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Climate change impact on hydropower generation and adaptation through reservoir operation in a Himalayan river, Tamor

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ABSTRACT

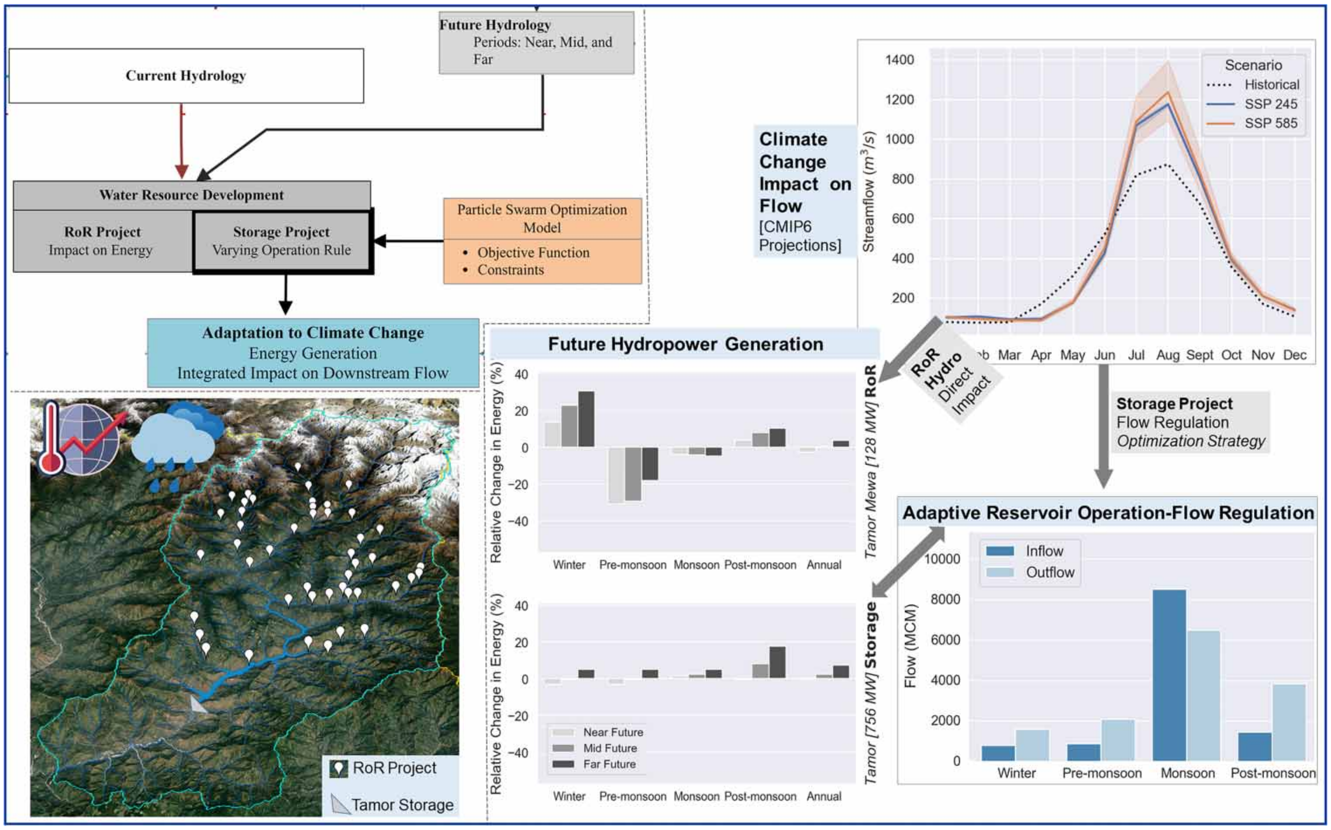
Integrated assessment of climate change impact and water resource development scenario is crucial for planning and management. In the Himalayan river basin, it is of utmost importance considering the vulnerability to climate change and the pace of water resource development. This study focused on Tamor river basin (TRB), investigating the impacts of climate change on the energy generation from hydropower projects and analyzes the adaptation through reservoir operation. Analyzing the three run-of-river (RoR) hydropower projects and a storage project, this study projects future energy generation. Results showed that RoR is highly susceptible to the impacts, demonstrated by significant reduction during pre-monsoon up to -53% and increment at annual scale up to 28%. In Tamor storage project, the particle-swarm optimization approach generated operational strategies according to altered streamflow conditions. This resulted in adaptation to the projected decrease in March-June flow through flexible operation rules, yielding positive impact on energy generation (up to +7.3% on an annual scale). The new set of rules will adapt to the flow deficit and increase the dry season flow downstream, almost by double than the historical baseline. This research highlights the significance of reservoir project and its optimized operation in effectively managing water under changing climate.

Key words: adaptation strategy, climate change impact, Himalayan river basin, hydropower, particle-swarm optimization, reservoir operation

HIGHLIGHTS

- An integrated assessment of the impact of climate change and reservoir operation is made.
- Decreasing RoR hydropower energy is projected during pre-monsoon in TRB.
- Optimized reservoir operation can be an efficient adaptation strategy.
- TSP can yield multiple downstream benefits under changing hydroclimate conditions.
- The development of a storage facility should be prioritized in the upstream region.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Global warming and associated climate change is a complex phenomenon that is under intense study by the scientific community for the risk it poses to sustainable human development (Chilkoti *et al.* 2017; IPCC 2023). Climate change ultimately affects water resources availability, both in terms of quantity and quality, by means of change in precipitation patterns, temperature, and associated alterations in snow melt, evapotranspiration, and river discharge (Piao *et al.* 2010; Grafton *et al.* 2013; Li *et al.* 2022). Therefore, climate change has a significant impact on associated water-use sectors such as hydropower, irrigation, domestic water supply, and the ecosystem (Schaefli 2015; Rasul & Sharma 2016; Habib-ur-Rahman *et al.* 2022).

The Hindu Kush Himalayan region, known as the water tower of Asia, is highly vulnerable to the climate change impacts (Bolch *et al.* 2019; Scott *et al.* 2019; Shrestha *et al.* 2021b; Yang *et al.* 2023). Studies have projected the change in water availability across the river basin and increase in hydrological extremes in terms of magnitude and frequency (McDowell 2002; Krishnan *et al.* 2019; Chhetri *et al.* 2021). An assessment of the impacts of climate change in this region is challenging due to the complex and heterogeneous hydrological system, characterized by multiple factors like topography, diverse vegetation, soil composition, and the spatio-temporal variability of meteorological conditions (Marahatta *et al.* 2021b; Panthi *et al.* 2021; Shin *et al.* 2021; Karki *et al.* 2023; Bista *et al.* 2024). Previous studies explored climate change impacts on water availability in major river basins in the central Himalayan region, in Nepal for Koshi (Devkota & Gyawali 2015; Kaini *et al.* 2021), Narayani (Bajracharya *et al.* 2018; Marahatta *et al.* 2021a; Singh *et al.* 2022), and Karnali (Dahal *et al.* 2020; Pandey *et al.* 2020). The impact is basin-specific and the future streamflow projections are accompanied by uncertainties associated with the emission scenario, climate models, hydrological modeling, and so on.

Due to the steep gradient and mountainous topography, Nepal is blessed with abundant hydropower potential (Shrestha 2016; WECS 2019; Baniya *et al.* 2023). Predominantly, hydropower projects in Nepal are run-of-the-river (RoR) type. Considering the planning and development scenario (DoED 2023), the contribution of RoR hydropower projects in the country’s electricity generation mix is expected to continue its dominance over other sources like storage-type hydropower and other renewables such as solar and wind power. Climate change can lead to reduction in river flows and directly influence water resource projects (Berga 2016; Wasti *et al.* 2022; Baniya *et al.* 2024). The hydrological response is likely to alter not only due to the impact of change in climatic parameters but also human intervention such as by way of reservoir operation and water extraction (Nam *et al.* 2012; Ghimire *et al.* 2023). RoR projects that rely heavily on water availability may not be sufficient for ensuring sustainable and long-term energy production (Shrestha *et al.* 2021a). Reservoir-based hydropower projects offer advantages in effectively adapting to climate change and addressing the limitations of run-of-the-river systems. Such projects are crucial in adapting hydropower to climate change impacts by regulating water flow to optimize energy generation, mitigate floods and droughts, increase resilience to downstream RoR projects, and ensure reliable energy generation amidst changing precipitation patterns and water availability.

One of the effective strategies for climate change adaptation is optimizing the reservoir rule curve under changing streamflow scenarios (He *et al.* 2020; Yaghoubi *et al.* 2020; Thomas *et al.* 2021; Dash *et al.* 2023; Ehteram *et al.* 2023). This adaptation strategy involves considering climate projections, water availability projections through the modeling approach, and optimization of reservoir operation to determine the most suitable operational rule curve (Beça *et al.* 2023). He *et al.* (2020) derived adaptive operation rules focusing on power generation for a cascade reservoir system based on future streamflow projections and found significant increase in the annual power generation (up to 4.8%). In the Narmada Basin (central India), Thomas *et al.* (2021) tested the simulation only and simulation-optimization framework for integrated reservoir operation of four reservoirs under climate change scenarios. The simulation-optimization led to better reservoir performance fulfilling the domestic water supply, environmental flow demand, and substantially reducing the irrigation and hydropower failures.

