Asian Journal of Engineering Geology, 2025, Vol. 2 Special Issue, ARC-15 of IAEG, Abstract No.: 272

Extended Abstract **DOI: https://doi.org/10.64862/ajeg.2025.2sp.118.272** **Open Access**

Erosion and Mass Wasting Processes in Post-Wildfire Mountainous Terrains: Impacts and Challenges

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Received: October 5, 2025, Accepted: November 6, 2025

Abstract: Post-wildfire mountainous terrains are prone to erosion, debris flows, shallow landslides, and rockfalls, especially with pre-existing instability events. While it remains challenging to directly attribute all landscape changes to fire alone, wildfires clearly initiate chains of geohazards by amplifying the effects of subsequent rainfall. In fractured rock mass, fire-induced thermal stress accelerates macrocrack development and mechanical weakening, reducing slope stability. In the soil or weathered rock zone, the loss of structure and infiltration capacity due to fire enhances runoff-driven erosion. Burn severity, local geology, and fire recurrence play critical roles, with climate change increasing both frequency and magnitude of these hazards. Despite advances in remote sensing and modeling, field validation and understanding of long-term degradation and recovery remain limited, underscoring the key role of engineering geologists in transdisciplinary hazard assessment and post-fire stabilization plans.

Keywords: ***Post-wildfire, Soil and rock degradation, Burn severity, Climate change.***

Introduction

Vegetation loss, organic combustion, development of water-repellent soil layers, degradation of soil physical and hydraulic properties, and thermal weathering of rock masses rapidly transform the hydrological and mechanical behavior of post-wildfire terrains. The frequency and extent of mass wasting and accelerated erosion in the post-fire period have been found to correlate strongly with site-specific geological conditions (Lainas et al., 2016) and the degree of burn severity (Shakesby, 2011; Kadakci Koca et al., 2024).

Post-fire hazard assessment challenges go beyond the physical impacts on soil and rock. Although recent methodological shifts from conventional field-based monitoring and spectral index analysis to integrated tools like UAV photogrammetry, InSAR, LiDAR, and machine learning (Deligiannakis et al., 2021; Cao et al., 2024), they are not yet embedded in practical guidelines. This gap is compounded by the high spatial variability of burn severity and ground conditions, which hinders accurate prediction of erosion and slope failures. Moreover, the absence of pre-fire baseline data and delayed landscape recovery obscures fire-induced impacts, underscoring the need for transdisciplinary hazard assessments grounded in both innovative technologies and fundamental geomechanical understanding.

Challenges in understanding post-wildfire erosion and mass wasting

One of the primary challenges in post-wildfire mountainous environments is the complex and spatially heterogeneous ground response to fire-induced disturbances, especially in relation to vegetation type, soil/rock properties, and burn severity. This variability complicates the prediction of erosion rates and the initiation mechanisms of mass wasting processes, including shallow landslides, debris flows, and rockfalls. The absence of pre-fire baseline data further complicates efforts to isolate fire-induced impacts from natural background variability. Although remote sensing tools offer wide spatial coverage, they often fail to capture near-surface mechanical weaknesses in real time. Additionally, even low-severity or unburned downslope areas are affected by intense gullying and shallow failures due to runoff from severely burned upper slopes in the catchment (Figure 1).

Figure 1, In the aftermath of wildfires a) shallow failures b) gullies filled with debris in the lower catchment.

Debris flows can persist up to three years post-fire, after which slope movements may evolve into shallow slides (Rengers et al., 2020). Root strength recovery and tree regrowth may take decades in some environments, adding further complexity to post-fire hazard assessment. Importantly, post-fire rockfall hazards are amplified by vegetation loss and thermal weathering, but remain difficult to assess due to uncertainties in location, magnitude, travel path, and persistence

(DeGraff et al., 2015). These observations collectively highlight that both spatial and temporal variability govern the persistence of post-fire erosion and mass wasting hazards, necessitating comprehensive, long-term hazard assessments.

Impacts on soil and rock landscapes

Wildfires have distinct impacts on soil and rock media. In soils and weathered zones of bedrock with loosened grains, fire alters surface conditions, reducing infiltration and increasing overland flow, which intensifies erosion and may trigger debris flows during the first post-fire storm (Thomas et al., 2021). In weathered or fractured rock masses, wildfires accelerate mineral transformations such as calcination and induce mechanical weakening. High temperatures or rapid heating cause thermal expansion, forming new macrocracks, propagating existing fractures, and inducing surface spalling (Sarro et al., 2021; Kadakci Koca, 2025). These thermal effects can result in rockfall or block toppling, either immediately or overtime. Susceptibility is heightened in areas already prone to such processes or where fire recurrence is common.

Future implications and the role of engineering geology

National institutions have their semi-quantitative guidelines for assessing post-fire hazards, mainly focused on debris flows and soil erosion. However, comprehensive frameworks for evaluating slope failures, such as rockfalls and shallow landslides, are still limited, largely due to the lower frequency and uncertainty of such events in relation to fire. With the increasing influence of climate change, reports of post-wildfire slope failures are becoming more frequent. While much of the research has emphasized wildfire-induced soil degradation and vegetation loss, the mechanisms responsible for strength loss in rock mass remain poorly understood. Notably, fire-induced effects such as thermal fatigue, mineral transformation, and fracturing in rock masses are still under-characterized in both field and laboratory contexts. Addressing post-fire erosion and mass wasting in mountainous regions requires a transdisciplinary and multi-temporal approach, prompting policymakers and public agencies to implement structured geohazard assessment protocols. These protocols must support both immediate emergency response and long-term monitoring. Future strategies should integrate high-resolution remote sensing (e.g., InSAR, LiDAR) with geotechnical field validation to improve early detection of unstable slopes. In this context, engineering geologists play a critical role by interpreting surface indicators (e.g., slope failure inventories, hydrological shifts), assessing subsurface lithology and hydraulics, and evaluating the mechanical behavior of soils and rocks. Beyond hazard assessment, they contribute to land use planning, slope stabilization, and the design of resilient infrastructure in fire-prone mountain regions.

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