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A Weak Link in the Chain: A Locally Fragile Lithology Behind an Unusual 2021 Debris Flow in the Lower Fluvial Zone of a Himalayan Catchment

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1. Introduction

Mandakini Catchment, located in the Central Himalayas, is one of the regions with the highest landslide density in India. This catchment lies within the transition zone between glacial (>3000 m) and fluvial (<2000 m) terrain and was the most severely affected during the 2013 North Indian Floods due to the outburst of a glacial lake. While lower fluvial zones are prone to more landslides, debris flows are clustered on steep, upper-catchment slopes (Sekar et al., 2026). So when a debris flow appeared in the lower fluvial reach of the catchment on 13-14 September 2021, at an elevation of 1400 m, a geomorphic setting that rarely produces this failure type, it stood out. The event occurred on agricultural land, bringing sediment into the first-order stream and along its path. This observation raises an important question: were local geological conditions, rather than topography alone, responsible for initiating the debris flow?

2. Field Evidence

Post-debris flow event field observations revealed that the site (30.3916°N , 79.0756°E) lies on a steep tributary slope that connects to the main valley. The exposed rock is interpreted as mica-rich schist exhibiting well-developed foliated surfaces with a visible muscovite/biotite sheen, and localised iron-oxide staining indicative of weathering (Fig 1). The rock mass possessed very low intact strength and disintegrated readily along closely spaced foliation planes, generating abundant angular debris throughout the failure track. The site lies within a regional lithological unit mapped as schistose grit, slate, quartzite, and volcanics. However, the mapping scale does not resolve the local occurrence of highly weathered mica-rich schist observed in the field.

Previous studies have documented that mica-rich schists associated with major tectonic zones, including the Main Central Thrust, commonly exhibit intense fracturing, pervasive foliation, and deep weathering (Anbarasu et al., 2009; Pandey & Sharma, 2022). These foliated discontinuities

provide preferential pathways for water infiltration and reduce shear strength under saturated conditions, making the slope particularly susceptible to rainfall-induced failure.

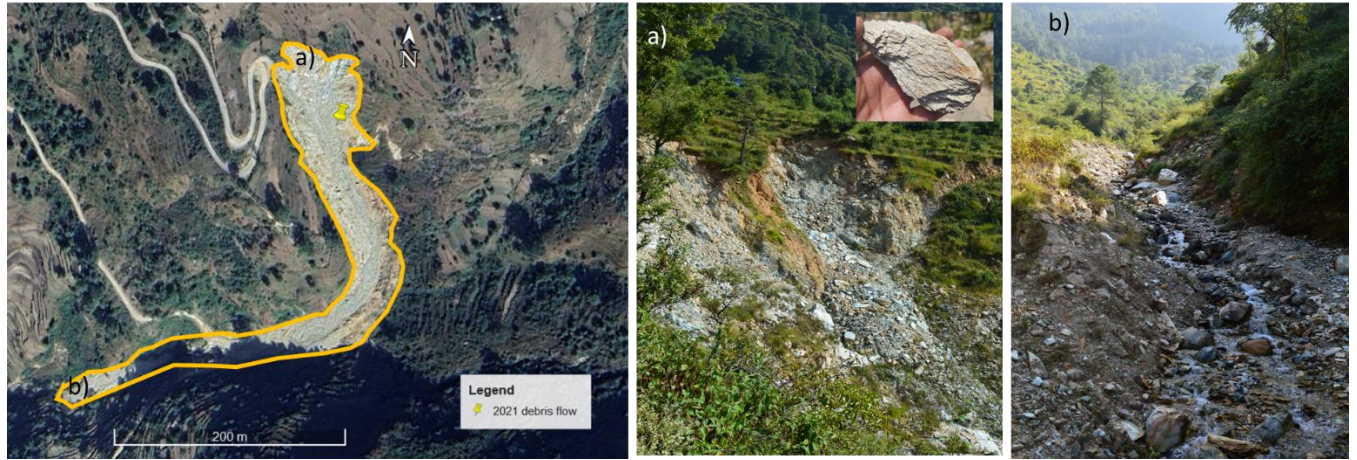


Figure 1. The left panel shows the Google Earth imagery of the 2021 debris flow event: a) Field observation showing the weathered mica-rich schist exposed along the failure scarp, and below that is the hand specimen showing pronounced foliation, platy parting and iron oxide staining; b) debris-filled channel downslope at the toe of the debris flow

3. A Closer Look at the Rainfall Data

To investigate the hydrometeorological conditions preceding the debris flow, rainfall was first examined using ERA5-Land reanalysis data (≈ 11 km spatial resolution). At this scale, the rainfall preceding the event was relatively modest, with no significant meteorological trigger. Hence, a higher resolution rainfall product for the Indian subcontinent was subsequently analysed.

