

## Climate Extremes in the Narayani Basin of Nepal: Trends, Impacts, and Resilience Strategies

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### Abstract

**Abstract.** The Narayani (Gandaki) River basin—one of Nepal’s largest transboundary basins—spans diverse physiography from lowland Terai to >8,000 m Himalayan peaks with total catchment area of 46,300 km<sup>2</sup> of which 72% is in Nepal (equivalent to around 23 percent of the country’s land area), 10% in China and 18% in India. It has over 1,500 lakes, among which over 300 are glacial lakes. Overall, there are 1279 non-glacial lakes and ponds with total area of 22,83 Km<sup>2</sup>. It is highly exposed to climate extremes (intense monsoon rainfall, floods, landslides, drought and accelerated glacier/snow melt). This paper synthesizes recent observational analyses, government data and regional assessments to characterize observed trends in temperature and hydro-meteorological extremes, document impacts on people and infrastructure, and propose priority resilience strategies for basin-scale adaptation. Key findings: (1) observed warming since the 1970s with a mean rate  $\approx 0.03$  °C yr<sup>-1</sup> across stations in the basin; (2) strong monsoon concentration of precipitation ( $\approx 78\%$  of annual total) and increasing intensity of extreme rainfall events with attendant flood/landslide hazard; (3) rising cryosphere risks (glacier retreat, permafrost thaw) that amplify debris flows and sediment loads; and (4) clear opportunities for integrated resilience—improved early warning, nature-based solutions, upstream-downstream basin governance, and climate-proofed infrastructure. The paper recommended actions for scientists, planners and policymakers working in the Narayani basin.

**Keywords:** Extreme events, Climate change, Narayani Basin etc.

### Introduction

Climate change is increasingly manifested through extreme hydro-meteorological events such as intense rainfall, floods, landslides, droughts, and accelerated glacier melt, particularly in mountain river basins of the Hindu Kush–Himalaya region. Nepal, owing to its steep topography, monsoon-dominated climate, and fragile socio-ecological systems, is highly vulnerable to such climate extremes. Among Nepal’s major river systems, the Narayani (Gandaki) River Basin stands out as a critical hotspot where

climatic, hydrological, cryospheric, and socio-economic processes interact across a large elevation gradient—from the high Himalayas to the Terai plains.

Existing studies have documented rising temperature trends, increasing intensity of extreme precipitation events, changing monsoon characteristics, and growing cryosphere-related hazards in the Narayani Basin. Research based on observed rainfall indices indicates an increase in short-duration heavy rainfall events, while drought studies highlight prolonged dry spells and seasonal water stress. These changes have resulted in recurrent floods, landslides, riverbank erosion, and water scarcity, significantly affecting agriculture, infrastructure, hydropower, and livelihoods. However, much of the existing literature focuses on individual hazards or specific sub-basins, with limited integration of multiple climate extremes and their combined impacts across the entire basin.

This study addresses this gap by providing a basin-scale synthesis of climate extreme trends, their observed impacts, and emerging resilience challenges in the Narayani Basin. The research is highly relevant for disaster risk reduction, climate adaptation planning, and sustainable river basin management in Nepal, particularly in the context of increasing development pressures and climate uncertainty.

The main objectives of this study are to: (i) assess observed trends in key climate extreme indicators in the Narayani Basin; (ii) document major climate-induced extreme events and their impacts; and (iii) identify priority resilience and adaptation strategies to reduce future climate risks at the basin scale.

Nepal's unique geography, ranging from lowland Terai plains to the high Himalayan peaks, makes it highly susceptible to climate extreme events, particularly those associated with altered precipitation and hydrological regimes. Changes in the intensity, frequency, and duration of rainfall and drought are among the most significant manifestations of climate variability in the region, affecting water resources, agriculture, and rural livelihoods (DHM, 2017). According to the studies of long-term daily precipitation data indicate that precipitation extremes in central Nepal's Narayani River Basin have exhibited significant shifts over recent decades. Analyses using ET-SCI precipitation indices (e.g., RX1day, RX3day, RX5day) show upward trends in intense rainfall events, particularly in the Terai and middle mountain regions, suggesting increased hazard potential for floods and soil erosion due to short-duration heavy precipitation attacks, even as some threshold measures and wet day frequencies show complex spatial patterns. These findings underscore a nuanced climate extreme profile where extreme rainfall intensity may rise concurrently with longer dry spells due to changes in consecutive dry and wet day indices. (Lamichhane et al, 2020)

