

Future climate risks in the Karnali River Basin in Nepal: implications for water, energy, and agriculture sectors

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Front cover photo: Majestic Himalayan Mountain Range as seen from Juphal, Karnali Province in Nepal (*photo:* Ashok Kshetri/Pexels)

Back cover photo: A glimpse of rural life where water, land, and labor shape mountain agriculture in central Nepal (*photo:* Saurav Pradhananga/IWMI)

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Key messages

- **Increased seasonality:** By the end of the century, climate change will intensify seasonal water variability, reducing dry season flows by up to 23% while increasing monsoon flows by up to 51% in the basin (SSP585 scenario).
- **Impact of climate change on energy generation:** Dry season energy production reliability will drop in hydropower projects like Upper Karnali, while wet season energy production may rise, complicating annual energy supply planning.
- **Increased water demand:** Irrigation water demand for paddy and wheat will increase, especially in pre-monsoon and winter periods, with water needs doubling during critical growth stages.
- **Possible solution:** Adopt an Integrated River Basin Management (IRBM) approach to address complex sectoral interlinkages by promoting conjunctive use of surface water and groundwater, coordinated reservoir operation for irrigation and hydropower, solar-powered irrigation expansion, and ecosystem-based recharge interventions.

1. Background

The Karnali River Basin is one of Nepal's major river systems and a vital source of water for hydropower generation, irrigation, and ecosystems in the western region of Nepal (Figure 1). The basin supports nearly 1.7 million people (NSO 2021) and holds significant potential for future development, particularly in energy and agriculture. However, the basin is highly sensitive to climate change and variability due to its complex topography, strong seasonality, and dependence on snowmelt and glacier melt from the Himalayas (Nepal and Shrestha 2015). Recent climatic trends suggest that rising temperatures and shifting rainfall are altering its hydrological regime across the region. It is critical to understand how future climate change will affect the basin's hydrology and water availability. Using the advanced SWAT+ (Soil and Water Assessment Tool Plus) model and high-resolution bias corrected Coupled Model Intercomparison Project Phase 6 (CMIP6) climate projections, we aim to provide scientific evidence to inform climate-resilient planning and water resources management in the Karnali River Basin.

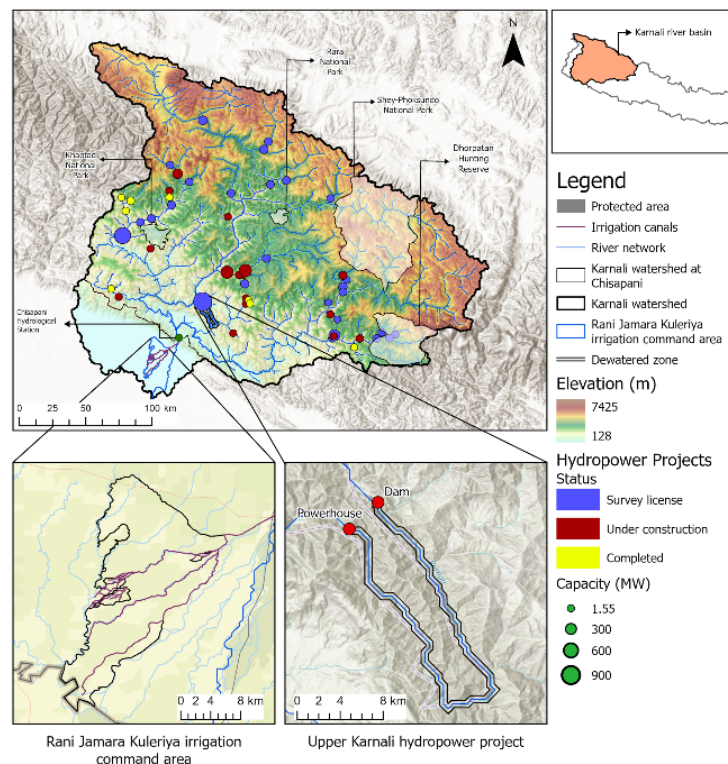


Figure 1. The Karnali River Basin with existing and planned projects, including three national parks and one hunting reserve. The gauging station is at Chisapani (green circle), used for model calibration and validation. The Rani Jamara Kuleriya Irrigation Scheme's intake is 1.5 km downstream, where irrigation water demand is calculated. The planned 900 MW Upper Karnali Hydropower Project shows the dam, powerhouse, and a 50 km dewatered zone where future energy demand is calculated. *Source:* Pradhananga et al. 2025

