

Disaster Patterns and Quantitative Risk Research of Dam-break Debris Flows in High-mountain and Steep-gorge Regions: A Case Study of the Yizhong River Basin in Deqin, Yunnan

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Disaster Patterns and Quantitative Risk Research of Dam-break Debris Flows in High-mountain and Steep-gorge Regions: A Case Study of the Yizhong River Basin in Deqin, Yunnan

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Abstract

In high-mountain and steep-gorge regions, traditional hydrological methods often significantly underestimate the peak discharge of dam-break debris flows by neglecting complex chain-like evolutionary processes. This study focuses on the Yizhong River in Deqin, Yunnan, emphasizing its typical "landslide-blockage-dam-break" dynamic disaster chain. By integrating a physical model of gradual breaching with Massflow dynamic simulations, a quantitative investigation of the entire process was conducted under extreme rainfall events (0.5% and 1% frequencies). The results indicate that the strong confinement of the V-shaped gully in the Yizhong River generates a pronounced "funnel effect," leading to intense kinetic energy conversion at the moment of breaching. Numerical simulations show that under the 0.5% extreme rainfall scenario, the

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instantaneous peak discharge at the breaching point reaches $927.2\text{m}^3/\text{s}$, which is 15.3% higher than the $804.2\text{m}^3/\text{s}$ calculated via traditional hydrological theory. Accordingly, a dynamic amplification factor ($\alpha = 1.15$) is defined, revealing the nonlinear evolutionary law of the fluid from potential energy storage to a kinetic energy surge. This study suggests that for high-energy dam-break debris flows, engineering design should shift from the traditional "static gravitational interception" paradigm to "dynamic kinetic energy dissipation," providing a quantitative reference for disaster prevention in similar high-altitude canyon areas of Southeastern Tibet.

Keywords: Rainfall, Debris flow, Dam-break, Massflow, Risk assessment

0. Introduction

China is among the countries most severely affected by debris flow disasters worldwide, with an affected area reaching 4.3 million km^2 , characterized by high frequency and devastating destructive power. Particularly in high-mountain and steep-gorge regions, catastrophic debris flows with immense initial kinetic energy often trigger multi-level secondary disasters, forming complex hazard chains. These events not only result in significant mass casualties but also pose a severe threat to regional infrastructure and property (Zhang et al. 2018). Specifically, dam-break debris flows triggered by short-term intense rainfall exhibit intensities far exceeding those of ordinary debris flows, leading to even greater destruction (Liu et al. 2010).

Notable historical cases illustrate this severity: (i) On April 9, 2000, a massive rockfall-landslide occurred in the Zhamunong Gully of the Yigong Tsangpo, Tibet. The resulting barrier dam blocked the Yigong Lake, and the subsequent breaching generated a peak discharge of $12.1 \times 10^4 \text{m}^3/\text{s}$, completely destroying roads along both riverbanks (Lu et al. 2000; Li et al. 2017). (ii) On August 8, 2010, extreme rainfall in Zhouqu, Gansu, triggered catastrophic debris flows that blocked the Bailong River, raising the water level by 10 m and submerging nearly one-third of the county urban area (Li et al. 2024; Wang et al. 2023). (iii) On August 14, 2010, the Hongchun Gully in Yingxiu, Wenchuan, experienced a rainfall-triggered debris flow that completely blocked the Minjiang River, causing the surging river to divert into the town and affecting over 8,000 people (Li et al. 2012; Tang et al. 2011).

To better mitigate the potential threats of debris flows, numerical simulation techniques are

commonly employed to predict outcomes under various extreme scenarios. Currently, mainstream debris flow simulation methods include Dynamic Analysis of Landslides in Three Dimensions (DAN-3D) ([Hungr 1995](#)), Smoothed Particle Hydrodynamics (SPH) ([Hungr 2008](#); [Sassa et al. 2010](#)), and Rapid Mass Movement Simulation (RAMMS) ([Christen et al. 2010](#)). These methods effectively reveal the dynamic evolution and hazard response areas of debris flows from initiation to deposition. In contrast to the aforementioned methods, this study utilizes the Massflow software, which is based on a depth-integrated continuum mechanics model. Massflow offers higher computational efficiency and superior capability in simulating the landslide-to-debris flow transformation within a hazard chain. Furthermore, it enables real-time simulation of the spatiotemporal evolution of diverse surface processes ([Ouyang et al. 2013](#); [Iverson and Ouyang 2015](#)).

