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Transboundary Threats from Glacial Lake Outburst Debris Flows in the Himalayas: Identification and Future Projections

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Abstract

The retreat of Himalayan glaciers and the expansion of glacial lakes due to global warming have increased the occurrence of glacial lake outburst debris flow (GLODF), posing a serious threat to downstream communities. However, there are gaps in understanding the changes in GLODF occurrence driven by climate change, which challenges disaster management and cross-border cooperation in the Himalayas. Considering this issue, we present a novel framework integrating environmental evolution, a process-driven indicator system, and a hybrid machine learning model to predict Himalayan GLODF occurrence in the 21st century. Our findings indicate ongoing temperature (0.27-0.60 ˚C/10a) and precipitation (1.30-5.00 %/10a) increases under both SSP245 and SSP585 scenarios. China-Nepal border remains a hotspot for cross-border GLODF. By 2100, it is projected that the number of catchments with high or very high probability and potential transboundary threats will increase by 96-101 (approximately a 2-fold increase). Our framework offers valuable long-term insights into Himalayan GLODF occurrence trends in response to climate change.

Keywords: Glacial lake outburst debris flow; Risk prediction; Transboundary hazard; Climate change; Himalayas

Main Text

1 Introduction

The Himalayas lie on the southern margin of the Qinghai-Tibet Plateau, spanning latitudes 26.35° N to 35.85° N, and longitudes 72.77° E to 95.43° E. With an area of approximately 66.22×10^4 km^2, the Himalayas extend for about 2136 km from west to east and 1122 km from north to south. The collision between the Indian and Asian Plates has led to the formation of various tectonic fault zones in the region from south to north, including the Main Frontal Thrust (MFT), the Main Boundary Thrust (MBT), and the Main Central Thrust (MCT), etc. Lithologically, the study area is dominated by Precambrian metamorphic rocks with continuous marine stratigraphy from the Ordovician to the Neoproterozoic and also has a total of 12,500 m of thick epigenetic sedimentary strata.

The Himalayan region is characterized by the widespread distribution of glaciers and glacial lakes and is highly susceptible to severe hazards. When the propagation pathways of glacial lake outburst floods (GLOFs) extend across national boundaries or intersect border ports and major transportation corridors located in downstream valleys, such events can pose substantial transboundary threats. At approximately 10:52 China Standard Time (UTC+8) on 26 August 2026, a glacier on the northern slope of Langtang Lirung in Nepal failed at an elevation of approximately 5,200 m a.s.l., triggering a high-energy ice-rock avalanche. The ice-rock mass rapidly descended to approximately 4,000 m, intensely scouring the terrain, entraining large volumes of loose material, and subsequently evolving into a large debris flow. After traveling approximately 22 km downstream at high velocity, the debris flow reached Gyirong Port, China, at an elevation of approximately 1,800 m a.s.l. The event devastated an area of approximately 0.7 km^2, destroying 27 buildings and associated facilities, while also causing substantial casualties and property losses in Nepal.

Although the event was initiated by glacier failure rather than a glacial lake outburst, it illustrates how high-mountain cryospheric hazards can transform into rapidly propagating debris flows and generate severe transboundary impacts along downstream valleys. Among such cryospheric hazards, GLOFs and associated debris flows represent an important and growing source of transboundary risk across the Himalayas.Under ongoing global warming, accelerated glacier retreat has promoted the rapid expansion and proliferation of glacial lakes across the Himalayas. At the same time, increasingly frequent and intense extreme climatic and hydrometeorological events may further enhance the likelihood of glacial lake outburst floods (GLOFs). Consequently, GLOFs and associated cascading hazards with transboundary impacts have become an increasingly prominent threat across the Himalayan region. Therefore, systematically characterizing the current distribution of Himalayan glacial lakes, identifying potential transboundary

threats posed by GLOFs, and further revealing the spatiotemporal evolution and future trends of transboundary GLOF-induced debris-flow hazards are critical research priorities for climate-change adaptation, disaster risk reduction, and coordinated transboundary risk management.

2 Distribution and Changes in Glacial Lakes

A total of 8,204 glacial lakes were identified across the Himalayan region, covering a total area of 635.13 km². Along the east-west gradient, the Eastern Himalayas contained the largest number and area of glacial lakes, with 3,496 lakes covering 271.04 km², followed by the Central Himalayas with 2,831 lakes covering 255.17 km² and the Western Himalayas with 1,877 lakes covering 108.92 km². A pronounced spatial asymmetry was observed between the southern and northern slopes of the Himalayas. A total of 5,698 glacial lakes, with a combined area of 399.44 km², were distributed on the southern slope, accounting for 69.45% of the total number of lakes and 62.89% of the total glacial-lake area, both substantially higher than the corresponding proportions on the northern slope. Glacial lakes were predominantly concentrated within the 4,000-5,600 m elevation range, which contained approximately 90% of all lakes, with a mean elevation of approximately 4,811 m a.s.l.