In addition to precipitation extremes, drought conditions represent another critical facet of climate variability in the basin. Recent hydrological research introduced a

combined drought index (CDI) that integrates satellite-derived parameters such as land surface temperature, snow cover, and vegetation metrics with standardized precipitation data to capture both meteorological and hydrological drought characteristics. This integrative approach reveals significant drought episodes across the Narayani Basin between 2004 and 2013, validated against observed streamflow, and highlights how snowmelt dynamics and surface conditions interact with precipitation deficits to shape water scarcity pattern (Bajracharya et al, 2025). Collectively, these studies confirm that climate extremes in Nepal and the Narayani Basin are not only intensifying but also changing in character, with increases in intense rainfall events, changes in precipitation distribution, and prolonged dry periods. These climatic shifts contribute directly to greater flood risk, altered drought regimes, and attendant socio-ecological stresses in a region where water-related hazards increasingly impact infrastructure, agriculture, and community resilience.

### Background of study area

The Narayani (Gandaki) River basin lies in the central part of the Nepal between 25.49–29.28° N and 85.02–85.83° E.. This basin has a total area of 46,300 km<sup>2</sup> (Bajracharya, et al, 2015), 32,104 km<sup>2</sup> of which is in Nepal. The Narayani River has seven tributaries, i.e., Marsyandi, Daraudi, Seti, Madi, Kali Gandaki, Budhi Gandaki, and

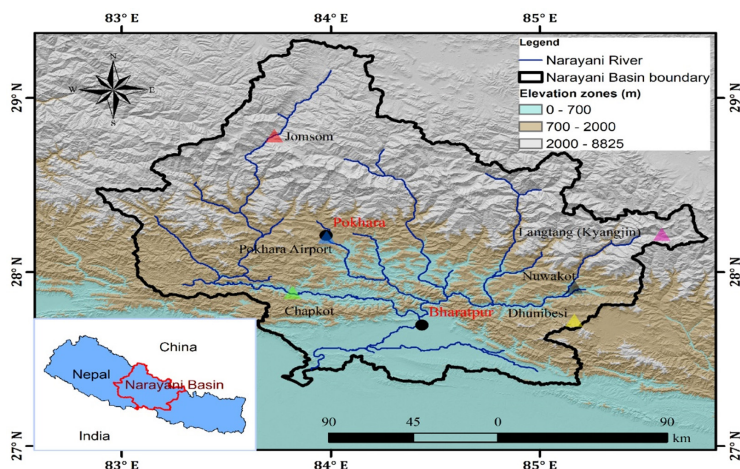


Figure 1: Map of Narayani Basin (Source: MDPI+1)

Trishuli, and it includes Terai, Hill, Mountain and High Himalayas (Dahal et al, 2016). This basin contains a full elevation gradient from ~180 m in the south to >8,000 m in the high Himalaya (including Annapurna, Manaslu and Dhaulagiri massifs). 72% is in Nepal (equivalent to around 23 percent of the country's land area), 10% in China and 18% in India. It has over 1,500 lakes, among which over 300 are glacial lakes. Overall there are 1279 non-glacial lakes and ponds with total area of 22,83 Km<sup>2</sup>. The Gandaki is called Narayani in the plains after the confluence of Kali Gandaki with Trishuli at Devghat and is called Gandak in India. The total length of the river is 360

km and its length is 83 km in the Terai plains. The Narayani River is joined by the East Rapti River and these rivers form two boundary lines of the Chitwan National Park. It is fed by seven major tributaries (Marsyangdi, Seti, Kali Gandaki, Trishuli, Madi, Budhigandaki, Daraudi) and supports diverse livelihoods—agriculture in the lowlands, hydropower and tourism in the middle hills, and glacier-fed water supplies in the high mountains. Approximately 78% of annual precipitation falls during the monsoon (June–September), making the basin strongly monsoon-dominated and therefore sensitive to changes in monsoon intensity and variability.