Current research on debris flow hazards in the Yizhong River basin often focuses on triggering mechanisms and dynamic erosion during flow processes([Table 1](#)). However, integrating regional rainfall data reveals a complex superposition effect between continuous antecedent rainfall, which recharges soil moisture saturation, and sudden short-duration intense rainfall. This effect not only exacerbates the dynamic erosion of the gully but also diversifies the resulting disaster patterns. To address these challenges, this study utilizes field investigation reports, UAV-based aerial photogrammetry modeling, rainfall data analysis, and Massflow numerical simulations to perform a full-process simulation of debris flow blockage and dam-break under extreme rainfall scenarios in the Yizhong River area. The simulation results facilitate a comparative analysis of peak discharges between dam-break debris flows and ordinary torrential debris flows under different rainfall scenarios. Furthermore, based on the discrepancy between theoretical hydrological calculations and simulation results, a dynamic amplification factor (α) is proposed. This factor provides essential theoretical support for assessing the risks associated with debris flow blockage and Dam-break in high-mountain and steep-gorge regions.

Table 1 Previous researchs on the Yizhong River debris flow

Research Theme	Conclusion	Author
Formation Mechanism	Systematically reviewed disaster history; identified "viscous gully-type"	(Wang 2016)

	characteristics; proposed engineering	
	solutions based on "interception +	
	drainage."	
Source Accumulation	Reveal the periodic correlation between	(Chen et al. 2022)
	surface deformation and soil moisture	
	Quantitatively simulated debris flow	
Disaster Characteristics	intensity for different return periods;	(Song et al. 2024)
	delineated hazard zones to provide	
	quantitative data for disaster prevention	

79 **1. Study Area**

80 The Yizhong River is located in Shengping Town, Deqin County, Yunnan Province, situated in the

81 longitudinal gorge zone of the Hengduan Mountains, exhibiting a typical high-mountain and

82 steep-gorge topography. The county features a well-developed river system, with the Yizhong

83 River serving as a first-order tributary of the Zhiqu River (Fig. 1). Influenced by Quaternary glacial

84 erosion, the Yizhong River basin presents a classic "V-shaped" glacial trough morphology. The

85 basin is characterized by dramatic topographic relief, with elevations rising from the base level at

86 the river mouth to 4,540 m at the summit, resulting in a total relief of approximately 1,474 m.

87 Within the main channel, which spans only 2,030 m in length, this extreme elevation gradient

88 provides a robust dynamic foundation for the instantaneous initiation and high-speed evolution of

89 debris flows. The bank slopes range between 30° and 80°, with an average longitudinal gradient of

90 765.70%. Due to the shearing effects of adjacent active fault zones, the upstream rock masses are

91 highly fragmented, with well-developed rockfall and landslides in exposed areas. These source

92 materials distributed along both sides of the gully provide a continuous supply of material for

93 debris flow activities. Spatially, the Yizhong River basin demonstrates significant vertical zonation

94 characteristics. In the source area above 3,900 m, the terrain is extremely rugged, where a steep

95 longitudinal gradient of 914% offers substantial potential-to-kinetic energy conversion space for

96 initial fluid acceleration. In the transportation and replenishment zone (3,300 m to 3,900 m),

97 intense lateral erosion and downcutting by the fluid lead to the influx of large volumes of source

materials from the gully banks, significantly expanding the scale of the debris flow. Upon reaching the accumulation zone below 3,300 m, although the gradient decreases to 293‰ and the channel adopts a stepped terrace morphology, extreme debris flows can still breach existing disaster prevention facilities under extreme rainfall conditions, directly impacting National Highway G214 and the residential areas of Deqin County, exhibiting formidable long-runout dynamic hazard characteristics (Fig. 2 and Fig. 3).

