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Anthropogenic drivers and their impact on the hydrological regime  
of Nepal: a reviewSayede Sara Sayedi<sup>1,2,3,\*</sup> , Kunwar K Singh<sup>1,2,4</sup> , Mary C Fabrizio<sup>3</sup> and Santosh Nepal<sup>5</sup> <sup>1</sup> Global Research Institute, William & Mary, Williamsburg, VA 23185, United States of America<sup>2</sup> AidData, William & Mary, Williamsburg, VA 23185, United States of America<sup>3</sup> Virginia Institute of Marine Science, William & Mary, Gloucester Point, VA 23062, United States of America<sup>4</sup> Center for Geospatial Analysis, William & Mary, Williamsburg, VA 23185, United States of America<sup>5</sup> International Water Management Institute, Nepal Office, Kathmandu 44600, Nepal

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E-mail: [ssayed@wm.edu](mailto:ssayed@wm.edu)**Keywords:** Nepal, hydrological regime, climate change, land use change, hydropower dams, water resources

## Abstract

Nepal's hydrological regime, shaped by steep topography, monsoon-dominated rainfall, and extensive cryospheric systems, offers a useful testbed for understanding how climate change and human activities are reshaping water resources in mountain regions globally. Despite abundant water sources, Nepal faces persistent water security challenges driven by extreme seasonality, rising temperatures, shifting precipitation patterns, and rapid land-use change. In this review, we synthesize current evidence on anthropogenic drivers of hydrological change in Nepal and draw lessons relevant to other data-sparse, high-mountain and monsoon-influenced regions. We find that warming-induced glacial retreat, altered snowmelt timing, and changing monsoon dynamics are intensifying wet-season flood risks while heightening dry-season water scarcity, patterns increasingly observed across the Himalaya, Andes, and other mountain systems. Human activities, including urban expansion, agricultural intensification, hydropower, and extraction of sediments from rivers, further modify river flows, reduce groundwater recharge, and increase vulnerability to extremes. Yet major uncertainties persist, especially concerning high-elevation hydrology, permafrost dynamics, sediment extraction, and the cumulative impacts of expanding infrastructure. Nepal's pronounced topographic and climatic gradients limit broad generalizations, underscoring the need for region-specific hydrological monitoring and modeling. These challenges mirror global limitations in mountain hydrology, where sparse observations and rapidly changing conditions constrain predictive capacity. By identifying key knowledge gaps and highlighting cascading impacts on agriculture, hydropower, domestic water supply, and aquatic ecosystems, this review emphasizes the urgency of strengthening monitoring networks and integrating uncertainty into water management and climate adaptation strategies. Nepal's experience offers broader insights for countries facing similar pressures at the intersection of climate change, development, and fragile mountain water systems.

## 1. Introduction

Human activities are reshaping hydrological regimes globally, undermining water management strategies grounded in historical patterns and posing significant challenges for both societies and ecosystems (OECD 2013). Nepal, located in the High Mountain Asia region, represents an important case for examining these dynamics, as its exposure to climate extremes and socioeconomic constraints

heighten its sensitivity to hydrological change (Miyan 2015, Chalise and Naranpanawa 2016, Bhandari 2023). Although the country encompasses 20% of the Himalayan Mountains (Apollo 2017) and spans ~147 500 km<sup>2</sup> with a population of ~30 million (NSO 2021), it increasingly struggles with seasonal water scarcity and uneven water availability throughout the year (Chaudhary and Aryal 2009). Despite abundant freshwater resources, some regions experience severe flooding during the monsoon season yet

lack sufficient water for domestic and agricultural needs during dry months (Merz *et al* 2003).

Nepal exhibits exceptional climatic diversity (Clemens *et al* 2021), ranging from tropical and subtropical zones to alpine and tundra/nival environments (Paudel *et al* 2021b). The national average annual temperature is  $\sim 14.5^{\circ}\text{C}$ , with regional means ranging from  $\sim 1.2^{\circ}\text{C}$  in the High Himalayas (up to 8848.6 m, Mt Everest; figure 1) to  $\sim 25^{\circ}\text{C}$  in the Terai lowlands (as low as 60 m; DHM 2024). Regional climates are shaped by the interaction of the South Asian summer monsoon, westerly winds, and steep topographic gradients. The monsoon, active from June to September, contributes 70%–80% of the country's annual rainfall. Precipitation varies substantially, from less than 200 mm in northern rain-shadow zones such as Mustang to more than 5000 mm in the central and eastern hills (Sharma *et al* 2020, Maharjan *et al* 2023). Orographic processes produce two rainfall peaks around 500–700 m and 2000–2200 m, with precipitation declining sharply at elevations exceeding 3000 m (Maharjan *et al* 2023).

Nepal's water resources are highly diverse in type and distribution (figure 2; Shrestha and Aryal 2011, Talchabhadel and Chhetri 2023). The country contains about 3800 glaciers, 2070 glacial lakes, more than 3000 non-glacial lakes and reservoirs, and nearly 6000 perennial and seasonal rivers (Bajracharya *et al* 2014, 2020, NLCDC 2021). River systems are sustained by three dominant sources of water: (1) snow and glacial melt that support year-around flow; (2) monsoon rains and groundwater recharge feeding rivers in the middle mountains, and (3) monsoon-fed seasonal rivers originating in the Siwalik range (figure 1; Shrestha *et al* 2018). About 60%–85% of annual river discharge occurs during the summer monsoon (Shrestha *et al* 2018). Most rivers flow from north to south and eventually join the Ganges River system in India.

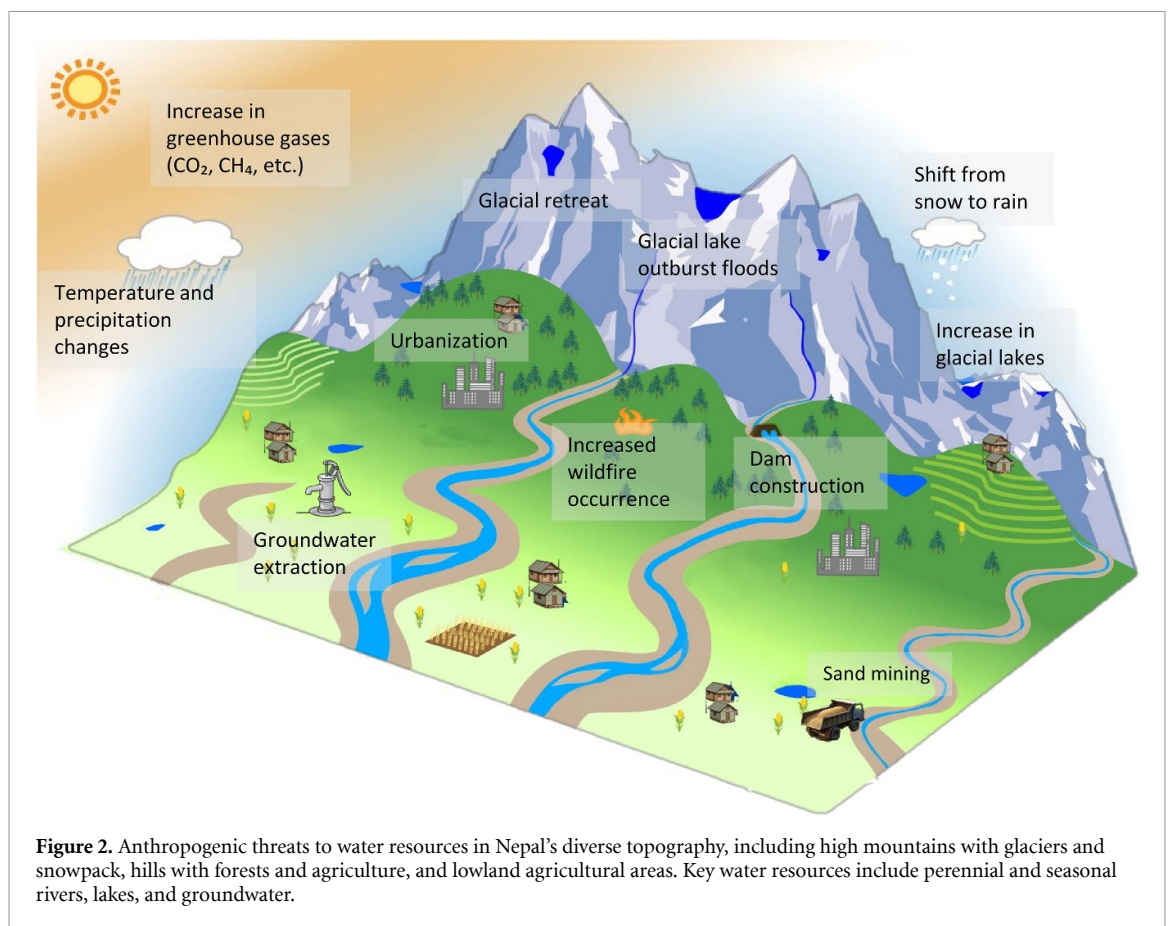
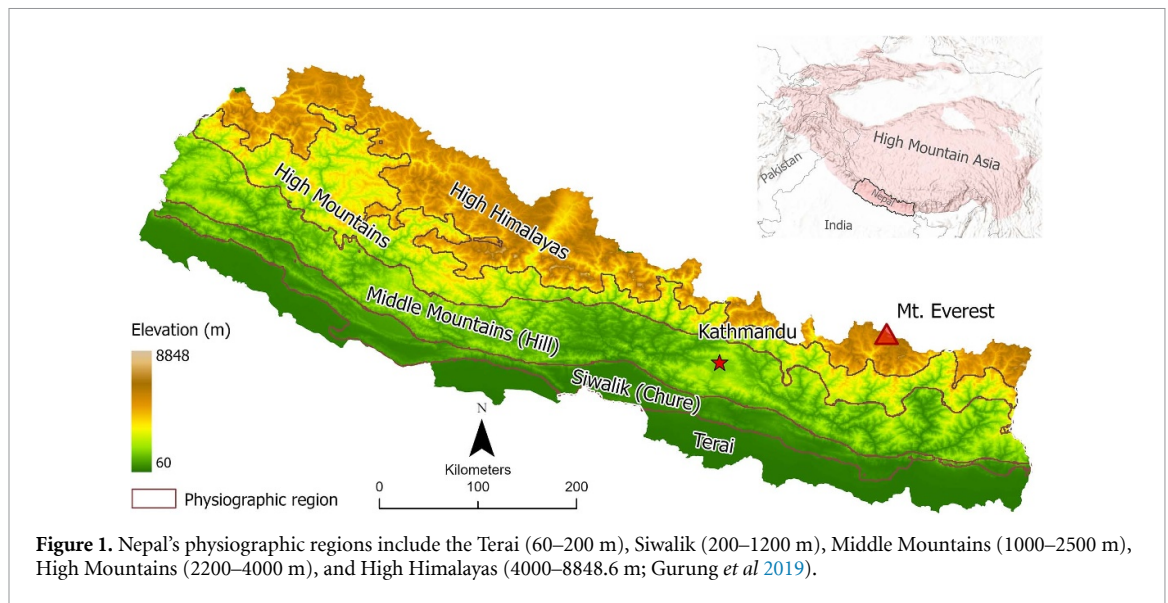
Over recent decades, Nepal has experienced substantial changes in water resources, including the seasonal disappearance of springs, accelerated glacial melting, altered snowfall patterns, overextraction of water, and increasing fragmentation of natural river flows (figures 2 and 3). These changes are expected to intensify as climate change, land-use conversions, and water infrastructure development accelerate (Nepal *et al* 2014a, Shrestha *et al* 2018, Nie *et al* 2021). Such alterations directly affect water-dependent sectors, particularly the agricultural and fisheries sectors, which support  $\sim 70\%$  of the population, more than half of whom are women (Dhakal *et al* 2022, NSCA 2022). Reliance on monsoon rainfall makes agriculture specifically vulnerable to shifts in rainfall timing and intensity, and increasing temperatures and extreme events (Karki and Gurung 2012, Choquette-Levy *et al* 2021, KC *et al* 2022). For example, in central Nepal, declining winter rainfall,

rising temperatures, and erratic monsoon patterns have reduced productivity of traditional crops such as wheat and cardamom (Subedi *et al* 2023, Tiwari *et al* 2023). Hydrological changes have also magnified the country's exposure to natural hazards. Intensifying monsoon rains increase the frequencies of flash floods and landslides (Harvey *et al* 2024). Rapid glacier retreat has increased the formation of glacial lakes (i.e. low-lying areas that accumulate meltwater), many of which are dammed by unstable moraines (figure 3; Compagno *et al* 2022).

