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Integrated modelling of the impacts of hydropower projects on the water-food-energy nexus in a transboundary Himalayan river basin

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HIGHLIGHTS

- Hydropower development in Himalayan region offer a low carbon development pathway.
- Hydropower development enhances food security, climate resilience and access to cleaner energy.
- Reservoir storage capacity supports flood regulation only if augmented by aquifer storage.
- The hydropower and irrigation benefits are robust under future climate scenarios.
- A transboundary electricity market is a pre-condition for efficient hydropower use due to seasonality.

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ABSTRACT

The sustainable development goals (SDGs) and the Paris agreement target a global cleaner energy transition with wider adaptation, poverty reduction and climate resilience benefits. Hydropower development in the transboundary Koshi river basin in the Himalayan region presents an intervention that can support the SDGs whilst meeting the regional commitments to the Paris agreement. This study aims to quantify the benefits of proposed water resource development projects in the transboundary basin (4 storage and 7 run-of-the-river hydropower dams) in terms of hydroelectric power generation, crop production and flood damage reduction. A hydro-economic model is constructed by soft coupling hydrological and crop growth simulation models to an economic optimization model. The model assesses the potential of the interventions to break the vicious cycle of poverty and water, food, and energy insecurity. Unlike previous studies, the model (a) incorporates the possibility of using hydropower to pump groundwater for irrigation as well as flood regulation and (b) quantifies the resilience of the estimated benefits under future climate scenarios from downscaled general circulation models affecting both river flows and crop growth. The results show significant potential economic benefits generated from electricity production, increased agricultural production, and flood damage control at the transboundary basin scale. The estimated annual benefits are around USD 2.3 billion under the baseline scenario and USD 2.4 billion under a future (RCP 4.5) climate scenario, compared to an estimated annual investment cost of USD 0.7 billion.

Abbreviations: ArcGIS, a geographical software extension for Environmental Systems Research Institute's (ESRI's) ArcMap; CO_2, carbon dioxide; DES, Directorate of Economics and Statistics; DSSAT, Decision Support System for Agrotechnology Transfer; ENVI, Environment for Visualizing Images; GAMS, General Algebraic Modeling System; GBM, Ganges–Brahmaputra–Meghna; GCS, geographic coordinate system; GIS, geographic information system; GWh, gigawatt hours; ha, hectare; IGBP, The International Geosphere Biosphere Programme; IPCC, Intergovernmental Panel on Climate Change; kg, kilogram; km^2, square kilometre; kWh, kilowatt hour; m^2, square metre; m^3, cubic metre; m^3/s, cubic metre per second; masl, metres above sea level; MIKE Basin, hydrological modelling platform based on ArcView GIS; MODIS, MODerate-resolution Imaging Spectroradiometer; MOD13Q1, the 16-days composite Terra MODIS NDVI 250 m grid data; MW, megawatt; NASA, National Aeronautics and Space Administration; NDCs, nationally determined contributions; NDVI, Normalized Difference Vegetation Index; RCP, Representative Concentration Pathway; REALM, the resource allocation model; ROR, run-of-the-river; SDGs, sustainable development goals; SEI, Stockholm Environment Institute; SWAT, the soil and water assessment tool; USD, United States Dollar; WaSIM, Water balance Simulation Mode; WEAP, Water Evaluation and Planning system; WEF, water, energy and food; WGS, world geodetic system; WRD, water resource development

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The robustness of the estimated benefits illustrates the climate resilience of the water resource development projects. Contrary to the commonly held view that the benefits of these proposed projects are limited to hydropower, the irrigation and flood regulation benefits account for 40 percent of the total benefits. The simulated scenarios also show substantial irrigation gains from the construction of the ROR schemes, provided the generated power is also used for groundwater irrigation. The integrated modelling framework and results provide useful policy insights for evidence-based decision-making in transboundary river basins around the globe facing the challenges posed by the water-food-energy nexus.

1. Introduction

The sustainable development goals (SDGs) of the United Nations emphasize the need for poverty reduction, hunger eradication, provision of cleaner energy and climate protection to secure human welfare and ensure planetary stability [1]. The Paris agreement and the subsequent nationally determined contributions (NDCs) reemphasize the commitment to protect the planet from dangerous climatic shifts and hence limiting the impacts on millions of people (eg: impact on livelihood and poverty levels that triggers mass migration) especially in the developing world by curtailing greenhouse gas emissions [2] and engaging in large scale adaptation [3]. Hydropower development in South Asia is an example of how the clean energy provision, poverty eradication, climate adaptation as well as mitigation, and economic development goals intertwine and hence is an ideal intervention that supports SDGs and the Paris agreement [4,5]. In South Asia, 281 million people are undernourished, 362 million people have no access to electricity and at least 600 million depend on biomass for cooking. Within this region, the highly populated (10% of the world population) Ganges–Brahmaputra–Meghna (GBM) transboundary (that spans China, Nepal, India and Bangladesh) basin that has highest concentration of rural poor (with limited access to energy, food and clean drinking water) in any given region of the world [6,7] while having largely untapped hydropower (eg: 42 GW in Nepal) [6,8] deserves particular attention.

Although the Ganges basin has enormous potential for multipurpose reservoirs and run of the river (ROR) projects (especially in Nepal), it ironically suffers from energy scarcity and inadequate irrigation facilities. Ganges sub-basins like the Koshi present a developmental conundrum as they tend to be underdeveloped with high levels of poverty and acute energy scarcity, despite their rich natural endowment with fertile soils and abundant water resources [9]. Frequent flood and drought events in the basin cause extensive physical and economic damages that translate into food insecurity, water scarcity, and rural poverty and persists in a vicious cycle, triggering large-scale migration out of the basin [10]. It is expected that the future climate shifts could significantly increase the frequency and severity of the flooding events in the region [11] and trigger increased flows of climate refugees [12]. One of the major development interventions expected to break this vicious cycle is the construction of multipurpose reservoir projects that tap the water-food-energy nexus [13] and provide additional benefits such as flood regulation and increased climate resilience [14,15]. This is in line with Nepal's NDC submitted to UNFCCC under the 2015 Paris Agreement, which envisages large-scale development of hydropower (4 GW of hydroelectricity by 2020 and 12 GW by 2030), promoting low carbon development [16]. It is furthermore argued that the development of hydropower can support the deployment of other kinds of intermittent (with peaks and troughs of electricity production) renewable sources such as wind [17] and solar energy as variation and intermittency of the sources can be tackled. The conventional hydropower projects with reservoirs can also act as pumped hydropower storage stations that can store excess energy produced by other renewables [18]. The IPPC report [19] highlights the importance of a rapid transition to a low emission development path in the energy, transportation and construction sectors, to achieve the target of limiting the global warming to 1.5 degrees. Developing hydropower in the Ganges–Brahmaputra–Meghna (GBM) basin can be a critical step in achieving the highly ambitious low emission path in South Asia, exemplified by the fact that the carbon intensity of electricity in India is 926 gCO_2/kWh [20] while the median carbon intensity for hydropower is 18 gCO2/kWh[21]. The potential of constructing additional dams in the Ganges basin of India is very limited due to existing hydropower exploitation, while the flood plains of Bangladesh are not suitable for the development of reservoirs [22]. Hence, the regional cooperation between upstream (Nepal) and downstream (India) countries is crucial for investing in water resource development (WRD) projects that can have significant impacts in food, water, and energy security in the basin [23].