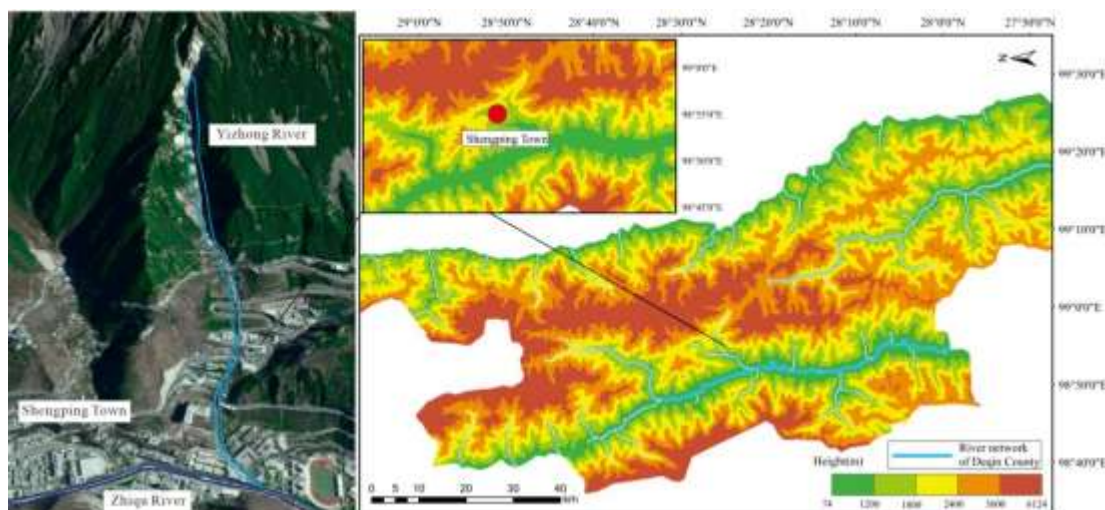


Fig. 1 Overview of the study area



Fig. 2 (a): Overview from the Yizhong River gully to Shenping Town; (b): Large amount of rockfall accumulation within the channel; (c): Impact of the debris flow outbreak on the G214 Road; (d): Scouring of a culvert in Shenping Town caused by the debris flow.