As glaciers thin and flatten, debris-covered ice surfaces form supraglacial ponds that may coalesce into larger lakes (Watson *et al* 2016). The proliferation of moraine-dammed and supraglacial lakes elevates the risk of Glacial Lake Outburst Floods (GLOFs), which involve the sudden release of stored meltwater, triggered by glacier calving, moraine failure, or seismic activity. Nearly one million people in Nepal have been considered at risk from GLOFs since the 1990s (Nie *et al* 2021, David Raj *et al* 2023, Taylor *et al* 2023). A recent example is the August 2024 GLOF in Thame village in the Everest region, which caused major infrastructure damage and community displacement (ICIMOD 2024). As of 2010, 14 GLOF events have been documented in Nepal with additional events originating in Tibet and affecting downstream Nepali communities (ICIMOD *et al* 2011, 2023).

Rising risks from anthropogenic drivers underscore the need for integrated water management approaches that address the connections among water, food, energy, and ecosystems (Pokharel *et al* 2024). While numerous studies have examined specific drivers, most notably climate-change and its impacts on high-altitude water systems (Nie *et al* 2021, Yao *et al* 2022, David Raj *et al* 2023, Khadka *et al* 2023), a comprehensive understanding of the combined impacts of multiple anthropogenic drivers is still lacking (Dainese *et al* 2024). Understanding interactions and feedbacks among drivers is particularly important, as these processes can either amplify or moderate hydrological change (Blöschl *et al* 2019).

In this review, we examine how anthropogenic drivers collectively influence the size, distribution, and connectivity of major water pools in Nepal and the fluxes that govern exchanges among them. Water pools are defined as the compartments where water is stored (e.g. surface water, groundwater), and fluxes as the processes that move water between pools (e.g. precipitation, infiltration, runoff, and evapotranspiration; Chapin *et al* 2012). Our focus is on the impact of climate change and land-related drivers, including land cover change and sand mining, on water availability, seasonal patterns, and connectivity of surface and sub-surface water systems. We also discuss uncertainties, data limitations, and knowledge gaps that complicate attribution and prediction. Based on these insights, we outline implications for policy and



water management and identify priority areas for future research. This synthesis of hydrological interactions and knowledge gaps provides vital insights for other climate-sensitive, data-scarce mountain regions facing similar anthropogenic pressures.

This review does not address soil moisture, atmospheric water vapor, water quality, water pollution, sedimentation, or water temperature, although these topics are critically important for Nepal's water management (Balkhi *et al* 2023). Our literature search

relied primarily on Scopus and Google Scholar. We prioritized recent publications to highlight the latest advancements, incorporating older works only when recent studies were unavailable or lacked coverage of specific topics. To ensure a balanced perspective, we aimed to represent studies that employed diverse approaches, including empirical field studies, modeling, and analyses based on global datasets. Due to limited studies at the national-scale, we incorporated findings from global, regional, national, and

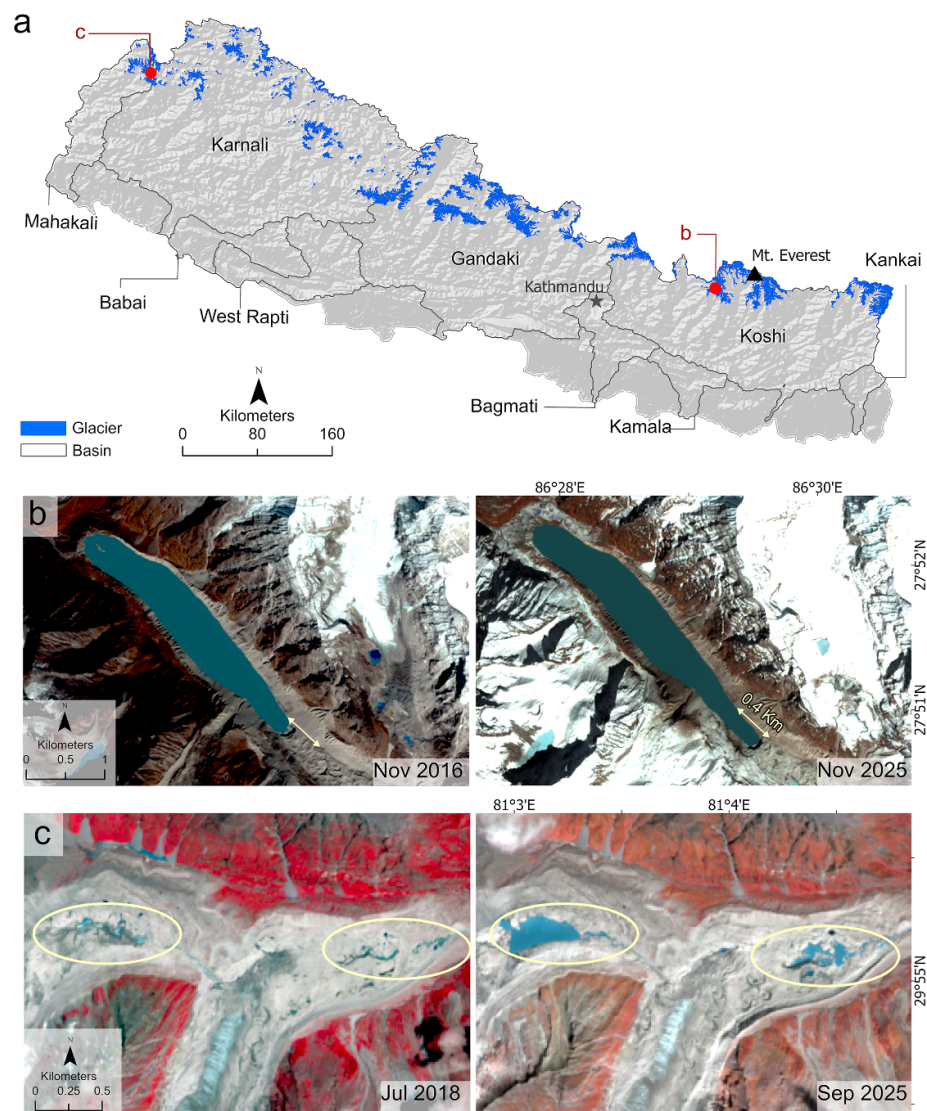


**Figure 3.** Examples of glacier retreat and glacier-lake expansion in Nepal as indicators of climate-driven surface-water change. (a) Major river basins of Nepal and glacier distribution, along with the locations of the two glaciers highlighted in this figure. (b) Tsho Rolpa glacial lake, located in the Koshi Basin of eastern Nepal at  $\sim 4550$  m. A comparison of 2016 and 2025 satellite imagery shows that the lake has expanded up-valley. This expansion is likely linked to glacier retreat or thinning, consistent with documented long-term lake growth in this basin (Kayastha and Maskey 2024). (c) Glacial lakes in the Karnali Basin of western Nepal. Two adjacent lakes at  $\sim 4430$  m (right) and  $\sim 4640$  m (left) have expanded and merged between 2018 and 2025. The areas of notable change are outlined in yellow. All satellite images use 10 m Sentinel-2 Level-1C and Level-2A obtained via Google Earth Engine. Images are displayed using false-color band combinations with enhanced visualization parameters. Contains modified Copernicus Sentinel data 2016, 2018, 2025.

watershed-level studies. Although we primarily relied on peer-reviewed articles, we occasionally considered reports published in English. We acknowledge that relevant and insightful documents written in Nepali were not consulted.

In this review, we categorize anthropogenic drivers into two groups: climate-change drivers and land-related drivers (e.g. land-cover change, sand mining). For each set of drivers, we first discuss the impacts of drivers on water pools and fluxes considering past observations as well as future projections. We next address uncertainties and important feedback mechanisms that could potentially alter Nepal's hydrological regime.

## 2. Anthropogenic drivers and the water cycle

### 2.1. Climate change

Air temperatures across Nepal exhibited a consistent warming pattern during the past few decades, and this trend is expected to continue. Since the mid-1970s, the annual mean temperature has increased by  $\sim 0.03$   $^{\circ}\text{C yr}^{-1}$  (Shrestha *et al* 2019b, Thakuri *et al* 2019). Rates of change vary significantly across geography, elevations and seasons, with the greatest increase observed in winter in the High Himalayas, where maximum winter temperatures increased by up to  $0.1$   $^{\circ}\text{C yr}^{-1}$  (from 1970 to 2014; DHM 2017). The smallest annual increase was observed

in the Terai, where the increased maximum temperature was estimated to be  $0.021\text{ }^{\circ}\text{C yr}^{-1}$  (from 1970 to 2014; DHM 2017). Researchers consistently report that maximum temperatures have risen faster ( $\sim 0.04\text{ }^{\circ}\text{C yr}^{-1}$ ) than minimum temperatures ( $\sim 0.02\text{ }^{\circ}\text{C yr}^{-1}$ ) throughout Nepal (Karki *et al* 2020, Poudel *et al* 2020).

In the Koshi River basin between 1962 and 2022, significant warming was primarily observed at higher elevations, with maximum temperatures increasing during the pre-monsoon in the High Himalayas ( $0.02\text{ }^{\circ}\text{C yr}^{-1}$ ) and during the post-monsoon ( $0.02\text{ }^{\circ}\text{C yr}^{-1}$ ) and winter ( $0.03\text{ }^{\circ}\text{C yr}^{-1}$ ) in the High Mountains. The daily maximum temperature increase in the Koshi basin was  $0.058\text{ }^{\circ}\text{C yr}^{-1}$  for the last four decades (Nepal 2016). Significant increases in average temperatures occur across multiple seasons, and recent warming is most pronounced in the upper Koshi River basin; however, the Siwalik and Terai regions exhibited significant cooling, particularly during the monsoon and winter seasons (Puri *et al* 2024). In high elevation areas of the Gandaki River basin in central Nepal, the greatest increases in maximum temperatures between 1960 and 2020 were observed in winter ( $0.06\text{ }^{\circ}\text{C yr}^{-1}$ ) and monsoon ( $0.05\text{ }^{\circ}\text{C yr}^{-1}$ ), while trends in other seasons were less consistent or lacked statistical significance (Chand *et al* 2021, Adhikari and Mathema 2023).