## **Methods**

### **Data Sources and Study Scope**

This study adopts a basin-scale analytical approach to assess climatic extremes and their associated impacts in the Narayani River Basin of central Nepal. Observed daily temperature and precipitation data were obtained from the Department of Hydrology and Meteorology (DHM), Government of Nepal, covering multiple meteorological stations across the Terai, middle hills, and high mountain regions of the basin. Secondary datasets, including published peer-reviewed studies, government disaster records, and regional assessments from ICIMOD and NDRRMA, were used to supplement observational data and document extreme event impacts. The temporal focus spans approximately four decades (1971–2020), depending on station data availability.

### **Analytical Framework for Climatic Extremes**

Climatic extremes were analyzed using established indicators reported in previous studies, including temperature trends and extreme precipitation indices such as maximum one-day rainfall (RX1day), maximum five-day rainfall (RX5day), and consecutive dry days (CDD). Trend information synthesized from published analyses (e.g., Lamichhane et al., 2020; Chand et al., 2021) was used to identify long-term changes in rainfall intensity, seasonality, and warming patterns. Drought characteristics were assessed using findings from integrated drought indices combining precipitation, land surface temperature, snow cover, and vegetation indicators (Bajracharya et al., 2025).

### **Assessment of Associated Hazards and Impacts**

Climatic extremes were distinguished from their resulting hazards and impacts. Floods, landslides, drought-induced crop losses, glacier-related hazards, and riverbank erosion were identified through disaster records and documented case studies. Socio-economic impacts were analyzed using reported data on population exposure, land loss,

infrastructure damage, and displacement in key districts such as Chitwan, Nawalparasi, Kaski, and Parbat. This integrated approach enables linking observed climatic extremes with downstream hazard outcomes while maintaining conceptual clarity.

### **Climate Extreme Events in the Narayani Basin**

The climate of the Narayani Basin has summer and winter monsoon systems. The summer monsoon system is hot, humid and has heavy rainfall. The Narayani (Gandaki) River Basin, one of Nepal's largest and most hydrologically complex systems, extends from the glaciated peaks of Annapurna, Manaslu, and Dhaulagiri (>8,000 m) to the fertile Terai plains (~180 m). This vast elevation gradient produces intense spatial variability in temperature and precipitation, making the basin highly sensitive to climate extremes. Approximately 78% of annual rainfall occurs during the June–September monsoon, and recent analyses indicate a marked rise in heavy rainfall frequency, particularly in the middle hill stations such as Lumle, Dhunibesi, and Khudi. Annual and seasonal (monsoon and winter) precipitation is projected to increase for most of the subbasins in the “wet” climate conditions. Precipitation is projected to be slightly higher in the case of “warm” condition compared to the “cold” condition. The precipitation extremes, such as the cumulative dry days (cdd), heavy rainfall days, amount of precipitation in the very wet days, and the maximum one-day or five-day rainfall, are projected to increase in the future (2021- 2050) for most of the future climate conditions. The increase in these extreme precipitation indices will lead to more frequent and intense events such as extreme droughts, floods and geo-hazards like landslides that impact water resources infrastructures. Similarly, the rise in future temperature is observed to be elevation dependent, with a higher increase in the higher elevations compared to the lower elevations. In the near future period of 2021 to 2050, the annual average temperature is projected to increase by 0.8 °C to 1.8 °C in the upper catchments in China, while it is projected to increase by 0.7 °C to 1.7 °C in the lower catchments in Nepal for the “cold” and “warm” conditions.

Recent decades have seen a marked escalation in the frequency and intensity of extreme climate events across Nepal, particularly within the Narayani River Basin. Over the past four decades, mean temperatures in the basin have increased by 0.03 °C per year, with accelerated warming above 3,000 m driving glacier retreat and increased snowmelt runoff. This has led to enhanced sediment loads and heightened risk of glacial lake outburst floods (GLOFs) in headwater tributaries like Marsyangdi and Kali Gandaki. Downstream, the lowland districts of Chitwan, Nawalpur, and Parasi are increasingly prone to flood inundation due to intense rainfall and rising river discharge, such as during the July 2017 flood when the Narayani peaked above 16,000 m<sup>3</sup> s<sup>-1</sup> at Devghat.