The Karnali and Mahakali River basins possess a combined theoretical hydropower potential of 36,180 MW, with a technical potential of 26,570 MW and an economic potential of 25,125 MW (K.C. et al. 2011). According to the Department of Electricity Development (DOED), only 92 MW of hydropower potential has been utilized to date, while projects totaling 1,337 MW are under construction. and an additional 3,432 MW have been issued survey licenses (DOED 2026a, 2026b, 2026c, 2026d, 2026e). Among the planned developments in the Karnali River Basin is a proposed run-of-river 900 MW Upper Karnali Hydropower Project, aimed at evaluating the projected impacts of climate change on hydropower generation by the end of the century.

In the Mid-Hills of western Nepal, numerous farmer-managed irrigation systems also rely on water from tributaries of the Karnali River. In the southern plains of the Karnali River Basin, the Rani Jamara Kulariya Irrigation Scheme irrigates an area of 38,300 hectares along with supporting a 2.5 MW hydropower component. This system is being used as a case study to evaluate changes in irrigation water demand for paddy and wheat under future climate scenarios by the end of the century.

2. Methodology

To assess the future impacts of climate change on the hydrology of the Karnali River Basin, this study applied a physically-based, semi-distributed hydrological model known as SWAT+ (Bieger et al. 2017). The model was calibrated and validated using observed streamflow and gridded climate data from the ERA5-Land (0.1°), ensuring an accurate representation of current hydrological conditions.

For future climate inputs, the study used four daily bias-corrected global climate model (GCM) datasets each for moderate (SSP245) and high-emission (SSP585) scenarios derived from the CMIP6. The data were downscaled to 0.1° spatial resolution using quantile mapping to correct biases in mean temperature and precipitation. The analysis included two future time periods: mid-century (2036–2065), and end-century (2071–2100) with the reference period of 1985-2014.

The model simulated key hydrological variables such as surface runoff, streamflow, evapotranspiration, and water yield across different seasons. The projected river flow was then used to calculate monthly hydroelectricity generation at the planned Upper Karnali hydropower plant site. Crop water demand for paddy and wheat in the Rani Jamara Kulariya Irrigation System was estimated using CROPWAT model (Smith 1992), and irrigation requirements were calculated based on future climate conditions. This comprehensive approach allowed the study to project how changes in temperature and precipitation would impact both hydropower generation and irrigation water requirements across the basin.

3. Key findings

3.1 Present hydrology

The hydrological regime of the Karnali River Basin is primarily governed by monsoon rainfall, which contributes nearly 80% of the annual precipitation between June and September. River discharge is strongly seasonal, with high flows during the monsoon months and low flows during pre-monsoon and winter seasons. The SWAT+ model was successfully applied to simulate river discharge at Chisapani, the outlet of the Karnali River Basin. Calibration and validation against observed discharge data demonstrated good model performance, with high values of the Nash-Sutcliffe Efficiency (NSE) (calibration:0.78; validation:0.70), coefficient of determination (R^2) (calibration:0.82; validation:0.75), and Kling-Gupta Efficiency (KGE) (calibration:0.74; validation:0.79). These results indicate that SWAT+ is capable of capturing the hydrological dynamics of the basin and is a reliable tool for assessing the impacts of future climate scenarios on river flows (Figure 2).

