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Climate Change Impacts on Hydrological Landslide Triggering in the Northern Himalayas

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Abstract: Hydrologically-induced shallow landslides represent severe threat to human life and infrastructure in the drainage basin of the largest river in northern Himalayas–the Yarlung Zangbo River Basin (YZRB). Shallow landslides in the cryosphere are jointly shaped by rainfall, glacier/snow melt and permafrost thaw, yet the relative contributions of these triggers remain unclear. Here we establish a mechanistic landslide triggering model for the YZRB and estimate that rainfall, glacier/snow melt and permafrost thaw contribute ~39.4%, 30.9%, and 29.7% to landslides, respectively, for the period 1991-2019. Future climate change will likely exacerbate landslide triggering, primarily due to increasing rainfall and permafrost thaw, whereas the contribution of glacier/snow melt decreases. The downstream YZRB is delineated as a hotspot for landslide triggering, but the middle stream is exposed to the greatest risk. This study yields new insights into landslide triggering mechanisms and provides guidelines for risk management in the Himalayas.

Keywords: ***Landslide, Rainfall, Cryosphere degradation, Risk evolution, Climate change, Himalaya.***

Introduction

Landslides are among the most destructive and frequent natural hazards in the Himalayas, causing significant socioeconomic losses each year. While individual triggers like rainfall, glacier/snow melt, and permafrost thaw have been studied, a holistic understanding of their relative contributions and how they will evolve under climate change has been lacking. In this study, we address this gap by establishing a mechanistic hydromechanical landslide-triggering model for the Yarlung Zangbo River Basin (YZRB, Figure 1), the largest river basin in the northern Himalayas. Their work systematically quantifies the role of different water sources in landslide activity and projects future risk under climate change scenarios.

Methodology

We developed an integrated modeling framework that couples a comprehensive hydrological module with a slope stability analysis. The hydrological module simulates key processes, including precipitation, glacier/snow melt, permafrost thaw, infiltration, runoff, evapotranspiration, and groundwater flow, which had been previously validated for the YZRB. The mechanical module assesses slope stability using the Factor of Safety (FOS), which is critically dependent on soil water content that influences soil weight and pore water pressure.

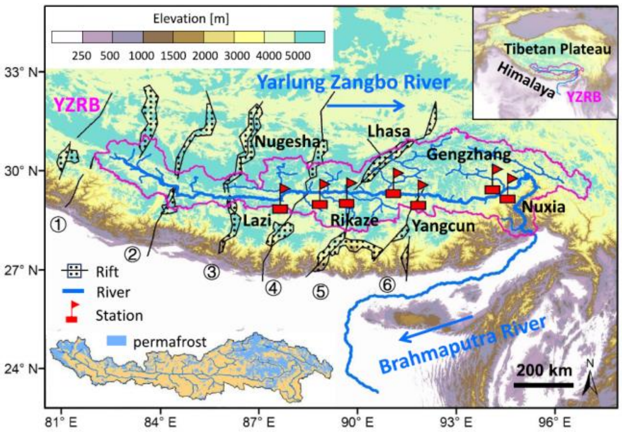

Figure 1, Geographic setting of the Yarlung Zangbo River Basin (YZRB).

To overcome the computational challenge of applying a physically-based model to such a large basin (~254,000 km^2) over a 110-year period (1991–2100), we introduced a sub grid parameterization scheme. This innovative approach leverages hydrological simulations at a 1 km resolution and downscales the soil moisture content to a 100 m resolution using the Topographic Wetness Index (TWI), enabling high-resolution slope stability analysis across the vast region.

Results

Relative contributions of landslide triggers

For the historical period (1991-2019), the study provided the first quantitative breakdown of landslide triggers in the YZRB: Rainfall was the dominant trigger, contributing 38.4%; Permafrost thaw contributed 32.8%; Glacier/Snow melt contributed 28.8%.

Spatially, the contribution of rainfall decreased from upstream to downstream, while meltwater was most significant in heavily glaciated areas. Temporally, landslides triggered solely by meltwater peaked in May-June, whereas the peak in the real-world combined scenario occurred in July-September, dominated by monsoon rainfall.

Projected landslide activity under climate change

Under both SSP2-4.5 and SSP5-8.5 climate scenarios, landslide activity is projected to intensify throughout the 21st century. The regional average landslide erosion rate is expected to increase from 0.39 mm/yr in the 1990s to 0.56 mm/yr (SSP2-4.5) and 0.69 mm/yr (SSP5-8.5) by the 2100s.