The impact on the hydrologic regime and energy generation is case specific, depending on basin characteristics, project design, reservoir regulation, and so forth (Vaidya *et al.* 2021; Wasti *et al.* 2022). The research on this avenue is still lacking in the central Himalayan river basin, integrating the climate change and water resource development scenario. Relying on future hydroclimate projections, previous studies focused on energy generation impact on RoR projects (Shrestha *et al.* 2016; Mishra *et al.* 2018; Bocchiola *et al.* 2020) and storage projects based on the simulation approach (Chinnasamy *et al.* 2015; Shrestha *et al.* 2021a; Bhattarai *et al.* 2022; Marahatta *et al.* 2022). Integrated studies on the impact of climate change on hydrology and hydropower energy generation and reservoir optimization approach as appropriate adaptation strategies still remain less-explored.

Focused on the Tamor River Basin (TRB), this study addresses two research questions: (1) How does climate change alter the projections of hydropower energy generation? (2) And how can the planned reservoir adapt to the future hydro-climatic conditions? This study further analyzes the combined impact of climate change and reservoir regulation on downstream water availability and the water-use sector. Previous studies (Bhatta *et al.* 2019; Khatri & Pandey 2021; Shrestha *et al.* 2021b; Poudel *et al.* 2022) emphasized the fact that TRB is highly vulnerable to climate change impacts. Bhatta *et al.* (2019) found that the future climate could decrease the streamflow by over 8.5% during the twenty-first century. Khatri & Pandey (2021) projected decrease in streamflow during the months of March to June. This underscores the importance of assessing the impact of hydropower generation and the integrated impact of the planned reservoir project, the Tamor Storage Project (TSP). Based on hydro-climatic projection assessed by Khatri & Pandey (2021), this study quantifies the impact on energy generation. Further, it develops the optimized operation rules for TSP as an adaptation strategy to climate change. Such information would be helpful in policy formulation and decision making on water allocation, development of water infrastructure, and integrated river basin management.

2. MATERIALS AND METHODS

2.1. Study area and datasets

The TRB, located in the eastern part of Nepal, is one of the major tributaries of the Koshi River (Figure 1). The total length of the river is about 190 km and the major tributaries of the river are Ghunsa, Sibuwa, Kabeli, and Mewa. TRB, with a catchment area of 6,045 km^2, varies in topography from 129 to 8,376 m. It receives an annual precipitation of around 2,298 mm and the average annual minimum and maximum temperatures are 10.7 and 21.9 °C (Bhatta *et al.* 2019).

Numerous water resource infrastructures have been planned and are under different stages of development. There are 7 operational and 17 under construction RoR hydropower projects with total installed capacity of 94 MW and 711 MW, respectively (DoED 2023). TSP has been planned along with the Tamor–Morang water transfer project for irrigation in the Terai plains (DoWRI 2019). In this study, three RoR hydropower projects with capacity greater than 50 MW (Mewa

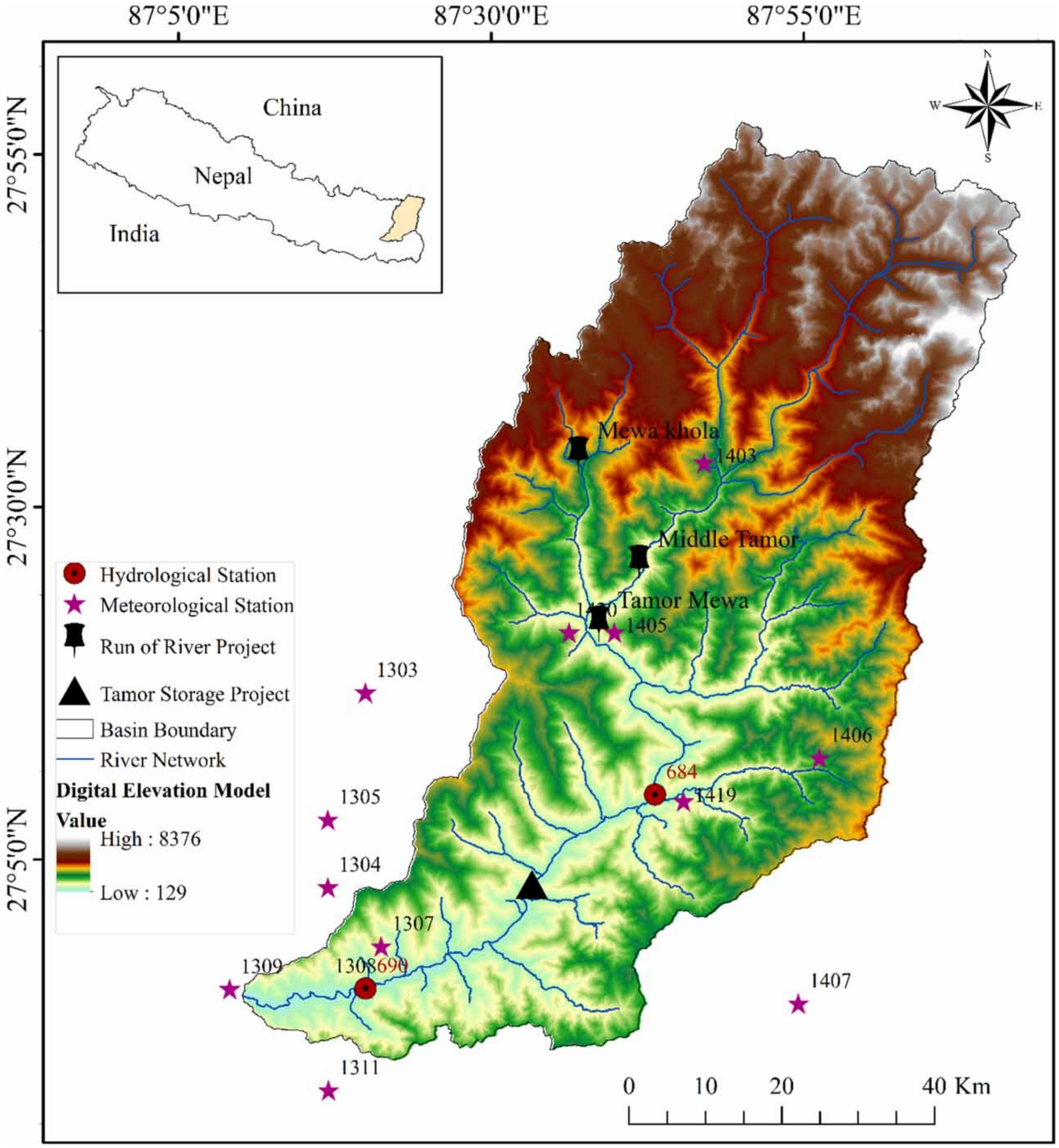


Figure 1 | Location, hydro-meteorological stations, hydropower, and elevation details of the Tamor River Basin.

Khola–50 MW, Middle Tamor–73 MW, and Tamor Mewa–128 MW) and a storage project (TSP–756 MW) are analyzed considering the planned water resources development in the basin.

The river basin information, geospatial map, and time-series data have been used by Khatri & Pandey (2021) for hydro-climatic modeling purposes. A Digital Elevation Model (DEM) with 30 m resolution was obtained from the Shuttle Radar Topography Mission (SRTM). Additionally, the land-use map (Uddin *et al.* 2015) was obtained from the International Centre for Integrated Mountain Development (ICIMOD) database. Furthermore, the soil map at a scale of 1:5,000,000 was acquired from the Soil and Terrain Database (SOTER), accessible online (https://www.isric.org/explore/soter) (Dijkshoorn & Huting 2009).

The hydrological and meteorological datasets were obtained from the Department of Hydrology and Meteorology (DHM), Nepal. Daily observed precipitation at 13 stations, temperature at 7 stations, and streamflow at 2 stations (Figure 1) were acquired from the DHM, spanning the period from 1989 to 2009.

The data related to hydropower design (Table 1) essential for energy calculations were obtained from the feasibility reports of the respective hydropower projects from the Department of Electricity Development (DoED), Nepal. The future streamflow time-series data required for energy calculations in each hydropower project are obtained from Khatri & Pandey (2021). For reservoir optimization purposes, information including storage-elevation-area curve, dam operational levels, and so on were obtained from the DoED, Nepal (Table 2).

