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How Will Melamchi Disaster 2021 Look Like in Warmer Temperature?

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Abstract: Global warming reshapes geohazard dynamics by influencing both precipitation and temperature. While precipitation remains the primary landslide trigger, temperature-driven changes in soil strength are often overlooked. This study integrates temperature-controlled shear testing with a physically based multi-hazard model to quantify thermal impacts on slope processes in Nepal's Melamchi catchment, affected by the 2021 debris flood. Laboratory ring-shear experiments on landslide soils revealed a linear reduction in friction angle with a 4.9 °C temperature increase, indicating thermal weakening. Incorporating this relationship into a calibrated multihazard model intensified hazard metrics without altering rainfall input. The warmer scenario increased peak discharge by 7%, sediment discharge by 36%, while producing longer runouts and higher impact pressures. These findings demonstrate that rising temperatures alone can amplify disaster severity, underscoring the importance of integrating thermally dependent soil properties into future multi-hazard assessments under climate change.

Keywords: ***Shear strength, Climate change, Geohazard modelling, Landslide, Debris flow, Slope stability.***

Introduction

Global warming influences geohazard dynamics primarily through changes in precipitation and temperature (Scaringi and Loche, 2022). While precipitation is widely recognized as the principal trigger of landslides and debris flows, the independent contribution of temperature to the evolution of such hazards remains comparatively unexplored. Mountain catchments are currently experiencing accelerated warming, with temperature increases projected to reach approximately 4.9°C (under a worst-case scenario) by the end of the century (Shrestha et al., 2016; IPCC, 2023). To address this gap, an integrated experimental–numerical framework was developed to isolate and quantify the effect of temperature on the mechanical behavior of landslide materials and to examine the resulting implications for multi-hazard dynamics. A ring shear device was modified to enable temperature-controlled shear testing, allowing direct observation of thermally induced variations in soil shear strength. The experimentally derived temperature–strength relationship was subsequently incorporated into a calibrated deterministic multi-hazard model to assess how a warming climate could alter landslide and debris-flow processes. The 2021 Melamchi disaster in Nepal was selected as a representative case study to demonstrate this approach.

Temperature-controlled shear experiments

Soil samples were collected from active landslide scarps and deposits within the Melamchi catchment. Thirty-six samples from four distinct spatial locations were tested under controlled laboratory conditions using the modified ring shear apparatus. Tests were performed under varying clay fractions, ranging from 8 to 26%, and normal stresses at 50, 100 and 150 kPa to characterize the typical soil response within the case study. The results revealed a systematic reduction in the friction angle of the soil with increasing temperature, particularly pronounced in fine-grained materials (Dhakal et al., 2025). This thermal weakening behavior was represented as a linear correlation between the clay fraction and the temperature-induced change in friction angle, forming the basis for subsequent model parameterization (Figure 1).

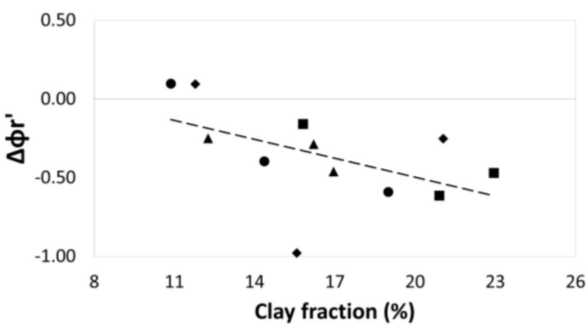

Figure 1, Effect of heating soil by 30°C on the residual friction angle according to the clay fraction of the tested specimens (Dhakal et al., 2025).

Multi-hazard modelling in a warmer scenario

The calibrated multi-hazard model (van den Bout et al., 2018) reconstructed the 2021 Melamchi disaster integrating post-disaster field data, remote sensing images, and soil mechanical properties. The hydrological simulation, driven by a 260 mm rainfall event distributed over 24 hours across a 173 km^2 catchment, reproduced the key flow processes with a spatial accuracy of 65% between the simulated and mapped debris-flow extent. The simulation along its boundary condition (as shown in Figure 2) yielded a peak discharge of 526 m^3/s and a total runoff volume of approximately 22.5 million m^3, while the maximum debris-flow height and velocity at the boundary outflow of the model reached 22.2 m and 17.7 m/s, respectively. The boundary outflow was aligned to match the headworks location of the Melamchi water supply project in Ambathan.