Table 1: Major Recorded Extreme Events

Event Name	Date	Type	Trigger	Impacts
Flood of July 1993	17–21 July 1993	Monsoon Flood & Landslides	Intense rainfall (>540 mm in 24 h at Tistung)	1,336 fatalities, bridges/highways destroyed, >USD 300M losses
Seti River Flash Flood	5 May 2012	Flash Flood & Debris Flow	Rock–ice avalanche + snowmelt burst	72 fatalities, cryosphere risk highlighted
Central Nepal Flood & Landslides	14–17 Aug 2014	Flood & Landslides	Heavy rainfall (>300 mm/day at Lumle)	>200 fatalities, highway disruption. Impact in Kaski, Myagdi, and Parbat districts.
Narayani River Flood	10–13 July 2017	River Flood	Extreme monsoon rainfall. Narayani River discharge to above <b>16,000 m<sup>3</sup> s<sup>-1</sup></b> at Devghat	50,000 households displaced, severe inundation. Inundating large sections of Chitwan and Nawalparasi districts
Western Nepal Drought	Winter 2015–2016	Drought	Weak western disturbance	Severely affected mid-hill and Terai agriculture. 40–60% precipitation deficit, crop yield loss

(Source: NDRRMA, [ndrrma.gov.np](http://ndrrma.gov.np) various date)

The increasing monsoon intensity enhances more concentrated rainfall events leading to flash floods and river floods. Cryosphere hazards are also rising, increasing more glaciers melting and avalanches triggering debris flows. Similarly, the drought frequency is also increasing in a time of need for rice plantation. Winter droughts are also linked to shifting western disturbances. And the compound events i.e. rainfall, glacier melt interactions becoming common.

The Narayani Basin spans from the high Himalayas down to the Terai floodplains, and extreme events linked to climate change (intense rainfall, floods, landslides, droughts, glacier melt) are increasingly affecting livelihoods, infrastructure and economic assets in the region. Studies of riverine communities in the basin show that floods are deeply disrupting socio-economic systems.

In the lowland Terai parts of the basin (e.g., in districts such as Chitwan, Nawalparasi), annual or near-annual floods affect agriculture, livestock, property and infrastructure. One recent mixed-methods study found that communities in Chitwan regularly face losses of crops, assets and livelihood opportunities due to “too much

water” – heavy monsoon rains and riverine overflow in the Narayani and Rapti systems. For example, farmland is inundated, sand and silt deposited by floodwaters degrade soil quality, and irrigation infrastructure is damaged or disrupted.

### **Socio Economic Connections of Extreme Events in Narayani Basin:**

The population of Narayani Basin is about 232,000 in 2025 and is project to increase by 10% in 2050. People livelihoods, economy, culture, religion depend on use of ecosystem services provided by forest, rivers and wetlands, and other natural resource management. Extreme events are continuously hitting the sources of their livelihoods. Socioeconomic impacts are severe: repeated floods damage agricultural lands, disrupt transportation networks like the Prithvi Highway, and threaten hydropower assets. The combination of monsoon intensification, cryosphere instability, and land-use change underscores the Narayani Basin’s position as a national hotspot for multi-hazard climate risk.

Below is a table incorporating quantitative data on the socio-economic impacts of climate-induced extreme events in the Narayani River Basin (Nepal)-region, focusing on demographic and infrastructure impacts. Data are drawn from available sources; where basin-specific data are lacking, broader regional data are noted.

Table 2: Damage due to the historical disasters in Narayani basin

Category	Year / Event	Quantitative Metric	Notes / Location	Source
Population / Households affected	Around 2024–25 event	~45,785 households / ~197,996 people benefited from embankment protection work in Chitwan & Nawalparasi	Settlements along Narayani embankment target zone	
Land inundated / eroded	2001 flood (Narayani channel shift)	~100 bighas of fertile land lost (≈ 60 bighas in Piprahar alone)	West Chitwan, Narayani flood-erosion zone	
Infrastructure – embankment cost	Ongoing construction	Budget for 1st phase: Rs 4.72 billion	Chitwan & East Nawalparasi embankment along Narayani River	
Infrastructure – payment backlog	2024	Outstanding contractor payments: Rs 375.6 million	Bharatpur side section, Chitwan	