The number of glacial lakes increased from 7,625 to 8,204, representing a net increase of 579 lakes (7.59%) from 1990 to 2015. Over the same period, the total glacial-lake area expanded from 561.66 to 635.13 km², corresponding to an increase of 73.47 km²(13.08%). Among the three longitudinal sectors, the Central Himalayas experienced the greatest relative increase in glacial-lake area, reaching 20.12%. Moreover, both the number and total area of glacial lakes on the southern slope increased more rapidly than those on the northern slope. The mean elevation of newly formed glacial lakes was approximately 5,001m a.s.l., higher than the mean elevation of glacial lakes that disappeared during the study period (4,918m a.s.l.). This elevation difference indicates an overall upward shift in glacial-lake development, suggesting that newly exposed topographic depressions associated with glacier retreat are increasingly facilitating the formation and expansion of glacial lakes at higher elevations.

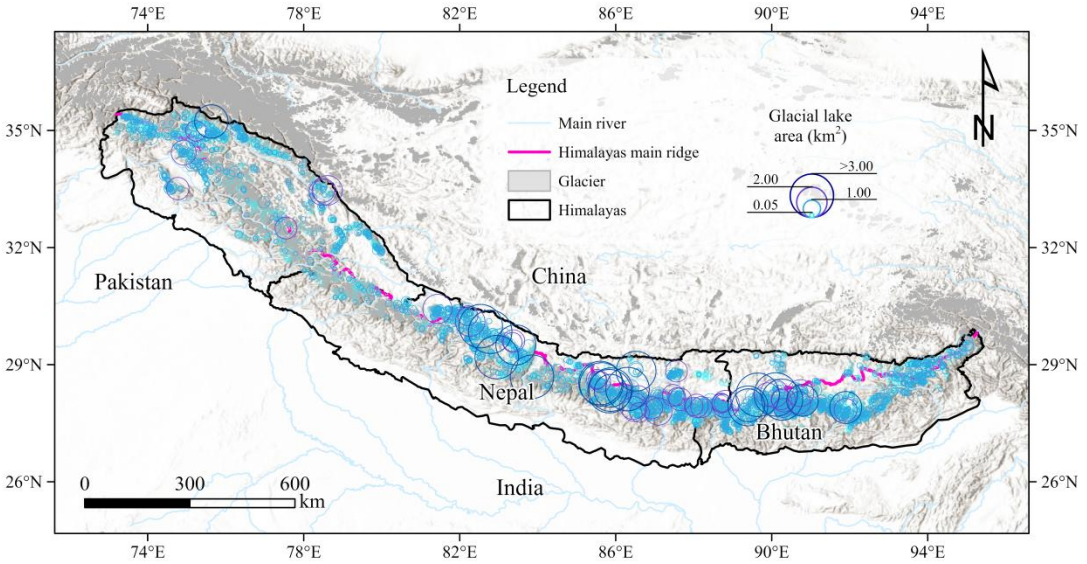

Fig. 1. Spatial distribution of glacial lakes in the Himalayas.

3 Identification of Transboundary Glacial Lake Outburst Debris-Flow Hazards

3.1 Identification Method

The Himalayan region was divided into 1,435 glacial-lake-containing catchments. A training dataset comprising 108 samples was established through a combination of literature review, remote-sensing interpretation, and field investigations, including 54 catchments with documented historical glacial lake outburst debris flows (GLODFs) as positive samples and 54 non-GLODF catchments as negative samples.

A process-driven indicator system was developed to characterize GLODF susceptibility by considering the complete hazard formation and propagation process. The indicators were organized into three major components: (1) upstream triggering conditions, including solid-material input into glacial lakes and fluid recharge; (2) lake and dam conditions, including the potential magnitude of lake outbursts and dam stability; and (3) downstream propagation and amplification conditions, including sediment erosion and entrainment, channel connectivity, and downstream propagation probability.