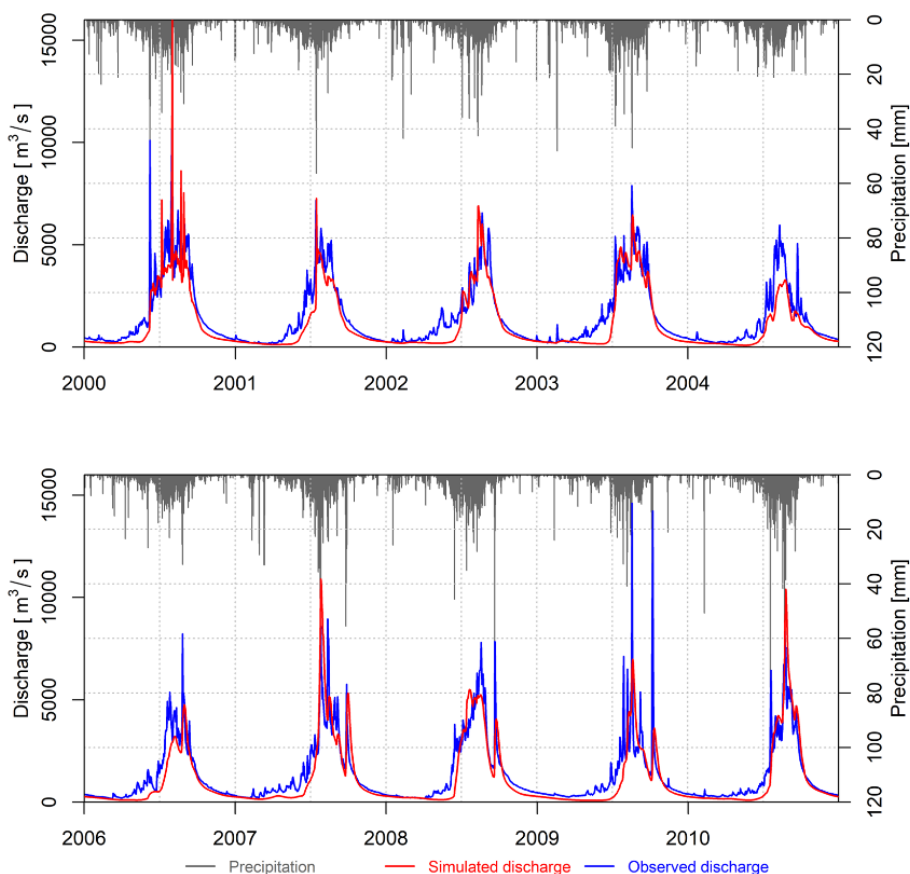


Figure 2. Observed (blue) and simulated (red) hydrograph and precipitation (grey) during the calibration (top) and validation (bottom) period.

Source: Pradhananga et al. 2025

3.2 Future climate projections

Climate projections based on CMIP6 indicate that the Karnali River Basin will experience substantial warming and a wetter climate, but with marked seasonal variability. Mean annual temperature is projected to increase by 1.2–1.5°C under SSP245 (2041–2070) and by up to 4.8°C under SSP585 (2071–2100), relative to the historical baseline (Figure 3). Warming is more pronounced in the winter months, increasing the frequency of hot days and altering rain and snow dynamics.

Annual precipitation is also projected to rise, but unevenly distributed across the year. Monsoon rainfall (July–September) is expected to increase by 18% under SSP245 and up to 51% under SSP585 by the end of the century. In contrast, winter and spring precipitation are projected to decline, leading to reductions in discharge ranging from 3% (SSP245) to 23% (SSP585) (Figure 3). This intensification of monsoon rainfall alongside reduced dry season precipitation points to heightened risks of flooding during the wet months and water scarcity during the dry months.