Climate models project sustained warming across Nepal, with pronounced regional and elevation-dependent differences in both rate and intensity (Bastola *et al* 2024, Marta *et al* 2023). By 2100, average temperatures are expected to rise by approximately  $1.3\text{ }^{\circ}\text{C}$ ,  $2\text{ }^{\circ}\text{C}$ – $4\text{ }^{\circ}\text{C}$ , and  $4\text{ }^{\circ}\text{C}$ – $7\text{ }^{\circ}\text{C}$  under low, moderate, and high greenhouse gas emission scenarios, respectively. These scenarios follow the Shared Socioeconomic Pathways (SSPs) framework—global narratives combined with climate forcing assumptions—and their approximate equivalents in the older Representative Concentration Pathways (RCPs): SSP1–2.6  $\approx$  RCP2.6; SSP2–4.5; and SSP5–8.5. Projected warming becomes increasingly uncertain under high-emission pathways (Almazroui *et al* 2020, GoN 2021, DHM 2024).

#### 2.1.1. Precipitation patterns and projections

In recent decades, Nepal's precipitation regime has shifted toward longer dry spells and, in many areas, longer wet spells, though the magnitude of these changes varies regionally. Consecutive dry days increased by about 10%–15% between the 1970s and 2015 (Maharjan *et al* 2023, Luo *et al* 2024), while consecutive wet days rose by roughly 22% nationwide over the same period (Luo *et al* 2024). Regionally, western Nepal has become wetter in recent years, with a greater frequency of extreme rainfall events since 2003. In contrast, eastern Nepal has trended drier, especially during the post-monsoon season (Luo *et al* 2024). Seasonally, post-monsoon rainfall has declined

across much of the country, pre-monsoon totals have increased in the Terai, rainfall has decreased in the High Himalayas, and monsoon rainfall has increased in the west and central hills but decreased in the east (DHM 2017, Karki *et al* 2017). These patterns suggest uneven regional changes and more frequent extremes in the west. Precipitation patterns reflect complex interactions between large-scale climate drivers, like the Indian Ocean Basin Mode, El Niño–Southern Oscillation (ENSO), and western disturbances, and Nepal's steep terrain, which creates strong windward–leeward contrasts. These interactions make generalizations about changes in precipitation challenging.

The mixed evidence for changes in precipitation extremes across Nepal results from the use of different precipitation data, spatial coverage, and analysis periods. For example, Luo *et al* (2024) identified a drying tendency, with maximum 1 d rainfall (RX1day) decreasing by 7%, rainfall on extremely wet days (R99pTOT) down by 20%, and fewer moderate to heavy rainfall days (R10, R20). Karki *et al* (2017) reported similar declines in moderate precipitation from 1970 to 2012. By contrast, Maharjan *et al* (2023) found intensification when comparing conditions in 1976–1995 with those in 1996–2015: RX1day, RX5day, and R20 increased by 5%–7%, and days with  $\geq 50\text{ mm}$  (R50) rose by nearly 8% in the later period.

Gridded and reanalysis products (e.g. APHRODITE, ERA5-Land) often diverge with gauge records maintained by the Department of Hydrology and Meteorology (DHM) due to interpolation errors or assimilation challenges over steep terrain (DHM 2017, Karki *et al* 2017, Sigdel *et al* 2022, Luo *et al* 2024). Findings from studies that rely on gridded or reanalysis products are sensitive to the timing of the study period, treatment of missing data and station heterogeneity, and the specific rainfall metrics analyzed (totals, wet-day frequency, intensity, or extremes; Karki *et al* 2017, Shrestha 2019b, Maharjan *et al* 2023). Trend inference also varies across methods: Mann–Kendall (including seasonal/autocorrelation-corrected variants), Sen's slope, and change-point tests can yield contrasting results if strong seasonality or multiple testing issues are not explicitly addressed (Gautam and Acharya 2012, Nepal 2016, Karki *et al* 2017, Thapa *et al* 2020, Maharjan *et al* 2023). Interpretation is further complicated by known measurement issues, such as snow undercatch and wind-induced error in precipitation gauges, and by evolving reanalysis products whose assimilation methods and data inputs change over time (Karki *et al* 2017, Veldhuijsen *et al* 2022, Luo *et al* 2024).

Future research should prioritize developing a harmonized workflow for precipitation-trend assessment in Nepal. This workflow should include standardized protocols for data quality control and station record homogenization, apply transparent gap-filling methods with quantified uncertainty, use trend

**Table 1.** Examples of projected precipitation changes for Nepal's three major river basins under SSP2-4.5 (approximately equivalent to RCP4.5) and SSP5-8.5 climate change scenarios. These results are drawn from comparable studies selected for consistency in reported outcomes. Time horizons represent the Near-Future (NF,  $\approx$  2020–2050), Mid-Future (MF,  $\approx$  2050–2070), and Far-Future (FF,  $\approx$  2070–2100) relative to baseline periods between 1957 and 2015. The number of stations contributing to each row ranges from 1 to 30.

| Basin          | NF       |          | MF       |          | FF       |          | References                  |
|----------------|----------|----------|----------|----------|----------|----------|-----------------------------|
|                | SSP2-4.5 | SSP5-8.5 | SSP2-4.5 | SSP5-8.5 | SSP2-4.5 | SSP5-8.5 |                             |
| Koshi          |          |          |          |          |          |          |                             |
| Low elevation  | 9        | 14.5     | 17       | 29       | 20       | 48.5     | Pradhan and Shrestha (2022) |
| Mid elevation  | 10       | 13       | 15       | 25       | 19       | 48       |                             |
| High elevation | 7.5      | 10       | 17       | 31       | 22.5     | 71       |                             |
| Gandaki        | 4        | 5        | 12       | 20       | 16       | 40       | Sigdel <i>et al</i> (2022)  |
| Karnali        |          |          |          |          |          |          |                             |
| Low elevation  | 5        | 9        | 7        | 9        | 6        | 6        | Pandey <i>et al</i> (2020)  |
| Mid elevation  | 5        | 8        | 9        | 11       | 11       | 13       |                             |
| High elevation | 4        | 7        | 10       | 10       | 13       | 17       |                             |

Model configurations: Pradhan and Shrestha (2022) used Coupled Model Intercomparison Project Phase 6 (CMIP6) models, specifically BCC-CSM2-MR, CanESM5, CNRM-CM6, and IPSL-CM6A-LR. Sigdel *et al* (2022) used 13 bias-corrected CMIP6 models: ACCESS-CM2, ACCESS-ESM1-5, BCC-CSM2-MR, CanESM5, EC-Earth3, EC-Earth3-Veg, INM-CM4-8, INM-CM5-0, MPI-ESM1-2-HR, MPI-ESM1-2-LR, MRI-ESM2-0, NorESM2-LM, and NorESM2-MM. Pandey *et al* (2020) used RCMs for precipitation from ICHEC-RCA4 and CNRM-CCAM.

tests that explicitly account for strong seasonality and serial dependence with appropriate field-significance adjustments, and incorporate formal sensitivity analyses across alternative baselines and analysis windows to ensure estimates are robust and comparable across studies (DHM 2017, Karki *et al* 2017, Maharjan *et al* 2023, Luo *et al* 2024).

Between 2030 and 2050, most regions of the country are projected to experience an increase in annual precipitation of less than 20% under either moderate or high emissions scenarios (DHM 2024, GoN 2021; table 1). This increase is largely due to monsoon precipitation, which is projected to rise by about 3% under SSP2-4.5 and nearly 8% under SSP5-8.5 at the national scale, with some western basins experiencing much larger increases (GoN 2021). In contrast, winter precipitation is projected to decrease under moderate scenarios (e.g.  $-5.8\%$  under RCP4.5) but increase under high emissions (e.g.  $7.2\%$  under SSP5-8.5), with strong regional contrasts (DHM 2024). By the end of the 21st century, mean precipitation in Nepal is projected to increase by  $\sim 3\%$ – $4\%$  under SSP1-2.6,  $\sim 11\%$ – $13\%$  under SSP2-4.5, and  $\sim 19\%$ – $23\%$  under SSP5-8.5, with greater uncertainty under higher emissions scenarios (Almazroui *et al* 2020, GoN 2021). However, these national averages mask large regional and seasonal variations. While most seasons are projected to see increases, pre-monsoon precipitation is expected to decline by  $\sim 8\%$  under SSP2-4.5 and  $3\%$  under SSP5-8.5 (GoN 2021). In drier regions, such as northern areas, annual precipitation could increase by up to  $110\%$  under SSP5-8.5, yet winter precipita-

tion is still projected to decline by  $11\%$ – $16\%$  (DHM 2024).

Projections across Nepal's major river basins consistently point to a seasonal imbalance, with monsoon and transitional seasons expected to become wetter, while winter shows the least and most uncertain change, raising concerns for dry-season water availability. At the same time, the range of projected values across studies is large, and results often diverge. For example, some studies project sharp pre-monsoon increases of up to  $30\%$  in the southwest (Bhattarai *et al* 2023), while others report declines in parts of the Koshi River basin (Agarwal *et al* 2014), highlighting the strong dependence of these outcomes on season, region, and modeling approach.

Projecting future precipitation in Nepal remains one of the most challenging aspects of climate modeling. Unlike temperature, which is relatively uniform and strongly constrained by global energy balance, precipitation is governed by small-scale processes such as cloud microphysics, convection, and orographic uplift. These processes occur at scales finer than those resolved by global climate models (GCMs), leading to biases and large inter-model variability (Prein *et al* 2015, DHM 2024). Although downscaling through regional climate models (RCMs) or statistical methods improves spatial representation (Prein *et al* 2015), uncertainties persist, particularly in mountainous regions like Nepal where precipitation is heterogeneous (Maharjan *et al* 2023). Sparse observational networks in high-altitude areas further compound

uncertainty, as limited data availability hampers both model calibration and the evaluation of satellite or reanalysis products (Fugger *et al* 2024, Miao *et al* 2024).

Uncertainty also stems from structural differences among models and the scenarios under which they are evaluated. CMIP-class models often disagree not only on the magnitude but even on the direction of precipitation change for a given location or season. This inconsistency reflects both model-specific formulations of atmospheric dynamics and the strong influence of natural climate variability, such as ENSO and the Indian Ocean Dipole, which can obscure long-term trends (Sharma *et al* 2020, Dawadi *et al* 2023). Finally, scenario uncertainty, including differences in future greenhouse gas emissions and land-use trajectories, increases toward the end of the century (Rounce *et al* 2023, Zekollari *et al* 2024).

Future studies should work to improve precipitation models by integrating station records with satellite and reanalysis products. For example, blending DHM rain gauge networks with Climate Hazards Group InfraRed Precipitation with Station, APHRODITE (Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources), or Tropical Rainfall Measuring Mission precipitation estimates to address gaps in high mountain regions (Maharjan *et al* 2023, Luo *et al* 2024). Bias correction and high-resolution downscaling methods need to be refined to better capture local variability and extremes. Using multi-model ensembles can help reduce uncertainty, and future research should emphasize approaches that make these ensembles more consistent and less biased for Nepal's complex terrain (DHM 2017, Karki *et al* 2017, Maharjan *et al* 2023, Luo *et al* 2024).

### 2.1.2. Changes in snowfall and snowmelt

Although snowfall in the high-elevation regions of Nepal constitutes ~10% of the total precipitation in the country (WEPA 2021), it sustains water availability during the dry season through snowmelt (Bookhagen and Burbank 2010, Kraaijenbrink *et al* 2021, Thapa *et al* 2021a) and inhibits glacier retreat by providing a protective layer from solar radiation (Malmros *et al* 2018, Nepal *et al* 2025). Since the 1980s, rising temperatures have reduced snow days and shifted precipitation from snow to rain, contributing to a sustained decline in snow cover extent, especially in lower elevations (Viste and Sorteberg 2015, Kattel and Yao 2024, Kuttippurath *et al* 2024, Nepal *et al* 2025). Between 2001 and 2021, Nepal lost 31% of its perennial snow and ice, the highest rate in the Hindu Kush Himalaya (Khan *et al* 2024, Bernat *et al* 2025). Basin-scale contrasts show significant snow cover loss in the high-elevation Koshi River basin (>4500 m, 2002–2014), but little change in the Gandaki and Karnali River basins, reflecting

differences in monsoon and westerly influence and elevation-driven snow–rain shifts (Thapa *et al* 2020, 2021b, Nepal *et al* 2025).