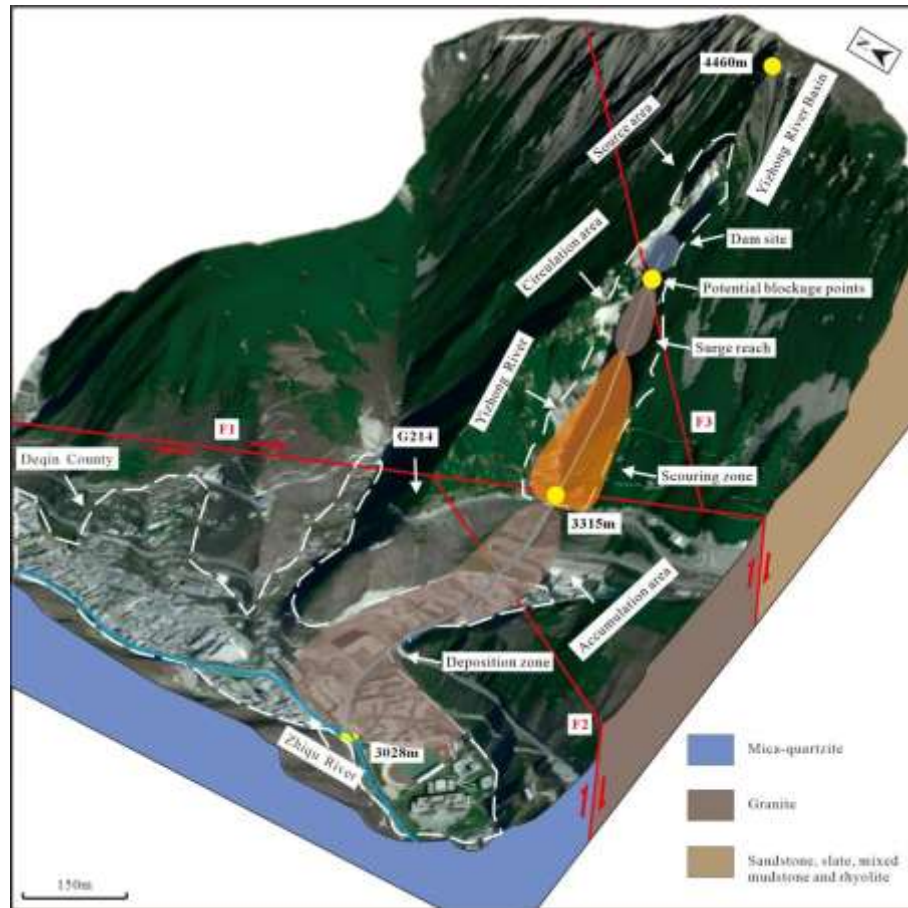


Fig. 3 3D Map of Deqin County Landform

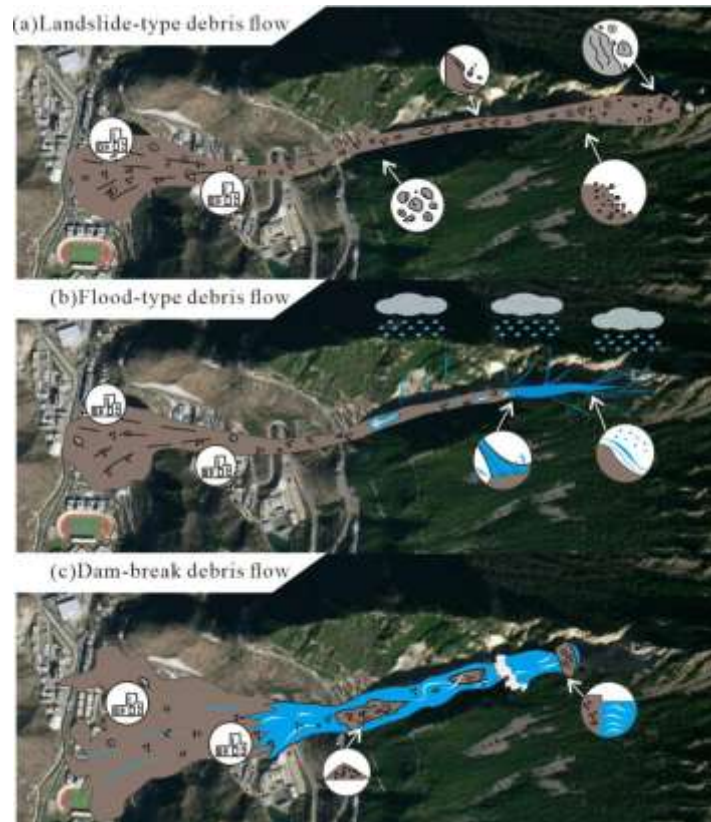
2. Regional chain-like disaster mechanism of debris flows

2.1 Disaster mechanism of debris flows

A geohazard chain is defined as a combination of two or more types of disasters within a geological environment that exhibit significant spatiotemporal evolutionary correlations (Li et al. 2008). This chain effect reveals the dynamic process by which a single disaster induces secondary hazards at specific stages of evolution. Complex topographic conditions and fragile geological structures constitute the hazard-prone foundation of the Yizhong River basin, while extreme rainfall serves as the core driving force triggering the "heavy rain-landslide-debris flow" hazard chain evolution.

In the Yizhong River area of Deqin, three primary debris flow hazards coexist: landslide-induced debris flows, torrential debris flows, and dam-break debris flows. These three hazard modes do not exist in isolation; instead, they demonstrate complex coupling relationships under the triggers

124 of extreme geological environments and climatic conditions(Fig. 4).



125

126 **Fig. 4** Three primary disaster mechanisms of debris flows are identified in the study area: (a) landslide-induced
127 debris flows triggered by high-position rock mass collapse; (b) torrential debris flows formed by short-term intense
128 rainfall that generates substantial surface runoff, which subsequently entrains source materials upon entering the
129 channel; and (c) dam-break debris flows initiated by the breaching of barrier dams that are formed when excessive
130 accumulation blocks the gully.

