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How Landslides Happen without Heavy Rainfall: Early Strong Runoff Coincides with Weak Geomaterials

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ABSTRACT

Intense rainfall is widely recognized as the primary trigger for landslides and is commonly used in early warning systems. Yet many unexpected failures occur during periods of little or even no rainfall, leading to ineffective warnings and failed evacuations. How landslides occur without heavy rainfall remains unexplored. Integrating field investigations, machine learning, remote sensing, and numerical simulations, we find that landslide disasters without heavy rainfall are

widespread: 75.7% of 1,118 catastrophic cases exhibit delayed onset, controlled by early rainfall, the Topographic Wetness Index, and landslide scale. For the first time, we identify three runoff-supply patterns (slope, gully, and creek supply) and two migration stages (surface and subsurface) that together govern strong runoff supply in confluence zones. Our work contributes an innovative perspective on the coupling mechanism of early strong runoff and weak geomaterials that trigger delayed failures, with 3 subsurface runoff stages—interflow, sliding-face flow, and return flow. These results clarify the hydro-geomaterial coupling behind delayed landslides and support improved early warning and prediction to reduce risk.

INTRODUCTION

Mountains cover ~24% of the Earth's land and host up to 2.289 billion people, many of whom live in landslide-prone terrain (Pepin et al., 2022; Snelthage et al., 2022). Landslides account for >50% of geological disasters annually (Petley, 2012; Shroder et al., 2021), and 3,876 events caused 163,658 deaths globally in the past two decades. In China—among the countries with the highest landslide fatalities—131,320 geological disasters were recorded in 2010–2020, with landslides comprising 70.7%. Notably, these landslides can occur hours to days after peak rainfall or during periods of little to no rainfall, which we term delayed landslides. Driven by tectonics and climate change, landslide risk is increasing (Armstrong et al., 2022; Egholm et al., 2013), and ~150,000 potential landslide sites remain in China (Deng et al., 2023).

Delayed landslides are widely documented across settings and can be highly destructive. The 1987 Val Pola landslide (Italy) occurred 8 days after intense rainfall (27 deaths), and the 2006 Leyte landslide (Philippines) followed 4 days after rainfall (1,110 deaths). In China, representative events include the 2017 Xinmo landslide (~8 days after peak rainfall; 83 killed or missing), the

2020 Hanyuan landslide (~42 h delay; 9 deaths), and the 2018 Baige rockslide (no rainfall on the event day but preceded by heavy rainfall; ~US\$870 million in losses).

Although rainfall correlates with landslide occurrence, the linkage is weak and complex (Rosi et al., 2021). California, for example, shows limited sensitivity of landslide frequency to large interannual rainfall variability (Murphy et al., 2022). Failures often lag rainfall peaks because pore-water pressure rises with delayed infiltration and subsurface redistribution (Vaughan and Walbancke, 1973; Iverson et al., 2015), while susceptibility is conditioned by weak geomaterials (Tian et al., 2020; Bunn et al., 2020). Yet geological context is frequently underemphasized (Zhang, 2018), and for delayed failures, effective water input can be spatially decoupled from the landslide body via runoff/seepage from upslope contributing areas (Berrocal et al., 1978; Priest et al., 2011), hindering prediction. Together, these observations point to antecedent rainfall and a lagged hydrologic response as key drivers of delayed failure (Iverson, 2000; Evans et al., 2007). Consequently, studies that jointly resolve hydrologic forcing and geological controls at regional to national scales remain scarce.

These gaps highlight the need to better constrain why and when delayed landslides occur. Long delays and large failures are particularly challenging to explain and forecast from event-time local rainfall (Chen et al., 2023; Kostić et al., 2023). We hypothesize that antecedent rainfall can generate strong runoff and seepage that migrate spatially, elevating pore-water pressure within weak geomaterials and triggering failure after rainfall peaks.

We assemble a delayed-landslide database spanning China's diverse tectonic and climatic settings to address three questions: How common are delayed landslides, what causes the delay, and what mechanisms govern it? We show how spatial runoff transfer produces temporal failure delays, laying theoretical and technical foundations for disaster-risk reduction.

MATERIALS AND METHODS

This study examines delayed landslides across China by integrating spatiotemporal analysis, field surveys, hydrologic modeling, and slope-stability simulations. We compiled 1,118 fatal landslides (1984–2021) from national databases, including timing, location, scale, and casualties, and matched each site to daily data from >2,400 meteorological stations via the Baidu Maps API. Landslides were classified using the updated Varnes criteria and evaluated for delay relative to peak rainfall, defined by intensity–duration thresholds from 29 regions ([Text S1](#)).