2.2. Methodology

Khatri & Pandey (2021) employed the Hydrological Engineering Center–Hydrological Modeling System (HEC-HMS) in TRB to estimate future stream flow based on outputs from CMIP6 climate model outputs. This study further quantifies the impact of climate change on hydropower generation from different RoR and storage projects in the river basin. This study has considered RoR hydropower projects with installed capacity of 50MW or larger as case studies: Mewa Khola, Middle Tamor, and Tamor Mewa. Additionally, the study provides the strategy for adaptation to climate change in the reservoir project by optimizing the rule curve. Figure 2 represents the overall methodological flowchart, and the following subsection describes it in detail. Since this study is a further extension of the authors' work in Khatri & Pandey (2021), the readers are requested to refer to it for details on activities inside the red dotted box in Figure 2 up to streamflow projections. However, a short summary has been presented in Section 2.2.1.

2.2.1. Future hydro-climatic projection

Currently, the Coupled Model Intercomparison Project (CMIP) entered into its sixth phase (i.e., CMIP6) and the climate models have improved some parameterization schemes for major physical and biogeochemical climate system processes (Cook *et al.* 2020; Zhu *et al.* 2020). Among the four Shared Socioeconomic Pathways (SSPs), two scenarios were selected: SSP 245, representing a medium forcing middle-of-the-road pathway, and SSP 585, a high-end forcing pathway.

To analyze future climatic projections, precipitation and temperature (min. and max.) time-series data up to 2,100 were obtained from five CMIP6-GCMs, namely, ACCESS-CM2, EC-EARTH3, INM-CM5-0, MPI-ESM1-2HR, and MRI-ESM2-0. These GCMs were selected based on the previous studies in the Himalayan river basins (Mishra *et al.* 2020; Chhetri *et al.* 2021) and downloaded from https://esgf-node.llnl.gov/search/cmip6/. Biases in the GCM data were corrected based on an empirical quantile mapping method (Pandey *et al.* 2020).

A hydrological model of the TRB was developed using the HEC-HMS model, developed by the US Army Corps of Engineers (Feldman 2000). This model is physically based and semi-distributed, capable of simulating hydrological processes within a watershed to predict river discharge and water balance (Halwatura & Najim 2013; Yuan *et al.* 2019). The Thornthwaite method is used to characterize evapotranspiration in the model for different climate scenarios. For sensitivity analysis, several parameters were initially selected based on other studies in other Himalayan basins. Among these parameters,

Table 1 | Information of selected RoR projects

S.No.	Hydropower project	Capacity (MW)	Gross head (m)	Design discharge (m^3/s)
1	Mewa Khola	50	198.8	33.0
2	Middle Tamor	73	132.0	73.7
3	Tamor Mewa	128	124.5	126.0

Table 2 | Physical data of the TSP

S.No.	Reservoir features	Tamor storage project
1	Dam height (m)	210
2	Full supply level (m.a.s.l)	550
3	Minimum operation level (m.a.s.l)	492
4	Installed capacity (MW)	756
5	Dead storage level (m.a.s.l)	475

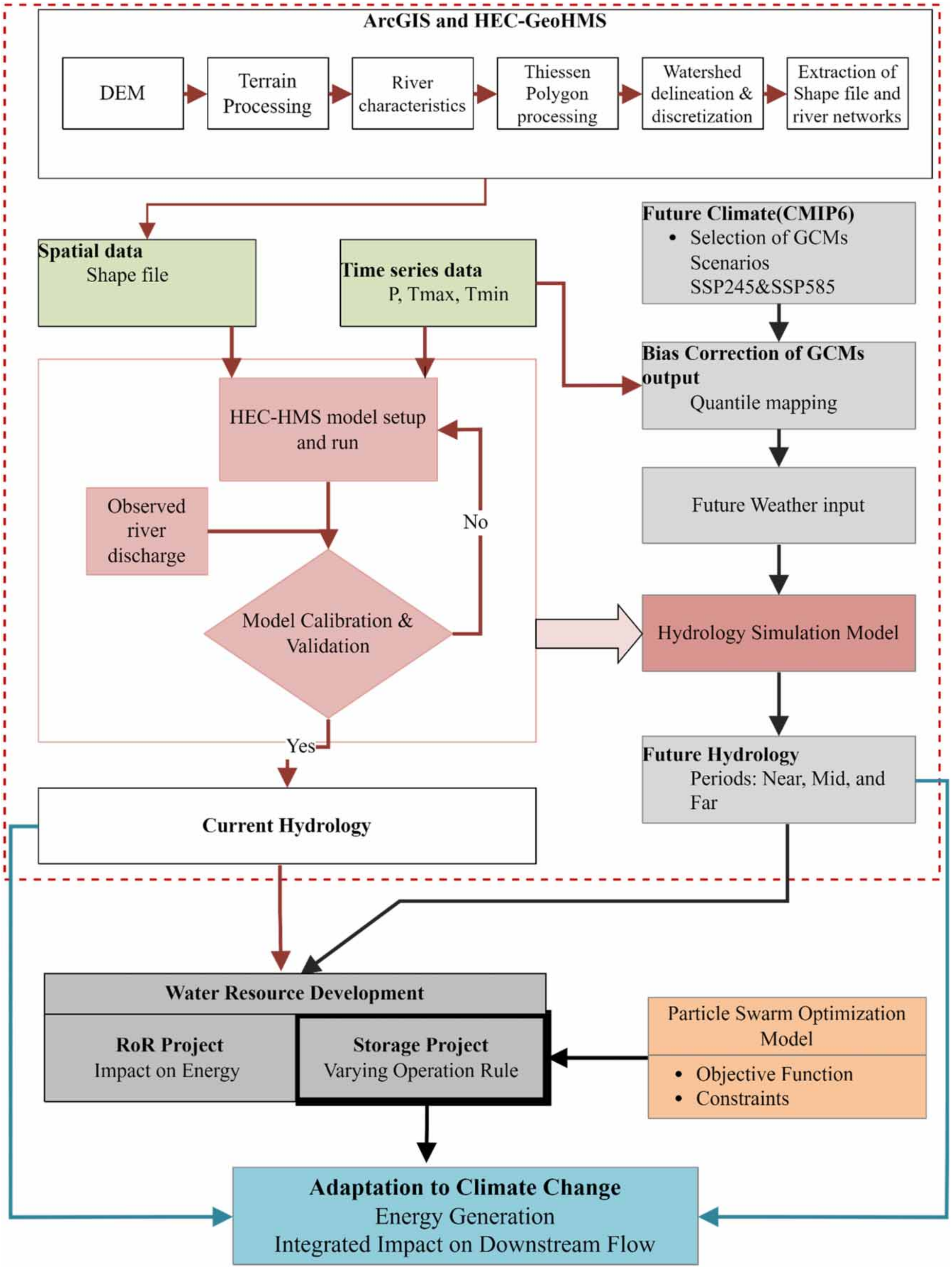


Figure 2 | Methodological framework for assessing climate change impacts on hydrological characteristics and hydro-energy generation in the Tamor River Basin (TRB). Please refer to Khatri & Pandey (2021) for the activities inside the red box.

imperviousness, lag time, conductivity, groundwater coefficient, and maximum storage were found to be the most sensitive to streamflow simulation. Multisite calibration approach at Majhitar and Mulghat enabled the model to capture the hydrologic response in the TRB. The bias-corrected future climate projections were then integrated into the calibrated model to obtain streamflow projections.

The ensemble approach of analyzing multiple GCMs helps mitigate the risks and uncertainties associated with relying on a single model (Turner & Annamalai 2012; Bhatta *et al.* 2019). All the results presented in this study are also based on the ensemble of projections from the five GCMs. With bias-corrected future rainfall and temperature time-series data, the calibrated HEC-HMS model was forced to simulate future streamflow at different intakes of the considered hydropower projects. For analysis purposes, the months are grouped into four prevailing seasons in the central Himalayan basin: pre-monsoon (Mar–May), monsoon (Jun–Sep), post-monsoon (Oct–Nov), and winter (Dec–Feb).

The details on methodological procedure and results on future rainfall, temperature, and streamflow projections in TRB have been presented in Khatri & Pandey (2021).

2.2.2. Energy projection

Hydropower generates the electrical energy by converting the potential and kinetic energy of river flow. Equations (1) and (2) below illustrate the formulas used to determine the energy generation:

$$\mathrm{P} = 9.81\ \eta\ \mathrm{Q}\ \mathrm{H}[\mathrm{KW}] \tag{1}$$

$$\mathrm{E} = \mathrm{P} \times \mathrm{t}\ [\mathrm{KWh}] \tag{2}$$

where P, η, Q, H, t, E are the power in KW, the overall efficiency of the project, design discharge in m^3/s, potential head in m, time in an hour, and total available energy, respectively.

The projected change in hydro-energy generation for three future periods – near future (2021–2045), mid-future (2046–2070), and far future (2071–2095) – was assessed using streamflow projection at the intake site obtained from the forcing of a calibrated HEC-HMS hydrological model by bias-corrected future climate datasets. In the case of TSP, the energy generation is obtained using optimized reservoir operation, described in the following section.