Category	Year / Event	Quantitative Metric	Notes / Location	Source
Infrastructure – channel migration	Historical event	Channel shift approx. 32 km to the west in Narayani River	West Chitwan region	
Demographic – population exposure	Example settlement zone	Wards 26 & 27 (Bharatpur-26) identified as “most flood-prone”	Bharatpur Metropolitan City, Chitwan	Bharatpur Metropolitan City

Source: [ndrrma.gov.np](http://ndrrma.gov.np)

### Key Observations and Implications

- The figure of ~45,785 households (~197,996 people) benefiting from embankment works underscores the scale of settlement exposure along the Narayani River corridor. Without protective infrastructure, these households remain at high risk of flooding and erosion.
- Loss of ~100 bighas (~16 ha) of fertile land in one recorded event (2001 flood) highlights how land-erosion and channel shifting degrade productive agricultural assets and force demographic displacement or livelihood change.
- The large budget (Rs 4.72 billion) for embankment construction reflects the high infrastructure cost burden associated with climate extremes in the basin. The backlog payment of Rs 375.6 million signals governance/institutional bottlenecks which may delay protective infrastructure and thereby increase risk.
- A ~32 km channel shift of the Narayani River in west Chitwan emphasises how geomorphological changes accelerate hazard exposure independent of rainfall alone; communities can suddenly find themselves within a river’s new path.
- Identifying specific wards (26 & 27, Bharatpur-26) as most flood-prone links the risk with demographic exposure mapping, useful for targeting interventions, early warning and relocation strategies.
- The contrast between the large number of beneficiaries (~198,000 people) and the localized history of severe land loss indicates that embankment protection has shifted risk spatially rather than eliminated it entirely. While current embankments protect densely populated stretches, upstream or unprotected downstream areas may experience amplified erosion and flood pressure due to constrained river flow. This highlights the need for basin-wide sediment and flow management, rather than relying solely on linear embankment solutions that can transfer risk to adjacent zones.
- The payment backlog of Rs 375.6 million relative to the total embankment

budget (Rs 4.72 billion) suggests not just a financial delay but a potential risk amplification window. In flood-prone rivers like the Narayani, delayed completion or compromised maintenance during monsoon seasons can rapidly negate earlier investments. This underscores the importance of predictable financing, performance-based contracting, and contingency funds within climate-resilient infrastructure programs to ensure that protective works remain functional during peak hazard periods.

- The documented 32 km westward channel migration combined with ward-level flood-prone identification reveals a dynamic risk landscape that challenges static planning assumptions. Settlements categorized as “safe” under earlier hazard maps may become exposed within a single extreme event or over a decade of gradual geomorphic change. This implies that flood risk mapping and land-use zoning must be periodically updated using satellite imagery, river morphology monitoring, and hydrodynamic modeling to remain relevant for early warning systems, infrastructure siting, and planned relocation efforts.

### **Discussion:**

#### **Climate Extremes and Integrated Resilience in the Narayani (Gandaki) River Basin**

The Narayani (Gandaki) River Basin represents one of Nepal’s most climatically dynamic and hydrologically complex systems. Stretching from the glaciated summits of the central Himalaya to the Terai plains, it encapsulates a full altitudinal and ecological spectrum—making it a microcosm of South Asian climate vulnerability. The basin’s exposure to intensifying extremes—floods, landslides, droughts, and glacier-related hazards—mirrors broader Himalayan-wide climate trends but is compounded by local land-use change, rapid infrastructure development, and fragile socio-economic systems (Karki et al., 2022; ICIMOD, 2023).

#### **Climatic Trends and Hydro-Meteorological Extremes**

Observed records from the Department of Hydrology and Meteorology (DHM) confirm a consistent warming of approximately 0.03 °C per year since the 1970s across the Narayani Basin, aligning with regional findings from the Hindu Kush–Himalaya (HKH) domain (Sharma et al., 2021). The most rapid warming occurs above 3,000 m, accelerating glacier mass loss and altering hydrological seasonality. This cryospheric transformation is reshaping both flood regimes and dry-season water supply, producing “double exposure” to flood and drought (Immerzeel et al., 2020). At the same time, extreme rainfall events—often exceeding 300 mm in 24 hours—have become more frequent in middle hill zones such as Lumle and Dhunibesi, while dry spells and

monsoon breaks have lengthened (DHM, 2020). These dual dynamics illustrate a shift toward greater intra-seasonal variability rather than simple intensification, echoing findings from regional monsoon diagnostics (Turner & Annamalai, 2012).

