

Debris Flow Susceptibility in the Jinsha River Basin, China: A Bayesian Assessment Framework Based on Geomorphodynamic Parameters

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Abstract. A major challenge in assessing debris-flow susceptibility at the scale of large mountainous river basins lies in the excessive reliance on simplified topographic metrics. Existing approaches often fail to account for the cascading and dynamically coupled interactions among channel gradient, discharge, and sediment supply. This oversight limits the accuracy and robustness of spatial predictions. To address this gap, we present a novel framework for debris-flow susceptibility assessment grounded in a process-based indicator system derived from geomorphic dynamics, using the Jinsha River Basin as a case study. Our method integrates key parameters that characterize landscape evolution—including stream power, extreme rainfall events, surface erodibility, and sediment connectivity—into a Naïve Bayes probabilistic classification model. By employing kernel functions, we accommodate both continuous and discrete variables, enabling the probabilistic estimation of debris-flow occurrence across small, medium, and large magnitude classes. Model validation across the Jinsha River Basin yields a prediction accuracy of 63%. Notably, empirical testing against the "8·21" Jinyang debris-flow event in 2023 reveals a high degree of spatial agreement between predicted high-risk zones and observed disaster footprints. Feature importance analysis indicates that surface erodibility is the dominant contributor to susceptibility, followed by connectivity, stream power, and extreme precipitation. Approximately 32,000 high-risk gullies (>200 m in length) exhibit a power-law distribution, clustering within a 30 km buffer on both sides of the main stem of the Jinsha and Yalong Rivers in their middle and lower reaches. These regions are shown to be strongly associated with infrequent but high-probability events, which tend to drive large-scale debris-flow disasters. Amid intensifying climate change and the rapid expansion of infrastructure in alpine canyon regions, the dynamic datasets we construct—such as stream power and sediment connectivity—offer a quantitative basis for risk-informed planning and mitigation. This modeling approach represents a scalable and physically grounded paradigm for debris-flow hazard assessment, offering broad applicability to other high-relief mountainous environments worldwide.

Keywords: Debris Flow; Bayesian; Geomorphodynamic Parameters; Jinsha River

1 Introduction

Debris flows in mountainous regions are characterized by active runoff erosion, significant topographic relief, and the interplay of tectonic uplift and river incision (Qiu et al., 2021; Ciccacese et al., 2020; Ye et al., 2023). These flows are triggered by various processes, including shallow landslides, runoff infiltration, channel mobilization, dam failure, and rapid snowmelt (Qiu et al., 2021; Ciccacese et al., 2020; Ye et al., 2023). Due to their high kinetic energy, debris flows pose significant risks to infrastructure, including roads, bridges, and buildings. Globally, debris flow-prone areas are concentrated in the Pacific Rim fold belt, the Alpine-Himalayan fold belt, and mountainous regions in Eurasia (Ye et al., 2023). In China, regions such as the Gongga Mountains, the western Loess Plateau, and the Jinsha River Basin are particularly vulnerable, with the latter contributing significantly to debris flow disasters in the country (Hu et al., 2020).

In recent decades, the ongoing global and regional climate warming has exacerbated the risks associated with debris flows by increasing the frequency of extreme weather events (Lu et al., 2021; Zhao et al., 2021). This highlights the urgent need for research on debris flows. Such research has informed the development of quantitative models, including the power-law relationship between mean intensity and rainfall duration (Coe et al., 2008; Badoux et al., 2009; Oorthuis et al., 2021; Hürlimann et al., 2019; Nikolopoulos et al., 2014), and the linear relationship between surge front velocities and flow depth (Mccoy et al., 2011). These advancements aim to enhance the working principles of monitoring and early warning stations to achieve more accurate debris flow forecasting. However, despite these efforts, debris flow disasters continue to occur, and the role of monitoring stations in regional safety remains limited. From 1999 to 2019, debris flows in China resulted in 4,742 deaths, with an average of 226 deaths per year. In 2010 alone, 2,073 people lost their lives. Notably, on August 7, 2010, a large debris flow in Zhouqu, Gansu, destroyed over 390 buildings (Zhang et al., 2018b); on June 28, 2012, debris flows occurred in ten gullies upstream of the Baihetan hydropower station, including the Aizi gully, resulting in the death or disappearance of 41 people (Hu et al., 2017); and on August 17, 2020, a debris flow occurred in Dayi, Sichuan, blocking a river and causing flooding (An et al., 2022). The uncertainty in the spatiotemporal distribution of extreme precipitation events, combined with insufficient understanding of regional debris flow risk assessment and patterns, has led to the absence of monitoring stations or improper site selection in some high-risk areas, thus limiting the effectiveness of early warning systems (Li et al., 2024).

Currently, numerical simulations based on momentum conservation, mass conservation, and rheological equations are commonly used to model the kinematic characteristics of material flow in debris-flow-prone gullies. These simulations provide key parameters, such as flow velocity and transport volume. However, accurately identifying potential debris flow locations in large-scale areas remains a significant challenge. In the past, there has been a heavy reliance on the direct interpretation of remote sensing images (Yi and Qu, 2018; Lyu et al., 2022; Hu et al., 2017), using abnormal reflectance from surface damage areas after debris flows, such as vegetation, bare soil, and gravel, as indicators. More recently, the