Landslides that occurred after peak rainfall were considered delayed. Delay time is defined as the elapsed time between the peak rainfall day and landslide occurrence ([Text S2](#)); the peak day is identified using regional I–D thresholds or, if not exceeded, the maximum daily rainfall within the preceding 30 days. To model controls on delay, we applied ensemble learning techniques.

Ten representative cases spanning elevation, scale, geomaterials, failure mechanisms, and climates were selected ([Table S1](#)). Field work and high-resolution imagery with a Digital Surface Model delineated geomorphology and confluence zones, from which three upstream runoff-supply patterns were identified. For hydrology, we applied the Soil Conservation Service Curve Number (SCS-CN) method (interception/infiltration losses; evapotranspiration neglected), Giandotti and Tournon concentration-time formulas, and an SCS unit hydrograph. Then, coupled MIKE SHE–SEEP/W–SLOPE/W simulations for BG, BL, and CHM reproduce infiltration, pore-pressure buildup, and associated factor-of-safety reduction in weak geomaterials. Here, weak geomaterials comprise three types: bedrock–regolith interface weak zones (CHM), bedding-related weak horizons in coal-bearing strata (BL), and densely fractured, highly weathered rock masses with joint-controlled weak planes (BG). Full methodological details are provided in the [Text S3–S7](#).

RESULTS

Antecedent rainfall and upstream runoff drive delayed landslide activation in 75.7% of post-peak precipitation events

Our analysis of 1,118 landslide cases with reported casualties in China from 1984 to 2021 revealed that 75.7% of rainfall-induced fatal landslides occurred at least 3 hours after peak rainfall, exhibiting delayed onset characteristics (Fig. 1a). Among these delayed cases, 32.0% occurred on days without rainfall (accumulative daily rainfall ≤ 0.1 mm). Specifically, 41.2% occurred 1-3 days after peak rainfall, 30.85% within 4-7 days, and 28.12% more than 7 days after peak rainfall (Fig. 1b). This distribution emphasizes the extended time frame in which rainfall can trigger landslides. In summary, rainfall-induced landslides exhibited a broad range of delays compared to peak rainfall, spanning from hours to weeks, with the majority occurring within one week.

Based on delay durations, landslides can be categorized into long-term delayed landslides (8–30 days), medium-term delayed landslides (4–7 days) and short-term delayed landslides (3 hours–3 days). As illustrated in Fig. 1c, the results indicate that rainfall, topographic wetness index (TWI), and landslide volume are the three primary factors influencing the spatiotemporal distribution of delayed initiation, with average importance scores of 22.3%, 17.1%, and 15.2%, respectively (Figs. S4–S6). Rainfall, as the most direct triggering factor, significantly impacts landslide stability by regulating the soil moisture content of the slope. Areas with higher TWI values exhibit stronger runoff accumulation capabilities, reflecting the combined effect of local slope and upstream drainage area. Landslide volume reflects the larger landslide area and depth, which may typically contribute to a broader confluence area.

The spatial migration of surface runoff triggers delayed landslides without heavy rainfall

Based on the 10 typical delayed landslide cases, we identified three primary patterns of upstream runoff concentration (Fig. 2a): i) slope supply (small-scale hollow-soil runoff supply); ii) gully supply (medium-scale dissected-gully runoff supply); iii) creek supply (large-scale watershed-concentrated runoff supply). Additionally, runoff supply can be categorized into two main components: fast surface runoff and slower subsurface runoff (Fig. 2b).

In the case of slope supply, the spatial migration of runoff occurs over short distances, which is associated with relatively short delays in landslide initiation. For instance, the small-scale catchment areas of the CHM, YBD, and QJB landslides are 0.49 km², 0.13 km², and 0.01 km², respectively. The average planar distance from the upper catchment to the landslides is 0.248 km, with an average delayed time of 15.9 hours. The average surface runoff transfer time is only 0.25 hours, corresponding to relatively short initiation delays for these landslides.

For gully supply, the spatial migration of runoff occurs over longer distances compared to the previous case, resulting in moderate delays in landslide initiation. For example, the average catchment area of the dissected gully in the BL, JKH, DG, and HY landslides is 0.86 km², with an average runoff migration distance of 1.105 km. The average delay in initiation for these four landslides is 65.5 hours. Thus, the moderate spatial migration of runoff in medium-scale catchments on dissected gully leads to a corresponding moderate delay in landslide initiation.