On average, between May and October, snowmelt accounts for approximately 12.5% of river discharge in Nepal (Bookhagen and Burbank 2010). On a basin level, estimates indicate that snowmelt contribution to river discharge ranges between 9% and 20.5% (Bookhagen and Burbank 2010, Thapa *et al* 2021b) and varies with season and elevation. In high-elevation sub-basins, snowmelt generally contributes a greater amount to river discharge than in low-elevation sub-basins. For example, in the Dudh Koshi basin (Mt. Everest region), snowmelt accounts for more than 40% of annual water inputs into the Pheriche sub-catchment (Mimeau *et al* 2019). Further at the Rabuwabazar gauging station in the Dudh Koshi basin, hydrological modeling shows that snowmelt contributes about 17% of annual flow from non-glaciated areas, plus an additional 10% from snowfall on glacier surfaces, giving a total contribution of 29% (Nepal *et al* 2014b, Nepal 2016). Similarly, in the nearby Langtang catchment in central Nepal, snowmelt contributes ~35% of annual runoff (Buri *et al* 2023, Fugger *et al* 2024).

The snowmelt period in Nepal and the eastern Himalayas is longer than in the central and western regions, a timing shift that heightens flood risk by increasing the likelihood of overlap with early monsoon rains (Panday *et al* 2011). This earlier onset of snowmelt in the eastern Himalayas is driven by rising temperatures in sub-basins such as the Langtang and Melamchi–Indrawati within the Koshi River basin (Stigter *et al* 2017, Baniya *et al* 2024). This earlier snowmelt occurs during the pre-monsoon and early monsoon seasons, compounding flood risk in meltwater-fed rivers. The co-occurrence of snowmelt and monsoon rains reduces the system's capacity to absorb runoff and increases flood risk. Unlike the historically gradual release of meltwater over several weeks or months, current conditions often produce faster, more concentrated flows (Panday *et al* 2011, Musselman *et al* 2018, Thapa *et al* 2020, Nepal *et al* 2025).

Climate change is expected to significantly alter snowmelt dynamics and river discharge in Nepal. Projections under RCP4.5 and RCP8.5 suggest that while overall discharge may increase due to higher rates of snowmelt and monsoon precipitation, the increase will occur primarily in the pre-monsoon and monsoon seasons, leaving winters and post-monsoon seasons drier (Dahal *et al* 2020). This pattern is concerning for downstream water availability, because snowmelt typically sustains river flow when rainfall tapers off. For example, in the Langtang basin the peak discharge is projected to shift from August to July by 2050 (Pradhananga *et al* 2014). The combined effects of reduced snowpack and earlier melting

diminish the steady contribution of meltwater during the post-monsoon season, reducing water availability for agriculture and hydropower and disrupting ecosystem stability (Immerzeel *et al* 2010, Wood *et al* 2020, Bajracharya *et al* 2024).

Apart from changes in the volume and timing of snowmelt, the dynamics of refreezing of meltwater are changing in response to climate change. In the Langtang catchment, ~21% of snowmelt refreezes, temporarily delaying its contribution to river flows (Veldhuijsen *et al* 2022). However, with projected temperature increases of 2 °C by 2050, refreezing is expected to decrease by 35%, leading to more immediate runoff and reducing the amount of meltwater that contributes to river flow later in the year (Veldhuijsen *et al* 2022). Higher temperatures can simultaneously reduce snowfall and snowpack while accelerating snowmelt, yet current estimates and future projections of snow dynamics within Nepal's hydrological regime remain highly uncertain (Ackroyd *et al* 2021).

Nepal's estimate of snow depth and cover remain severely limited by both satellite constraints and the absence of long-term ground validation (Smith and Bookhagen 2018, Chandel and Ghosh 2021, Nie *et al* 2021). Current assessments rely primarily on satellite remote sensing, yet uncertainties remain high due to the scarcity of *in situ* observations (Mudbhari *et al* 2022, Bajracharya *et al* 2023, Luo *et al* 2024); only twelve snow stations exist nationwide (DHM [n.d](#)), leaving most high-altitude regions entirely unmonitored. MODIS and Landsat products are commonly used to address these gaps (Thapa *et al* 2020, Khan *et al* 2024), but they face persistent challenges, including coarse spatial resolution (e.g. MODIS 500 m; Friedl *et al* 2002, Khan *et al* 2024), frequent cloud contamination (Thapa *et al* 2021b, Veldhuijsen *et al* 2022), misclassification in debris-covered terrain and mountain shadows, and spectral confusion with bright surfaces such as glacial lakes (Khan *et al* 2024). Even with cloud-gap interpolation or higher-resolution Landsat mapping, these issues persist, and reported accuracies for snow cover detection across the Hindu Kush Himalaya vary widely from 46% to 90% depending on season and landscape (Thapa *et al* 2021b, Khan *et al* 2024).

### 2.1.3. Glacial retreat and GLOFs

Like glaciers in other mountainous regions throughout the world, rising temperatures have led to glacial retreat in Nepal. Between 1980 and 2010, Nepal's glaciers exhibited a varied pattern of shrinkage, with annual reductions in glaciated areas ranging from 1 to 5 km<sup>2</sup> (Khadka *et al* 2023). From 2000 to 2019, glaciers across high mountain areas of Asia experienced an average specific-mass change of  $-0.22 \pm 0.05$  meters water equivalent (w.e.) per year, meaning the annual loss was equivalent to removing a uniform

~0.22 m layer of water from the entire glaciated area (Hugonnet *et al* 2021). Glacial retreat is projected to continue throughout the 21st century, and glaciers in the high mountains of Asia, including Nepal, could lose between 49% (SSP1-1.9) and 89% (SSP5-8.5) of their area by 2100 relative to 2020 extents (Bosson *et al* 2023). Losses are expected under all SSP scenarios until about 2040, after which the rate depends on future (and uncertain) greenhouse gas emissions. Mass- and volume-based projections of loss show similar changes, with all Himalayan subregions projected to lose at least 35% of present-day glacier volume by 2100 because they are out of equilibrium with the current climate (Miles *et al* 2021). Under future warming scenarios, losses for South Asia East (including Nepal), may be as high as 60%–100% of glacier mass with peak mass-loss between 2025 and 2030, after which the net rate of glacier mass loss is projected to decline (Rounce *et al* 2023).

Similar to snowmelt, glacial meltwater plays a crucial role as a buffer during the dry seasons (Pritchard 2019). In the lowlands (Terai) of Nepal, the contribution of glacial meltwater to river discharge is estimated to range between 10% and 30% (Biemans *et al* 2019). As glaciers retreat, the resulting changes in the volume and flow rate of meltwater can significantly alter the region's hydrology, potentially causing shifts in water availability, river flow dynamics, and flood risk. The Ganges River basin, for example, exhibited an increase in annual excess discharge of between 2000 and 2016, with excess discharge defined as water originating from the net loss of glacier mass and reaching 84 m<sup>3</sup> s<sup>-1</sup> (Brun *et al* 2017). However, as glaciers lose more mass, excess discharge is likely to decrease in the region (Huss and Hock 2018, Hock *et al* 2019). Himalayan glacial lake volumes are expected to peak between 2040 and 2050 (Compagno *et al* 2022). Afterward, lake volumes are projected to decline as the supply of meltwater diminishes (Huss and Hock 2018, Hock *et al* 2019, Rounce *et al* 2023, Zekollari *et al* 2024).

The effects of climate change on the seasonality and spatial patterns of glacial meltwater in Nepal remain poorly described due to limited high-elevation observations and complex cryospheric–hydrological interactions. In the Upper Dudh Koshi River basin, snow- and glacier-melt contributions to annual streamflow are estimated to range from 4% to 60%, depending on model configuration and definitions used (Mimeau *et al* 2019). In the Langtang catchment, projections suggest increased water availability during the next several decades with limited seasonal shifts, although large-scale glacier models often fail to capture key high-altitude processes (Ragettli *et al* 2016). These wide ranges underscore the substantial uncertainty that remains in both current estimates and future projections of meltwater contributions to streamflow.

Extensive glacial retreat and mass loss in Nepal are reshaping the hydrological landscape, leading to the formation of new glacial lakes (figure 3), even at lower elevations ( $\sim 2450$  m above sea level; Kandel *et al* 2023) and increasing risks of GLOFs. Between 2000 and 2015, a study of 153 glacial lakes in Nepal found a 15.6% increase in their area, with growth occurring primarily at elevations of 4000–6000 m (Shugar *et al* 2020). This expansion rate is the highest rate observed in the Himalayas (Nie *et al* 2017). A distinctive feature of Nepal is its high proportion of moraine-dammed lakes, formed as glaciers retreat and leave behind unstable debris dams (Zheng *et al* 2021). These lakes develop when retreating glaciers deposit moraines that act as natural dams. About 32% of Nepal's moraine-dammed glacial lakes are at high or very high risk of causing GLOFs, and new high-risk areas likely to emerge by the end of the century, particularly under high greenhouse gas emission scenarios (Zheng *et al* 2021).

Uncertainty in glacier measurement and modeling in Nepal remains high due to data scarcity, complex terrain, and modeling limitations. Monitoring of high-altitude glaciers is sparse, and harsh conditions combined with poor station maintenance further compromise data quality (Nepal *et al* 2014b, Mimeau *et al* 2019). Precipitation, a key driver of glacial mass balance, remains poorly observed at the elevations where most glaciers occur (Bookhagen and Burbank 2010, Shrestha and Aryal 2011, Dawadi *et al* 2023). Glacier-specific uncertainties include difficulties in accurately representing debris-covered glaciers, supraglacial ponds, and ice cliffs (Watson *et al* 2016, Mimeau *et al* 2019) as well as limited knowledge of ice thickness and conditions at the ice-bedrock or ice-debris interface (Hugonnet *et al* 2021). Additional uncertainty arises from simplified representations of internal glacier hydrology, such as englacial water storage, and omission of avalanche contributions to glacier accumulation (Mimeau *et al* 2019). Errors also occur when converting volume-based metrics to mass-based changes, and projections of future melt remain uncertain as glacier areas shrink and the timing and volume of meltwater runoff continue to shift (Rounce *et al* 2023, Zekollari *et al* 2024).