Given the current largely unmet needs of power, irrigation, and flood regulation that hinder regional development, there is substantial scope for using WRD projects as engines for low carbon growth and climate resilient rural development utilizing the energy-water-food nexus. Previous research identified 11 high potential WRD projects in the Koshi river basin, of which 4 are storage and the remainder run-of-the-river (ROR) dams [24]. However, despite the potentially large multiple benefits, the basin-wide impacts of these proposed WRDs have never been quantified. There is a need for a systematic analysis of these impacts to assist informed decision-making, including an assessment of how potential changes in climate conditions, especially rainfall, could affect the performance of the hydroelectric projects. The study presented here aims to estimate the economic benefits of hydropower generation, increased crop farming using irrigation water, and the reduction of flood damage due to the proposed dam projects in the Koshi basin, and the sustainability of these benefits under future climate scenarios. A recent assessment by the World Bank [6] of proposed reservoir projects in the Ganges basin, which includes the Koshi basin, found that the lion's share of the expected benefits from upstream water storage dams accrue from hydropower generation, while the irrigation and flood control benefits are much smaller. Furthermore, given the low reservoir storage volume relative to the flow of the river, the report identified the use of groundwater aquifers as an alternative option for irrigation and flood water storage. The viability of this option depends heavily on the availability of electricity for pumping groundwater. Hence, the focus of this study is to also assess the potential impact of hydropower development on the possibilities for pumping groundwater to enhance irrigated agriculture and create space for flood water storage.

The performance of the identified WRD projects depends on factors such as river flow, water management rules, and upstream and downstream water use. A basin-scale analysis is therefore essential for integrated water resources management [25]. In order to assess the basin-wide economic benefits of the WRD projects and their sustainability in the light of future climate change, a coupled hydro-economic model is developed, paying special attention to the economic value of the storage space and irrigation capacity that can be created by surface and groundwater using hydroelectric power from the proposed set of dam projects in the Koshi basin and the stability of these benefits under future climate change [26]. Applying such an integrated model allows addressing the complex interplay of the water, food and energy nexus through optimization of the aggregate benefits, given possible trade-offs. The integrated modelling framework will be further elaborated below, following a brief description of the case study area.

2. Study area

The *Koshi* is one of South Asia's most important transboundary river basins, flowing through China, Nepal and India. The river originates in the Himalayan highlands and drains into the Ganges in the low plains of India. The river is approximately 730 km long with a catchment area of 87,311 km^2, of which 33% is located in China, 45% in Nepal, and 22% in India [27]. The river basin can be broadly divided into four physiographic regions: the Terai plains (60–200 masl); the hills (200–4000 masl), the mountains, and the trans-Himalaya extending into the Tibetan Plateau (above 4000 masl) [28]. The predominant agricultural system is cereal based, especially rice, wheat, and maize, in combination with livestock. The river and basin provide biodiversity and ecosystem services that sustain the lives and livelihoods of 40 million basin inhabitants [29]. The high average annual water availability (564 m^3/s at the major outlet *Chatara)* in Nepal offers considerable potential for hydropower development upstream and irrigation downstream, but the marked seasonality of precipitation results in flooding during the monsoon months and shortage of water (often acute) in the pre- and post-monsoon seasons.

The location of the Koshi river basin in South Asia, and the 11 proposed WRD projects, distinguishing between storage and ROR dams, are presented in Fig. 1. The Arun III, Bhote Koshi, Lower Arun, Sundarijal, Sun Koshi 3, Tama Koshi, and Upper Arun are ROR schemes, while the Dudh Koshi, Sapt Koshi, Sun Koshi, and Tamor are storage dams. The Sun Koshi and Sapta Koshi storage dams located in the Nepal mid hills are the largest hydropower producers, with a design capacity that is equal to almost three quarters (73%) of the predicted increase in hydropower generation in the Koshi river basin.

Current estimates indicate that the unmet water demand in the dry periods across the basin is about 660 million m^3, which is projected to increase to around 1000 million m^3 in 2050 [27]. The complex challenges facing the Koshi river basin include the growing demand for water, food and energy and the need to reduce the often catastrophic impacts of flooding, especially downstream in the densely populated state of Bihar in India. Addressing these challenges requires a comprehensive, integrated hydro-economic decision-support tool to improve understanding of the potential trade-offs and synergies involved.

3. Integrated hydro-economic modelling framework

3.1. Integrated hydro-economic modelling

Hydro-economic models are increasingly used as a decision-support tool for guiding and implementing water policy decisions, especially in relation to irrigated agriculture [30,31], climate change [32,33], and to a lesser extent hydropower [34,35]. There are two main kinds of modeling approaches: a modular or compartmental approach and a holistic approach [see 36 and 37 for a more detailed literature overview]. Modular models are created by coupling independent hydrological and economic sub-models, while holistic models are created as a single integrated model which solves all interdependent components and their causal relationships simultaneously [37]. Some holistic models are farm management models that are extrapolated to the basin scale [38]. A holistic model was developed recently for hydroelectric projects in Nepal [39], which is able to identify and assess the physical trade-offs in meeting multiple objectives, such as minimizing deficits in hydropower and irrigation water supply. A major issue with holistic models is that the complexities of the relationships they aim to assess are often stylized in order to be able to operationalize them, limiting their practical applicability. Examples of holistic hydro-economic model applications are presented in [39–41]. The coupling of independently developed hydrological and economic models allows for the inclusion of more relevant details in both realms [36]. Examples of modular models include different hydrological simulation models coupled with economic models such as REALM [42] or MIKE Basin-based economic optimization models [43], WaSIM coupled with a non-linear economic model [30], SWAT coupled with a linear economic