131 2.2 Conditions for hazard chain formation

132 (i) Abundant source material for debris flows. As shown in Fig. 5, the F1, F2, and F3 faults cross
133 and penetrate the upstream, midstream, and downstream sections of the Yizhong River basin,
134 respectively, forming a complex geological structure. Influenced by intense tectonic shearing and
135 stress concentration, rock masses such as shale, slate, and rhyolite, which are widely exposed in
136 the basin, are extremely fragmented. The thickness of the completely-to-highly weathered zone is
137 substantial, reaching several meters in some areas. These fragmented rock masses have produced a
138 large volume of fine-grained interstitial fillers through intense physical weathering. Together with
139 extensively developed fractures, this significantly reduces the overall stability of the rock and soil

masses. Furthermore, due to the steep gully bank slopes and steep longitudinal gradients, mountain floods—with their strong scouring and entrainment capabilities—exert intense erosion on the toe zones of the bank slopes. This results in the high development of adverse physical geological phenomena, such as landslides and rockfalls of the bank slope materials, providing abundant source conditions for debris flow outbreaks (Table 2).

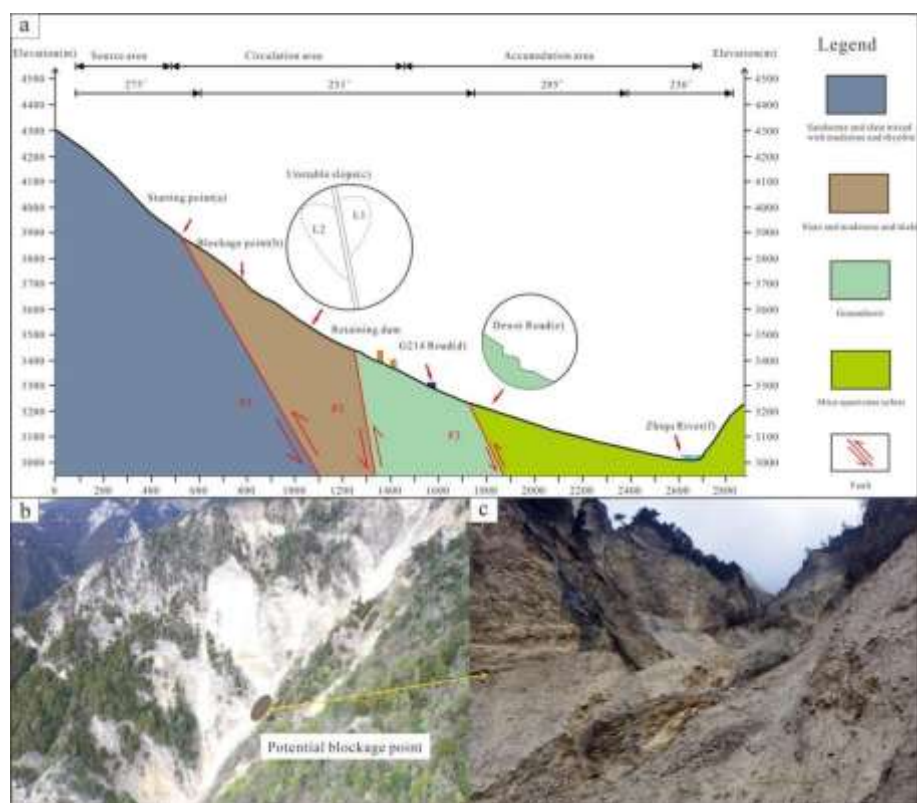


Fig. 5 (a):Cross-section profile of the Yizhong River gully and locations of monitoring points;(b):Locations of potential blockage points along the gully;(c):Photograph of the gully with shallow accumulation.

Table 2. Statistical Table of Major Solids Source Areas in the Yizhong River

Source type	Landslide	Collapse	Active gully flushing	Spalling zone	Gully bank collapse	Ice accumulati on layer	Slope erosion area	Total
Area (10^4m^2)	2.2			18.5	1.25	0.50	2.20	24.65
Volume (10^4m^3)	15.5	0.22	0.5	16.5	1.8	2.0	1.98	38.50
Removable volume (10^4m^3)	3.1	0.22	0.5	0.55	0.9	2.0	0.066	7.34
Maximum displaceme	0.31	0.17	0.15	0.44	0.18	0.20	0.033	1.48

nt at one
time
(10^4m^3)

