

Sediment Dynamics, Glacial Hazards, and the Climate Change Impacts on Rivers of Nepal

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Abstract: Nepal's rivers originate in some of the youngest and most active mountains on Earth, transporting sediment through the Ganges to the Bay of Bengal. This paper examines how climate change is reshaping sediment movement. Although Nepal's rivers retain most of their natural sediment load, sudden extreme events driven by glacier collapse and slope failure are increasingly disrupting steady, monsoon-linked seasonal flows. The Hindu Kush Himalaya is warming faster than the global average, particularly above 4,000 meters, a phenomenon known as elevation-dependent warming. Regional glaciers have lost roughly 10% of their area since 1990, with ice loss accelerating by approximately 65% in the last decade compared with the previous decade. The eastern Himalaya could lose up to three-quarters of its remaining glacier volume by 2100 under continued warming. These trends increase the likelihood of extreme events without proving climate change caused any single event. The 26 August 2026 disaster, when a glacier collapse above the Lhende Khola valley triggered a flood killing over 1,300 people along the Rasuwa and Bhotekoshi corridor, illustrates increasingly unpredictable glacial lake outburst floods. The paper also presents SWAT model results for the West Rapti basin, comparing observed sediment yield with future projections under SSP 2-4.5 and SSP 5-8.5. Recommendations include physical mitigation, sudden-onset event monitoring, and improved tools for understanding extreme events.

Keywords: Sediment dynamics, Glacial lake outburst flood (GLOF), Climate change, Elevation-dependent warming, SWAT, West Rapti basin, Nepal Himalaya.

Introduction

Nepal is drained by an estimated 6,000 rivers and rivulets, spanning about 45,000 km, all within the Ganga basin (DSCWM, n.d.). Nepal contributes 40–47% of the Ganga's average annual discharge, rising to about 70% during the dry season, and has a theoretical hydropower potential of 83,000 MW (WECS, n.d.). Its four major river systems—the Mahakali, Karnali, Gandaki and Koshi—join the Ganga in India, which flows into the Ganges–Brahmaputra–Meghna (GBM) delta and the Bay of Bengal (Figure 1).

Sediment dynamics sustain this system. Himalayan sediment has historically built and maintained the GBM delta, offsetting subsidence and sea-level rise (Islam et

al., 1999; van Staveren et al., 2017), while seasonal deposition replenishes nutrients across the Tarai and Gangetic plain (van Staveren et al., 2017). Sediment also influences reservoir sedimentation, hydropower infrastructure lifespan, channel migration and flood hazards (WECS, n.d.). The Ganges–Brahmaputra system carries approximately 1 billion tonnes of sediment annually (Islam et al., 1999), historically building land in Bangladesh's tidal plains. However, Landsat analysis of the Sundarbans coastline (1975–2022) indicates that modest accretion until the mid-1990s gave way to erosion, peaking at -17 km^2 annually as upstream interventions accumulated (IntechOpen, 2024).

Historically, Nepal's rivers transported sediment gradually with the monsoon. Recent events indicate a more abrupt regime driven by high-altitude slope failure and glacier collapse. This paper examines climate-driven changes in sediment dynamics and hazards, presents SWAT results for the West Rapti basin under two emission scenarios, analyses the 26 August 2026 Rasuwa–Bhotekoshi disaster, and proposes recommendations.

Methodology

This study combines a desk-based synthesis with hydrological modelling. The synthesis draws on government and institutional sources (DSCWM, n.d.; WECS, n.d.; ICIMOD, 2026), peer-reviewed and technical literature, and aggregated reporting by USGS, GFZ Helmholtz Centre, Reuters, AP, BBC and The Kathmandu Post (2026 Nepal–Tibet floods, 2026), with debris estimates from UNDP (The Kathmandu Post, 2026). Figures for the August 2026 disaster are provisional and were current as of early September 2026.

Annual sediment yield (t/ha) in the West Rapti River Basin was simulated with the Soil and Water Assessment Tool (SWAT) for an observed/calibration period of 2003–2014 and future projections to 2100, driven by CMIP6 output from the EC-Earth3-Veg model (EC-Earth Consortium, 2019a, 2019b) under the SSP2-4.5 and SSP5-8.5 scenarios. The simulation was

initialised in 2015, and a warm-up period was run but excluded from the reported output to let soil and channel storage states stabilise. Annual precipitation, maximum temperature and minimum temperature from the same model were examined as spatial grid-cell averages. These are not station records, and the coarse model resolution smooths topographic extremes, so the results describe long-term regional trajectories rather than absolute local extremes.



Figure 1, Nepal's four major river systems join the Ganga in India and continue to the Bay of Bengal (map: bluebird-electric.net, n.d.).