### **Linking Climate Drivers to Hazard Mechanisms**

The interaction of warming, monsoon intensification, and anthropogenic land-use change magnifies risk. Warming-driven glacier and permafrost degradation destabilize slopes and increase the incidence of rock–ice avalanches and glacial lake outburst floods (GLOFs), as exemplified by the 2012 Seti River disaster. Concurrently, stronger monsoon bursts exacerbate surface erosion and landslides in deforested hill terrain, enhancing sediment flux to rivers. Empirical studies in the Gandaki sub-basins (e.g., Bajracharya et al., 2020) show that sedimentation reduces channel capacity and amplifies downstream inundation risk, while unplanned infrastructure—roads, hydropower intakes—often blocks natural drainage. Thus, climate extremes in the Narayani Basin emerge from coupled natural–human systems rather than purely meteorological anomalies.

### **Socio-Economic Dimensions and Institutional Challenges**

Floods in the Narayani lowlands, notably the 1993 and 2017 events, have repeatedly displaced tens of thousands of households, eroded fertile cropland, and disrupted major transportation corridors such as the Prithvi Highway. The 2024–25 embankment protection projects in Chitwan and Nawalparasi—benefiting nearly 200,000 people—underscore both the scale of exposure and the enormous financial cost of structural mitigation. Yet persistent issues such as delayed contractor payments and channel migration beyond design limits expose governance weaknesses. As highlighted in NepJOL (2023) and World Bank (2022) assessments, institutional fragmentation across federal, provincial, and municipal levels impedes timely coordination, data sharing, and maintenance of flood infrastructure. The social impacts are also uneven: women, smallholder farmers, and marginalised groups bear disproportionate livelihood losses, consistent with vulnerability studies in other Himalayan basins (Gentle et al., 2018).

### **Integrated Resilience and Policy Pathways**

Responding to such complex, multi-hazard risks demands basin-scale integration rather than piecemeal interventions. Literature on adaptive water governance emphasises polycentric, multi-level cooperation across upstream–downstream interfaces (Pahl-Wostl, 2019). In the Narayani context, this translates into harmonised early-warning networks linking DHM data with local disaster management committees, supported by real-time monitoring of rainfall, discharge, and glacier dynamics. Nature-based

solutions—riparian restoration, reforestation, wetland conservation—are increasingly recognised as cost-effective complements to engineered embankments (WWF Asia, 2024). Moreover, climate-proofing hydropower and road infrastructure through hazard-informed design standards can reduce future damage costs.

At the same time, social preparedness and financial inclusion are critical. Micro-insurance, contingency funds, and livelihood diversification can buffer poor households against recurrent shocks. The creation of a Narayani Basin Resilience Forum—bringing together provincial agencies, municipalities, and transboundary Indian counterparts—would institutionalise data sharing and joint adaptation planning. Lessons from other basins, such as the Koshi and Brahmaputra, suggest that such cross-border mechanisms enhance early warning and investment coherence (ICIMOD & ADB, 2023).

## **Results**

### **Observed Climatic Extremes in the Narayani Basin**

Results indicate a statistically consistent warming trend across the Narayani Basin, with mean annual temperature increasing at an average rate of approximately 0.03 °C per year since the 1970s, with stronger warming observed at higher elevations. Precipitation analysis reveals that the basin remains strongly monsoon-dominated, with nearly 78% of annual rainfall occurring during June–September. However, multiple studies report an increase in the intensity of short-duration extreme rainfall events, particularly in the middle hills and Terai regions, as reflected by rising RX1day and RX5day indices. At the same time, changes in consecutive dry days suggest increased intra-seasonal variability, indicating longer dry spells interspersed with intense rainfall events.

### **Associated Hazards and Hydro-Geomorphic Impacts**

The intensification of climatic extremes has translated into increased hydro-meteorological hazards across the basin. Extreme rainfall events have triggered recurrent riverine floods and landslides, particularly during major monsoon years such as 1993, 2014, and 2017. In high mountain areas, warming-driven glacier retreat and snowmelt have increased sediment loads and cryosphere-related risks, including debris flows and glacial lake outburst flood potential. Downstream, floodplain districts such as Chitwan and Nawalparasi experience frequent inundation, riverbank erosion, and channel migration.