In contrast, creek supply induces large-scale, long-distance spatial migration, resulting in prolonged delays in landslide initiation. For example, the average catchment area of the cross-watershed concentration regions in the BG, XM, and ZBS landslides is 8.22 km², with an average runoff migration distance of 2.98 km. The average delayed initiation time for these three landslides is 164.3 hours. Therefore, the long-distance spatial migration of runoff in large-scale, cross-watershed catchments leads to extended delays in landslide initiation.

Overall, spatial runoff transfer at different scales results in varying delay times, causing disasters from delayed landslides even without heavy rainfall, with different initiation durations.

Early three-step process of water-geomaterial interaction triggering delayed landslides

Simulations of three representative cases reveal a three-stage water-geomaterial interaction process (Fig. 3) that drives delayed landslide initiation: interflow (Q1), sliding-face flow (Q2), and return flow (Q3). These stages correspond to three failure modes based on different water-supply dynamics and material responses.

For small-sized soil landslides, the combination of strong Q1 and moderate Q2 leads to failure. During intense rainfall, Q1 increases pore water pressure (PWP), reducing soil resistance. After rainfall, Q2 further weakens the slope. In the CHM landslide, the rainfall peaked at 8 mm/h at 9:30 PM. Simulations show Q1 reached 9000 m³/h, raising PWP at mid-slope (Point B) by 71.4%, reducing the safety factor from 1.7 to 1.4. Post-rainfall, sliding-face peaked at 3000 m³/h at 12:30 AM. At slope foot Point C, PWP dropped by 28.9%, and the safety factor fell to 0.96 by 1:00 AM, leading to failure.

For large-scale soil landslides, an initial surge in Q2 followed by sustained Q3 drives instability. Heavy rainfall sharply increases Q2, weakening soil strength. Continued flow leads to Q3 development, ultimately triggering failure. In the BL landslide, a daily rainfall of 56 mm on July 5 led to a peak sliding face flow of 2600 m³/2h. Over the following four days, PWP at Point B rose by 36.7%, and the safety factor dropped from 1.28 to 1.15. Q3 developed by July 9, peaking at 800 m³/2h on July 19—the landslide day. At Point C, PWP rose from -11.4 kPa to 18.3 kPa, and the safety factor decreased to 0.96, causing slope collapse.

For rock landslides, a consistent Q2 and strong Q3 jointly cause failure. In weak rock zones, early stable Q2 creates low-strength rock-soil conditions. Sustained flow boosts Q3, gradually reducing rock strength. In the BG case, early Q2 was stable at 2000 m³/4h. With a cumulative rainfall of 46 mm from September 9–15, Q2 increased to 2,600 m³/4h, raising PWP at Point B by 29.3% and reducing the safety factor to 1.13. Continued recharge pushed Q3 to 3800 m³/4h by the landslide day, dropping the safety factor to 0.98 and causing failure.

DISCUSSION

We first assess the broader relevance of delayed landslides through spatial patterns. Although our analysis centers on China, whose tectonics include extensive fault zones, and fold belts (Cai et al., 2022; Ding et al., 2022), our 1,118 cases span diverse landforms and climates, providing a useful basis for comparison.

Moreover, our results also advance public understanding, identification, and early warning. First, contrary to common messaging that the occurrence of landslide requires heavy rain, we show failures can occur during periods of little to no rainfall. Second, beyond surface deformation indicators (Casagli et al., 2023; Leinauer et al., 2023), explicitly considering runoff-supply patterns within the mechanism whereby early strong runoff coincides with weak geomaterials enhances the detection of concealed hazards, because effective water input may be spatially decoupled from the landslide body. For operational use, runoff-supply patterns can be classified by the size and channelization of the upslope contributing area outside the landslide body (see Text S8 for definitions and classification criteria); however, more refined and globally transferable classification schemes remain an important target for future work. Third, delayed landslides differ mechanistically from rainfall-threshold and coseismic failures: lagged subsurface redistribution

(Iverson, 2000; Paronuzzi and Bolla, 2023) and, often, runoff/seepage supply from contributing areas beyond the landslide body that can elevate deep pore pressure after rainfall peaks, rather than near-synchronous shallow pore-pressure responses or transient dynamic loading (Baum et al., 2010; Bontemps et al., 2020; Keefer, 1984). Accordingly, early-warning logic should extend beyond rainfall thresholds by explicitly accounting for upslope runoff supply and monitoring time-lagged slope responses, including deformation/acceleration and anomalies in spring discharge (e.g., sudden increase or drying).

Looking ahead, this China-focused study of rainfall-induced delayed landslides can catalyze research across other landslide types and regions. Nonetheless, key gaps remain in constraining microscale processes and developing transferable, practice-oriented quantitative criteria and warning thresholds. Addressing these gaps will require hydrological tracing, higher-frequency rainfall–runoff observations, and in situ pore-pressure monitoring.