Three hybrid machine-learning models, namely WOA-SVC, WOA-RF, and WOA-GTB, were developed by coupling conventional machine-learning algorithms-support vector classification (SVC), random forest (RF), and gradient tree boosting (GTB)-with the whale optimization algorithm (WOA). These models were subsequently applied to assess the spatial susceptibility of GLODFs across the Himalayas.

Potential transboundary GLODF hazards were further identified by simulating downstream outburst-flow pathways using the Modified Single-Flow-direction (MSF) model. A minimum angle of reach of 3 ° was adopted to constrain the maximum potential runout distance under a worst-case scenario. A glacial-lake catchment was classified as

posing a potential transboundary threat when the simulated propagation pathway originating from that catchment crossed an international boundary.

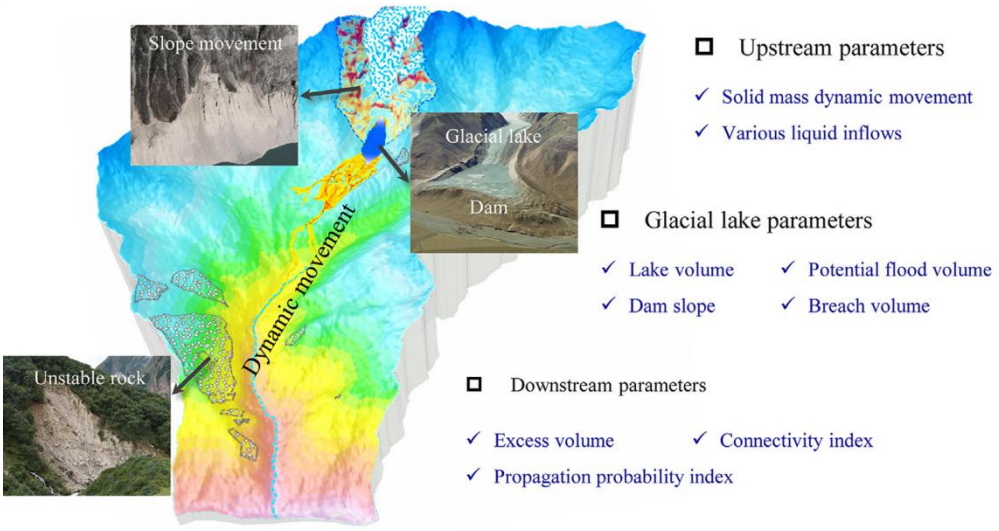

Fig. 2. Process-driven indicator system for glacial lake outburst debris-flow susceptibility.

3.2 Distribution of Transboundary Hazards

The results indicate that approximately 34% of glacial-lake-containing catchments across the Himalayas fall within the high or very high GLODF susceptibility levels. The proportions of catchments classified as very low, low, moderate, high, and very high susceptibility are 14.63%, 17.91%, 31.99%, 19.65%, and 15.82%, respectively. Catchments with high to very high susceptibility levels are predominantly distributed in belt-like patterns along both sides of the main Himalayan ridge, with marked concentrations in the Central and Eastern Himalayas. In contrast, catchments located farther from the main ridge, as well as those in parts of the Western Himalayas, generally exhibit lower susceptibility.

A total of 128 catchments with potential transboundary threats (CPTTs) were identified, including 23 very-high-susceptibility catchments and 29 high-susceptibility catchments. Approximately 65% of the high- to very-high-susceptibility CPTTs are concentrated along the China-Nepal border, highlighting this region as the most prominent hotspot of transboundary GLODF threats across the Himalayas.