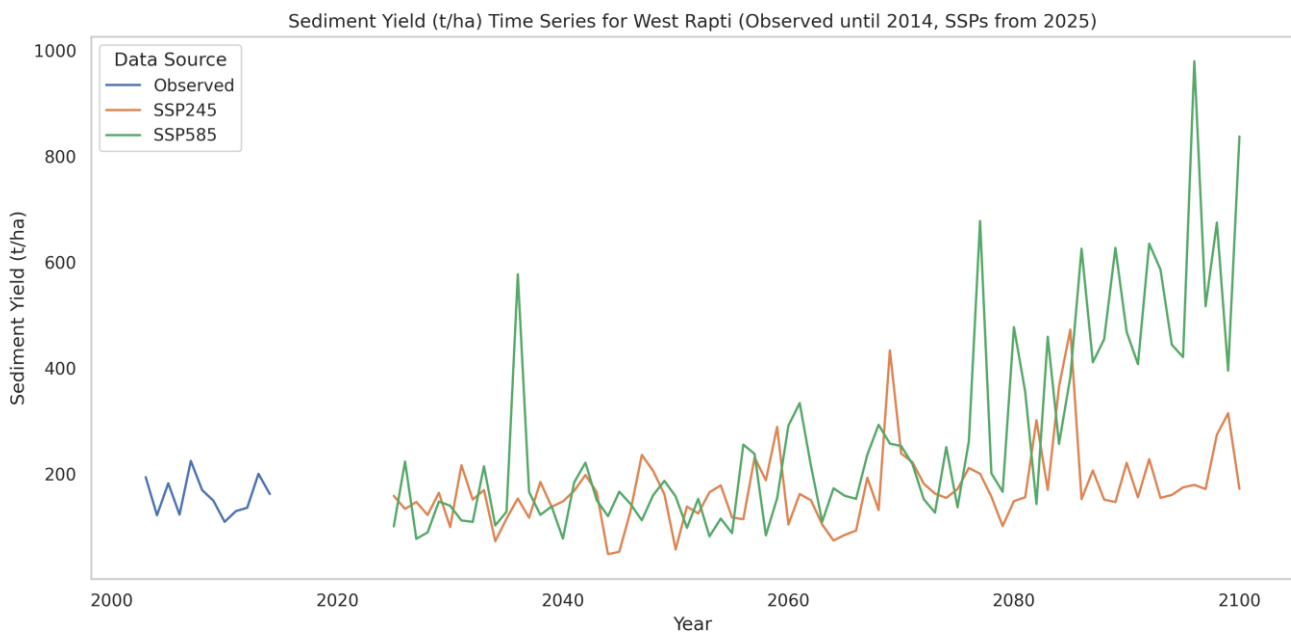


Figure 2, SWAT-simulated annual sediment yield for the West Rapti River Basin: observed/calibration period against CMIP6 (EC-Earth3-Veg) projections under SSP2-4.5 and SSP5-8.5.

Results and Discussion

A Warming Himalaya and a Retreating Cryosphere

The Hindu Kush Himalaya (HKH) is warming faster than the global average, particularly at higher elevations, a pattern known as elevation-dependent warming. Warming rates increased from 0.074 °C per decade globally during the 20th century to 0.1 °C per decade in the HKH (1901–2014), 0.2 °C per decade (1951–2014), and 0.5 °C per decade above 4,000 m. An additional 2.6–4.6 °C of HKH warming is projected by 2100 under CMIP5 scenarios (ICIMOD, 2026; Sabin et al., 2020).

HKH glacier area declined by about 12% between 1990 and 2020, some monitored glaciers thinned by up to 27 m since 1975, and approximately 89% of the last 50 years recorded net negative ice mass balance. Ice loss during the 2010s was about 65% faster than in the previous decade (ICIMOD, 2026). Under 3 °C of warming, the eastern Himalaya, including Nepal, could lose up to 75% of its present-day glacier volume by

2100. Accelerated melting allows water to accumulate behind moraine dams, while warming destabilises surrounding slopes and hanging ice (ICIMOD, 2026; Dhakal, 2026). This provides context for the 2026 disaster but does not prove climate change caused it.

EC-Earth3-Veg projections indicate gradually increasing annual precipitation under both scenarios, more steeply under SSP5-8.5, concentrated along southern slopes and central mid-hills. Annual maximum temperatures exceed 23 °C by 2100 under SSP5-8.5, while minimum temperatures approach 14 °C, with sub-zero minima in northern high-altitude grids and warmer conditions in southern lowlands.