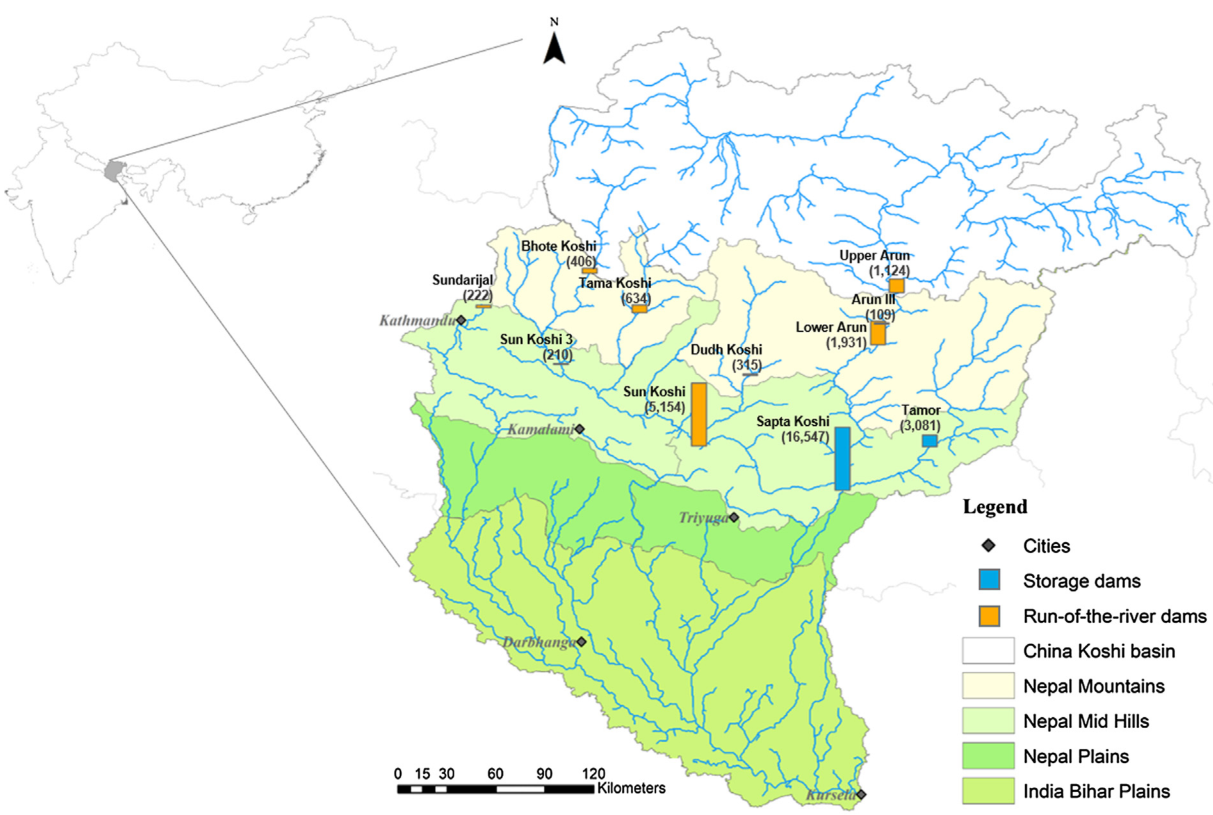

Fig. 1. Location of the proposed storage and run-of-the-river dams in the Koshi river basin in Nepal (design capacity in GWh between brackets).

model [44], and WEAP coupled economic optimization model [32]. The modular models can be soft coupled where component models run independently and results are fed into the optimization model or hard coupled where models run interdependently with feedback loops with an interface [30]. The development of hard coupled models are resource and time intensive and hence only a few case studies report to use them [30,31]. A hard coupled WEAP and economic optimization model is reported in [33]. Groundwater use optimization is considered only in few modular models like one reported in [32,45]. In the case of the Koshi river basin, a previous study uses a modular approach by coupling SWAT, MIKE Basin and an economic optimization model (for the whole Ganges basin) while crop water requirements are simulated using the FAO's CROPWAT [6].

The present study uses a modular approach in which the outputs of the Water Evaluation and Planning System model (WEAP) and the crop model, Decision Support System for Agrotechnology Transfer (DSSAT) are soft coupled with an economic optimization model. Both simulation models provide the necessary input for the subsequent economic optimization of the aggregate benefits of building the proposed set of hydropower dams. The interactions between the different model components are presented in Fig. 2. Driving the models are current and future climate conditions, where the latter is based on the Intergovernmental Panel on Climate Change's (IPPC) Representative Concentration Pathway (RCP) 4.5 from its 5th Assessment Report. The RCP 4.5 is a future climate scenario in which 4.5 W/m^2 radiative forcing from anthropogenic emission of greenhouse gases is assumed in 2100 relative to pre-industrial levels [45]. The climate data for this was downloaded from the MarkSim DSSAT weather file generator (http://gisweb.ciat.cgiar.org/MarkSimGCM/). In case of the modular approach used here, it is easier to develop, calibrate and solve individual hydrologic, agronomic and economic models with increased probability of convergence to an optimal solution. In addition to the increase in methodological rigor due to the use of separate modelling approaches for the various components, it saves significant time and resources required to simplify and integrate the model components operating at different scales into a holistic model and assure the effective use of future climate scenarios derived from downscaled general circulation models (GCM). The current model balances the objectives of water allocation, hydropower generation, climate adaptation and management of extreme events and provides outcomes that are relevant to policy making. The model considers groundwater management, flood regulation and future climate scenarios for both river flows and crop growth as additional aspects compared to previous attempt to model WRD projects in the Koshi river basin [6].