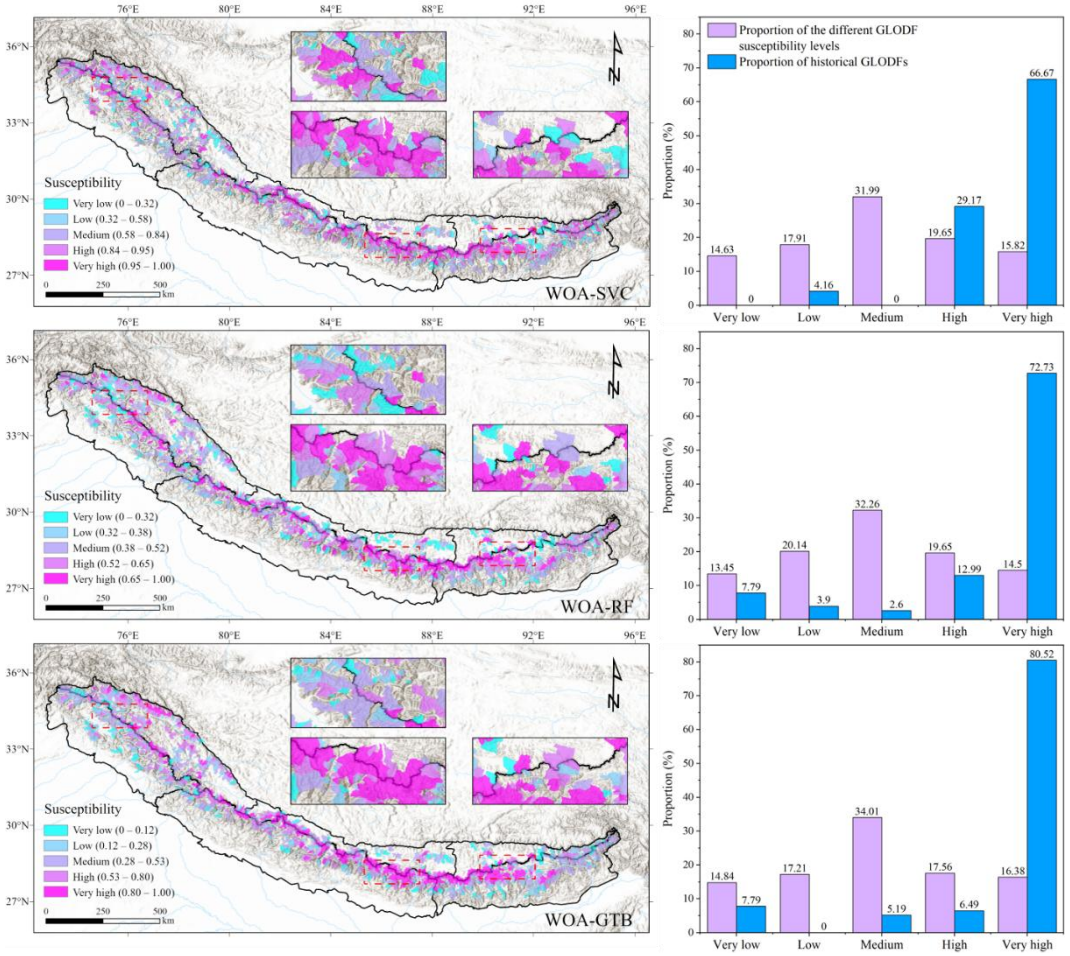

Fig. 3. Spatial distribution of glacial lake outburst susceptibility derived from the three models.

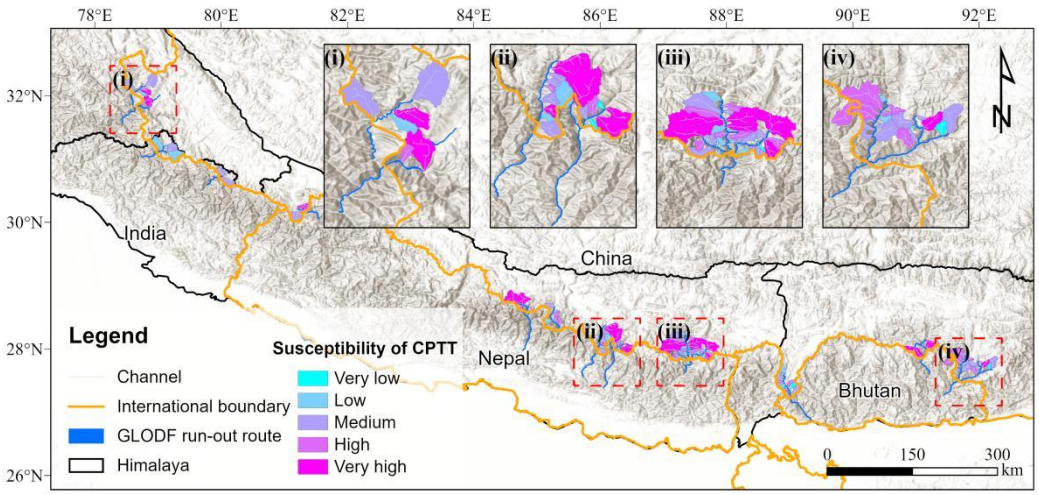

Fig. 4. Susceptibility zoning of glacial lake outburst debris flows posing transboundary threats.

