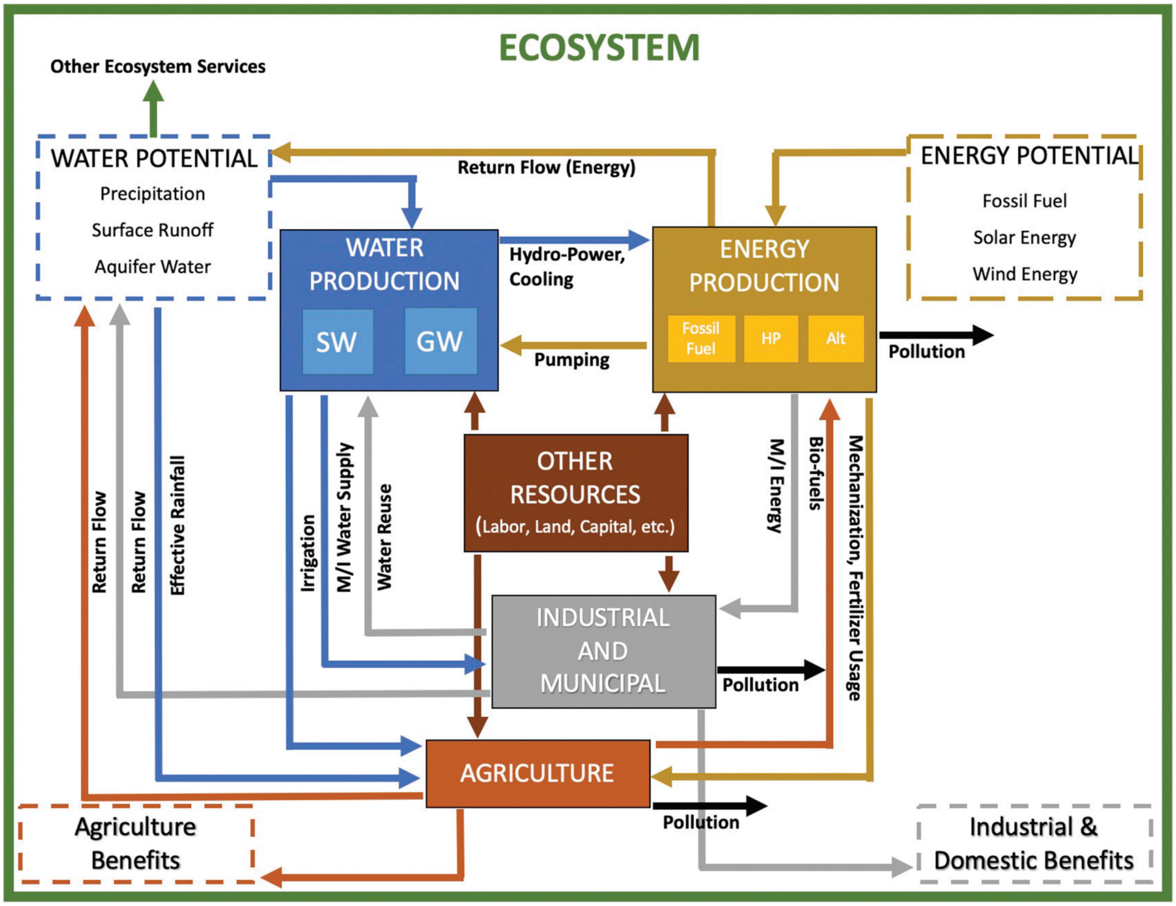

Fig. 3. Linkages between sectors in WNEWM approach.

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".