WEAP is a decision support software in itself, developed by the Stockholm Environment Institute (SEI) for evaluating water resources development, climate change impacts, and water management scenarios across varying spatial and temporal scales [46–48]. It has been used in a number of river basins worldwide to assist decision-makers in water planning and policy analysis. In this study, WEAP was calibrated for the Koshi basin using the results from a previous hydrological study conducted using the SWAT model to predict the likely impact of proposed reservoir projects on downstream flow, hydropower generation, and water storage under different scenarios [28,49]. WEAP utilizes a water mass balance with upstream-downstream flows in a river system, taking into account water withdrawals and water inflow in a sequential manner. The Koshi basin was set up in the WEAP model with 127 catchment demand nodes to represent 127 agricultural demand sites and to quantify the water supply and hydropower generation. It also considers the impact of sedimentation and loss of storage capacity and hydropower production for the considered planning horizon. Nevertheless, the impact of a possible reduction in sediment load on crop farming in the basin could not be modelled given the dearth of data.

The DSSAT agronomic model can simulate the growth, development, and yield of up to 42 crops as a function of the soil-plant-atmosphere dynamics and is used to simulate the growth of the two principal crops in the Koshi basin (wheat and rice) for different levels of irrigation water and fertilizer under simulated weather conditions. The DSSAT crop simulations are used to provide calibrated response functions while the WEAP outputs (surface water allocation, hydropower production and reservoir storage) act as constraints under baseline (2010) and RCP 4.5 (2050) climate scenarios within the economic optimization model. The soft coupled model is used to estimate the benefits of hydroelectric power generation, crop production, and flood damage reduction, while balancing the augmentation of irrigation using groundwater pumping, creating aquifer storage space, and using hydroelectricity for pumping. The economic optimization model is coded using the General Algebraic Modeling System (GAMS) for mathematical programing and optimization [50]. The estimated surface water and aquifer storage space are plugged into a flood damage function to assess the potential benefits of flood damage reduction [51]. In order to ensure optimality, the effect of a reallocation of surface water among different irrigation districts is also explored.

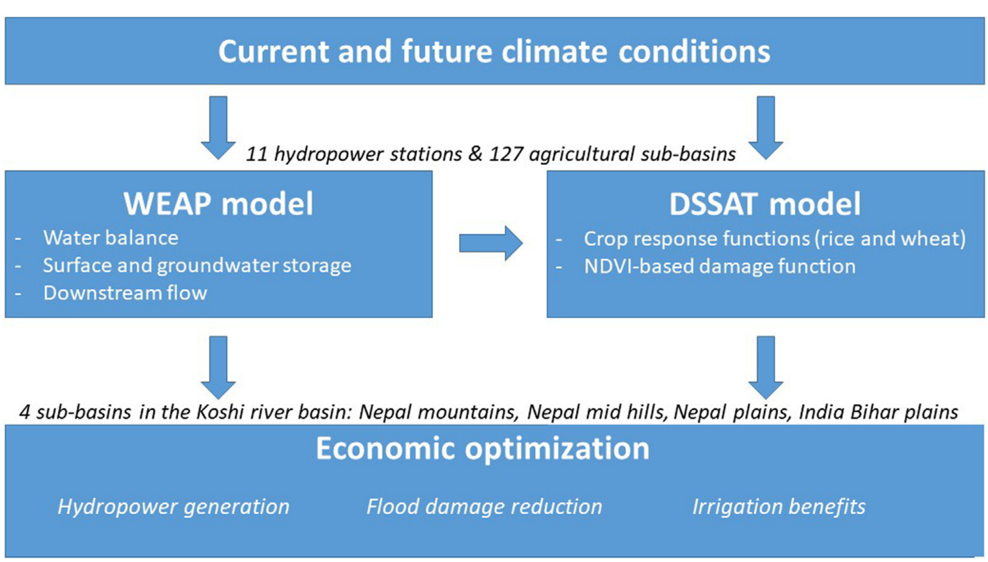

Fig. 2. The integrated hydro-economic modeling approach showing the soft coupling among the WEAP, DSSAT and economic optimization model.

3.2. Economic optimization model

In hydro-economic models, water allocation is evaluated based on the value it creates [37]. The economic optimization model maximizes the basin-wide economic benefits from hydropower production, irrigation of crops, and flood damage reduction under baseline and future (RCP 4.5) climate scenarios. As stated, the simulated WEAP model outputs are taken as constraints on surface water, electricity production, and reservoir storage capacity. The various functions in the integrated model are described in the subsequent sections. The objective function can be written as folows;

$$\text{Maximize} \quad \sum_i P^e R^i + m\sum_k I^k + p\partial D^b\left(\frac{F^b}{\sum_i S^i + \sum_k G^k}\right) \tag{1}$$

where $R^i$is the hydropower generated in monthly steps by the ith reservoir calculated by the WEAP model, P^e is the assumed sales price of hydroelectricity, I^k is the irrigation benefit from the two major crops viz. rice and wheat in the kth agricultural sub-basin, m is a basin-wide benefit multiplier to proxy the indirect basin impacts, D^b is the basin-wide agricultural damage associated with a flood event probability p, and ∂ is the flood damage multiplier to approximate the aggregate flood damage costs including, for example, temporary business interruption as an indirect flood effect. Instead of simulating future flood events and calculating the damage avoided due to reservoir projects, we assume that the flood control benefit of a dam is a function of its storage capacity ($\sum_i S^i$), which is in turn a fraction of the total flow (F^b) in a normal year. For storage capacity, we also added groundwater pumping ($\sum_k G^k$) to represent the storage capacity created in underground aquifers if the hydroelectric power from a dam is also used for groundwater-based irrigation. The objective function is maximized under current and future climate conditions.

Agricultural benefits are calculated under baseline and future climate conditions in terms of the yield gain in major crops due to the dam building, in particular the storage dams:

$$Y_{mk} = A_{mk}\,(b_0^{mk}(1 - e^{(-b_1^{mk}W^{mk})})(1 - e^{-b_2^{mk}X^{mk}})) \text{ for each agricultural sub-basin } k \tag{2}$$

where Y_{mk} is the yield of the mth crop in the kth agricultural sub-basin, using water (W^m) and fertilizer (X^m), andA_{mk}, b_0^{mk}, b_1^{mk}, and b_2^{mk} are function parameters. The parameter values are derived using the simulated DSSAT crop model results per agricultural sub-basin. The calibrated DSSAT model is simulated with different combinations of irrigation water and fertilizer use under baseline and RCP 4.5 climate scenarios and the resultant dataset is used to calibrate the Mitscherlich-Baule agronomic production function specified in (Eq. (2)). This production function describes the yield response to an increase in the main input factors limiting crop growth, in this case irrigation water and fertilizer application. A similar procedure is followed in [52] using a quadratic production function. The Mitscherlich-Baule production function is preferred here because this functional form has been shown to be biologically and physically more realistic [51].