2.2.3. Reservoir optimization

Reservoir operation optimization encompasses a range of approaches, from traditional methods to more recent advancements in metaheuristic algorithms, including genetic algorithm (GA), Particle-Swarm Optimization (PSO), genetic programming (GP), and ant colony optimization (ACO). Population-based algorithms, such as GA and GP, operate by maintaining a population of candidate solutions and evolving them over generations. By contrast, swarm-based algorithms like PSO and ACO employ a swarm or colony of particles that cooperate and communicate to explore the search space and discover optimal solutions. Global studies (Almufti *et al.* 2019; Jahandideh-Tehrani *et al.* 2020) have investigated the applicability and advantages of PSO in various domains. PSO can tackle a range of challenging optimization problems with faster convergence rates and higher accuracy than other algorithms (Kong *et al.* 2017; Chen *et al.* 2020). Lamsal *et al.* (2023) tested the applicability of PSO for analyzing cascade reservoir optimization in the Koshi River Basin under multiple inflow scenarios.

To address the limitation of the PSO algorithm getting trapped in local optima, an enhanced version known as Elitist-Mutated PSO (EMPSO) with improved convergence rate developed by Kumar & Reddy (2007) and applied for reservoir optimization by Lamsal *et al.* (2023) was used in this study. The EMPSO model was run for future flow time-series at TSP dam and new reservoir operational rules were obtained under climate change scenarios: SSP 245 and SSP 585. The overall optimization model is described briefly in the following section, with the detailed mathematical formulation and framework mentioned in Lamsal *et al.* (2023).

(a) **Objective function**

This study aims to maximize annual and pre-monsoon hydropower generation at TSP in both the baseline and future periods, taking into account the context of climate change under two scenarios: SSP245 and SSP585. To accomplish this objective, the optimization process is carried out through the following two steps.

At first, the objective function Equation (3) maximizes the firm power (minimum monthly generation capacity in a year) for the given flow conditions.

$$\text{Minimize } Z_1 = \max(\,1 - (PE^n))_{n=1}^{12} \tag{3}$$

The objective function [Equation (4)] maximizes the overall annual hydropower generation, considering the maximized firm power obtained in the first step.

$$\text{Minimize } Z_2 = \sum_{n=1}^{12} (1 - (PE^n) + \max(0, \mathit{firm} - Po^n)^2) \tag{4}$$

$$PE^n = \left(\frac{Po^n}{Po_{max}}\right) \tag{5}$$

$$Po^n = \frac{g{*}\rho{*}\eta{*}Q^n{*}H^n}{10^6} \tag{6}$$

where PE^n is the generation capacity during month n, Po^n is the power generation during n month, Po_{max} is the maximum installed capacity in megawatts (MW), n is the Nov……. Oct months, η is the hydroelectric plant efficiency, g is the acceleration due to gravity in meter per second square (m/s^2), ρ is the density of water in kg per meter cube (kg/m^3), and *firm* is the optimum firm power obtained from the first step.

(b) **Constraints**

A reservoir system requires the application of distinct constraints on decision and state variables. In this context, decision variables pertain to the releases made from the reservoir, while state variables correspond to the storage volume within the reservoir.

The water balance constraint is presented in Equation (7).

$$S_{n+1} = S_n + I_n - R_n \tag{7}$$

For $n = 1$ to 11

where S_{n+1} is the storage at the beginning of time period $(n+1)$, S_n is the storage at the beginning of time period (n), I_n is the inflow during time period (n), and R_n is the outflow during time period (n).

The storage constraint is presented in Equation (8).

$$S_{\min} < S_{n+1} < S_{\max} \tag{8}$$

For $n = 1$ to 12

where $S_{\min}$ is the minimum storage volume and $S_{\max}$ is the maximum storage volume.

The ecological stream flow constraint is given in Equation (9).

$$R_n \geq MDR \tag{9}$$

where MDR is the minimum downstream environmental release.

3. RESULTS AND DISCUSSION

Figure 3 shows the impact of climate change on future streamflow at the TSP dam site (Khatri & Pandey 2021). The projected decrease in March to May (entire pre-monsoon) and June (early monsoon) under the SSP 245 and 585 scenarios is prevalent at all considered project sites across the TRB. This altered hydrologic regime, resulting from projected changes in climatic patterns, will impact the planned water resources development in the TRB. The to-and-fro impact of climate change and planned water resource projects are discussed in the following sections.

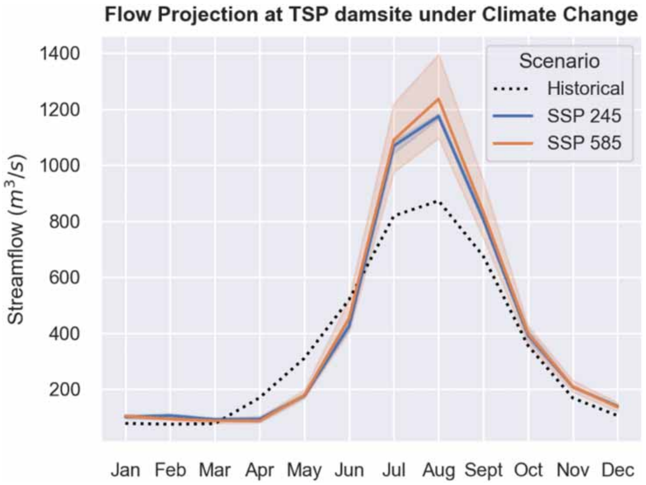


Figure 3 | Future streamflow projection at the dam site of TSP under climate change scenarios (Khatri & Pandey 2021).

3.1. Hydro-energy projection under changing climate

3.1.1. RoR projects

RoR projects are directly dependent on available streamflow for energy generation and, therefore, highly sensitive to climate change impact on the hydrologic regime. At annual scale, energy is projected to increase across all time windows for all three projects (Figure 4), except the slight (<4%) decrease projected for the Mewa and Tamor Mewa hydroprojects under SSP 245. The installed capacity (design discharge) constraint of a given hydropower project limits energy generation, despite projected increased flow in the river during the monsoon. Decrease in future pre-monsoon flow across TRB translates into a reduction in pre-monsoon RoR energy generation in all future scenarios (Figure 4). The reduction can be as low as −52.8% in the case of the Mewa Khola hydroproject in the near future under SSP 585.

Lamichhane *et al.* (2022) found that streamflow in the Kankai river basin (adjacent to TRB) is expected to decrease in the pre-monsoon and increase in other periods in most cases under both scenarios. This future occurrence of pre-monsoon water deficit is also anticipated by this study. Additionally, monsoon energy is expected to decrease (up to 5%) in all three projects owing to the reduced streamflow in June, except for an increase in the Mewa Khola hydropower under SSP 585. Winter and post-monsoon energy generations are projected to increase for all projects under all future scenarios. The rate of increment is higher in SSP 585 compared to SSP 245 as seen in the future streamflow projections.

Previous studies (Bajracharya *et al.* 2018; Marahatta *et al.* 2022; Baniya *et al.* 2024) anticipated increased streamflow in the Himalayan river basin, thereby potentially leading to an increase in hydropower generation. Our findings suggest that the climate change impact is project specific and the energy potential will increase on an annual scale, although with a higher rate of fluctuation at seasonal scale. Under climate change scenarios, the response of RoR hydropower projects is highly dependent on location, watershed hydrology, and design (Wasti *et al.* 2022). The Mewa Khola hydroproject is located at the tributary of TRB at a higher elevation and with smaller catchment area compared to the other downstream RoR projects. This difference in hydrologic dynamics of the tributary sub-basin might have caused variation in the future energy generation trend for Mewa Khola compared to the other two projects.

3.1.2. Tamor storage project

The impact of climate change-induced hydrologic alteration on energy generation is minimal for TSP compared to RoR projects. At the annual scale, the energy generation is projected to increase up to 7.5% compared to the historical baseline of 3852.1 GWh. The hydropower generation with the optimized rule curves is also observed to decrease in winter and the pre-monsoon season in the far future under the scenario SSP245 (Figure 4). Similarly, in the near future, under scenario SSP585, the slight decline (up to 3.1%) is observed during winter and in the pre-monsoon. However, the decrease in hydropower energy generation is relatively very small compared to the range projected in case of the RoR projects. Overall, it is anticipated to increase in all seasons after mid-future under both scenarios.