Incorporating thermally weakened soil parameters, as derived from the experimental data, into the model resulted in a warmer scenario simulation that captured the likely evolution of the same event under elevated temperature conditions. The warmer scenario produced a measurable increase in the overall hazard intensity. The peak discharge increased from 526 m^3/s to 565 m^3/s, representing a 7% rise. The peak discharge came with a half an hour delay suggesting the abruption in process chain. Similarly, the peak sediment discharge increased from 2262.6 kg/s to 3090.7 kg/s, with a 36% rise. These changes were spatially represented as percentage change from present to warmer scenarios over the modelling domain as shown in Figure 2. In summary changes associated with longer landslide runouts, enhanced channel erosion, larger landslide dams, and amplified impact pressures along the valley walls, all of which signify a more intense and prolonged hazard cascade.

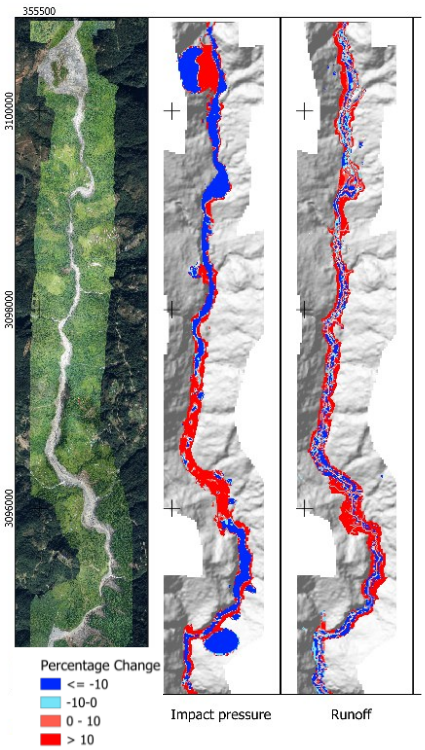

Figure 2, Percentage change in the hazard scenario for various physical processes as a result of 4.9°c warming.

Conclusion

This study demonstrates that even without altering the magnitude of the hydrological input, an increase in temperature can modify the intensity and timing of cascading hydro-geomorphic hazards. Incorporating thermally dependent soil strength parameters into the model revealed that warming conditions promote faster slope failures, higher sediment yields, and increased flood inundation, leading to more destructive process chains. The results emphasize the critical role of temperature as an indirect trigger but significant driver of hazard amplification in warming mountain environments. Consequently, it is essential that future hazard modelling frameworks need to explicitly include temperature-sensitive mechanical properties of soils to capture the evolving nature of climate-driven extremes. The present work highlights the need for further experimental and numerical studies aimed at refining thermal–mechanical relationships in geomaterials and understanding their broader implications for future mountain hazard evolution.

References

Dhakal, O. P., Acharya, R. P., Thapa, A. B., and Tuladhar, B. M. (2025). Influence of temperature on the residual shear strength of landslide soil: Role of the clay fraction. Bulletin of Engineering Geology and the Environment, 84(8), 1–20. https://doi.org/10.1007/s10064-025-04405-w

Intergovernmental Panel on Climate Change (IPCC). (2023). Summary for policymakers. In H. Lee and J. Romero (Eds.), Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Available at: https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

Scaringi, G., and Loche, M. (2022). A thermo-hydro-mechanical approach to soil slope stability under climate change. Geomorphology, 401, 1-7. https://doi.org/10.1016/j.geomorph.2022.108108

Shrestha, S., Shrestha, M., and Babel, M. S. (2016). Modelling the potential impacts of climate change on hydrology and water resources in the Indrawati River Basin, Nepal. Environmental Earth Sciences, 75(4), 280. Available at: https://link.springer.com/article/10.1007/s12665-015-5150-8#citeas

Van den Bout, B., Jetten, V., Keesstra, S., Nachtergaele, J., de Roo, A., and Hessel, R. (2018). OpenLISEM Multi-Hazard Land Surface Process Model. University of Twente.