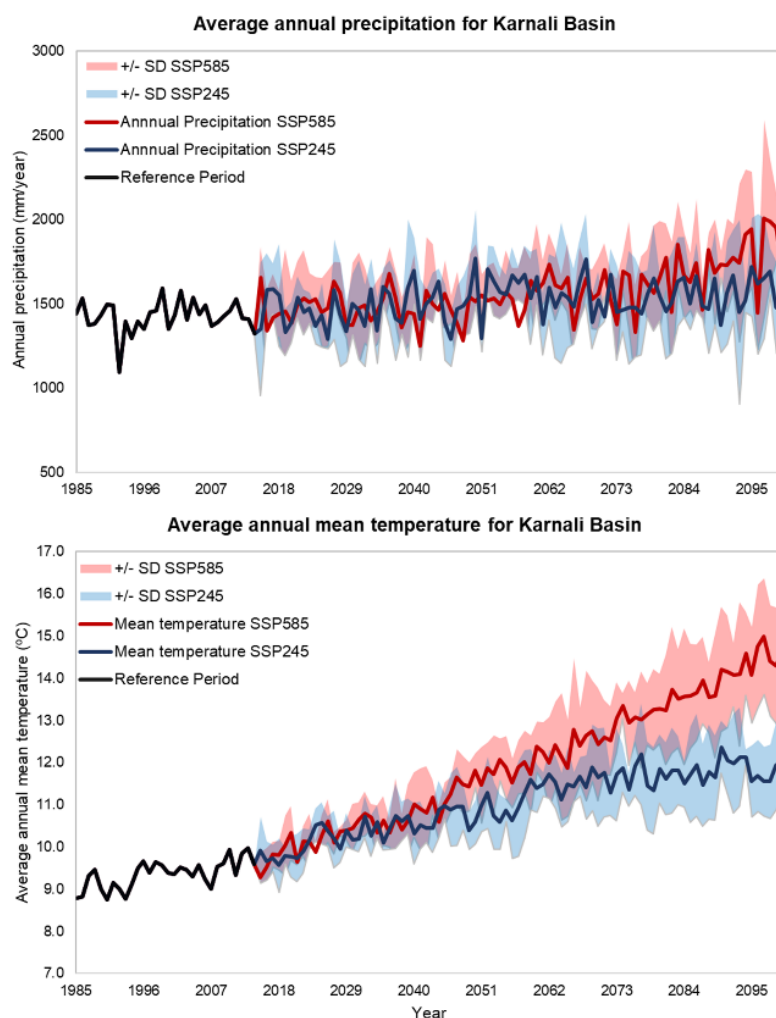


Figure 3. Average annual precipitation sum (left) and average annual mean temperature (right) for the Karnali basin for the reference period (1985-2014) and future periods (2015-2100). The colored bands represent the ensemble range of four models, and the solid bold lines represent the ensemble mean.
 Source: Pradhananga et al. 2025

3.3 Water availability

Climate projections based on CMIP6 indicate significant changes in discharge patterns. Annual discharge is projected to increase in the future, driven by higher monsoon rainfall and accelerated snow and glacier melt due to rising temperatures. However, changes are not uniform across seasons. During the monsoon season (June–September) and post-monsoon season (October–November), an increase of up to 51% increase is projected by the end of the century in SSP585 scenarios. This intensification of rainfall will most likely lead to higher peak flows and greater flood risk. A notable decline (3–23%) in flow is projected during both the winter season (December–February) and pre-monsoon season (March–May) by the end of the century (Figure 4).

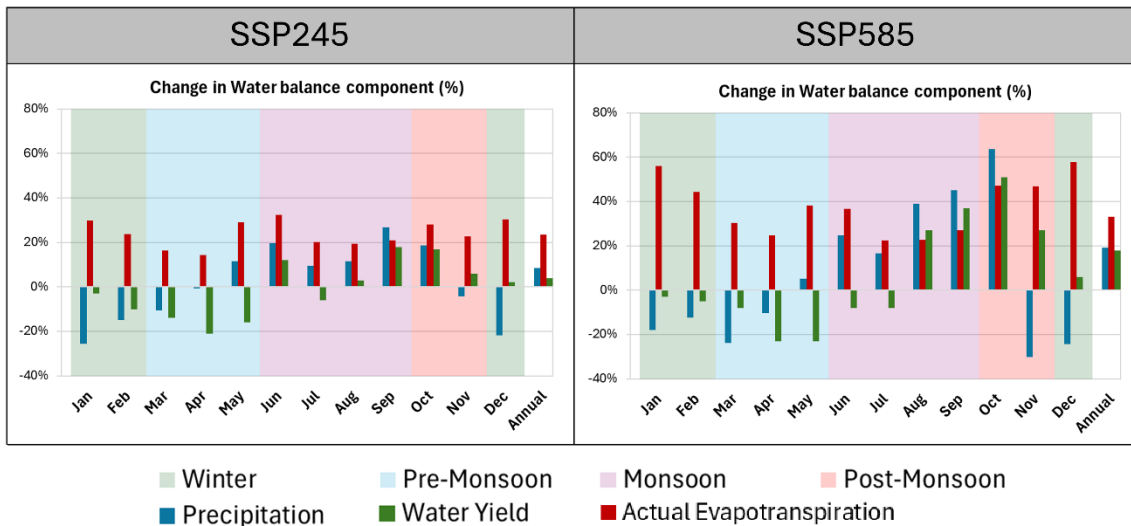


Figure 4. Change in the water balance components (Precipitation, Actual Evapotranspiration and Water Yield) by the end-century (2071 - 2100) with respect to the reference period (1985 – 2014). The pale background color represents four seasons: winter (DJF), pre-monsoon (MAM), monsoon (JJAS), and post-monsoon (ON).
 Source: Pradhananga et al. 2025