Rainfall extracted from the NCMRWF MERA regional reanalysis (≈ 4 km resolution) revealed an antecedent rainfall pulse from 6 September onward. It was observed that 7 September (58.7 mm), 11 September (42 mm) and 13 September (23 mm) received significant rainfall during the week preceding the debris flow, resulting in a cumulative weekly rainfall of approximately 180 mm (Fig. 2). This also highlights the presence of a localised rainfall event, which was largely smoothed in the ERA5-Land product.

Although the rainfall preceding the failure was considerable, it was not exceptional relative to the rainfall conditions typically associated with debris flow initiation in the lower fluvial zone of the catchment. A regional seismicity check shows a M4.7 earthquake on 11 September, approximately 22 km from the failure site and outside the catchment. Given its distance and the absence of evidence for an immediate slope response, no coincident seismic trigger was identified. The debris

flow occurred two to four days after the major rainfall pulse rather than during the period of maximum daily rainfall, suggesting that antecedent wetting and progressive pore-pressure build-up played a greater role than an instantaneous rainfall peak. Such a lag is consistent with rainfall-induced failures in foliated metamorphic rock masses, where infiltration along discontinuities gradually reduces shear strength (Anbarasu et al., 2009; Pandey & Sharma, 2022).

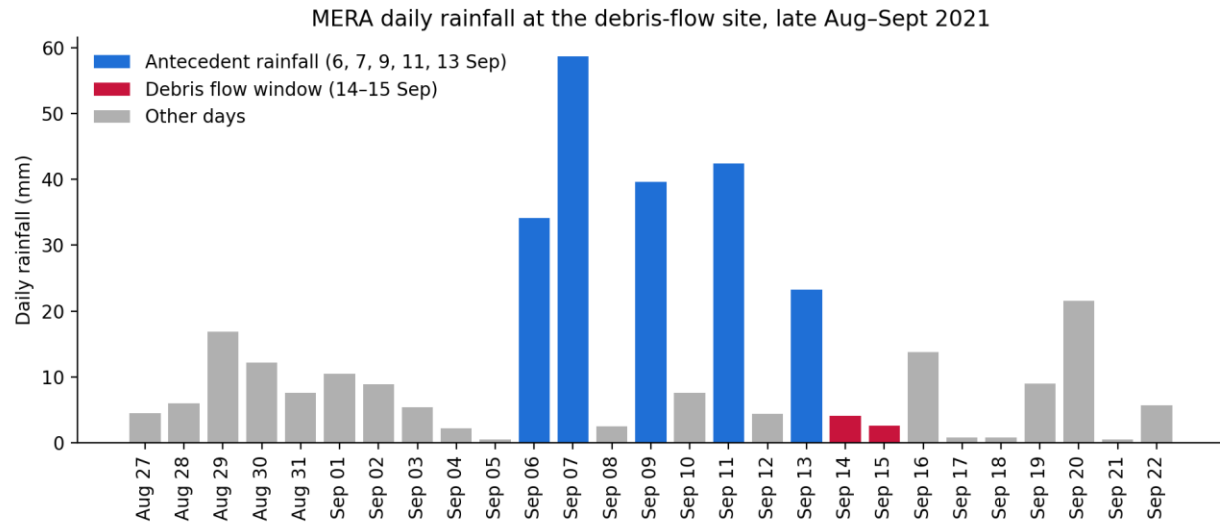


Figure 2. MERA daily rainfall (≈ 4 km resolution) at the debris-flow site, late August–September 2021. The antecedent pulse preceding the 14–15 September failure is highlighted in blue colour by a week.

When considered together with the field observations and rainfall data analysis, the findings suggest that there were two major controlling factors at the failure site: the locally fragile lithology and the rainfall magnitude over the week prior to the event. Additionally, an anthropogenic contribution cannot be ruled out either, as it is located on a terraced agricultural landscape and ill-maintained terraces are a recognised destabilising factor in the mountains (Crosta et al., 2003), though further studies are required to confirm its contribution.

4. Conclusion

A single field visit and a corrected, higher-resolution rainfall analysis together reframe this debris flow: not as an extreme rainfall event, nor as a rainfall-free one, but as a substantial antecedent rainfall pulse acting on a locally fragile, foliated lithology that the regional geological map does not resolve. Also, whether the terraced-land irrigation added a further, compounding influence remains an open question this short visit could not settle. This case study highlights that rainfall



alone cannot fully explain debris-flow initiation in the Himalayas and demonstrates the importance of integrating field geology with meteorological analysis to identify local controls on slope instability.

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