Sediment Yield in the West Rapti Basin

Table 1 and Figure 2 compare observed and simulated sediment yield. The mean observed yield for 2003–2014 was 158.8 t/ha. Mean simulated yield in the future period was 165.7 t/ha under SSP2-4.5 and 260 t/ha under SSP5-8.5, and the highest single-year yield, 980 t/ha, occurred under SSP5-8.5 in 2096, the model's most extreme simulated year. Both scenarios simulate

higher and more volatile sediment yield than the observed baseline, and SSP5-8.5 diverges sharply after mid-century, consistent with the accelerating, high-magnitude regime described below.

Table 1, Simulated annual sediment yield, West Rapti River Basin (t/ha)

Scenario / period	Mean yield	Peak yield
Observed, 2003–2014	158.8	not reported
SSP2-4.5, future	165.7	not reported
SSP5-8.5, future	260	980 (2096)

From Gradual Transport to Sudden Mobilisation: The 26 August 2026 Event

The August 2026 event differs in kind from monsoon-paced transport. No rain was reported at Rasuwadhi district headquarters that morning. At 08:37 NPT a seismic signal near Langtang Lirung, later confirmed by USGS and GFZ analysis as a glacier collapse rather than an earthquake, marked the fall of about 0.2 km² of ice and rock from roughly 5,200–5,400 m, some 1.2 km into the Lhende Khola valley (2026 Nepal–Tibet floods, 2026). Within seven minutes the flood destroyed the Gyirong Port border crossing, and it reached Syabrubesi within roughly ten minutes of entering Nepal. The debris field extended along 72 km of the Trishuli–Bhotekoshi corridor, and some victims were carried 240 km downstream into India.

As of early September 2026, at least 1,342 people were confirmed dead and 4,886 missing in Nepal, about 1.6 million people were affected, 13 hydropower projects were damaged, and 68 suspension bridges were destroyed or damaged (2026 Nepal–Tibet floods, 2026). More than 1.5 m of silt was deposited in the main disaster zone, UNDP estimated 2.2 million tonnes of debris in the Bhotekoshi–Trishuli corridor (The Kathmandu Post, 2026), and 200–490 million m³ of ice, rock and debris was mobilised in the triggering collapse (2026 Nepal–Tibet floods, 2026). At least 26 glacial lake outburst or glacier-collapse events have occurred since 1977, and their occurrence is increasing rather than steady (Dhakal, 2026; 2026 Nepal–Tibet floods, 2026).

Conventional sediment-yield modelling calibrated on monsoon-season data will systematically miss such episodic, high-magnitude pulses. They warrant separate representation in planning for reservoirs, irrigation intakes and downstream infrastructure.

Glacial Lake Hazard and Cascading Failure

Scientific inventories put Nepal's glacial lake count at roughly 2,070–3,000, of which 47 are classified as potentially dangerous (21 in Nepal, 25 in Tibet and 1 in India) (Dhakal, 2026). Damaging outbursts are becoming more frequent: Dig Tsho (1985), Tam Pokhari (1998), the 2016 Gongbatongshacuo breach in Tibet that reached the Bhote Koshi (about USD 70 million in damage), Thyanbo near Thame (2024), Tilgau and

Rasuwadhi (2025, 9+ dead) and the 2026 collapse. Three of these six occurred in the last two years (Dhakal, 2026).

These hazards are not isolated. Research on high-mountain process chains shows that glacier and permafrost degradation, ice or rock avalanches, moraine-dam breaches, landslide-dammed rivers and secondary outbursts can trigger one another within minutes to hours, shortening the time available for warning (Frontiers in Earth Science, 2019; Chen et al., 2023; npj Natural Hazards, 2026; PreventionWeb, 2026). The July 2025 Rasuwadhi outburst and the August 2026 disaster occurred along the same river corridor within thirteen months of each other (PreventionWeb, 2026). The 2026 event is therefore evidence that cascading multi-hazard failure, previously a theoretical risk, is now a demonstrated possibility for Nepal.

Warning Performance and Institutional Response

River gauges were designed for gradual monsoon floods, while automated stations at Bhote Koshi and Syabrubesi were destroyed before issuing alerts. DHM was informed at 09:00, and SMS alerts began at 09:15, sending 679,295 messages within one minute. China's formal cross-border notification arrived nearly five hours after the flood entered Nepal (2026 Nepal–Tibet floods, 2026).

Nepal has lowered Tsho Rolpa by about 3 m and Imja Tsho by 3.4 m, introducing early warning systems. Imja Tsho's sensors and sirens cover six settlements and 71,752 people. A USD 36.1 million Green Climate Fund programme supports GLOF risk reduction for 2.3 million people, while over 21,000 security personnel were mobilised after the disaster. However, mitigation covers only 2 of roughly 20 priority lakes, monitoring remains monsoon-focused, and Nepal–China data-sharing arrangements remain incomplete. Meanwhile, development continues in valleys vulnerable to sudden flooding (Dhakal, 2026; UNDP, 2026).