CONCLUSION

Delayed landslides can occur out of phase with local rainfall peaks because externally supplied runoff and seepage raise pore-water pressure within weak geomaterials after rainfall. Across China, prevalence patterns, representative-case hydrology, and coupled slope-stability simulations indicate that spatial runoff transfer governs this lag, underscoring early-warning strategies that integrate runoff-supply context and deformation signals rather than rainfall thresholds alone.

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FIGURE CAPTIONS

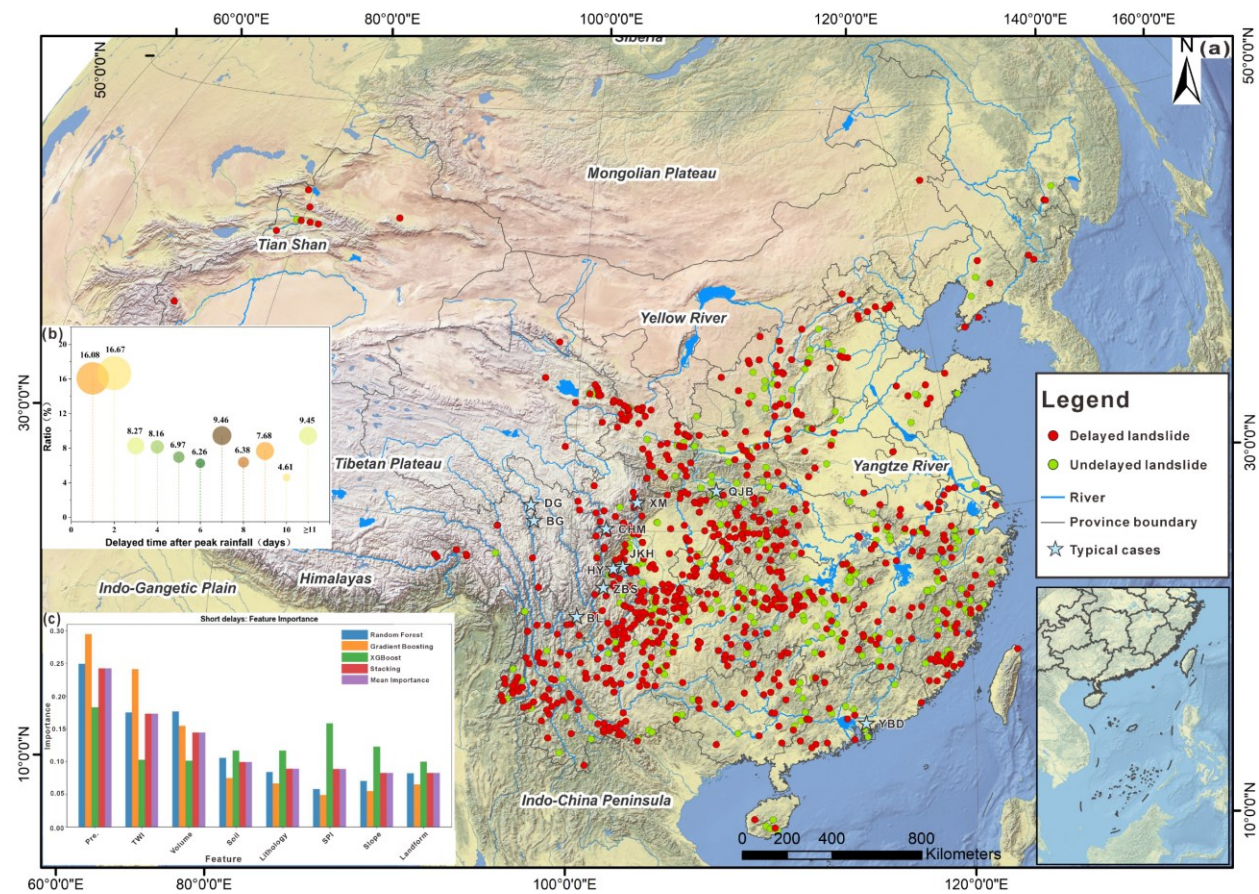
Figure 1. Spatiotemporal distribution and delay characteristics of 1,118 fatal landslides in China since 1984. (a) Spatial distribution of all landslides; cases with delayed initiation relative to peak rainfall are highlighted by solid red dots (75.7% of the total). **(b)** Proportions of landslides

with different delay times. **(c)** Factor importance for short-lag delayed landslides (41% of delayed cases). The detailed information of the 10 representative landslides is listed in [Table S1](#).