4 Future Evolution of Transboundary Glacial Lake Outburst Debris-Flows

4.1 Climate-Related Hazard Drivers

Six CMIP6 global climate models (GCMs) that exhibit relatively good performance in simulating temperature and precipitation over the Tibetan Plateau were selected. Two future emission scenarios, SSP2-4.5 and SSP5-8.5, were considered, and projected changes during 2020-2100 were evaluated relative to the 1981-2014 baseline period. The climate model outputs were first bias-corrected using empirical quantile mapping (EQM). Precipitation was spatially downscaled using ordinary kriging interpolation, whereas temperature was downscaled using the ANUSPLIN method, which explicitly accounts for the effects of elevation.

Relative to the baseline period (1981-2014), the projected changes in the annual mean temperature of the Himalayas from 2020 to 2100 under the SSP245 and SSP585 scenarios are illustrated in Figure 6(a), as simulated by six models. The projected change rates will reach 0.27℃/10a (25th to 75th percentile range: 0.24-0.33℃/10a) and 0.60℃/10a (0.53-0.76℃/10a) under the SSP245 and SSP585 scenarios, respectively. Relative to the baseline period (1980-2014), Figure 6(b) illustrates the anticipated changes in annual precipitation in the Himalayas from 2020 to 2100 under the SSP245 and SSP585 scenarios. The projected annual precipitation increase rates in the Himalayas are expected to be 1.3%/10a (0.53% to 3.36%/10a) and 5.0%/10a (3.01% to 9.47%/10a), respectively.

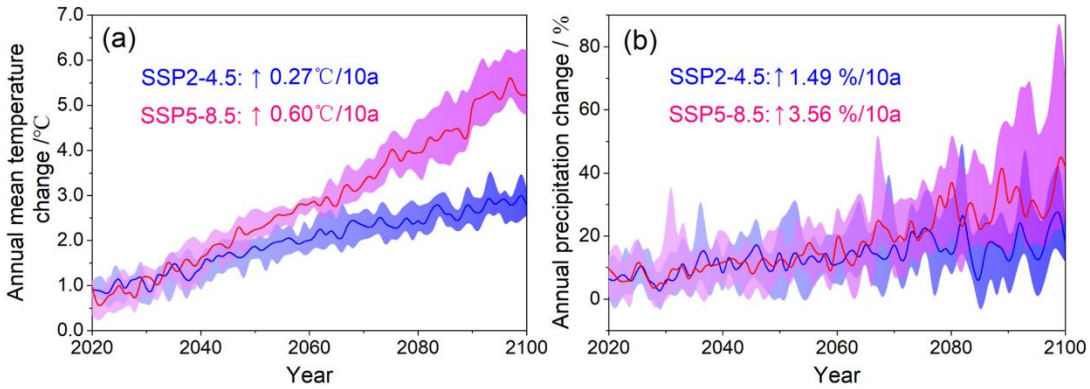

Fig. 5. Projected change of (a) annual mean temperature and (b) annual precipitation during 2020-2100 under SSP245 and SSP585 scenarios relative to the baseline period (1981-2014) over the Himalayas. The shaded areas represent the 25th-75th percentile ranges across the six GCMs

4.2 Projected Changes in Transboundary Hazards

The number of catchments with high to very high GLODF occurrence probabilities across the Himalayas is projected to increase from the current 467 to 614 by 2100. Meanwhile, the GLODF occurrence probability index (OPI) is projected to increase to approximately

1.27-1.30 times its current level, with the Western Himalayas emerging as a new hotspot of GLODF activity. At the basin scale, the Indus River Basin is projected to exhibit the highest future OPI, reaching approximately 1.3–1.4 times the current level by 2100. The Chenab and Gandak basins are also expected to experience substantial increases in GLODF occurrence probability.