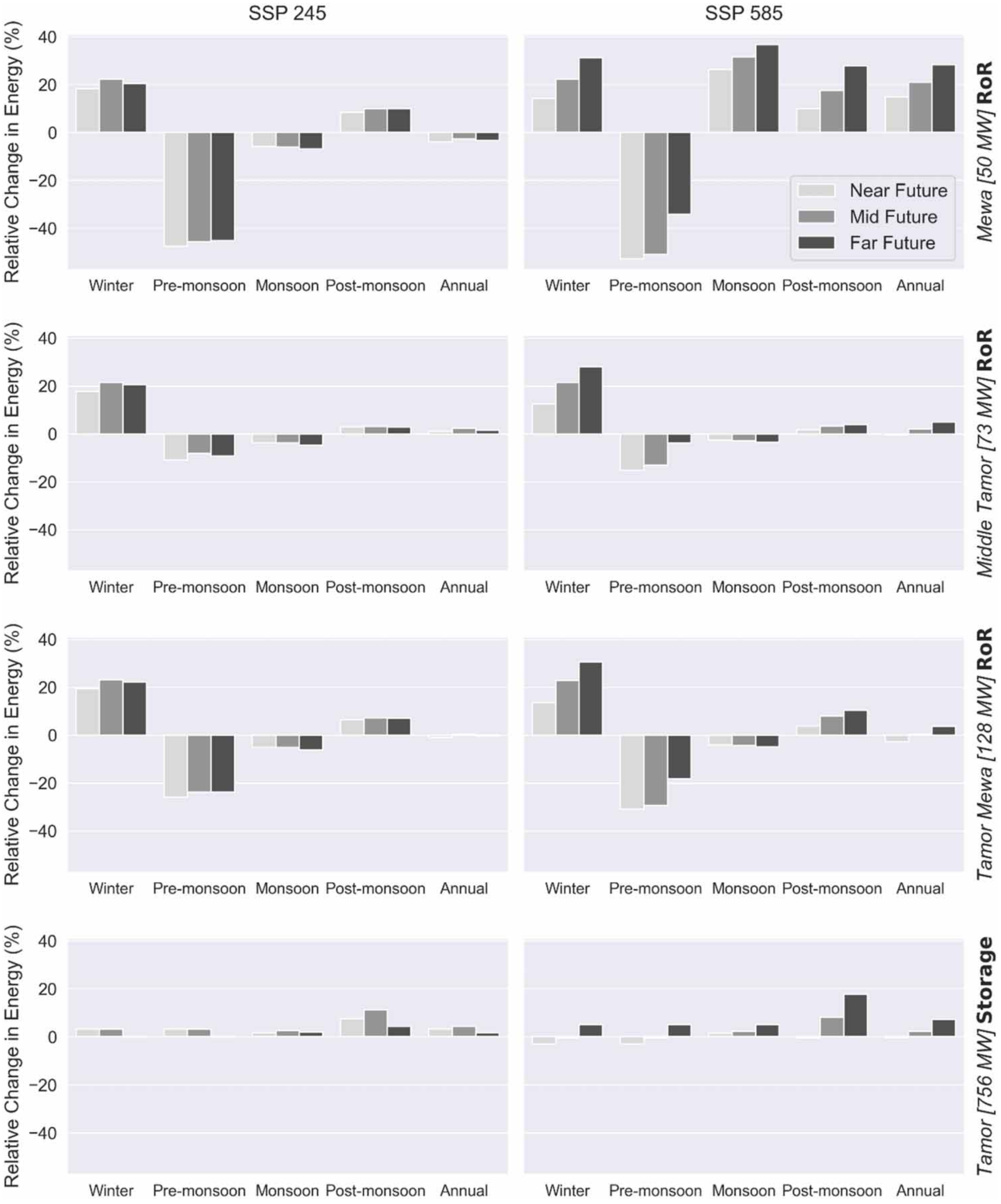


Figure 4 | Projected relative change in energy generation from different hydropower projects.

The results from other energy impact studies in reservoir projects (Ali *et al.* 2018; He *et al.* 2020; Ehteram *et al.* 2023) reveal a similar range of projected change in the future. In the Budhigandaki storage project, average annual energy generation is projected to vary in the range of −5 to +12% during the mid-century (Bhattarai *et al.* 2022). However, in the reservoir simulation of Kulekhani storage project by Shrestha *et al.* (2021a), annual energy generation is projected to decrease by 13% due to a reduction in water availability. In our study, optimization results show that annual energy generation decreases only under the SSP585 scenarios in the near future, while it increases in all future scenarios at TSP. This variation in findings could be due to the difference in the basin's hydrologic characteristics, optimization-simulation approach, and considered future climate projections. Shrestha *et al.* (2021) relied on CMIP5 projections, whereas this study incorporates the CMIP6 datasets. Also, the response to climate change is basin specific and unique for each project configuration and reservoir regulation.

3.2. Integrated impacts of climate change and adaptive reservoir operation on downstream hydrologic regime

Climate change is likely to alter the streamflow, leading to the inapplicability of historically developed reservoir operation strategy. Planned water resources development in TRB will influence hydrologic responses, particularly downstream of TSP. Reservoir operation, a key adaptation strategy for climate change impacts on hydropower generation, involves optimizing the rule curve. The analysis encompasses both the baseline case, representing existing conditions, and future scenarios considering projected climate changes. Through the optimization model, the rule curves (Figure 5) are fine-tuned to optimize the dam operation strategies involving water release and storage volume. Figure 5 demonstrates the optimized operational strategies at different future periods under the climate change scenarios. To maximize the energy generation in future, the shift in historically optimized operation rule is needed. For instance, the higher water availability during the monsoon and post-monsoon seasons necessitates adjustments in reservoir filling operation in the far future under SSP 585.

Notably, the optimized rule curve successfully addresses the inflow deficit during the pre-monsoon season caused by reduction in pre-monsoon flow resulting from climate change. This highlights the advantage of a seasonal storage-type project, providing operational flexibility and acting as a cushion against external stimuli (Thomas *et al.* 2021; Bhattarai *et al.* 2022; Marahatta *et al.* 2022) such as altered hydrology under changing climate. The flow deficit from March to June is visually evident in Figure 3, demonstrating the impact of climate change on pre-monsoon seasonal flow. By overcoming this deficit through multiple operation rules (Figure 5), reservoir management ensures a more reliable water supply during this critical season. Under all future periods and climate change scenarios, the outflow (dam-regulated flow) is projected to remain double the inflow (flow under climate change) during the winter, pre-monsoon, and post-monsoon seasons (Figure 6).

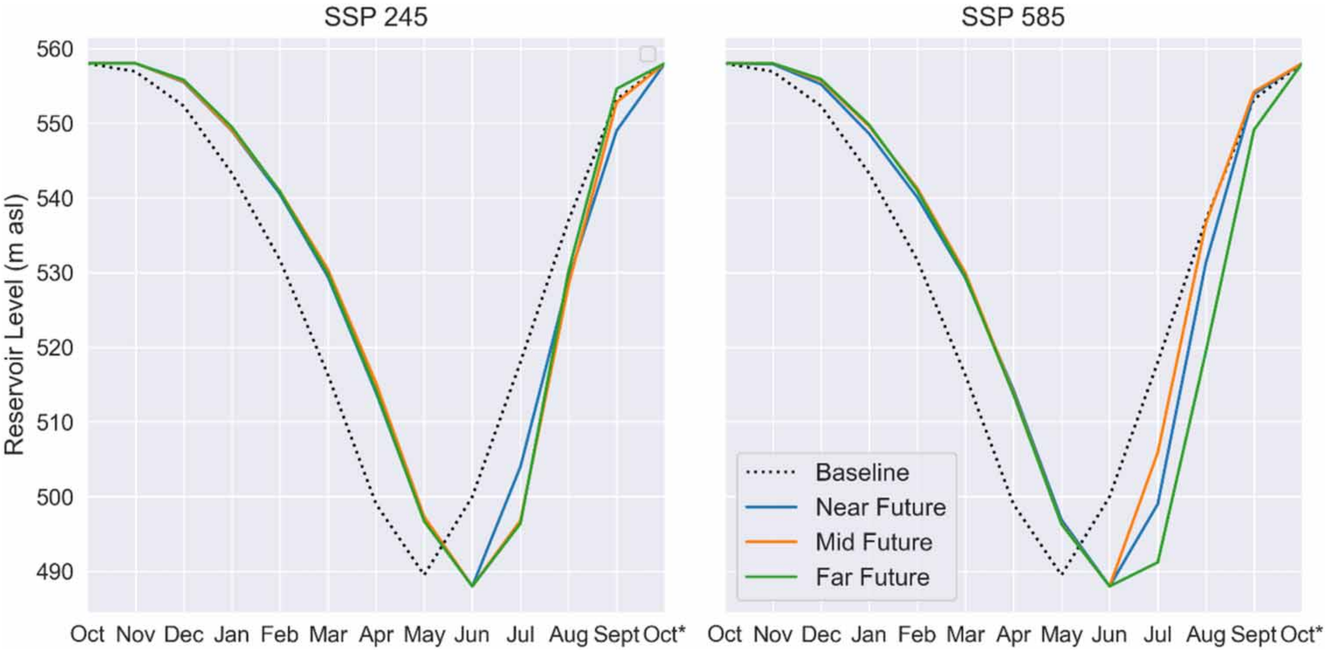


Figure 5 | Optimized rule curve for baseline and future scenarios.