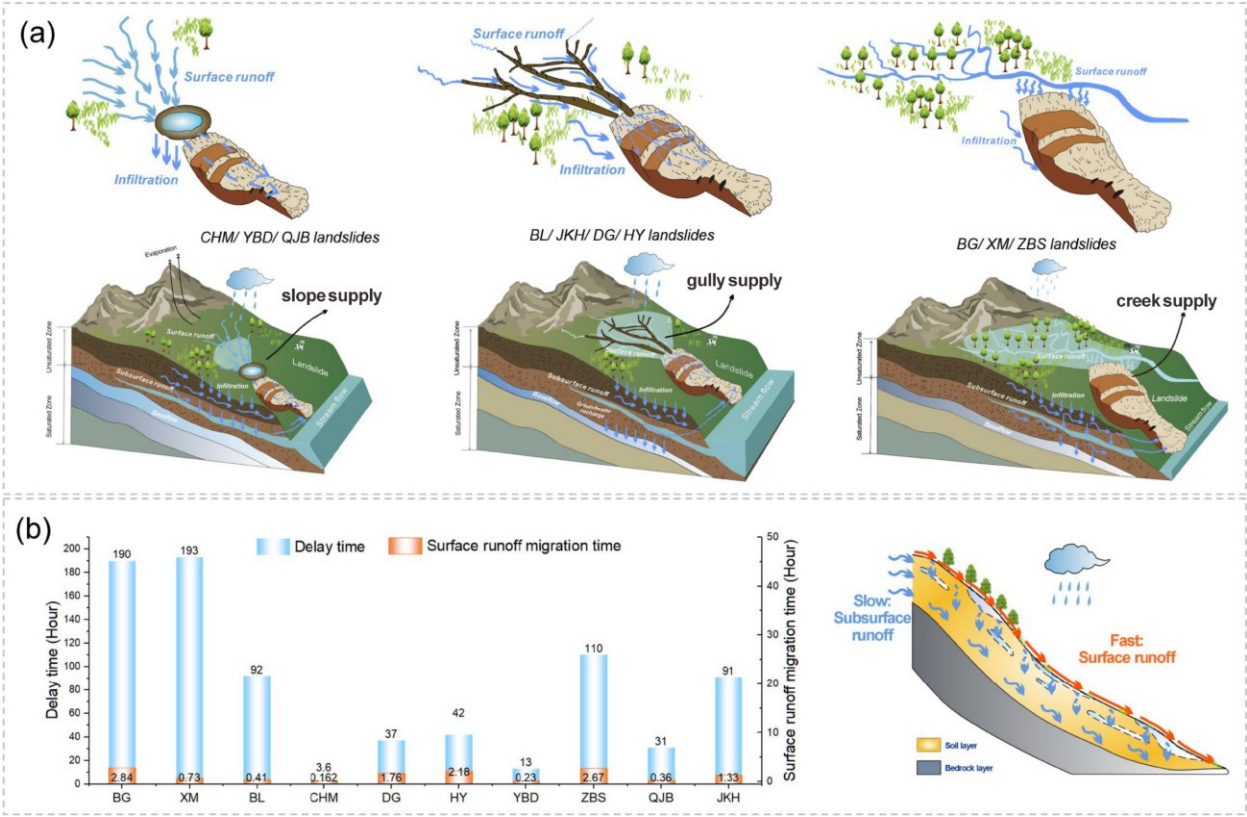
Figure 2. Runoff-supply patterns, corresponding cases, and hydrologic calculations. **(a)** Three upstream runoff-supply patterns: slope supply (backslope runoff/rills; CHM, 2020), gully supply (gullies/incised channels; BL, 2018), and creek supply (perennial channels; BG, 2018). and creek supply (perennial channels; BG, 2018). **(b)** Conceptual schematic of surface vs. subsurface runoff for the 10 cases, highlighting subsurface contributions to delay.

Figure 3. Soil–water coupling and hydrological stages driving delayed landslide instability under three runoff-supply patterns. Panels show profiles, runoff supply, and simulated factor-of-safety evolution for **(a)** CHM (colluvium in a hollow along a weak bedrock–regolith interface), **(b)** BL (reactivated deposit over weak coal-bearing sandstone–mudstone bedding), and **(c)** BG (weathered serpentinite in a densely fractured zone with joint-controlled weak planes). **(d)** Schematic of the three runoff-supply patterns; Q1–Q3 denote interflow, sliding-face flow, and return flow, respectively.

315 Figure 1



318 Figure 2



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