#### 2.1.4. Permafrost thawing

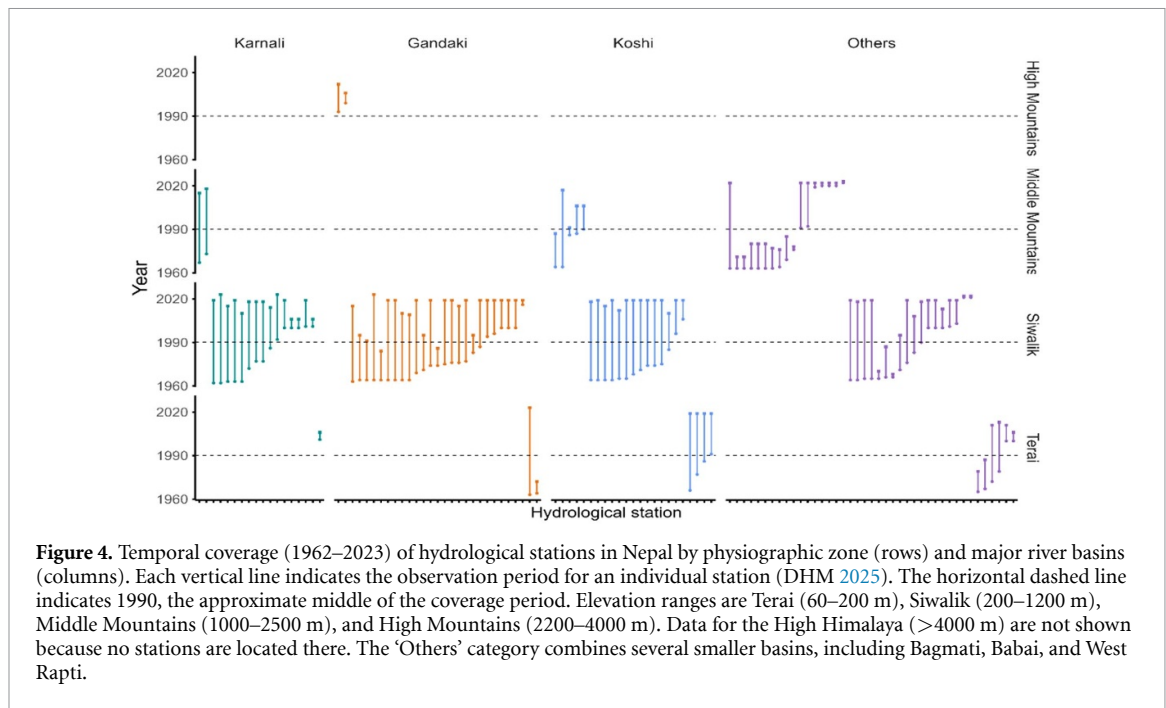
Alpine permafrost, which is more sensitive to climate change than Arctic permafrost, exhibits significant thawing and degradation with rising temperatures (Cheng *et al* 2022). Specific studies about Nepal's alpine permafrost, which is estimated to cover an area of 6,400–16,100 km<sup>2</sup> (Gruber *et al* 2017), are scarce, but insights from other regions suggest that accelerated thawing could significantly alter Nepal's hydrological regime. Permafrost degradation contributes water to river systems, destabilizes glacial and moraine dams, and increases the frequency of GLOFs

(Veh *et al* 2022). Processes associated with permafrost degradation such as ground-ice melt, soil subsidence, and reduced subsurface storage, could alter both the timing and magnitude of river flows, but the net impact on dry-season water availability and flood risks remains uncertain.

Global alpine research suggests that acceleration of thawing permafrost can modify groundwater flow (Hayashi 2020, Kuang *et al* 2024), peak discharge, and low-flow conditions in rivers (Qin *et al* 2022). It also alters subsurface drainage and the groundwater storage (Walvoord and Kurylyk 2016), though such changes have not yet been documented in Nepal (Gruber *et al* 2017). Insights from the Qinghai–Tibet Plateau suggest that permafrost degradation in the Himalayas is likely to reduce shallow subsurface water storage (Gao *et al* 2020, 2025), because a deepening active layer and steep slopes accelerate vertical and downslope drainage, weakening the frozen layer's role in retaining near-surface moisture. At the same time, thawing often enhances deeper infiltration and subsurface connectivity, opening new flow pathways and allowing water to move more freely into deeper or downslope soil horizons (Walvoord and Kurylyk 2016, Lafrenière and Lamoureux 2019). These contrasting responses can cause short- to mid-term increases in groundwater contributions to streams, followed by potential long-term declines as shallow storage diminishes (Walvoord and Kurylyk 2016, Kuang *et al* 2024). Because intact permafrost promotes rapid surface runoff, its degradation would generally reduce, rather than amplify, surface runoff relative to current frozen conditions (Baral *et al* 2023a). No studies, to our knowledge, have examined these specific permafrost-related effects within Nepal or the broader Hindu Kush Himalaya, creating a major source of uncertainty in hydrological projections (Vishwakarma *et al* 2022). Addressing this gap should be a priority for future research.

#### 2.1.5. Alterations to rivers

Changes in seasonal precipitation and meltwater dynamics affect flow and water availability in Nepal's rivers, a pattern that will continue with climate change. Analysis of streamflow from 23 hydrological stations across Nepal for 1965–1995 (Gautam and Acharya 2012) shows that about two-thirds of stations exhibited no significant changes in annual or seasonal flow. Where trends occurred, annual river flows declined more often than increased, monsoon-season flows showed mixed directions but no consistent pattern, and pre-monsoon and winter flows increased consistently, likely reflecting contributions from snow and glacier melt during dry periods. Large basins ( $>5000$  km<sup>2</sup>) generally exhibited no trends. The Koshi River basin recorded the highest proportion of significant changes in river discharge (streamflow), with upward trends (24%

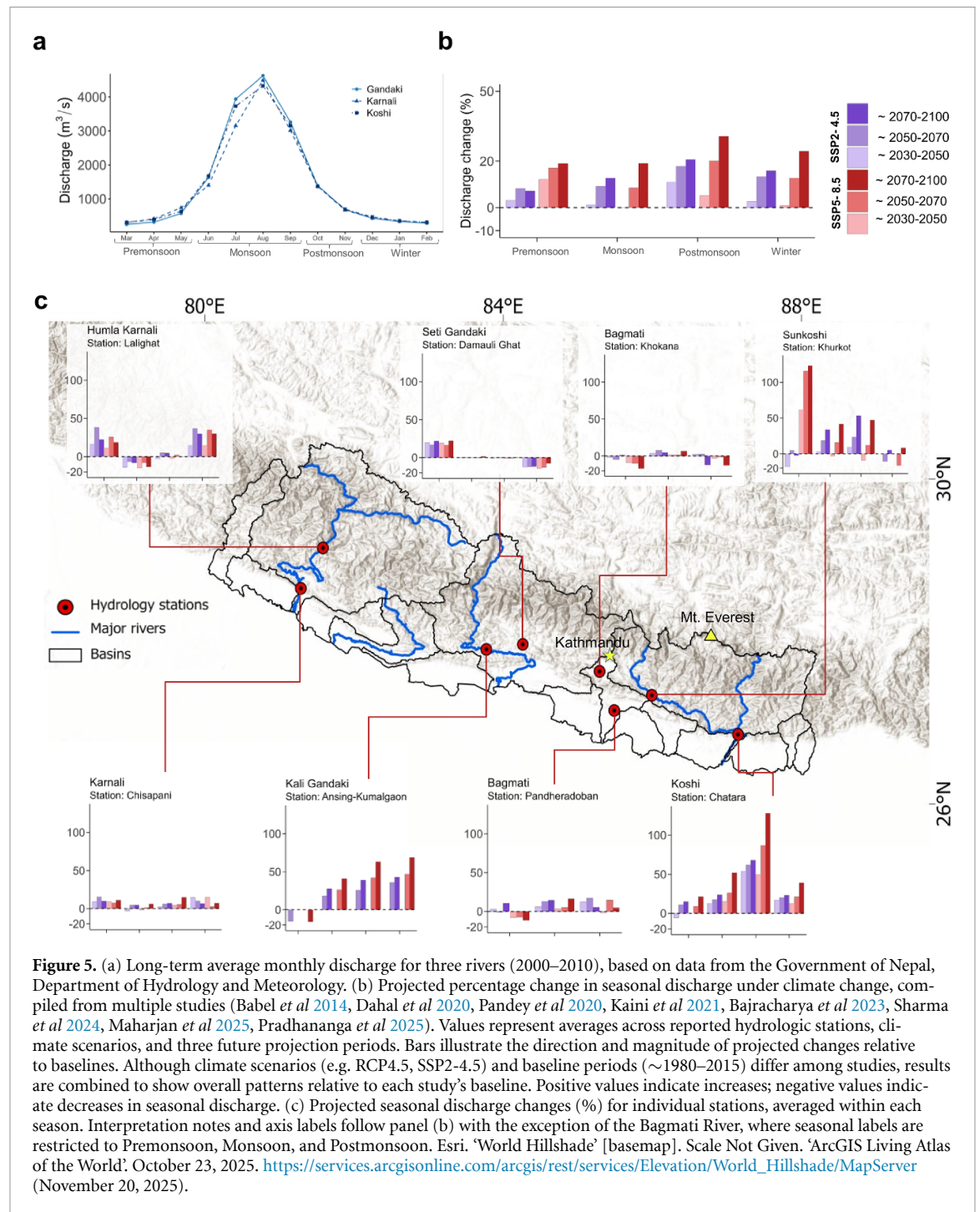


of stations) outnumbering declines (12% of stations; Gautam and Acharya 2012). A subsequent analysis that broadened the time period of study (1962–2015) and included six stations in the lowlands identified basin-specific change points between 1984 and 2003 (Aryal *et al* 2023). In the period after the change point, mean annual discharge decreased by  $\sim 6\%$  in major rivers (Karnali, Narayani, and Koshi rivers) and  $\sim 8\%$  in medium rivers (West Rapti, Bagmati, and Kankai rivers). Notably, sharp declines in mean annual discharge occurred in the Bagmati River ( $-1.9 \text{ m}^3 \text{ s}^{-1}$  per year) and increases occurred in the Kankai River ( $2.07 \text{ m}^3 \text{ s}^{-1}$  per year; Aryal *et al* 2023). In the Babai River, median monthly flows declined in 6 of 12 months after 2002, spanning both wet and dry seasons (Aryal *et al* 2024), signaling a reduced flow regime with moderate variability that heightens the risk of seasonal water stress, and potentially affects agricultural production, hydropower generation, and ecosystem resilience.

Assessing changes in streamflow in Nepal over recent decades is limited by short and spatially uneven gauge records, with most monitoring stations concentrated in the Siwalik (figure 4) and limited representation of high-altitude (>3000 m) hydrology (Gautam and Acharya 2012, Luo *et al* 2024). Many records contain multi-year gaps or inconsistencies, and flood discharges are often estimated by extrapolating from measurements taken during low flows, a process that introduces substantial uncertainty (Chandel and Ghosh 2021). Region-wide generalizations in streamflow trends are often unreliable because observed trends in annual and seasonal flows are spatially heterogeneous, with some rivers showing decreases, others showing increases,

and many exhibiting no change in discharge (Gautam and Acharya 2012, Aryal *et al* 2023). Moreover, most studies analyze total streamflow without resolving its components (runoff, baseflow, snowmelt, glacier melt), each of which may change independently and sometimes in opposing directions, further obscuring long-term understanding (Chandel and Ghosh 2021, Lamichhane *et al* 2024a).

Future projections across Nepal indicate broad agreement among studies: average annual river discharge will likely increase under climate change (figure 5). While the magnitude of that increase varies by climate scenarios and future timeline, nearly all studies indicate wetter futures on an annual basis, largely driven by the intensification of the summer monsoon (Babel *et al* 2014, Bajracharya *et al* 2018, 2023, Dahal *et al* 2020, Lamichhane *et al* 2024a, Chaulagain *et al* 2025). Yet, when examined at seasonal and monthly scales, the signal is more complex. Projections consistently indicate stronger monsoon flows (e.g.  $+60\%$  to  $+124\%$  in the Karnali under SSP5-8.5; Lamichhane *et al* 2024a), while winter and pre-monsoon flows decline across many basins, and post-monsoon flows remain variable. However, annual average increases are largely an artifact of a few extreme monsoon months, with flows in most other months projected to decline. In effect, such intra-annual patterns suggest greater flows overall, but lower availability during some months, because surplus monsoon water manifests as floods while dry-season shortages persist. While Nepal’s rivers are likely to become wetter overall, the timing, distribution, and form of runoff will shift in ways that increase variability in water availability, creating a hydrological future of wetter annual means but more pronounced seasonal deficits and surpluses.