(ii) Concentrated rainfall. According to the multi-year rainfall monitoring data from 2017 to 2021 in the Yizhong River basin, the average annual precipitation in recent years is 526.8 mm. The period from May to October represents the concentrated rainfall season, with precipitation accounting for approximately 76.3% of the total annual rainfall. Debris flow activities are primarily concentrated between June and September each year (Fig. 6). Continuous infiltration from this long-duration seasonal rainfall causes the pore water pressure within the slope soil to rise steadily, keeping a large volume of loose material in a critical state of saturation and extreme instability. To accurately reconstruct the triggering mechanism under extreme conditions, this study introduces a 2-hour short-duration intense rainfall model based on the Chicago Design Storm (Liao et al. 2019). The key peak-position coefficient was determined to be 0.2334 through fitting measured data from field rainfall stations in the study area. This extreme value reflects a significantly advanced rainfall peak, characteristic of a typical advanced-peak hyetograph. Under such extreme rainfall patterns, the peak intensity is reached shortly after the onset of rainfall. The violent instantaneous precipitation rapidly transforms into powerful surface runoff, generating fierce hydraulic scouring. This causes the source materials, already near the edge of saturation, to undergo instantaneous liquefaction and instability, triggering large-scale shallow landslides (Guan et al. 2023; Yu et al. 2024). During high-speed transport, the landslide mass rapidly mixes with the runoff, completing the transformation from a solid state to a solid-liquid two-phase flow, thereby activating highly destructive landslide-induced debris flows. Records of high-frequency disaster outbreaks in this basin in recent years confirm that such extreme antecedent rainfall-driven excitation is the core factor for the rapid initiation of the "heavy rain-landslide-debris flow" hazard chain in this region.

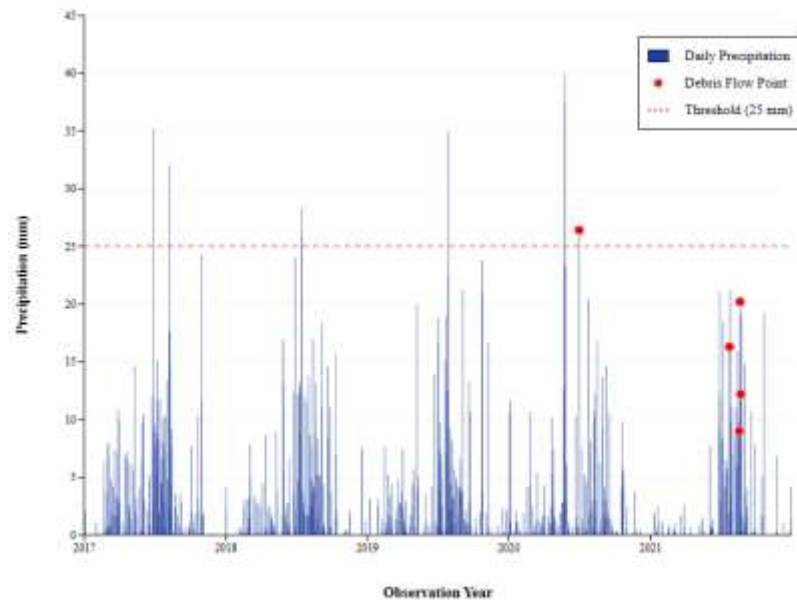


Fig. 6 Daily rainfall monitoring data from 2017 to 2021 (data provided by the China Geological Environment Monitoring Institute)

(iii) High risk of channel blockage due to topographic structures. The tributary of the Yizhong River exhibits a near-perpendicular intersection with the main channel, characterized by an extremely narrow cross-section and steep bed gradients in the confluence area. When high-position unstable slopes, triggered by short-duration intense rainfall, form large-scale debris flows that rapidly converge into the gully, the confinement of the narrow and deep channel, combined with surface runoff, causes coarse particles and boulders within the debris flow to collide continuously. This leads to energy dissipation and siltation within the gully, forming significant barrier dams. Such unique topographic structures not only restrict the flow space but also greatly increase the risk of channel blockage. This, in turn, induces a rapid rise in the gully water level, eventually evolving into a breaching event that releases catastrophic mountain floods (Chen et al. 2024).