3.4 Hydropower generation

The planned Upper Karnali Hydropower Project will generate approximately 3466 GWh per year with, with majority about 2806 (~81%) GWh in wet season and about 660 GWh (~19%) GWh in dry season. Future energy projections show an overall increase in annual energy generation potential for the Upper Karnali Hydropower Project across most climate scenarios. Under the SSP245 scenario, annual generation is projected to increase by up to 7% by the end of the century whereas under the high-emission SSP585 scenario, annual generation could increase by up to 10%, primarily driven by higher monsoon flows. The study also projects a decline of 15% in dry season energy output by the end of the century, particularly under SSP585 (Figure 5).

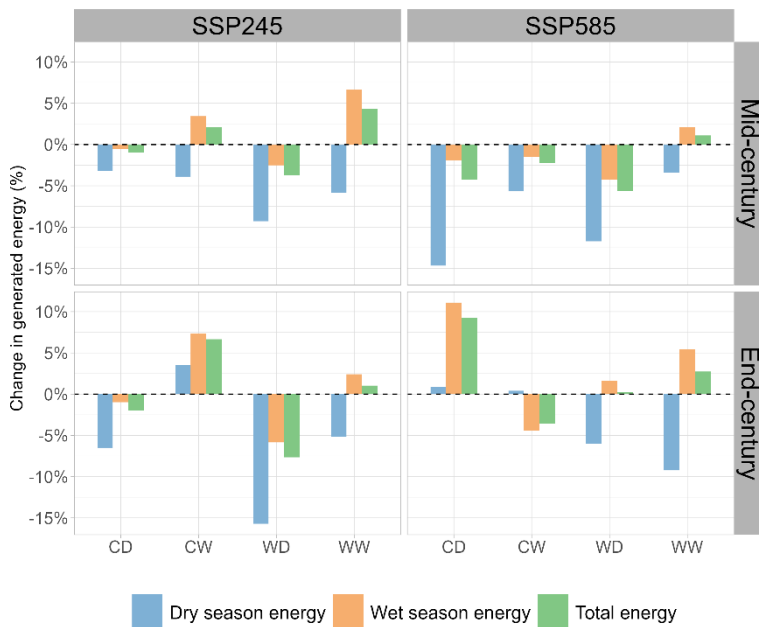


Figure 5. The change in dry, wet, and annual energy generation of the Upper Karnali Hydropower Project under two future scenarios for mid-century and end-century periods.
 Source: Pradhananga et al. 2025

3.5 Irrigation water requirements

By the end of the century—under the SSP245 scenario—the irrigation water requirement for paddy is projected to increase by approximately 11% compared to the historical baseline. Under the high-emission SSP5-8.5 scenario, the requirement increases by up to 17%. For wheat, which is grown during the dry winter season, the irrigation water requirement is projected to increase by 10% under SSP245 and by up to 16% under SSP585 (Figure 6). This increase is attributed to rising temperatures and reduced winter precipitation, which lowers effective soil moisture and increases irrigation dependency.