Many rivers in Nepal are expected to experience increased annual flows, but this trend is not consistent across the entire river network. For example, mean annual discharge in the Tila River (western Nepal, elevation ~2160 m) is expected to decline by 13%–22%, with reductions across nearly all months and seasons under RCP4.5 and RCP8.5 scenarios (Pandey *et al* 2020). Similarly, the Marsyangdi River (elevation ~370 m) is projected to show a 6%–19% decrease in average discharge, likely driven by enhanced evapotranspiration (Mudbhari *et al* 2022). In contrast, streamflow in the nearby Kaligandaki River is expected to increase (figure 5). In the upper

Bagmati River (elevation ~180 m), pre- and post-monsoon flows are projected to decline, intensifying seasonal water stress despite higher annual averages (Babel *et al* 2014).

Sub-basin contrasts are also evident, such as in the Dudh Koshi River basin, where reduced snowfall and snowmelt are projected to shift the system from melt-dominated to rain-dominated by the late century, even as overall river flows increase (Nepal 2016). These findings suggest that the projected national scale increase in streamflow may partly reflect the dynamics at lower elevations, where hydrology stations are concentrated and where runoff

increases can strongly amplify downstream flows. In contrast, stations at higher elevations and those in low elevations with small drainage areas (e.g. the upper Bagmati) are expected to exhibit different trends.

Uncertainty in future discharge projections for Nepal stems from a combination of climate projection scenarios, model structure, and assumptions about future conditions. Many studies rely on short climate and streamflow (less than three decades) and a sparse observational baseline (figure 4), increasing the risk of conflating natural variability with long-term change (Gautam and Acharya 2012, Bhattarai *et al* 2023).

A second source of uncertainty arises from the climate model inputs that drive hydrological simulations. GCMs often produce contrasting runoff trends under same forcing, reflecting differences in how physical processes are represented and the influence of internal climate variability (Agarwal *et al* 2014, Babel *et al* 2014, Thapa *et al* 2021a). This divergence is especially pronounced for precipitation, where one model may project substantial increases while another may project decline for the same basin and time horizon (Mudbhari *et al* 2022).

Hydrological modeling frameworks add further complexity to these uncertainties. Nepalese studies primarily use the SWAT model for rainfall-runoff simulation, and although this model is widely applied in Himalayan basins, it has well-documented limitations in representing cryospheric processes (Krysanova and Arnold 2008). While SWAT performs reliably for rainfall and runoff, its snow and glacier melt components are comparatively weak, reducing model performance in snowmelt-dominated catchments (Krysanova and Arnold 2008, Pandey *et al* 2020, Bajracharya *et al* 2023). As a result, projections may underestimate or mischaracterize discharge changes driven by accelerated melting under climate change. Model accuracy is further constrained by the quality of digital elevation models, soil maps, and land-cover datasets, which in the Himalayas are often coarse, inconsistent in resolution, or incomplete due to rugged terrain and observational challenges (Khan *et al* 2024, Chaulagain *et al* 2025). Finally, many hydrological studies (figure 5) assume static land cover in future simulations, overlooking likely changes in agricultural, deforestation, or infrastructure development that could alter runoff generation (Sharma *et al* 2024, Chaulagain *et al* 2025).

Future research on streamflow response to climate change should move beyond reliance on short hydrological and climate records and adopt approaches that better capture discharge dynamics in Himalayan basins. Integrating isotope tracers with hydrological models can help disentangle contributions of rainfall, snowmelt, glacier melt, and groundwater, providing an external benchmark for model performance (Chandel and Ghosh 2021). Models also

need enhanced cryospheric modules that incorporate sublimation, refreezing, avalanche inputs, and changing glacier albedo, as current tools consistently underestimate meltwater contributions (Nepal 2016). Improved precipitation inputs require high-resolution downscaling and refined bias-correction methods, while multi-model ensembles combined with explicit uncertainty quantification can strengthen discharge trend projections (Dahal *et al* 2020, Lamichhane *et al* 2024a). Additionally, paleo-hydrological studies using ice cores or lake sediments can extend streamflow records to centuries or millennia (Guo *et al* 2025), offering critical context for understanding long-term climate-streamflow relationships at high elevations and other areas. Together, these research directions could build a more reliable foundation for projecting future streamflow under climate change.

## 2.2. Land alterations

Hydrological processes are shaped by land characteristics and climate, with certain components of the water cycle, such as baseflow, being more strongly impacted by land features than by climate factors (Tomer and Schilling 2009). Globally, human-induced changes in land cover have resulted in a 5% decrease in terrestrial evapotranspiration and a 7.6% increase in runoff, primarily due to an increase in the number of reservoirs and the degradation of wetlands (Sterling *et al* 2013). Land use changes in Nepal, such as urban expansion and fluctuations in forest cover, sand and gravel mining from riverbeds and floodplains, hydropower development, and water diversions, have significantly altered the hydrological regime (Baral *et al* 2023b).

### 2.2.1. Land-cover change

Nepal's land cover has undergone major transitions, driven by rapid urban expansion and fluctuations in forest and cropland extent. Forests and croplands remain the dominant land-cover types (figure 6; table 2), but urban growth since the 1990s contrasts sharply with steady declines in agricultural land and notable forest recovery (Fox *et al* 2019, Bista *et al* 2021, Ojha *et al* 2022, Devkota *et al* 2023, Koirala and Bashyal 2025). These shifts reflect broader socioeconomic changes, including human migrations, farm abandonment, and forest conservation efforts (Ning *et al* 2023). While these trends represent overarching national patterns, regional trajectories remain highly heterogeneous.

Research on land-use impacts on Nepal's hydrology remains limited, with a notable absence of comprehensive spatial analyses across the country. The studies summarized in table 3, though regional in scope, consistently show that urban expansion and the decline of agricultural land reduce baseflow, while the spread of built-up areas intensifies surface

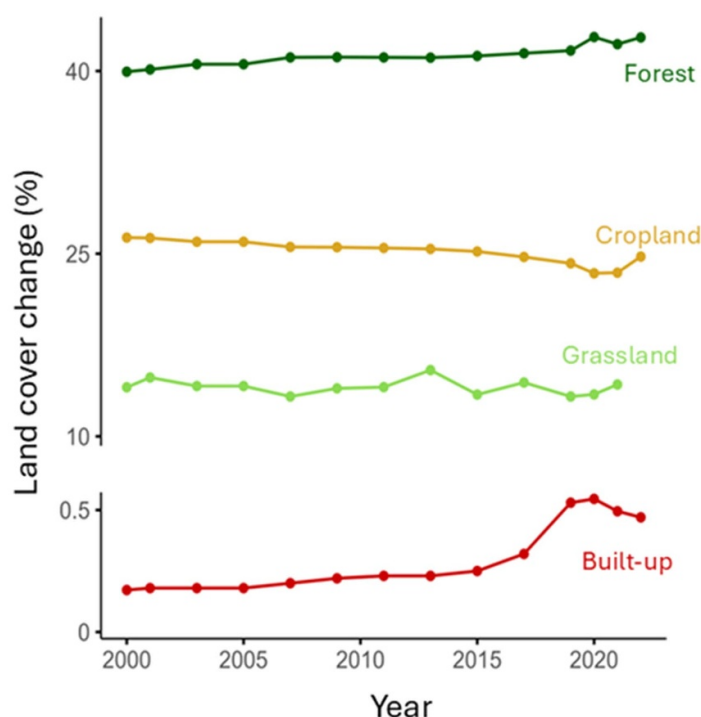


**Figure 6.** Land cover change in Nepal from 2000 to 2022. Trends in forest, cropland, grassland, and built-up cover are shown using the ICIMOD land-cover dataset, which is based on 30 m resolution Landsat imagery. Forest, cropland, and grassland are shown on the same y-axis, while built-up cover (<1%) is plotted on a separate axis to make its trend visible (Data source: FRTC 2022).

**Table 2.** Land use and land cover across Nepal's physiographic regions, indicating regional land area percentages and the proportional composition of major land use and cover types for 2022.

| Physiographic region    | Percent of land area | Major land use and cover percent <sup>a</sup> |
|-------------------------|----------------------|-----------------------------------------------|
| High Himalayas          | 24%                  | Barerock (58%); Snow and Glacier (25%)        |
| High Mountains          | 21%                  | Forest (55%); Cropland (18%)                  |
| Middle Mountains (Hill) | 29%                  | Forest (63%); Cropland (30%)                  |
| Siwalik                 | 12%                  | Forest (72%); Cropland (20%)                  |
| Terai                   | 14%                  | Cropland (68%); Forest (23%)                  |

<sup>a</sup> Data source: FRTC 2022

runoff. Although forest cover has increased nationally through the establishment of community forests, localized deforestation and ongoing forest degradation in some mid-hills and western watersheds continue to alter infiltration and groundwater recharge, underscoring the need for systematic research across different watersheds at the national scale (Aryal *et al* 2021).

Community forestry programs have often relied on fast-growing pine plantations, which differ ecologically from native broadleaf forests. Hydrologically, fast-growing pine plantations can intensify water stress by intercepting more rainfall, increasing evapotranspiration, and reducing dry-season streamflow (Ghimire *et al* 2012, Badu *et al* 2019, Jin *et al* 2025). The intensive use of community forests, such as litter removal and trampling, can compact soils, lower infiltration and contribute to greater runoff, erosion, and sediment loss (Badu *et al* 2019). In contrast,

less disturbed sites show improved soil structure and infiltration capacity, suggesting that careful management can enhance groundwater recharge and stabilize landscapes.

Alterations in land use, coupled with prolonged dry periods, have led to the degradation of many springs that are used by communities for household water, with effects especially pronounced in the Hill region (Adhikari *et al* 2020). At the watershed scale, forest clearance and land fragmentation have been directly linked to declining spring discharge (Pandit *et al* 2024). National reviews emphasize the reduction in infiltration and groundwater recharge in regions such as Kathmandu, where extensive agricultural land and forest cover have been converted to built-up areas, and in parts of the mid-hills and the Rangun Khola watershed, where localized deforestation and agricultural expansion have occurred (Sharma *et al*

**Table 3.** Land use changes in selected catchments over specified time periods, with corresponding hydrological metrics, showing percentage changes and/or total values, along with source reference.