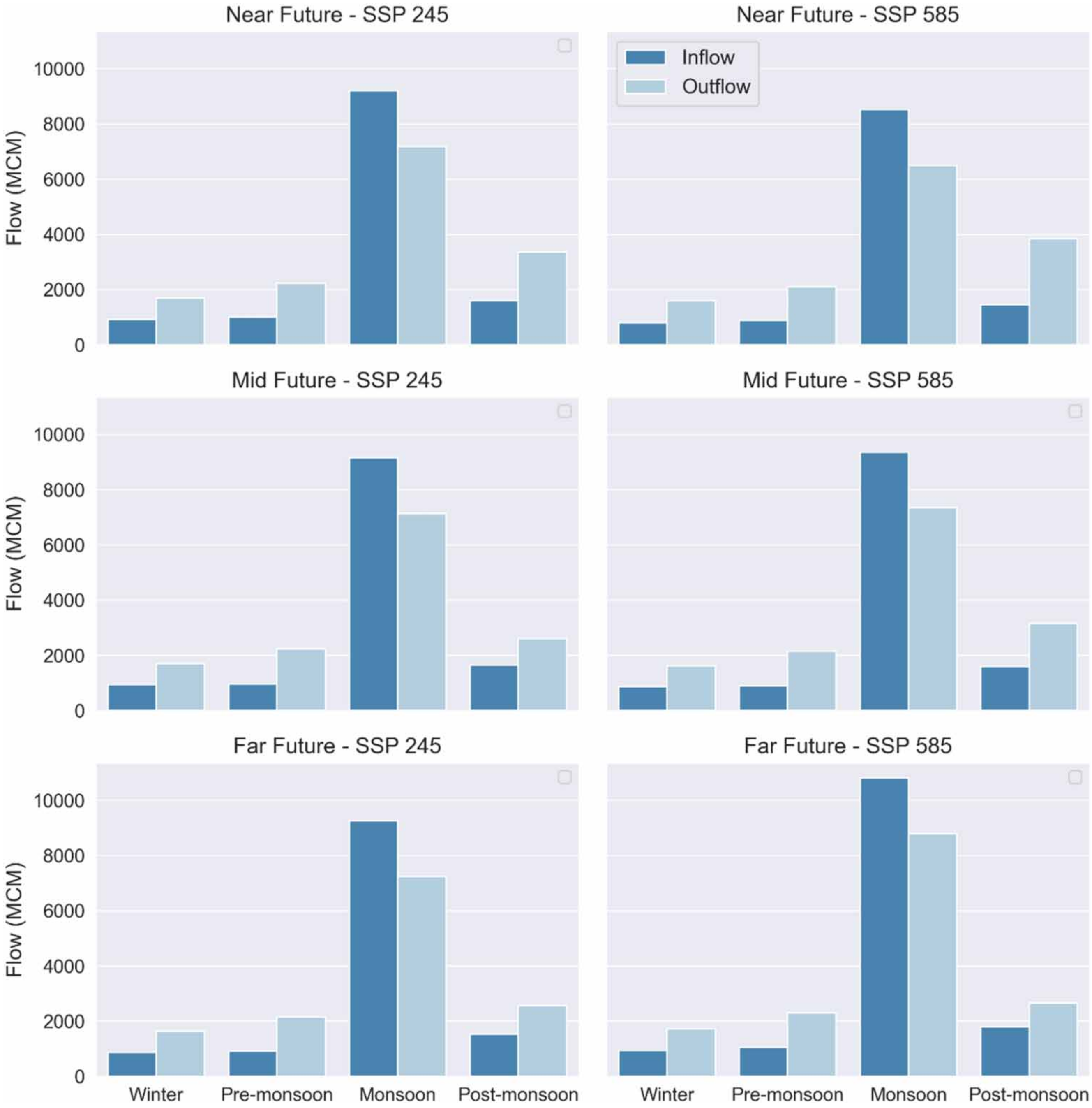


Figure 6 | Seasonal inflow at TSP dam site and outflow from the dam site after reservoir regulation under future climatic scenarios. Inflow represents the streamflow projected under climate change impact and outflow represents the regulated water using optimized operation rule for respective inflow. MCM: Million cubic meter.

The projected increase in inflow at the dam site during monsoon will translate into increased hydrologic extremes under the no reservoir regulation scenario, i.e., without the development of TSP. Reservoir operation will enhance flood control, although the higher increments are more pronounced under climate change scenarios. Regulation of TSP dam inflow is anticipated to increase flow during the low-flow season downstream of the dam. This would yield positive impacts on the planned Tamor–Morang River diversion project through multipurpose benefits such as irrigation in the Terai and hydropower generation. At the Koshi Basin scale, regulated flow from TSP supports integrated river basin management and can enhance water security through the food-water-energy nexus approach (Chinnasamy *et al.* 2015; Nepal *et al.* 2021). Furthermore, it enhances the environmental (ecological) flow management. These downstream benefits contribute to the overall enhancement of the local ecosystem and the socioeconomic well-being of the downstream communities.

Considering the adaptive benefit from the storage project in the TRB, the planning and development of such types of projects in the upper region would positively influence energy generation and other water-use sectors within the basin. The considered RoR projects in this study are likely to be affected by the hydrologic impact of climate change. In the present context, no storage projects are identified and planned in the TRB other than TSP. The presence of a storage facility upstream of the planned RoR projects and its optimized operation would interact with such hydrological impacts and cascade positive benefits to the downstream water resource projects.

4. CONCLUSIONS

This study applied an integrated approach combining climate modeling, hydrological analysis, hydropower energy model, and reservoir operation optimizations in a Himalayan river basin. This approach provides insights into how changing climate patterns affect water availability and hydropower generation (depending on project location, type, design), and informs strategies for optimizing reservoir operations to adapt to these impacts. The streamflow projections in TRB were used for hydropower energy modeling and reservoir optimization purposes. The hydropower production from the studied RoR projects is projected to increase at annual scale (up to 28%). However, the energy in RoR projects is anticipated to decrease primarily during the pre-monsoon season (up to −52.8%). To address the reduction in the March–June flow and the energy in the future, six operational rule curves of TSP were generated using the EMPSO algorithm. The optimized rule curves maximize the hydropower generation and demonstrate adaptive tendencies to projected change in the hydroclimate. The optimized reservoir operation can facilitate storage of monsoon flow and nearly double downstream flow during other seasons. The flexible rule curves, under combined impact of climate change and reservoir operation strategies, are expected to yield positive benefits through increased energy generation (up to 7.3% in TSP during the far future) and regulated flow.

The future water availability and energy potential of TRB are highly dependent on the interplay between climate change and water resource development scenarios. This study is based on limited choices in climate change projections, lumped hydrological model parameters, and the single-objective reservoir optimization framework. Further studies can incorporate additional factors such as sedimentation, hazards, land-use change, economic modeling, and other water infrastructures. This study is of practical importance for informed decision making under changing climate and optimum water resource development at the basin scale.

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AUTHOR CONTRIBUTIONS

D.K. contributed to conceptualization, methodology, data curation, formal analysis, investigation, software, writing – original draft, visualization. **V.P.P.** contributed to conceptualization, methodology, resources, writing – review & editing, supervision. **G.R.L.** contributed to conceptualization, methodology, software, formal analysis, investigation, writing – review & editing, visualization. **R.B.** contributed to conceptualization, methodology, formal analysis, investigation, writing – original draft, writing – review & editing, visualization.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Ali, S. A., Aadhar, S., Shah, H. L. & Mishra, V. 2018 Projected increase in hydropower production in India under climate change. *Scientific Reports* **8**, 12450. https://doi.org/10.1038/s41598-018-30489-4.

Almufti, S. M., Yahya Zebari, A. & Khalid Omer, H. 2019 A comparative study of particle swarm optimization and genetic algorithm. *Journal of Advanced Computer Science & Technology* **8**, 40. https://doi.org/10.14419/jacst.v8i2.29401.

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

Baniya, R., Talchabhadel, R., Panthi, J., Ghimire, G. R., Sharma, S., Khadka, P. D., Shin, S., Pokhrel, Y., Bhattarai, U., Prajapati, R., Thapa, B. R. & Maskey, R. K. 2023 Nepal Himalaya offers considerable potential for pumped storage hydropower. *Sustainable Energy Technologies and Assessments* **60**, 103423. https://doi.org/10.1016/j.seta.2023.103423.

Baniya, R., Regmi, R. K., Talchabhadel, R., Sharma, S., Panthi, J., Ghimire, G. R., Bista, S., Thapa, B. R., Pradhan, A. M. S. & Tamrakar, J. 2024 Integrated modeling for assessing climate change impacts on water resources and hydropower potential in the Himalayas. *Theoretical and Applied Climatology*. https://doi.org/10.1007/s00704-024-04863-4.

Beça, P., Rodrigues, A. C., Nunes, J. P., Diogo, P. & Mujtaba, B. 2023 Optimizing reservoir water management in a changing climate. *Water Resources Management* **37**, 3423–3437. https://doi.org/10.1007/s11269-023-03508-x.

Berga, L. 2016 The role of hydropower in climate change mitigation and adaptation: A review. *Engineering* **2**, 313–318. https://doi.org/10.1016/J.ENG.2016.03.004.

Bhatta, B., Shrestha, S., Shrestha, P. K. & Talchabhadel, R. 2019 Evaluation and application of a SWAT model to assess the climate change impact on the hydrology of the Himalayan river basin. *CATENA* **181**, 104082. https://doi.org/10.1016/j.catena.2019.104082.