The irrigation benefit I_k is then calculated as the economic value increment of additional crop yield minus the cost of fertilizer and electricity for groundwater pumping:

$$I_k = \sum\nolimits_m ((Y_{mk} - Y_{mk}^b)P^{mk})L^{mk} - \gamma W_m^{gk} L^{mk} - \theta X_m^{gk} L^{mk} \tag{3}$$

where Y_{mk}^b is the current crop yield for agricultural sub-basin k and crop m; Y_{mk} is the crop yield with additional irrigation and fertilizer, P^{mk} is the crop price; γ is the unit cost of electricity, W_m^{gk} is the groundwater pumped for irrigation per ha in the kth sub-basin, θ is the unit cost of fertilizer, X_m^{gk} is the use of fertilizer per ha, and L^{mk} is the amount of land used for the mth crop in the kth sub-basin.

For simplicity, the area allocated to each crop is assumed to remain the same, although this assumption can be relaxed by allowing the model to optimize cropping patterns across all 127 agricultural sub-basins:

$$L^{mk} \le L_b^{mk} \tag{4}$$

where the irrigated area L^{mk} must be less than or equal to the current land area L_b^{mk} under the mth crop in the kth sub-basin.

Similarly, the amount of surface water irrigation W_m^k must be less than or equal to the sum of the water allocation W_m^{ak} calculated by WEAP and the groundwater pumped up using hydroelectric power W_m^{gk} in each sub-basin during the crops' growth season:

$$W_m^k \le W_m^{ak} + W_m^{gk} \tag{5}$$

The total amount of groundwater pumped up in each district W^{gk} is furthermore assumed to be less than or equal to the sustainable recharge capacity WS^{gk}:

$$W^{gk} \le WS^{gk} \tag{6}$$

Environmental flow constraints are not imposed in the optimization model as they are accounted for already in the WEAP model simulations. Given the abundant availability of groundwater for irrigation in this specific case study region, there are only negligible trade-offs in utilizing surface water for industrial and domestic applications and these are hence not considered any further here.

The energy required for pumping up the groundwater in kWh is calculated using Eq. (7):

$$E_k^g = 0.002725 H_k^g G_k \tag{7}$$

where G_k is the quantity of irrigation water required in the kth sub-basin in m^3, and H is the hydraulic head in the district. The total amount of electricity used for pumping groundwater E^g must be less than or equal to the electricity produced by all hydro-electric projects taken together:

Table 1
Basic input parameters and underlying assumptions in the economic optimization model.

Parameter	Value for Nepal & India	Source	Remarks
Electricity price	USD 0.06 per kWh	Average price per kWh from https://data.gov.in/	World Bank (2014) assumed a maximum price of USD 0.1/kWh
Price of nitrogenous fertilizer	USD 0.12 per kg	Average price of urea in Nepal and India	46% N content assumed
Basin level agricultural benefit multiplier	1.3	Expert opinion	Assumed to be comparable to estimated multiplier of 1.5 for the Indus river
Rice and wheat prices (farm gate)	Rice USD 0.165 per kg Wheat USD 0.190 per kg	Directorate of Economics and Statistics (DES), India	Wheat prices are slightly higher in Nepal (USD 0.210 per kg)
Rice and wheat area in the basin	Rice 1,523,799 ha Wheat 1,106,119 ha	DES, India; Ministry of Agriculture, Nepal	Area in Indian and Nepalese districts within the basin
Transfer and distribution losses	0.25	http://data.worldbank.org	Losses range from 0.18 in India to 0.31 in Nepal
Flood damage to agricultural production	0.4	NDVI analysis of Koshi basin	Average change in NDVI during flood events is used to proxy agricultural damage
Basin level water flow level in normal year	52,731 million m^3	[58]	

$$E^g \leq \sum_i R^i \tag{8}$$

where R^i is the amount of electricity produced by the hydropower projects.

Finally, the basin-wide avoided agricultural damage costs D^b (i.e. the flood control benefits) in the objective function are further specified by Eqs. (9) and (10), where Eq. (9) captures the space created by groundwater pumping for flood water storage and Eq. (10) the amount of flood damage based on previous flood events in the Koshi basin, reflected by the agricultural damage factor ϵ:

$$\sum_k G^k = \sum_{m,k} W^g_{mk} \tag{9}$$

$$D^b = \epsilon \sum\nolimits_{m,k} ((Y_{mk})P^{mk})L^{mk} - \gamma W^{gk}_m L^{mk} - \theta X^{gk}_m L^{mk} \tag{10}$$

3.3. Model calibration

The basic input parameters and underlying assumptions used for the benefit functions are provided in Table 1, while Table 2 presents the calibrated parameters for the Mitscherlich-Baule crop response production function in Eq. (2). All prices are for the base year 2010. A remote sensing assessment was carried out to estimate the agricultural damage factor ϵ due to flooding. Agricultural damage was proxied here through the assessment of changes in the density of vegetation on agricultural land using the Normalized Difference Vegetation Index (NDVI). The 16-days composite Terra MODIS NDVI 250 m grid data (MOD13Q1) for the entire Koshi river basin were acquired from February 2000 to December 2014. The time series consisted of 23 16-day composite periods per year. One tile (h25v06) provided basin-wide coverage. A total of 345 tiles were obtained from the NASA Earth Observation gateway (reverb.echo.nasa.gov). The coordinate system of all images was defined in GCS_WGS_1984 from the sinusoidal projection using ArcGIS. The images were then clipped using the Koshi river basin boundary shape file, and the mean value of NDVI was extracted for the agricultural land cover class as derived from the IGBP land cover image (from Spatial Analyst Tools, Zonal statistics). In order to extract the agriculture pixel NDVI from the MODIS data, the land cover attribute data were resampled at 250 × 250 m resolution using the image processing software ENVI (Environment for Visualizing Images) pixel aggregate function.

Fig. 3 shows the NDVI over time and impact of the flood events on NDVI. The sharp declines during the months June-July can be attributed to floods. The average percentage decline in NDVI was calculated from the derived data and used as an approximation for the level of agricultural damage.