| Study area                                      | Land use type or change (%)                                                                                                                                                              | Time period | Hydrologic metrics                                                                                                                                       | Change (%) or value                                                                                          | References                      |
|-------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|---------------------------------|
| Kathmandu Valley—Bagmati                        | 30% increase in built-up area                                                                                                                                                            | 2000–2010   | Surface runoff contribution to streamflow                                                                                                                | 27% increase                                                                                                 | Pokhrel (2018)                  |
|                                                 |                                                                                                                                                                                          |             | Lateral flow contribution to streamflow                                                                                                                  | 25% decrease                                                                                                 |                                 |
|                                                 |                                                                                                                                                                                          |             | Groundwater flow contribution to streamflow                                                                                                              | 21% decrease                                                                                                 |                                 |
|                                                 | 6% increase in built-up area per decade                                                                                                                                                  | 2020–2050   | Mean flow<br>Low flow                                                                                                                                    | 1.3% increase<br>3.45% decrease                                                                              | Lamichhane <i>et al</i> (2024b) |
|                                                 | 190% increase in built-up area                                                                                                                                                           | 1990–2040   | Surface runoff contribution to basin water yield<br>Groundwater flow contribution to basin water yield<br>Lateral flow contribution to basin water yield | 66% increase<br>21.62% decrease<br>9% decrease                                                               |                                 |
|                                                 | 21% increase in built-up area; 20% decrease of agriculture; 0.9% decrease of forest                                                                                                      | 2020–2050   | Seasonal river runoff                                                                                                                                    | 21% decrease to 35% increase                                                                                 | Lamichhane and Shakya (2019)    |
| Jikhu Khola catchment                           | Natural broadleaf forest<br>Pine plantation                                                                                                                                              | 2010–2011   | Rainfall interception (% of gross rainfall)                                                                                                              | 22.6%<br>19.4%                                                                                               | Ghimire <i>et al</i> (2012)     |
| Roshi Khola catchment                           | Regenerating broadleaf, intensively used<br>Predominantly planted pine, less intensively used<br>Mixed pine–broad-leaved, more intensively used<br>Religious forest, minimally disturbed | 2015        | Saturated hydraulic conductivity (range of median values across depths levels)                                                                           | 21–52 mm h <sup>−1</sup><br>34–98 mm h <sup>−1</sup><br>16–21 mm h <sup>−1</sup><br>19–75 mm h <sup>−1</sup> | Badu <i>et al</i> (2019)        |
|                                                 | Regenerating broadleaf, intensively used<br>Predominantly planted pine, less intensively used<br>Mixed pine–broad-leaved, more intensively used                                          | 2015–2016   | Stemflow (% of incident precipitation)                                                                                                                   | 1.6%<br>0.6%<br>1.3%                                                                                         | Badu <i>et al</i> (2022)        |
| Nepal (5465 springs across 12 research studies) | Increasing urbanization and the expansion of settlement areas                                                                                                                            | Various     | Spring flow                                                                                                                                              | Dried up (16%);<br>Declining (~60%)                                                                          | Chauhan <i>et al</i> (2023)     |
| Rangun Khola watershed (1122 springs)           | Deforestation and land fragmentation                                                                                                                                                     | 1990–2018   | Spring flow                                                                                                                                              | Dried up(2%);<br>Declining (73%)                                                                             | Pandit <i>et al</i> (2024)      |

2016, Chauhan *et al* 2023). Urbanization increases the extent of impervious surfaces, altering recharge dynamics, and promoting over-extraction of groundwater, with semi-urban areas showing especially high levels of spring modification (Chauhan *et al* 2023).

Haphazard infrastructure development, including roads, tunnels, and irrigation canals, disrupts hill-slope hydrology and groundwater pathways, contributing to spring drying and reduced seasonal flows (Chauhan *et al* 2023, Pandit *et al* 2024). The disappearance of ponds and wallows, once important recharge features, has further weakened spring resilience (Sharma *et al* 2016). Collectively, these findings indicate that local forest loss, urban expansion, and infrastructure development exert the strongest and most widespread impacts on spring resources in Nepal.

Accurately representing land-use and land-cover dynamics is essential for reliable hydrological projections, as changes in forests, croplands, and urban areas directly alter runoff, recharge, and evapotranspiration. These changes are shaped by complex socio-economic, demographic, and policy factors, and their hydrological impacts are often non-linear and regionally variable (Acharya *et al* 2023). Neglecting future land-use trajectories risks misrepresenting interactions with climate change, particularly because combined effects on water-yield components are rarely additive. As a result, projections of groundwater depletion, flood risk, or hydropower potential may be systematically biased, limiting the reliability of hydrological models for water management and planning under climate change.

Future hydrological projections should incorporate dynamic land-use and land-cover trajectories derived from observed historical trends and linked to plausible climate scenarios. This requires generating high-resolution, annually updated land-use maps that capture cropland expansion, forest regrowth, and urbanization, supported by expanded ground-based monitoring networks to improve calibration and validation of land surface models. Remote sensing approaches, particularly those used to estimate evapotranspiration, also need methodological improvements to reduce biases caused by mixed land covers and complex topography. Currently, most studies are concentrated in the Bagmati River basin; extending similar analyses to other regions of Nepal is essential given their distinct climatic regimes and land-use pressures.

#### 2.2.2. Sand and gravel mining

Sand and gravel mining in rivers and floodplains alters river flow and water velocity by modifying riverbed morphology and sediment transport dynamics (Koehnken *et al* 2020). Sediment removal deepens and sometimes widens the riverbed, changing channel morphology and stability (Kondolf 1997,

Bajracharya and Tamrakar 2007, Hackney *et al* 2020). While incision and steepening can locally increase stream power (Kondolf 1997), widening often produces a shallower channel that may reduce flow velocity and increase turbulence (Hackney *et al* 2020). Sand and gravel removal also reduces the sediment supply to the river, intensifying bed and bank erosion as the channel seeks to reestablish its sediment balance (Kondolf 1997, Hackney *et al* 2020). Although research on the broader impacts of sand and gravel mining is limited, studies of the Seti Khola River in central Nepal document significant hydrodynamic effects, including inundation of mining sites and nearby settlements, hydraulic ponding and backwater flooding, altered channel roughness, and enhanced bank erosion and cliff collapse (Fischer *et al* 2022). A separate study across seven rivers documented a sharp rise in sand-mining pits, with some rivers showing a 350% increase between 2011 and 2023, though trends fluctuated during the study period (Kshetri 2025). Unregulated mining can expand barren land along riverbanks and elevate flood risks during peak monsoon flows (Fischer *et al* 2022). The largely illegal and unmonitored nature of this activity raises serious environmental concerns (Hoffmann 2021, Koyuncu *et al* 2021, Hatlebakk 2023, Fabrizio *et al* 2025), yet it remains an important income source for many rural communities (UNEP 2019).

#### 2.2.3. Hydropower and irrigation development

Nepal's topography and abundant water resources, particularly in its highlands, offer substantial potential for hydropower development (Sharma and Awal 2013). Utilizing only 2% of its estimated hydropower capacity (Agrawal and Pandey 2019), 175 hydropower projects >1 MW are currently operational, and these projects generate 3009 MW of electricity (MoEWRI 2025a). Moreover, 18 plants that generate <1 MW each, generate a total of 14 MW (MoEWRI 2025b). Most hydropower dams are 'run of river' dams, except for one reservoir dam, the Kulekhani Reservoir Dam on the Kulekhani River (60 MW; Shrestha *et al* 2021). Run-of-river dams are thought to have a lower impact on the river's hydrological regime than reservoir dams, because run-of-river dams do not submerge large upstream areas (Kuriqi *et al* 2021). However, they still modify flow regimes, especially during the dry season, by creating dewatered reaches downstream of the diversion structure (ADB 2018, Neupane *et al* 2022). Throughout Nepal, significant changes in river dynamics have been observed after dam construction. For instance, the Kali Gandaki Hydropower Dam in north-central Nepal reduced downstream discharge by diverting water to the powerhouse, creating a dewatered zone (Baniya *et al* 2021). Between 2006 and 2019, downstream discharge declined by up to 85% during the pre-monsoon season and up to 94% during the winter season (Baniya *et al* 2021).

Although river infrastructure such as hydropower dams and barrages (type of dam with multiple gates used to control the amount of water flow) alter river flow, their broader impacts on aquatic communities and the connectivity of aquatic ecosystems in Nepal remain understudied (Fabrizio *et al* 2025). River connectivity encompasses longitudinal, lateral, vertical, and temporal aspects, which are crucial for sustaining ecological, hydrological, and geomorphological processes (Wohl 2017). Disruptions to connectivity can lead to ecological imbalances, affecting species composition, sediment transport, and floodplain dynamics (Palmer and Ruhi 2019). Globally, river infrastructure has caused substantial reductions in connectivity, with about half of the world's rivers affected, and nearly 10% experiencing major losses in connectivity (Grill *et al* 2019). In Nepal, the rapid expansion of hydropower dams and barrages suggests similar declines in connectivity (Tachamo-Shah *et al* 2025), but standard indices of river connectivity and systematic ecological monitoring are lacking in Nepal. Several studies have raised concerns about aquatic habitat degradation due to reduced connectivity (Shaha and Paudel 2016, Gillette *et al* 2022). For example, agricultural water diversion projects in the Western Himalayas have reduced discharge in headwaters and weakened connections between the river and its riparian zone (Tachamo Shah *et al* 2020). Quantitative analysis on river connectivity in Nepal is lacking, but would be useful for better understanding the ecological, cultural, and economic impacts of river infrastructure (Fabrizio *et al* 2025).

Irrigation practices in Nepal aim to mitigate seasonal water variability particularly between November and June when water availability is lowest (Thapa and Scott 2019). From 1990 to 2019, the Government of Nepal implemented twelve major irrigation projects, supplying water to 570 000 hectares of agricultural land (DWRI 2019). To cope with dry-season deficits, farmers increasingly rely on groundwater (Tachamo Shah *et al* 2020). This reliance has grown markedly in the lowlands, where seasonal rivers dominate and prolonged dry periods occur. Between 2011 and 2022, the proportion of farmers using tube wells rose from 26.9% to 36.4%, and the share of cultivated land irrigated by tube wells increased from 29.8% to 41.7% (CBS 2013, 2023). These changes reflect a growing dependence on groundwater for irrigation despite an overall 8% reduction in total irrigated area (CBS 2013, 2023). By 2018, total groundwater use in the Terai reached roughly 22% of the annual groundwater recharge, up from 10% in 1996 (Shrestha *et al* 2018). In the Koshi River basin, groundwater withdrawals equivalent to 30% of dry-season streamflow have reduced baseflow in the Koshi River by up to 4% (Khan *et al* 2022). Groundwater table fluctuations are particularly significant in the Terai, where groundwater levels interact with wetlands and smaller water bodies

that support local ecosystems and influence seasonal water availability (Ghimire and Regmi 2024). Unlike glacial lakes, low-elevation surface water bodies such as lakes and wetlands remain understudied, and the broader impact of irrigation on these aquatic systems is not well understood. Comprehensive assessments of the hydrological balance of these low-elevation lakes and wetlands are necessary (Bhuju *et al* 2012, Khatiwada *et al* 2021).

### 3. Compound uncertainties from anthropogenic drivers

Uncertainty intensifies when climate-driven changes in hydrological regimes are influenced by human interventions. Activities such as infrastructure, hydropower operations, water diversions, and irrigation withdrawals alter the timing and distribution of river flows, often obscuring, or even overpowering, climate signals (Nepal *et al* 2014a, Arheimer *et al* 2017). However, many human activities are poorly monitored or undocumented, including the operation of dams and diversions, and groundwater extractions. Urban expansion, deforestation, reforestation, road and infrastructure construction, sand mining, and other land-use changes modify infiltration rates, recharge processes, evapotranspiration, hydrological connectivity, and sediment transport, complicating efforts to attribute observed seasonal patterns in river flow to a single driver.

Moreover, nonlinear feedback or threshold effects that are unaccounted can introduce model uncertainty and lead to bias in estimates of how different anthropogenic drivers affect the water cycle (Clark *et al* 2016). Examples include (1) fire–albedo–melt interactions where black carbon deposition from wildfires reduces surface reflectivity and accelerates snow and ice melt (Sarangi *et al* 2020, You and Xu 2022, Pokharel *et al* 2023), and (2) infrastructure–demand feedback, where dams and irrigation increase water and energy availability, stimulate agricultural expansion, and facilitate population growth. Such processes can accelerate change or trigger abrupt shifts in system behavior, phenomena which are poorly represented in most climate–hydrology models, especially in data-sparse regions like Nepal and other high-mountain nations.

Unlike the emerging global pattern, which suggests upstream areas may experience increased streamflow in a warming climate while downstream areas experience a decline (Feng and Gleason 2024), climate projections for Nepal generally indicate an increase in downstream flows. This mismatch suggests the presence of structural biases in models such as SWAT that are calibrated to short, low-elevation records of rainfall and runoff. In addition, model omissions of explicit representation of cryosphere

dynamics, reservoir operations, and irrigation practices may contribute to observed deviations in predictions from global models, rather than reflecting a true departure from globally observed hydrological system functions in high mountain areas like Nepal and elsewhere.