Crucially, the relative contributions of the triggers are shifting (Figure 2). The contribution of rainfall is increasing, projected to rise from 38.4% to ~46.9% under SSP5-8.5 by 2100; The contribution of glaciers/snow melt is steadily decreasing due to warming-induced glacier retreat and snow cover loss; The contribution of permafrost thaw increases until around 2070 before declining. This trend indicates that the YZRB may have already passed the "peak water" tipping point for glacier runoff, with future landslide triggering becoming increasingly dominated by rainfall and, in the near-term, permafrost thaw.

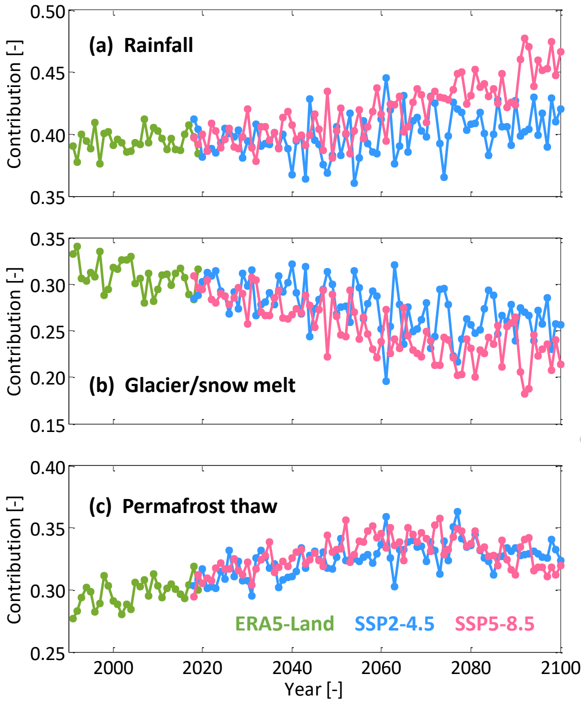

Figure 2, Temporal evolution of the relative contribution of different hydrological triggers to landslides.

Evolution of socioeconomic risk

By integrating landslide simulations with projections of GDP and population, the study assessed the landslide risk to GDP and population (Figure 3) and their long-term evolution: GDP risk is projected to increase continuously throughout the 21st century, with a more drastic rise under the high-emission SSP5-8.5 scenario. High-risk areas coincide with economically developed, landslide-prone regions like the Parlung Zangbo and Nyang Qu basins. Population risk, in contrast, shows a general declining trend, primarily attributed to projected population decrease in the region due to environmental degradation.

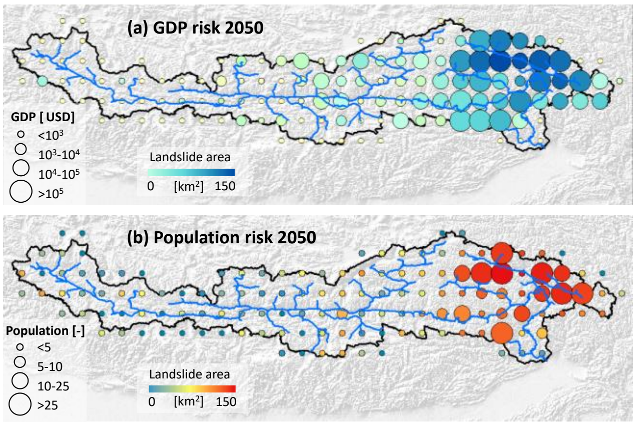

Figure 3, Spatial distribution landslide risks to GDP and population in 2050 under SSP5-8.5.

The impact of tectonics on landslide triggering

The YZRB is highly tectonically active, with widespread faults and fractures. The study demonstrated that these structures, which act as conduits for water drainage into the bedrock, play a critical role in landslide dynamics. Simulations comparing permeable versus impermeable bedrock showed that ignoring this drainage leads to an overestimation of landslide volume, especially during the non-monsoon season. This finding challenges the conventional assumption of an impermeable soil-bedrock interface in landslide models, particularly in tectonically active regions.

Conclusion and outlook

This study establishes a pioneering mechanistic framework for understanding and projecting hydrological landslide triggering in the northern Himalayas. It reveals that future landslide activity will be increasingly dominated by rainfall, while the role of glacier/snow melt diminishes. The research highlights the importance of considering tectonic controls on hydrology and provides a critical risk assessment that separates economic from human population exposure.

The proposed subgrid parameterization scheme represents a significant step towards facilitating physically based landslide modeling over large regions. This opens the door for the future integration of landslide modules into Earth System Models, improving our understanding of landslides' role in landscape evolution and the global carbon cycle. The findings offer novel insights and practical guidance for disaster risk management and climate resilience building in the vulnerable Himalayan region.