Recommendations

We recommend that Nepal: (1) expand physical mitigation beyond Tsho Rolpa and Imja Tsho to all roughly 20 high-risk lakes; (2) build sudden-onset monitoring using seismic and satellite-based detection for glacier collapse and avalanche-triggered floods, distinct from monsoon gauges; (3) secure binding, real-time cross-border data-sharing with China; (4) integrate glacial and sediment hazards into hydropower, road and settlement project approvals in high-risk valleys; (5) strengthen DWRI and DHM capacity to track episodic, high-magnitude sediment pulses separately from monsoon transport; and (6) reconstruct discharge, sediment, debris volumes and warning performance to calibrate models against unprecedented events (Dhakal, 2026).

Conclusions

Nepal's sediment transport is shifting from gradual monsoon flows to sudden, high-magnitude pulses caused by glacier collapse and slope failure. West Rapti simulations indicate higher, more variable sediment yields under both scenarios, while the 26 August 2026 disaster highlights the limitations of monsoon-focused monitoring. Mitigation, monitoring, cross-border data sharing and post-event analysis must address sudden-onset hazards.

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Author contributions

Conceptualization: R.B. Thapa and K.R. Kafle; Methodology: R.B. Thapa, K.R. Kafle, and K.L. Shrestha; Data analysis: R.B. Thapa; Writing, original draft preparation: R.B. Thapa; Writing, review and editing: K.R. Kafle and K.L. Shrestha; Supervision: K.R. Kafle. All authors have read and approved the final manuscript.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. CMIP6 EC-Earth3-Veg datasets are publicly available through the Earth System Grid Federation (ESGF). The SWAT model outputs generated and analyzed during the study are available from the authors on reasonable request.

Declarations

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

References

- 2026 Nepal–Tibet floods: Aggregated reporting. (2026). USGS, GFZ Helmholtz Centre, Reuters, AP, BBC, and The Kathmandu Post.
- bluebird-electric.net (n.d.). The River Ganges [Map]. Available at: [oceanography/Rivers/The_River_Ganges.htm](https://bluebird-electric.net/oceanography/Rivers/The_River_Ganges.htm)
- Chen, N., et al. (2023). Small outbursts into big disasters: Earthquakes exacerbate climate-driven cascade processes of glacial lake failure in the Himalayas. *Geomorphology*, 422, 108539.
- Dhakal, B. (2026, August 31). Around 200 lakes across the Himalaya could burst: Why Nepal faces a slow-motion emergency. *Nepal News*.
- DSCWM (n.d.). National river inventory statistics. Government of Nepal, Department of Soil Conservation and Watershed Management.
- EC-Earth Consortium (2019a). EC-Earth3-Veg model output prepared for CMIP6 CMIP (Version 20200225). Earth System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.642>
- EC-Earth Consortium (2019b). EC-Earth3-Veg model output prepared for CMIP6 ScenarioMIP (Version 20200225). Earth System Grid Federation. <https://doi.org/10.22033/ESGF/CMIP6.727>
- Frontiers in Earth Science (2019). The state of remote sensing capabilities of cascading hazards over High Mountain Asia.
- ICIMOD (2026). Hindu Kush Himalaya glacier outlook. International Centre for Integrated Mountain Development.
- IntechOpen (2024). Landsat-based analysis of Sundarbans coastline erosion and accretion, 1975–2022.
- Islam, M. R., Begum, S. F., Yamaguchi, Y., and Ogawa, K. (1999). The Ganges and Brahmaputra rivers in Bangladesh: Basin denudation and sedimentation. *Hydrological Processes*, 13(17), 2907–2923.
- npj Natural Hazards (2026). Permafrost degradation and mass-movement cascades, western Himalaya.
- PreventionWeb (2026). Nepal flood disaster exposes cascading threats in Himalayas.
- Sabin, T. P., Krishnan, R., Gómara, I., and Rajendran, K. (2020). Temperature changes over the Himalaya. In R. Krishnan, J. Sanjay, C. Gnanaseelan, M. Mujumdar, A. Kulkarni, and S. Chakraborty (Eds.), *Assessment of climate change over the Indian region: A report of the Ministry of Earth Sciences (MoES)*, Government of India (pp. 235–250). Springer.
- The Kathmandu Post (2026, September 2). Bhotekoshi floods left 2.2 million tonnes of debris, UNDP estimates.
- UNDP (2026). Green Climate Fund approves \$36.1 million to help Nepal protect lives and livelihoods from glacial flood risks.
- van Staveren, M. F., et al. (2017). Tidal river management in the Ganges–Brahmaputra delta, Bangladesh.
- WECS (n.d.). Water resources of Nepal in the context of climate change. Government of Nepal, Water and Energy Commission Secretariat.