4. Results

4.1. Hydroelectric power

The hydroelectricity production simulated by the WEAP model in each season after the dams are constructed under the baseline scenario is shown in Table 3. The monsoon season is June-September, while the pre-monsoon is from March to May and the post-monsoon covers October and November. The aggregate electricity generation is almost 30 thousand GWh, of which 85% originates in the Nepalese mid hills and 15% comes from the Nepalese mountains. Hence, all the hydropower dams benefit Nepal. The storage dams are responsible for the lion's share of the electricity production (84%), the remainder is from the ROR dams. The total production of the 11 dams is more than four times current electricity consumption in Nepal and considerably more than the projected electricity demand of 17,869 GWh in 2027/28 [53]. As expected, electricity production peaks in the monsoon season and reduces to very low levels in winter. The amount and pattern of production indicates that transnational electricity trade will be required to sell surplus power during the monsoon months and to buy back power in the winter months (December-February) to manage the deficit. This will require considerable investment in transmission line infrastructure. The success of the 370 MW hydro-electric project at Chhukha in Bhutan with transmission lines to Phuntsholing in India that distributepower to four Indian states illustrates the feasibility of such a trading system. The costs of construction of the project were recovered within the first 5 years of its' operation in the case of Chhukha project [7].

4.2. Crop production

The storage dams provide a storage capacity of close to 8.4 billion m^3, which could supply additional water for irrigation, drinking, and industrial use. The ROR dams have no capacity to store water for irrigation, but provide electricity that can be used to pump up groundwater for additional irrigation. Fig. 4 shows the potential water supply to different parts of the basin from the dam projects in different months as simulated by the WEAP model. The simulations show that the Bihar plains downstream in India receive by far most of the water compared to the Nepalese mountains, mid hills and plains, and are hence the largest beneficiaries.

The predominant economic use of the additional water supply is irrigation. Fig. 5 shows the additional output values per hectare generated by the transition to intensified irrigated agriculture in the main sub-basins in Nepal and India under baseline and future climate conditions. It should be noted that these output values reflect gross margins for rice and wheat, hence the reason for their relatively high values per hectare. These values account for the additional irrigation water and fertilizer application costs, but they remain gross of regular production costs (e.g. labour, material and machinery costs). From Fig. 5, it can be observed that the increase in output value is always higher for wheat than for rice, and the absolute value increase for both wheat and rice is highest in the Nepal plains. The relative increase in output value under climate change compared to baseline conditions varies from 3 to 30% in the Nepal plains and mountains. Although the Bihar plains in India are a major beneficiary of the increase in water supply as a result of the hydropower dam building in Nepal, the impact of the additional irrigation water on crop output values is limited compared to the increase in crop yield values in Nepal. On average across the whole basin, the increase in output value in India is between 27% (rice) and 35% (wheat) lower than in Nepal.

4.3. Economic benefits of multipurpose dam construction

An overview of the estimated economic benefits associated with the proposed multi-purpose dams in Table 4. The total economic benefits generated by the hydroelectric power projects under the baseline scenario are almost USD 2.3 billion per year, with the greatest contribution coming from hydroelectric power (61%), followed by increased

Table 2
Parameters for the crop response function (Eq. (2)) under the baseline and RCP 4.5 scenario.

Sub-basin	Crop	Baseline			RCP 4.5 (2050)		
		b_0	b_1	b_2	b_0	b_1	b_2
Nepal mountains	Rice	2527	0.00079	0.0280	4000	0.0020	0.0065
	Wheat	2361	0.063	0.1011	2567	0.0631	0.1011
Nepal mid hills	Rice	3500	0.0041	0.0115	3500	0.0031	0.0105
	Wheat	3337	0.0092	0.0642	3404	0.0072	0.0657
Nepal plains	Rice	6000	0.0467	0.00751	6000	0.0467	0.0080
	Wheat	3412	0.00348	0.1270	3381	0.0032	0.1555
India Bihar plains	Rice	2177	0.1659	0.00979	2501	0.0018	0.0079
	Wheat	3392	0.00759	0.02923	3303	0.0105	0.0271

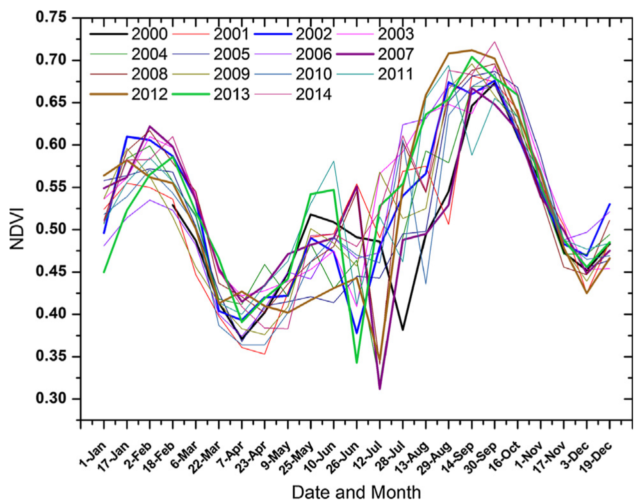

Fig. 3. Changes in NDVI in the Koshi river basin over the period 2000–2014.

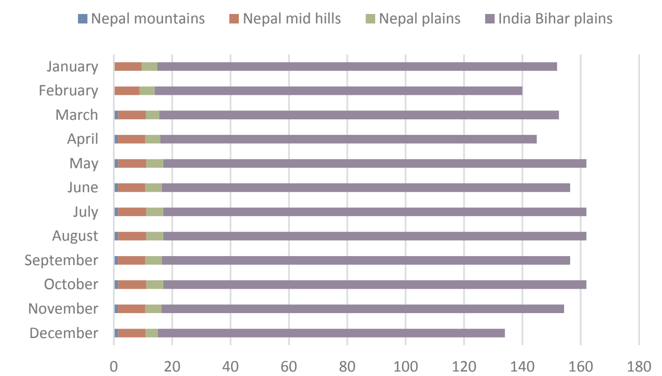

Fig. 4. Simulated water supply in million m^3 from the dam projects to different parts of the Koshi river basin each month.