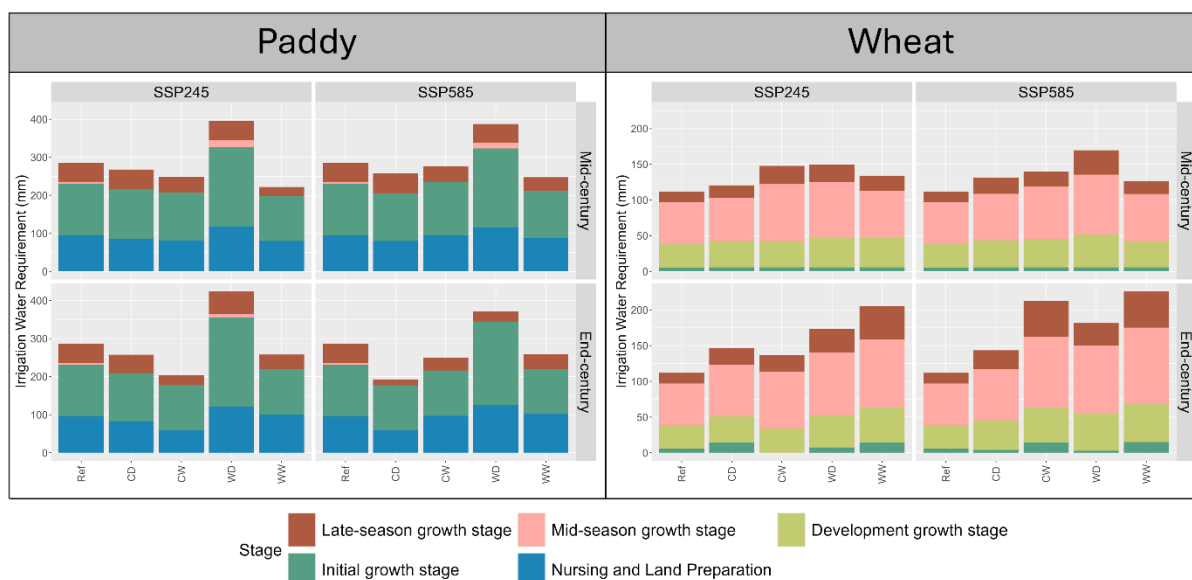


Figure 6. Irrigation Water Requirement for paddy (left) and wheat (right) for the five stages of the crop life cycle (nursing and land preparation, initial growth stage, development growth stage, mid-season growth stage, and late-season growth stage). *Source:* Pradhananga et al. 2025

4. Implications for policy and planning

The projected changes in seasonal runoff in the Karnali River Basin present several important implications for policy and planning:

1. Increased monsoon runoff may exceed existing infrastructure capacity in flood-prone areas, highlighting the need for better flood management and water storage.
2. Reduced rainfall and snowmelt will limit post-monsoon and winter water availability, affecting irrigation and groundwater recharge.
3. Lower dry season rainfall and baseflow will raise irrigation demand for wheat and reduce hydropower generation when energy demand peaks.
4. Rising temperatures will increase evapotranspiration, further reducing available water and heightening irrigation needs during key cropping and energy periods.
5. Shifts in monsoon timing and reliability—including delayed early rains—may disrupt crop calendars.

To address these challenges, policy and planning should incorporate climate-informed flow scenarios into hydropower feasibility studies and design standards. Irrigation management strategies must prepare for increased demand by improving water-use efficiency and adjusting crop calendars to align with shifting rainfall patterns. Flood and drought preparedness should be strengthened through early warning systems, updated reservoir operation rules, and improved river training works. Finally, Integrated River Basin Management (IRBM) approaches should be adopted to address complex sectoral interlinkages, balancing seasonal trade-offs, protecting ecosystem needs, and coordinating multi-sectoral water demands in a changing climate.

5. Policy recommendations

1. Mandate climate-informed design flow assessments and firm energy estimates for all proposed and upcoming hydropower projects as part of the feasibility study. Climate projections indicate that dry season flows will decrease, resulting in reduced power generation during those months. Relying on historical flow data may cause design flaws and inaccurate power generation estimates. Testing future climate scenarios can help identify and manage upcoming financial and operational risks.
2. Develop and prioritize storage and multipurpose reservoirs, as dry season precipitation is projected to decrease and mean temperatures are projected to increase. These reservoirs will capture excess monsoon runoff for dry months and supports hydropower, irrigation, and groundwater recharge.
3. Revise irrigation schedules based on forecasted weather and climate projections and encourage the adoption of water-efficient irrigation methods especially for winter crops. This study projects an increase in irrigation water requirements for both paddy and wheat during the critical growth period by the end of the century as rising temperatures and delayed rainfall increase crop water stress. Without modern irrigation methods and crop calendar adjustments, irrigation systems will likely face shortages during critical stages.

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