3. Peak discharge for blockage-Dam-break and simulation

parameters

3.1 Peak discharge for blockage-Dam-break

The calculation of peak discharge for debris flow barrier dam breaching primarily draws upon the

dynamics system of reservoir dam-break. The unsteady flow partial differential equations proposed by Saint-Venant in 1871 established the theoretical foundation for quantitative analysis in this field (Herrmann 1976). Building on this, Xie made systematic contributions to various breaching scenarios. For instantaneous total breaching, he derived the peak discharge formula at the dam site by combining analytical solutions of continuous and discontinuous waves. For gradual breaching modes, he proposed an approximate solution for peak discharge by coupling the principle of equal wave and inflow rates with empirical formulas for breach erosion (Xie 1990). To construct the dynamic model, this study adopts the simplified calculation method proposed by Zhang, which includes three core assumptions: (i) Given the extremely short duration of the blockage and dam-break, the hydrograph is simplified into a linear distribution (Fig. 7); (ii) It is assumed that no seepage occurs within the dam body prior to breaching, and overflow is driven solely by upstream inflow; (iii) It is assumed that the time to reach peak discharge is one-third of the total dam-break duration (Zhang 2018). This simplified model, used in conjunction with classical theories, provides a critical benchmark for validating the numerical simulation parameters in this paper.

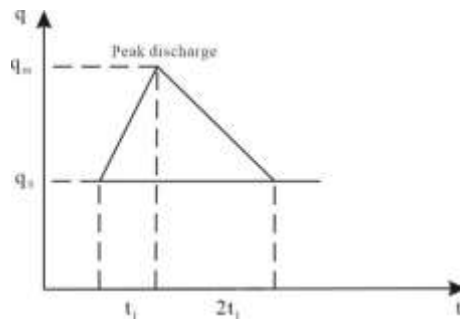


Fig. 7 Discharge hydrograph of debris flow during the breach process(Modified from Zhang 2018)

The total volume of the dam body is calculated based on the gully morphology and the dam height:

$$W = \frac{H_0^2 B}{2I} \quad (3-1)$$

B is the gully width at the blockage point (m); H_0 is the height of the dam body (m); I is the longitudinal gradient of the gully at the blockage point.

The total inflow volume is calculated based on the upstream debris flow discharge and the total

duration of the dam-break process:

$$W_{IN} = 3q_0 t_1 \quad (3-2)$$

The total outflow volume can be calculated using a simplified hydrograph:

$$W_{ALL} = \frac{(q_0 + q_m) \cdot t_1}{2} + \frac{(q_0 + q_m) \cdot 2t_1}{2} \quad (3-3)$$

Since the total outflow volume equals the sum of the dam body volume and the total inflow volume, the following relationship can be obtained:

$$q_m = q_0 + \frac{H_0^2 B}{3It_1} \quad (3-4)$$

To determine the duration of the breaching process t_1 , the formula for gradual breaching without resistance on a sloping bed is introduced (Xie 1993):

$$q_1 = \frac{1 - \left\{ 1 - \left[1 - (1 - \beta_m)^n \right]^{\frac{1}{t}} \right\}^{\frac{1}{n}}}{1 - \beta_m^n} q_m \quad (3-5)$$

$$t_1 = -\frac{E}{\lambda \sqrt{g\rho}} \ln \left[1 - (1 - \beta_m)^n \right] \quad (3-6)$$

$$\beta_m = \left(1 - \frac{Eb_m}{\rho W} \right)^{\frac{1}{n}} \quad (3-7)$$

$$b_m = \frac{WKH_0}{3E} \quad (3-8)$$

$$K = \varphi W^{-0.577} \quad (3-9)$$

$$\rho = KH_0 \quad (3-10)$$

E is the cross-sectional area per unit length (m^2); ρ is the average volumetric sediment concentration percentage; λ is the discharge parameter (obtained as 0.3 from reference tables); n is the storage capacity exponent (typically taken as 1.5); β_m is the water depth at the dam site (m); b_m is the breach width (m); K is the erosion coefficient; and φ is the soil coefficient (determined as 2.66 based on field geological investigations). By substituting each parameter into the formulas, the instantaneous peak discharges at the potential blockage-dam-break points were obtained for

both 1% and 0.5% rainfall frequencies.

Although an increase in rainfall intensity theoretically leads to a larger volume of source material accumulation, this study adopts a consistent scale for the barrier dam model, considering the narrow and steep topography of the blockage section in the Yizhong River. The model parameters were derived from field geological investigation reports, aiming to clearly compare the differences between the initial discharge—directly determined by rainfall conditions—and the peak discharge after breaching.