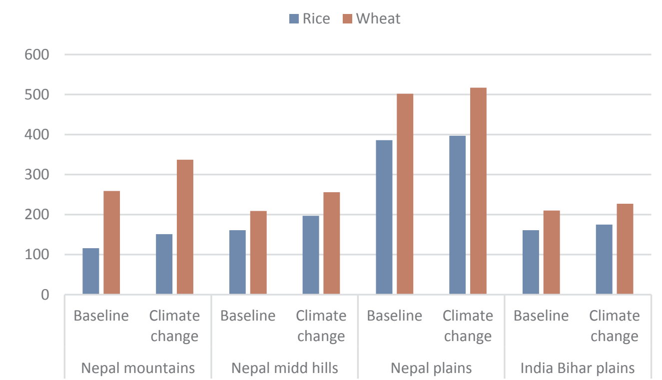

Fig. 5. Increase in the output value of the two main food crops in the Koshi river basin in 2010 US dollars per ha over the status quo due to dam building under baseline and future climate conditions.

irrigated crop production (36%). The estimated benefits from reduced flood damages are limited to 3%. The irrigation and flood regulation benefits together account for around 40% of all the estimated benefits, countering the commonly voiced view that the benefits of the Koshi basin reservoir projects are limited to hydropower. The World Bank study [6] for all dams in the Ganges basin (including the Koshi river basin) estimated that a large majority of the total benefits of between 74% and 90% are expected from increased hydropower alone, with a limited share associated with increased irrigation and the societal value of the water ecosystem. The latter could, however, not be quantified. The lack of value assigned to the non-hydroelectric benefits of the hydropower projects in studies such as [6] is due to the assumption of low marginal benefits and underestimation of the impact of using hydroelectricity for groundwater pumping, which offers both irrigation and flood water regulation benefits. Nevertheless, it should be noted that we assumed the possibility of electricity trade so that excess electricity produced during peak flow periods can be used during low flow periods. This is especially applicable to the ROR projects. The estimated flood control benefits of USD 70 million per year result from an estimated 27% reduction in flood losses from large flood events (that reduce the NDVI by up to 40%), accrue especially to the impoverished state of Bihar in India. Around 85% of the flood regulation benefits shown by the model are obtained through groundwater pumping and creating aquifer storage capacity. Significant flood regulation is only possible through the creation of sufficient aquifer storage capacity and the implementation of effective methods and technologies to recharge aquifers with the flood water. The electricity required for groundwater pumping appears to be less than 1% of the total amount of electricity generated by the dams according to the optimization model. The estimated benefits under the baseline scenario of USD 2.3 billion per year outweigh the estimated annual costs of USD 0.68 billion for the 11 hydropower projects (based on [6], with an initial investment of USD 12.5 billion discounted over the next 50 years at a 5% discount rate).

Under the future climate scenario RCP 4.5, the annual benefits for all dam projects increase by 7% from USD 2.28 billion to USD 2.43 billion, mainly due to the USD 130 million increase in benefits from

Table 3
Projected hydropower generation and water storage increase following the construction of the hydropower dams in the Koshi river basin.

Dam	Type	Available storage (million m^3)	Hydropower generation (GWh)				
			Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Nepal mountains							
BhoteKoshi	ROR	–	47	100	187	72	406
Tama Koshi	ROR	–	38	161	372	63	634
Dudh Koshi	Storage	162	25	34	209	47	315
Upper Arun	ROR	–	169	279	451	225	1124
Arun III	ROR	–	8	33	60	8	109
Lower Arun	ROR	–	364	524	695	348	1931
Nepal mid hills							
Sundarijal	ROR	–	27	61	113	21	222
Sun Koshi 3	ROR	–	25	54	94	38	210
Sun Koshi	Storage	3040	242	501	3627	784	5154
Sapta Koshi	Storage	4420	761	2375	10,716	2695	16,547
Tamor	Storage	760	81	553	2189	258	3081
Total		8382	1787	4676	18,712	4558	29,733

Table 4
Summary of the estimated economic benefits of multipurpose dam construction in the Koshi river basin under baseline and future climate scenarios.

	Baseline scenario		Future climate scenario	
	2010 Billion USD/year	%	2010 Billion USD/year	%
Hydroelectric power generation	1.39	61.0	1.39	57.3
Additional crop production	0.82	36.0	0.95	39.0
Flood control	0.07	3.0	0.09	3.7
Total	2.28	100	2.43	100

irrigated crop production, although the relative change in annual flood control benefits under climate change is considerable as well (29%). The gain in the estimated benefits under the future climate change scenario reflects increased resilience capacity provided by the surface and groundwater irrigation facilities as highlighted by [53]. Note that future crop yields are expected to fall by 5% from baseline conditions if the dams are not built. It is to be noted that agriculture provides one third of GDP and employs two thirds of the rural people in the Ganges basin [54] and hence any reduction in production and profitability of the staple crops can have far reaching social and economic impacts. Furthermore, if hydroelectricity is considered a zero emission source, the Koshi basin hydropower projects could save around 2.9 million tonnes of CO_2 per year. Based on an average carbon price of USD 15 per tonne of CO_2 and the assumption that 50% of the hydroelectricity generated would replace non-renewable (coal-based) electricity, the potential emission reduction benefits would be around USD 21.5 million per year, increasing the aggregated benefits to USD 2.30 billion per year. If electricity prices were to be revised in a sensitivity analysis from the assumed USD 0.06/kWh to USD 0.09/kWh, the hydroelectric power benefit alone would increase to USD 2 billion.

Finally, marginal values for the surface water constraint were examined across all 127 sub-basins to assess whether the allocation calculated by the WEAP model is economically optimal. Marginal values were positive, but very low in 14 of the 127 sub-basins (11%), which suggests that reallocation of the surface water entitlements across these agricultural sub-basins might further enhance the aggregate benefits from crop production. Relaxing the restriction of water allocation to each district, however, resulted in an additional benefit of merely USD 10 million.

4.4. Environmental and social impacts

The environmental and social impacts of the 11 hydropower dams were not evaluated quantitatively in the same level of detail as the benefits from hydropower generation, increased crop production and the expected reduction of flood damages in the hydro-economic modelling framework. The environmental and social impacts are, however, considered crucial [55], especially in the case of the storage dams, and will therefore be discussed here in a more qualitative manner.

The impact of the 7 ROR dams on the surrounding environment and communities living in the Koshi river basin is expected to be much more benign in view of the fact that the water flows will remain largely unaltered, there is no displacement of people or submergence of land. The three storage dams Dudh Koshi, Sun Koshi and Tamor will cause 25 to 65 km^2 of land to be submerged with limited displacement of people. However, in the case of the Sapta Koshi dam, the largest hydropower dam, 195 km^2 (19,500 ha) is expected to get inundated and some 75,000 people may have to be displaced [56].