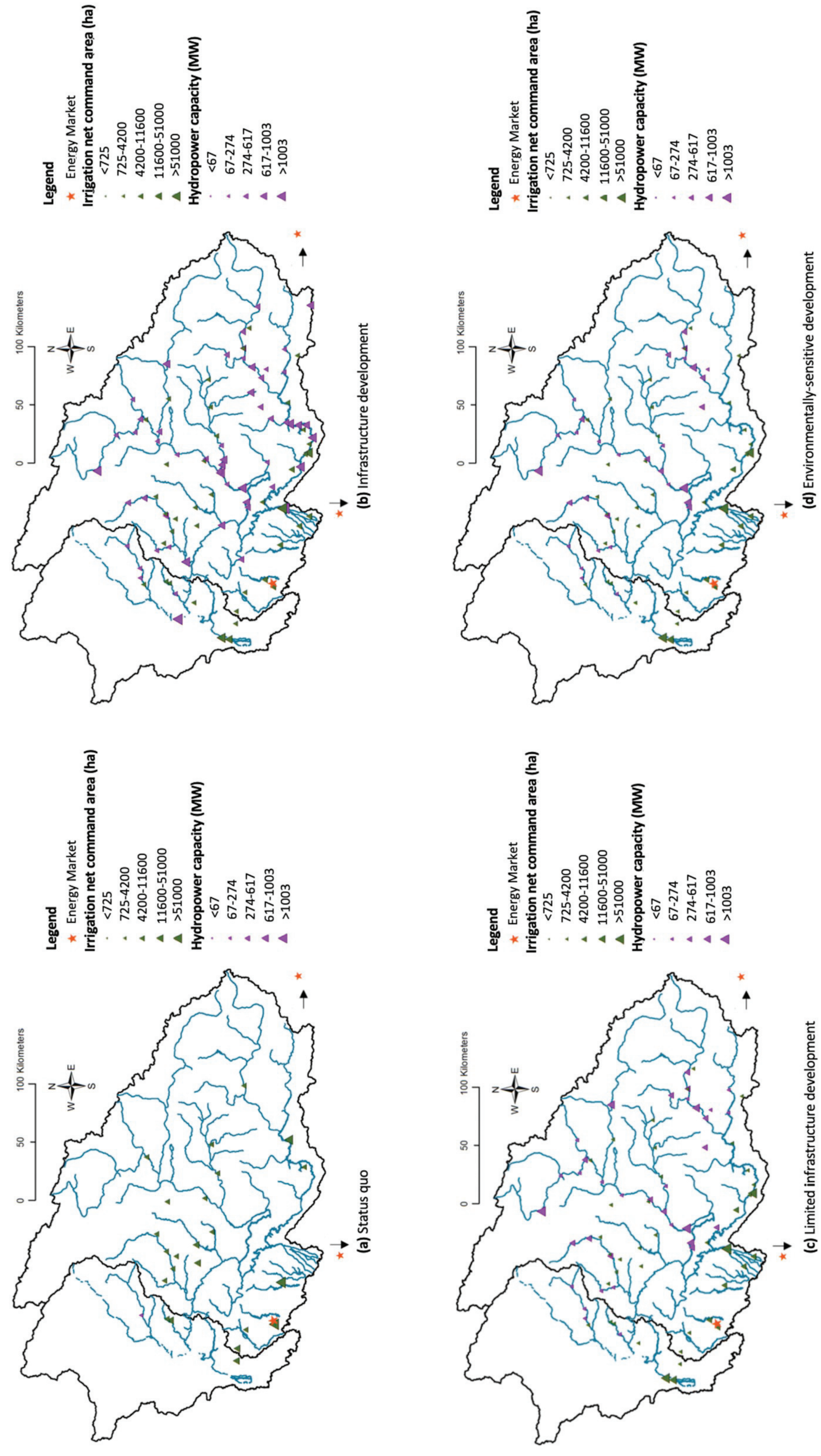

Fig. 4. Location of infrastucture projects in scenarios modeled using the WNEWM.

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.