Many hydrological frameworks have been developed and validated on long, continuous river records, particularly in Europe and North America where observations extend to the 19th century (Probst and Tardy 1987). In contrast, Nepal's hydrological records, like those of other High Mountain Asia countries such as Bhutan, India, China, and Pakistan, are relatively short and discontinuous, with limited observations at high elevations where snow and ice dominate runoff (Caretta *et al* 2022, Mudbhari *et al* 2022, Bajracharya *et al* 2023). Without expanding the temporal range and continuity of such records, model calibration, change detection, and climate-change impact assessments will remain highly uncertain (Biswas and Tortajada 2016, Krabbenhoft *et al* 2022).

#### 4. Implications for management and policy

Evidence-based water management is vital in Nepal, where water security underpins food production, flood risk, and livelihoods. As a High Mountain Asia country, Nepal also illustrates challenges shared across mountain regions globally, which is consequential given that 1.5 billion people are expected to depend heavily on mountain runoff by mid-century (Caretta *et al* 2022). The studies reviewed in this paper consistently highlight significant limitations and uncertainties due to limited empirical evidence and observations from hydrological systems. Expanding meteorological stations in under-represented regions throughout high mountain areas, particularly in western and eastern Nepal, is crucial to improve the representativeness and reliability of atmospheric and cryospheric observations (Karki *et al* 2017, Miao *et al* 2024, Wang *et al* 2024). Similarly, establishing a network of hydrological stations across Nepal's diverse topography is necessary for continuous monitoring of streamflow in high- and low-elevation rivers and streams. River gauge placements should facilitate flow assessment upstream and downstream of all major dams and barrages. Although several rivers are gauged in Nepal, independent monitoring of rivers is needed to ensure the accuracy and completeness of hydrological information. Accurate measurements of precipitation, including snowfall, and glacial attributes such as ice thickness, mass balance, snow dynamics, and permafrost volume are also critical (Lama *et al* 2015) but are currently lacking. Even for relatively well-documented metrics, such as glacial area, significant uncertainty persists,

with some estimates varying by up to a factor of two (Azam *et al* 2021). Additionally, comprehensive spatio-temporal assessments of groundwater volume and spring discharge rates are needed to inform management of Nepal's subsurface water resources, which are critical for drinking water and irrigation during dry seasons (pre-monsoon, winter, and post-monsoon).

Comprehensive water inventories must be conducted across the diverse physiographic regions and watersheds of Nepal with sufficient temporal frequency to accurately estimate water pools and fluxes. To achieve this, substantial and sustained support from the government of Nepal is required as is commitment from research institutions. Current watershed-level hydrology studies exhibit significant spatial bias, with studies primarily concentrated in central Nepal. For glacier and snow-related research, Nepal often relies on global or regional analyses (e.g. Himalayas), or on a limited number of focused studies in small watersheds, such as Langtang and Dudh Koshi in north-central Nepal, which has become the prime area for most high-altitude research on snow and glacial processes. In contrast, studies examining the hydrological response of lowlands to climate and land-use change are predominantly focused on the Bagmati River basin (home to Kathmandu). Few studies investigate the impact of anthropogenic drivers on the hydrological regime of rivers in other watersheds. This narrow geographic scope of current research is insufficient for informed decision-making, given that spatial variability in hydrological response across Nepal appears significant. A spatially broader and more comprehensive body of work is needed to establish a consensus on hydrological regimes across the country's diverse regions. This situation mirrors a systemic issue in the Global South, where limited observational networks and research funding compromise the ability to capture high spatial variability, and complicate climate adaptation and water resource management (Caretta *et al* 2022).

Nepal's hydrological regime has been studied for decades, and these investigations provide a valuable foundation, but expanding data coverage and improving monitoring networks are critical for advancing the science needed to inform effective resource planning. To make informed decisions, responsible government agencies must prioritize and support the development and application of standardized methods to obtain robust, long-term meteorological and hydrological observations. Monitoring networks are often costly, especially in high-elevation, snow- and glacier-dominated regions. As in many other low-income countries, Nepal faces financial and technical constraints to the independent development and maintenance of such networks. Consequently, international aid and collaboration are essential to bridge these gaps (Stumm *et al* 2021, Wagnon *et al* 2021, Khadka *et al* 2024) to ensure

comprehensive monitoring of water systems in high-altitude mountainous regions in Nepal and elsewhere so that challenges posed by climate change can be effectively addressed. While Nepal operates one of the more open data-sharing systems in South Asia, further efforts to streamline access and improve timely data sharing between government agencies and universities, alongside investment in local capacity to ensure Nepal-based researchers are involved in the co-development of hydrological and climate-change models, are essential to reduce reliance on potentially biased global and regional simulations.

Decision makers must recognize that land management and environmental policies affect multiple components of the water cycle, with impacts that may be immediate or delayed, localized or widespread, and moderate or extreme. Historically, Nepal's water governance has been influenced by sectoral interests, limiting integrated management approaches essential for long-term sustainable development and climate resilience (Biggs *et al* 2013). This sectoral approach creates significant challenges, weakening the nexus among water, energy, food, and ecosystem sectors (Baral *et al* 2023b). The lack of coordination and cooperation among sectors obstructs progress, especially because the impacts of climate change are cross-sectoral (Baral *et al* 2023b, Pokharel *et al* 2024).

A prevalent assumption in national water policies (2002 & 2005) is that Nepal has a water surplus (Johnson *et al* 2021, Sharma *et al* 2023); this assumption led to the development of policies that prioritized water accessibility for household use, irrigation, and hydropower. Such policies often overlooked the diverse threats to water resources and failed to fully account for ecological effects (Johnson *et al* 2021). As such, the potential for long-term environmental consequences of anthropogenic activities has not been addressed (Johnson *et al* 2021). Some progress has been made, however. For instance, a minimum downstream flow of 10% of the minimum monthly average discharge is required at all dams (Government of Nepal 2001, Adhikari 2012). Run-of-river dams must now be designed to maintain flows that occur 45% of the time (Bhattarai and Shrestha 2023). However, violations of these policies remain largely unchecked due to the absence of independent monitoring and inadequate enforcement of environmental regulations (ADB 2018, ISET 2020). The National Water Resources Policy of 2020 adopts Integrated Water Resources Management (IWRM) principles and establishes river basin organizations to enhance water resource management. The policy seeks to sustainably conserve, manage, and develop water resources for economic prosperity and social transformation (Investopaper 2020).

Land-use changes have significantly impacted water fluxes and pools in Nepal, demonstrating that policies that are seemingly unrelated to water can

have profound long-term effects on water resources. Nepal's land-use policies evolved alongside shifting political regimes, with each regime influencing water dynamics in different ways. Before 1951, land-use policies focused on maximizing economic output by use of unpaid labor and land taxation, resulting in widespread deforestation and agricultural expansion. After 1951, the focus shifted toward agricultural land redistribution, marking a significant change in land management. Subsequently, policies emphasized land conservation and community involvement (Nepal *et al* 2020). A major milestone in sustainable land management was the introduction of community-based forests in 1978, which played a pivotal role in forest restoration at the national level. By 2018, forests covered 44.47% of Nepal's land area, doubling the coverage observed in 1992 despite ongoing urban development (Fox *et al* 2019, Paudel and Adhikari 2021a). Some studies, however, question whether these efforts have restored native species and fully functional forests (Shrestha 2019a). Many economic sectors such as energy and agriculture have a direct influence on hydrological regimes. Due to the interconnected nature of natural and economic resources, changes in one sector can trigger cascading effects in the other. For example, water used for energy production can reduce its availability for irrigation, and the extraction of groundwater to supplement surface irrigation can affect groundwater pools. An integrated and holistic approach to resource management is essential to effectively address these complex dependencies. Although IWRM offers such an approach, critics argue that its water-centric focus limits its effectiveness (Benson *et al* 2020). Alternative frameworks, such as water-energy-food and ecosystem-based approaches, offer more comprehensive frameworks and can help recognize and address synergies and trade-offs (Huntington *et al* 2021).

Even if Nepal takes all possible actions to manage its water resources effectively, the magnitude of climate-driven change remains largely beyond its control, reflecting a wider environmental injustice in which many low-emitting nations bear disproportionate impacts despite contributing little to global greenhouse gas emissions (Crippa *et al* 2021, IPCC 2023). This reality underscores the urgent need for the international community to act on mitigating global greenhouse gas emissions (UNFCCC 2025). Anthropogenic climate change is already reshaping the country's hydrology and will continue to do so, as evidenced in this review. These changes have the potential to impact millions of people in Nepal and millions more downstream in the Ganges River basin, the most populous river basin in the world. Nepal can benefit from climate-change adaptation by enhancing resilience, promoting sustainable agriculture, and improving water management while empowering communities to adapt to change.

## 5. Conclusion

This review synthesized the impacts of anthropogenic drivers on Nepal's hydrological regime, while highlighting critical knowledge gaps, understudied processes, and key sources of uncertainty. Our review demonstrates that climate change, manifested through rising temperatures and shifting precipitation patterns, intensifies flood risks while exacerbates seasonal water shortages. Glacial retreat and earlier snowmelt reduce the buffering capacity of meltwater and amplify seasonal imbalances that adversely affect downstream sectors dependent on a year-round consistent water supply. In parallel, human activities such as land-use change, sand mining, hydropower development, and river diversions have altered river flows, fragmented aquatic ecosystems, reduced groundwater recharge, and increased vulnerability to extreme hydrological events, further compounding water scarcity and flood risks.

This review underscores that many of these impacts remain poorly quantified, particularly for components such as permafrost, springs, lowland lakes, and dammed and diverted rivers, contributing to high uncertainty in current assessments of the country's future water security. Nepal's extreme topographic variability and diverse climate zones further limit the ability to generalize hydrological responses, emphasizing the need for spatially and temporally focused studies to capture local and regional dynamics.

Alterations to the hydrological regime pose significant risk to water-dependent sectors, including the domestic water supply, sanitation, agriculture, hydropower, and subsistence fisheries, with direct implications for food security, human health, and livelihoods. Addressing these challenges requires integrated, adaptive water management strategies and infrastructure planning that incorporate both immediate and long-term impacts, particularly for climate-sensitive and socially vulnerable communities (Fabrizio *et al* 2025). Closing critical knowledge gaps, such as feedback mechanisms among hydrological drivers and water cycle components, will improve the accuracy of future projections and inform evidence-based policy interventions. This review emphasizes the urgency of incorporating these findings into water management policies and infrastructure planning.

Importantly, while this review focuses on Nepal, the challenges identified, including high topographic and climatic variability, reliance on meltwater- and rainwater-dependent systems, along with limited observational data, are emblematic of many mountainous, climate-sensitive regions worldwide. The synthesis, methods, and research priorities highlighted here provide insights that are broadly applicable to other data-scarce mountain systems, offering a

framework to enhance global understanding, monitoring, and management of hydrological change under evolving climate and land-use pressures.

## Data availability statement

No new data were created or analysed in this study.

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## Open research

All datasets used are publicly available, with the exception of the data used for Figure 5a, which are available from Nepal's Department of Hydrology and Meteorology (DHM).

## Author Contribution

SSS, KKS, and MCF conceptualized the study. SSS drafted the manuscript and prepared the visualizations. KKS and MCF provided supervision and guidance. SN contributed data for selected figures. All authors participated in the review and editing of the manuscript.

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