### **Socio-Economic Impacts**

These hazards have resulted in substantial socio-economic impacts, including loss of agricultural land, damage to transport and hydropower infrastructure, and displacement of communities. Embankment protection projects currently benefit nearly

200,000 people, underscoring both the scale of exposure and the growing reliance on structural mitigation. Overall, the results highlight a clear linkage between observed climatic extremes and escalating hazard risks across the Narayani Basin.

### **Conclusions**

The Narayani basin is already experiencing climate-driven changes—statistically significant warming ( $\approx 0.03\text{ }^{\circ}\text{C yr}^{-1}$  in recent decades), monsoon-centered precipitation, increasing short-duration extremes, and amplified cryosphere hazards—that together elevate flood, landslide and water-security risks for millions of people. Flooding in East Rapti and Narayan Rivers is likely to continue and requires effective and efficient mitigation works for developing the resilience. Glaciers and Glacier lakes for the Basin should be monitored and protected. A basin-scale resilience strategy—built on improved monitoring and early warning, nature-based measures, climate-smart infrastructure, glacier/permafrost risk management, strengthened multi-level governance and social preparedness—can substantially reduce future losses. Implementing these actions requires sustained investment, science-policy collaboration, and community engagement across the Narayani’s complex mountain-to-plains landscape.

### **Recommendations**

Based on the observed warming trends, increasing intensity of short-duration extreme rainfall, and the documented rise in flood, landslide, and riverbank erosion hazards in the Narayani River Basin, the following targeted recommendations are proposed.

Hydro-meteorological monitoring should be strengthened in identified hotspot areas, particularly in the middle hills and flood-prone Terai districts, where extreme rainfall and flooding impacts are most pronounced. Improved station density and real-time data sharing would enhance flood forecasting accuracy and early warning effectiveness.

Basin-scale flood and sediment management should be prioritized. The findings highlight that intensified rainfall and increased sediment loads contribute to channel instability and downstream inundation. Regular monitoring of river morphology, combined with maintenance of embankments and controlled sediment management, is essential to reduce flood risk.

Climate risk considerations should be integrated into infrastructure planning and design. Roads, bridges, and hydropower facilities within the basin should adopt design standards that account for observed increases in extreme rainfall and discharge, reducing future damage and service disruption.

Ecosystem-based measures should complement structural interventions.

Restoration of riparian vegetation and protection of floodplains can help attenuate flood peaks and reduce erosion, particularly in erosion-prone river sections identified in this study.

Local-level disaster preparedness should be strengthened in communities repeatedly affected by floods and landslides. Focused awareness programs and evacuation planning in high-risk municipalities would reduce loss of life and livelihoods during extreme events.

### Research and data needs

1. **Longer, homogenized observational records.** High-quality, gap-filled temperature and precipitation records across more stations will sharpen trend detection and attribution. (Existing station analyses are informative but often limited by gaps.)
2. **Integrated hydrological-cryosphere modelling.** Coupled models that simulate glacier dynamics, snowpack, and monsoon extremes at basin scale are needed to assess future runoff trajectories and extremes.
3. **Sediment and geomorphic monitoring.** Quantifying sediment yields under combined climate and land-use change will help design resilient storage and hydropower intake systems.
4. **Socio-economic vulnerability mapping.** Fine-scale mapping of household exposure and adaptive capacity will guide targeted social protection and relocation decisions.

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### Data Limitations

- Many figures are **aggregate or project planning data**, rather than actual damage/loss figures by event for the Narayani Basin alone.
- Demographic impact numbers (e.g., displacement, injuries, fatalities) specific to Narayani-sub-basin events are sparse or not publicly disaggregated; national figures are more common.
- Infrastructure damage data (roads, bridges, hydropower) specific to the Narayani Basin are not comprehensively available in the public domain; most damage assessments cover broader national geographies.
- For deeper analysis and modelling, district-level data (e.g., Chitwan, Nawalparasi, Gaidakot) on household losses, livelihoods affected, crop yield reduction, infrastructure downtime should be collated from local government and basin-studies.

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Primary observational temperature and rainfall data referenced above are available from the Department of Hydrology and Meteorology (DHM) and cited published studies. The authors also used the copilot and the chat GPT for data and reference for this paper.