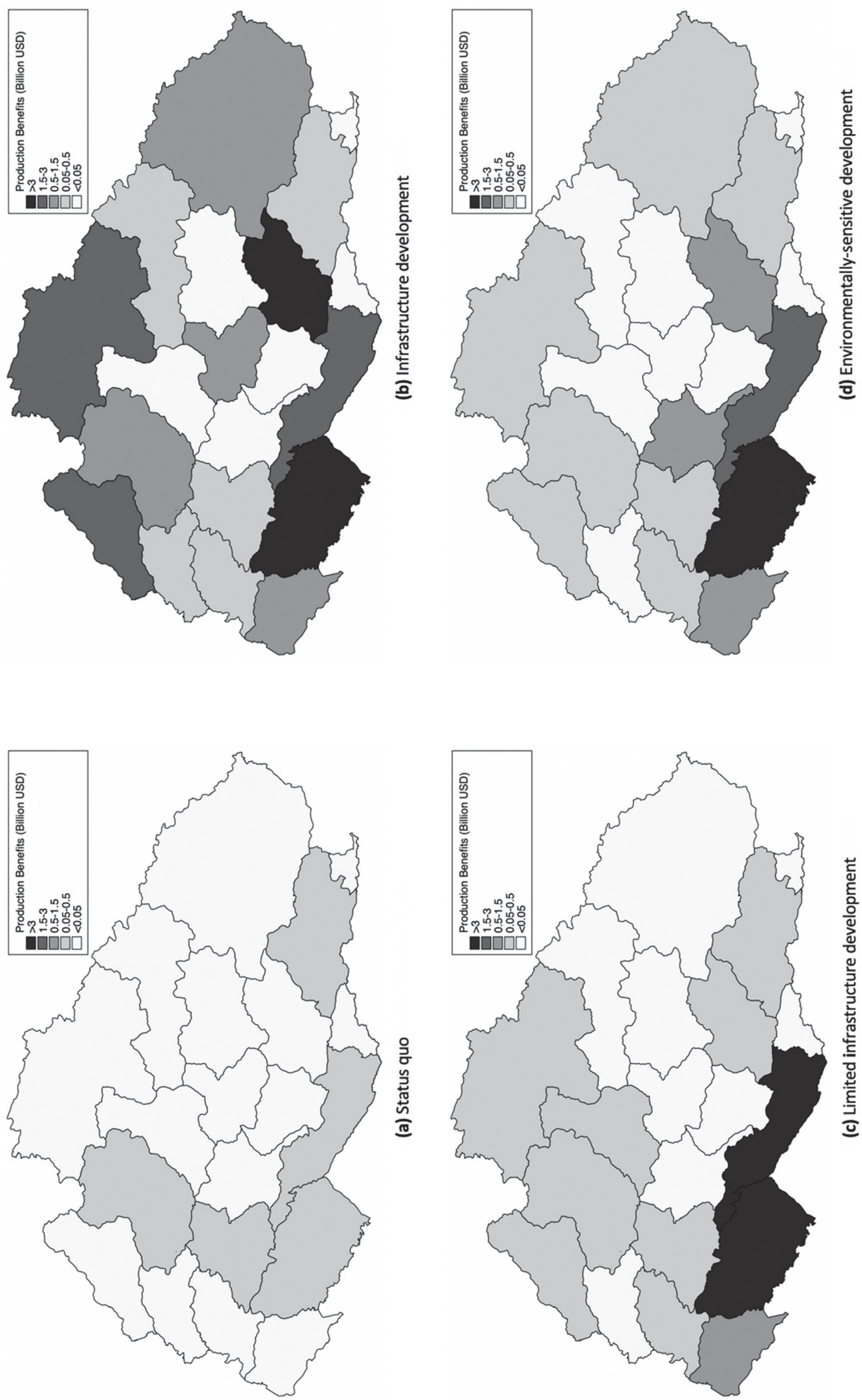

Fig. 5. Distribution of economic productivity throughout districts of the Karnali-Mohana and Mahakali River Basins.

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.

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Disclaimer

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Declaration of competing interest

None.

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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.

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