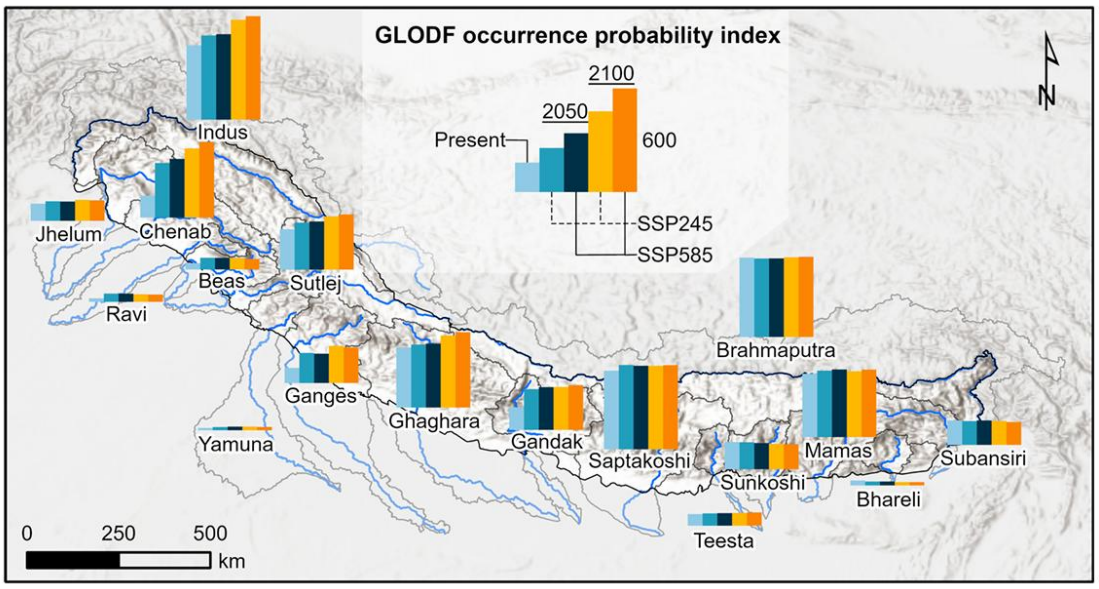

Fig. 7. Changes in the basin-scale GLODF occurrence probability index across the Himalayas.

Both the number of catchments posing transboundary threats and their susceptibility levels are projected to increase in the future. By 2050, the number of high- to very-high-susceptibility transboundary catchments is projected to increase to 92-96, and further to 96-101 by 2100, approximately twice the current number. By 2100, transboundary catchments along the China–Nepal border are projected to account for approximately 60% of the total susceptibility index across the Himalayan region. In contrast, transboundary catchments along the China-India border are expected to exhibit the most rapid increase in susceptibility, potentially reaching approximately 2.6 times the current level.

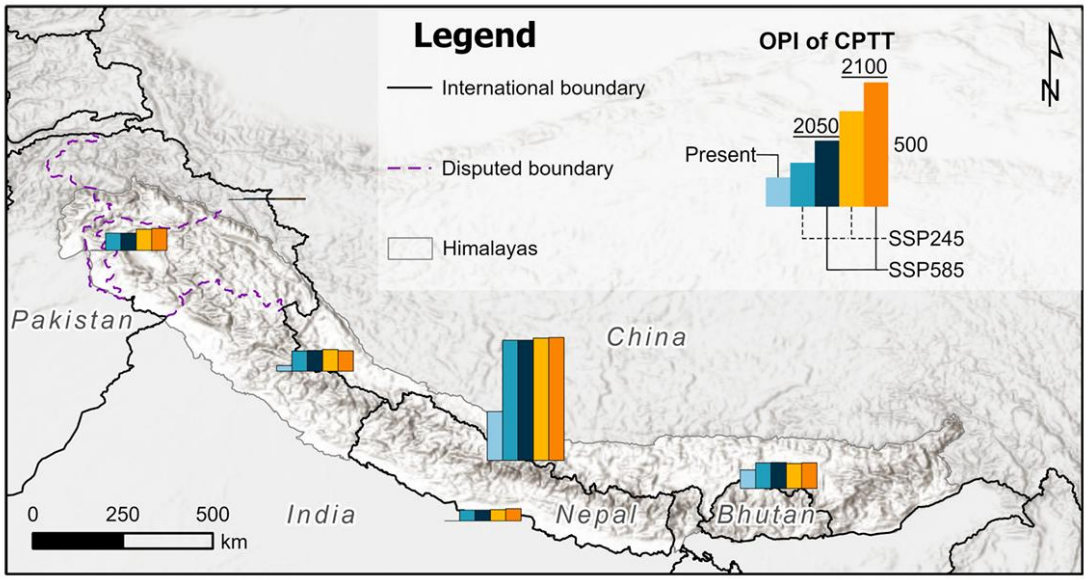

Fig. 8. Projected changes in the occurrence probability index (OPI) of catchments with potential transboundary threats (CPTTs) across the Himalayas.

5 Implications for Disaster Risk Reduction

The findings highlight the need to strengthen transboundary monitoring, early warning, and risk-information sharing across the Himalayan region, particularly along high-risk border areas. Priority should be given to catchments where rapidly evolving glacial lakes, high GLODF susceptibility, and downstream exposure coincide. Integrating remote sensing, ground-based monitoring, and scenario-based assessments could support anticipatory action and coordinated disaster risk reduction across national boundaries.

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