Bhattarai, U., Devkota, L. P., Marahatta, S., Shrestha, D. & Maraseni, T. 2022 How will hydro-energy generation of the Nepalese Himalaya vary in the future? A climate change perspective. *Environmental Research* **214**, 113746. https://doi.org/10.1016/j.envres.2022.113746.

Bista, S., Baniya, R., Sharma, S., Ghimire, G. R., Panthi, J., Prajapati, R. & Talchabhadel, R. 2024 Hydrologic applicability of satellite-based precipitation estimates for irrigation water management in the data-scarce region. *Journal of Hydrology* **636**, 131310. https://doi.org/10.1016/j.jhydrol.2024.131310.

Bocchiola, D., Manara, M. & Mereu, R. 2020 Hydropower potential of Run of river schemes in the Himalayas under climate change: A case study in the Dudh Koshi Basin of Nepal. *Water* **12**, 2625. https://doi.org/10.3390/w12092625.

Bolch, T., Shea, J. M., Liu, S., Azam, F. M., Gao, Y., Gruber, S., Immerzeel, W. W., Kulkarni, A., Li, H., Tahir, A. A., Zhang, G., Zhang, Y., 2019 Status and Change of the Cryosphere in the Extended Hindu Kush Himalaya Region. In: *The Hindu Kush Himalaya Assessment* (Wester, P., Mishra, A., Mukherji, A. & Shrestha, A. B., eds.). Springer International Publishing, Cham, pp. 209–255. https://doi.org/10.1007/978-3-319-92288-1_7.

Chen, H. T., Wang, W. C., Chen, X. N. & Qiu, L. 2020 Multi-objective reservoir operation using particle swarm optimization with adaptive random inertia weights. *Water Science and Engineering* **13** (2), 136–144.

Chhetri, R., Pandey, V. P., Talchabhadel, R. & Thapa, B. R. 2021 How do CMIP6 models project changes in precipitation extremes over seasons and locations across the mid hills of Nepal? *Theoretical and Applied Climatology* **145**, 1127–1144. https://doi.org/10.1007/s00704-021-03698-7.

Chilkoti, V., Bolisetti, T. & Balachandar, R. 2017 Climate change impact assessment on hydropower generation using multi-model climate ensemble. *Renewable Energy* **109**, 510–517. https://doi.org/10.1016/j.renene.2017.02.041.

Chinnasamy, P., Bharati, L., Bhattarai, U., Khadka, A., Dahal, V. & Wahid, S. 2015 Impact of planned water resource development on current and future water demand in the Koshi River basin, Nepal. *Water International* **40**, 1004–1020. https://doi.org/10.1080/02508060.2015.1099192.

Cook, B. I., Mankin, J. S., Marvel, K., Williams, A. P., Smerdon, J. E. & Anchukaitis, K. J. 2020 Twenty-First century drought projections in the CMIP6 forcing scenarios. *Earth's Future* **8**, e2019EF001461. https://doi.org/10.1029/2019EF001461.

Dahal, P., Shrestha, M. L., Panthi, J. & Pradhananga, D. 2020 Modeling the future impacts of climate change on water availability in the Karnali River Basin of Nepal Himalaya. *Environmental Research* **185**, 109430. https://doi.org/10.1016/j.envres.2020.109430.

Dash, S. S., Sahoo, B. & Raghuwanshi, N. S. 2023 An integrated reservoir operation framework for enhanced water resources planning. *Scientific Reports* **13**, 21720. https://doi.org/10.1038/s41598-023-49107-z.

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

Dijkshoorn, K. & Huting, J. 2009 *Soil and Terrain Database for Nepal*. ISRIC – World Soil Information.

DoED 2023 *Project Database – Status and License*. Department of Electricity Development, Nepal.

DoWRI 2019 *Irrigation Master Plan 2019*. Department of Water Resources and Irrigation, Kathmandu, Nepal.

Ehteram, M., Ahmed, A. N., Chow, M. F., Latif, S. D., Chau, K., Chong, K. L. & El-Shafie, A. 2023 Optimal operation of hydropower reservoirs under climate change. *Environment, Development and Sustainability* **25**, 10627–10659. https://doi.org/10.1007/s10668-022-02497-y.

Feldman, A. D. 2000 *Hydrologic Modeling System Technical Reference Manual*. Hydrol. Model. Syst. HEC-HMS Tech. Ref. Man., no. March, p. 148.

Ghimire, S., Shrestha, S., Hok, P., Heng, S., Nittivattanaon, V. & Sabo, J. 2023 Integrated assessment of climate change and reservoir operation on flow-regime and fisheries of the Sekong river basin in Lao PDR and Cambodia. *Environmental Research* **220**, 115087. https://doi.org/10.1016/j.envres.2022.115087.

Grafton, R. Q., Pittock, J., Davis, R., Williams, J., Fu, G., Warburton, M., Udall, B., McKenzie, R., Yu, X., Che, N., Connell, D., Jiang, Q., Kompas, T., Lynch, A., Norris, R., Possingham, H. & Quiggin, J. 2013 Global insights into water resources, climate change and governance. *Nature Climate Change* **3**, 315–321. https://doi.org/10.1038/nclimate1746.

Habib-ur-Rahman, M., Ahmad, A., Raza, A., Hasnain, M. U., Alharby, H. F., Alzahrani, Y. M., Bamagoos, A. A., Hakeem, K. R., Ahmad, S., Nasim, W., Ali, S., Mansour, F. & El Sabagh, A. 2022 Impact of climate change on agricultural production; Issues, challenges, and opportunities in Asia. *Frontiers in Plant Science* **13**, 925548. https://doi.org/10.3389/fpls.2022.925548.

Halwatura, D. & Najim, M. M. M. 2013 Application of the HEC-HMS model for runoff simulation in a tropical catchment. *Environmental Modelling & Software* **46**, 155–162. https://doi.org/10.1016/j.envsoft.2013.03.006.

He, S., Guo, S., Yang, G., Chen, K., Liu, D. & Zhou, Y. 2020 Optimizing operation rules of cascade reservoirs for adapting climate change. *Water Resources Management* **34**, 101–120. https://doi.org/10.1007/s11269-019-02405-6.

IPCC 2023 *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1st edn. Cambridge University Press, Cambridge. https://doi.org/10.1017/9781009325844.

Jahandideh-Tehrani, M., Bozorg-Haddad, O. & Loáiciga, H. A. 2020 Application of particle swarm optimization to water management: An introduction and overview. *Environmental Monitoring and Assessment* **192**, 281. https://doi.org/10.1007/s10661-020-8228-z.

Kaini, S., Nepal, S., Pradhananga, S., Gardner, T. & Sharma, A. K. 2021 Impacts of climate change on the flow of the transboundary Koshi River, with implications for local irrigation. *International Journal of Water Resources Development* **37**, 929–954. https://doi.org/10.1080/07900627.2020.1826292.

Karki, N., Shakya, N. M., Pandey, V. P., Devkota, L. P., Pradhan, A. M. S. & Lamichhane, S. 2023 Comparative performance of regionalization methods for model parameterization in ungauged Himalayan watersheds. *Journal of Hydrology: Regional Studies* **47**, 101359. https://doi.org/10.1016/j.ejrh.2023.101359.

Khatri, D. & Pandey, V. P. 2021 Climate Change Impact on the Hydrological Characteristics ofTamor River Basin in Nepal Based on CMIP6 Models. In *Presented at the Institute of Engineering Graduate Conference*.

Kong, A. L., Liang, S., Li, C. L., Liang, Z. F. & Chen, Y. 2017 Optimizing micro-grid operation based on improved PSO. *Journal of Hohai University (Natural Sciences)* **45** (6), 550–555. https://doi.org /10.3876/j.issn.1000-1980.2017.06.012.

Krishnan, R., Shrestha, A. B., Ren, G., Rajbhandari, R., Saeed, S., Sanjay, J., Syed, M. A., Vellore, R., Xu, Y., You, Q., Ren, Y., Shrestha, A. B., 2019 Unravelling Climate Change in the Hindu Kush Himalaya: Rapid Warming in the Mountains and Increasing Extremes. In: *The Hindu Kush Himalaya Assessment* (Wester, P., Mishra, A. & Mukherji, A., eds.). Springer International Publishing, Cham, pp. 57–97. https://doi.org/10.1007/978-3-319-92288-1_3.

Kumar, D. N. & Reddy, M. J. 2007 Multipurpose reservoir operation using particle swarm optimization. *Journal of Water Resources Planning and Management* **133**, 192–201. https://doi.org/10.1061/(ASCE)0733-9496(2007)133:3(192).

Lamichhane, P., Mishra, Y. & Bhattarai, P. 2022 Assessment of future water availability and irrigation water demandunder climate change in the Kankai River Basin, Nepal. *Journal of Earth Science & Climatic Change* **13**, 639.

Lamsal, G. R., Basnyat, D. B., Kafle, M. R. & Baniya, R. 2023 Optimal operation of cascading reservoirs in Koshi river basin. *International Journal of Energy and Water Resources*. https://doi.org/10.1007/s42108-023-00243-2.