Re-allocating say 1% of the hydropower benefits for catchment-wide afforestation would generate USD 14 million annually, enough for the afforestation of between 15,000–35,000 ha annually (USD 400–1000/ha/year). This can potentially largely offset the environmental costs of the submerged area of land. The costs of displacement and social disruption as a result of the Sapta Koshi dam are much more difficult to assess and quantify. Social resistance to the building of this dam may be substantial, and financial compensation may need to be carefully considered, based on the principle of benefit sharing. The storage dams alone, under baseline conditions, generate approximately USD 1.2 billion per year. Based on its design capacity, the Sapta Koshi dam would account for 66% of those benefits (USD 791 million per year). It would probably take more than a couple of percent points from the dam's total benefits to financially compensate those communities that would have to be relocated because of the dam building.

At the same time, the building of the storage dams upstream is expected to significantly affect flood risks downstream, especially possible loss of life and livelihoods in the much more densely populated plains in Nepal and Bihar, India. Although no official records exist of the total number of people who have lost their lives as a result of previous floods, especially Bihar in India has a long history of catastrophic flooding, most recently in 2008 and 2016/17 [57].

Additionally, the estimated results show that the net hydroelectric power available after meeting groundwater pumping energy needs would be enough for up to 4.5 million households (assuming 1010 kWh per capita per year which is the mean electricity consumption in India of a 5 members-household). There are 39.8 million people or around 7.96 million households living in the Koshi river basin. Thus, if used exclusively for the Koshi basin inhabitants, the hydroelectric projects have the potential to provide power to all households who currently have no access to the electricity grid (44% of the population). Improved access to modern forms of energy can significantly reduce poverty through enhanced economic growth, employment opportunities and other services provision [56]. However, such an outcome requires important complimentary infrastructure investments to enhance energy and market access. The estimated groundwater irrigation benefits are contingent upon a functional transboundary electricity market, as electricity production benefits would mainly occur in the upstream sub-basins, as well as supportive social and economic development interventions from central and local governments.

5. Conclusions and policy implications

The novelty of this study is that it is one of the very few attempts in the developing world to construct an integrated hydro-economic modelling framework to quantify the benefits associated with WRD projects in the water-food-energy nexus, highlighting how the estimated benefits are spatially distributed across a transboundary river basin under different climatic scenarios. Policy demand for this kind of information has increased exponentially over the past decade. Water policy typically faces the classical dilemma that the implementation costs of policy interventions can relatively easily be quantified. Quantifying the benefits of these interventions is usually much harder. The results of the integrated hydro-economic model, combining the WEAP and DSSAT model in an economic optimization procedure show that the expected benefits from the proposed multipurpose WRD projects in one of the poorest regions in South Asia can be significant in terms of generated electricity and enhanced agricultural production at the basin scale. The possible basin-wide flood protection benefits through the creation of aquifer storage, identified in a recent World Bank study for the Ganges basin were also quantified in this study, but appear to be limited, and highly dependent on the available technology to use groundwater aquifers to store floodwater. The estimated benefits under the baseline scenario of USD 2.3 billion gross per year outweigh the estimated annual costs of USD 0.68 billion for the 11 hydropower projects. Even if the investment costs would be twice as high as estimated to account for cost overruns (or vice versa, if the benefits would only be half of what they are expected to be based on this study), the benefits from the 11 projects would still outweigh their costs, generating a net benefit of USD 0.9 billion per year (or USD 0.5 billion if the benefits would be 50% less than estimated here). These results are robust when accounting for future climate change. The results highlight the fact that the development of hydropower in the Koshi basin can support the mitigation and adaptation goals of the Paris agreement and achieve the SDGs within the basin.

A key question is to what extent these net benefits offset the possible negative environmental and social implications of the 4 storage dams located in Nepal's mid hills sub-basin. These local environmental and social impacts were not further quantified in this study for a number of reasons. First, because the main objective of the study was to develop and apply an integrated hydro-economic modelling framework to quantify in particular the benefits associated with hydropower generation, irrigated agriculture and flood regulation based on existing market prices. Secondly, the quantification of the negative social and environmental externalities of hydropower often requires a different methodological approach, typically based on non-market valuation methods. A future extension of the current model could include such non-market values along with market values.

Another option would be to start with the implementation of the proposed ROR schemes since they have the lowest environmental and social displacement impacts, but their contribution to energy security in the basin is limited to 15%. Larger scale storage dams need to be constructed to secure increasing demand for electricity. To this end, there is a clear need for benefit sharing mechanisms to ensure that everyone who is in some way affected by the hydropower dams will benefit, especially local communities currently living in areas that will be submerged by the hydropower reservoirs. Transboundary collaboration is called for to realize the projected low-carbon economic development in the whole Koshi river basin. An energy market needs to be created to address high and low peak demand and allow trading between the low and high population density areas in the Koshi river basin, and adequate efficient irrigation facilities have to be put in place in order to be able to realize also the increase in food security.

The potential for flood regulation benefits highlighted in the previous World Bank study by storing floodwater underground in groundwater aquifers contributed least to the total estimated benefits (< 5%). More research is needed to further assess the behavior of groundwater aquifers following increased pumping and recharge efforts, and the subsequent impacts on flood risks and the avoided financial damage to lives and livelihoods downstream of the proposed hydropower dams.

Finally, the findings reported here have important policy implications for achieving water, food and energy security, as well as mitigating the impacts of climate change. Benefits derived from hydropower, irrigation and flood moderation can serve as a catalyst for economic and social development, and help to achieve a number of the Sustainable Development Goals, including ending hunger, alleviating poverty and providing increased access to water and energy services as well as support the goals of the Paris agreement. However, the development of the proposed projects will critically depend on building mutual trust and favourable regional cooperation between India and Nepal. The probable impacts of future climatic changes on the food, water and energy security of the region and the developmental prospects offered by the WRD projects evaluated here might provide the political momentum for regional cooperation. It could offset the climate impacts on rural economy and enhance food security, subsequently reduce the chances of mass migration from this highly populated and impoverished region. The developed integrated hydro-economic modeling framework is generic enough to be applicable elsewhere in the Ganges–Brahmaputra–Meghna (GBM) basin and other regions of the developing world to assess the economic benefits of multipurpose hydro-projects in the context of the water-food-energy nexus.

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