Li, X., Long, D., Scanlon, B. R., Mann, M. E., Li, X., Tian, F., Sun, Z. & Wang, G. 2022 Climate change threatens terrestrial water storage over the Tibetan Plateau. *Nature Climate Change* **12**, 801–807. https://doi.org/10.1038/s41558-022-01443-0.

Marahatta, S., Aryal, D., Devkota, L. P., Bhattarai, U. & Shrestha, D. 2021a Application of SWAT in hydrological simulation of complex mountainous river basin (Part II: climate change impact assessment). *Water* **13**, 1548. https://doi.org/10.3390/w13111548.

Marahatta, S., Devkota, L. P. & Aryal, D. 2021b Application of SWAT in hydrological simulation of complex mountainous river basin (Part I: Model development). *Water* **13**, 1546. https://doi.org/10.3390/w13111546.

Marahatta, S., Bhattarai, U., Devkota, L. P. & Aryal, D. 2022 Unravelling the water-energy-economics-continuum of hydroelectricity in the face of climate change. *International Journal of Energy and Water Resources* **6**, 323–335. https://doi.org/10.1007/s42108-021-00174-w.

McDowell, N. 2002 Melting ice triggers Himalayan flood warning. *Nature* **416**, 776–776. https://doi.org/10.1038/416776a.

Mishra, S. K., Hayse, J., Veselka, T., Yan, E., Kayastha, R. B., LaGory, K., McDonald, K. & Steiner, N. 2018 An integrated assessment approach for estimating the economic impacts of climate change on river systems: An application to hydropower and fisheries in a Himalayan River, Trishuli. *Environmental Science & Policy* **87**, 102–111. https://doi.org/10.1016/j.envsci.2018.05.006.

Mishra, V., Bhatia, U. & Tiwari, A. D. 2020 Bias-corrected climate projections for south Asia from coupled model intercomparison project-6. *Scientific Data* **7**, 338. https://doi.org/10.1038/s41597-020-00681-1.

Nam, D. H., Udo, K. & Mano, A. 2012 Climate change impacts on runoff regimes at a river basin scale in central Vietnam. *Terrestrial Atmospheric and Oceanic Sciences* **23**, 541. https://doi.org/10.3319/TAO.2012.05.03.03(WMH).

Nepal, S., Neupane, N., Belbase, D., Pandey, V. P. & Mukherji, A. 2021 Achieving water security in Nepal through unravelling the water-energy-agriculture nexus. *International Journal of Water Resources Development* **37**, 67–93. https://doi.org/10.1080/07900627.2019.1694867.

Pandey, V. P., Dhaubanjar, S., Bharati, L. & Thapa, B. R. 2020 Spatio-temporal distribution of water availability in Karnali-Mohana Basin, Western Nepal: Climate change impact assessment (Part-B). *Journal of Hydrology: Regional Studies* **29**, 100691. https://doi.org/10.1016/j.ejrh.2020.100691.

Panthi, J., Talchabhadel, R., Ghimire, G. R., Sharma, S., Dahal, P., Baniya, R., Boving, T., Pradhanang, S. M. & Parajuli, B. 2021 Hydrologic regionalization under data scarcity: Implications for streamflow prediction. *Journal of Hydrologic Engineering* **26**, 05021022. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002121.

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., Friedlingstein, P., Liu, C., Tan, K., Yu, Y., Zhang, T. & Fang, J. 2010 The impacts of climate change on water resources and agriculture in China. *Nature* **467**, 43–51. https://doi.org/10.1038/nature09364.

Poudel, A., Bhattarai, U. & Bhattarai, P. 2022 Climatic variability change analysis in Tamor River Basin Projected by CMIP6 Model. In *Presented at the Institute of Engineering Graduate Conference*.

Rasul, G. & Sharma, B. 2016 The nexus approach to water–energy–food security: An option for adaptation to climate change. *Climate Policy* **16**, 682–702. https://doi.org/10.1080/14693062.2015.1029865.

Schaefli, B. 2015 Projecting hydropower production under future climates: A guide for decision-makers and modelers to interpret and design climate change impact assessments. *WIREs Water* **2**, 271–289. https://doi.org/10.1002/wat2.1083.

Scott, C. A., Zhang, F., Mukherji, A., Immerzeel, W., Mustafa, D., Bharati, L., 2019 Water in the Hindu Kush Himalaya. In: *The Hindu Kush Himalaya Assessment* (Wester, P., Mishra, A., Mukherji, A. & Shrestha, A. B., eds.). Springer International Publishing, Cham, pp. 257–299. https://doi.org/10.1007/978-3-319-92288-1_8.

Shin, S., Pokhrel, Y., Talchabhadel, R. & Panthi, J. 2021 Spatio-temporal dynamics of hydrologic changes in the Himalayan river basins of Nepal using high-resolution hydrological-hydrodynamic modeling. *Journal of Hydrology* **598**, 126209. https://doi.org/10.1016/j.jhydrol.2021.126209.

Shrestha, H. M. 2016 Exploitable potential, theoretical potential, technical potential, storage potential and impediments to development of the potential: The Nepalese perspective. *Hydro Nepal* **19**, 1–5. https://doi.org/10.3126/hn.v19i0.15340.

Shrestha, S., Bajracharya, A. R. & Babel, M. S. 2016 Assessment of risks due to climate change for the Upper Tamakoshi Hydropower Project in Nepal. *Climate Risk Management* **14**, 27–41. https://doi.org/10.1016/j.crm.2016.08.002.

Shrestha, A., Shrestha, S., Tingsanchali, T., Budhathoki, A. & Ninsawat, S. 2021a Adapting hydropower production to climate change: A case study of Kulekhani Hydropower Project in Nepal. *Journal of Cleaner Production* **279**, 123483. https://doi.org/10.1016/j.jclepro.2020.123483.

Shrestha, S., Bae, D.-H., Hok, P., Ghimire, S. & Pokhrel, Y. 2021b Future hydrology and hydrological extremes under climate change in Asian river basins. *Scientific Reports* **11**, 17089. https://doi.org/10.1038/s41598-021-96656-2.

Singh, R., Kayastha, S. P. & Pandey, V. P. 2022 Climate change and river health of the Marshyangdi Watershed, Nepal: An assessment using integrated approach. *Environmental Research* **215**, 114104. https://doi.org/10.1016/j.envres.2022.114104.

Thomas, T., Ghosh, N. C. & Sudheer, K. P. 2021 Optimal reservoir operation – A climate change adaptation strategy for Narmada basin in central India. *Journal of Hydrology* **598**, 126238. https://doi.org/10.1016/j.jhydrol.2021.126238.

Turner, A. G. & Annamalai, H. 2012 Climate change and the South Asian summer monsoon. *Nature Climate Change* **2**, 587–595. https://doi.org/10.1038/nclimate1495.

Uddin, K., Shrestha, H. L., Murthy, M. S. R., Bajracharya, B., Shrestha, B., Gilani, H., Pradhan, S. & Dangol, B. 2015 Development of 2010 national land cover database for the Nepal. *Journal of Environmental Management* **148**, 82–90. https://doi.org/10.1016/j.jenvman.2014.07.047.

Vaidya, R. A., Molden, D. J., Shrestha, A. B., Wagle, N. & Tortajada, C. 2021 The role of hydropower in South Asia's energy future. *International Journal of Water Resources Development* **37**, 367–391. https://doi.org/10.1080/07900627.2021.1875809.

Wasti, A., Ray, P., Wi, S., Folch, C., Ubierna, M. & Karki, P. 2022 Climate change and the hydropower sector: A global review. *WIREs Climate Change* **13**, e757. https://doi.org/10.1002/wcc.757.

WECS 2019 *Assessment of Hydropower Potential of Nepal*. Water and Energy Commission Secretariat, Kathmandu.

Yaghoubi, B., Hosseini, S. A., Nazif, S. & Daghighi, A. 2020 Development of reservoir's optimum operation rules considering water quality issues and climatic change data analysis. *Sustainable Cities and Society* **63**, 102467. https://doi.org/10.1016/j.scs.2020.102467.

Yang, L., Zhao, G., Mu, X., Liu, Y., Tian, P. & Puqiong, D. 2023 Historical and projected evolutions of glaciers in response to climate change in High Mountain Asia. *Environmental Research* **237**, 117037. https://doi.org/10.1016/j.envres.2023.117037.

Yuan, W., Liu, M. & Wan, F. 2019 Calculation of critical rainfall for small-Watershed flash floods based on the HEC-HMS hydrological model. *Water Resources Management* **33**, 2555–2575. https://doi.org/10.1007/s11269-019-02257-0.

Zhu, H., Jiang, Z., Li, J., Li, W., Sun, C. & Li, L. 2020 Does CMIP6 inspire more confidence in simulating climate extremes over China? *Advances in Atmospheric Sciences* **37**, 1119–1132. https://doi.org/10.1007/s00376-020-9289-1.

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