Table 3 Peak discharge parameters at debris flow blockage and breaching points in the Yizhong River basin

Condition	H ₀ (m)	I	B(m)	W(m ³)	λ	φ	K	ρ	β	t ₁ (s)	q ₀ (m ³ /s)	q _m (m ³ /s)
Dam1(1%)	8	0.41	26.55	2072.73	0.3	3.65	1.5	0.12	0.95	13.16	560.9	683.7
Dam2(0.5%)											681.38	804.18

The debris flow discharge in the Yizhong River gully was calculated using the Hydrological model based on rain-to-runoff transformation based on long-term rainfall data, from which the debris flow blockage coefficient was back-calculated:

$$Q_c = Q_p (1 + \phi) D_c \quad (3-11)$$

Q_c is the peak discharge of the debris flow (m³/s); Q_p is the peak discharge of the rain-flood (m³/s); D_c is the debris flow blockage coefficient (assumed as 1 in this context); and Φ is the sediment correction factor for debris flows. The value for $1+\Phi$ was obtained as 3.2 by referencing the "Code for Investigation of Debris Flow Landslides Prevention and Control (DZ/T 0220-2006)."

Table 4 Calculation results of debris flow discharge based on the Hydrological model based on rain-to-runoff transformation

Condition	1+Φ	Rainfall discharge(m ³ /s)	Debris flow discharge(m ³ /s)
1%	3.2	91.2	291.84
0.5%	3.2	103.1	329.92

The calculation results indicate that under the influence of 0.5% frequency rainfall, the debris flow discharge in the Yizhong River gully can reach 329.92m³/s. Based on the previously calculated peak discharge at the blockage-dam-break point, the maximum blockage coefficient of the gully is determined to be 2.44.

257

258 3.2 Simulation parameters settings

259 In this study, a Massflow numerical model of the Yizhong River basin was constructed using a
 260 high-precision 2-meter resolution Digital Elevation Model (DEM) obtained through low-altitude
 261 UAV photogrammetry. To simulate the initiation mechanism of debris flows in the Yizhong River,
 262 the model not only accounts for existing source material reserves within the gully but also
 263 dynamically incorporates the "primary active volume" from landslides and rockfalls along the
 264 gully banks through quantitative accounting of solid material sources during the initiation stage.
 265 Based on this source accounting method, a retrospective inversion validation was performed using
 266 typical debris flow disasters from 2021 in this basin. By fitting the simulations to multiple
 267 measured disaster events, the key dynamic parameters were finalized: the barrier dam height was
 268 set at 8 m, with a cross-sectional area of approximately 131.75m², forming a reservoir capacity of
 269 approximately 2,072.73m³. The fluid density was set to 2,000kg/m³, the friction coefficient was
 270 0.22, and the turbulence coefficient was 200m/s²(Table 5).

271 **Table 5** Parameters of four simulated working conditions

Classification	Rainfall frequency(%)	Rainfall(m ³)	Source volume ^a (m ³)	Turbulence coefficient(m/s ²)	Frictional
Landslide-type	0.5	4.47×10 ⁴	14.28×10 ⁴	200	0.22
Flood-type	0.5	4.47×10 ⁴	8.46×10 ⁴	250	0.2
Dam-break	1	4.07×10 ⁴	13.29×10 ⁴	200	0.22
Dam-break	0.5	4.47×10 ⁴	14.49×10 ⁴	200	0.22

272 To construct the rainfall-driven scenarios, this study comprehensively analyzed the long-duration
 273 precipitation sequences from 1954 to 2020 in Deqin County. By applying the storm-runoff
 274 calculation method from the "Hydrological Manual of Yunnan Province," the source initiation
 275 scales under 1% and 0.5% rainfall frequencies were calculated and compared with non-dam-break
 276 debris flows. Under extreme scenarios, the rainfall intensity reaches its peak shortly after initiation.

$$^a \rho_m = \frac{\rho_s V_s + \rho_w V_w}{V_s + V_w} \rightarrow R_u = \frac{\rho_m - \rho_w}{\rho_s - \rho_m}, R_u = \frac{V_s}{V_w} \rho_m \text{ is the debris flow density, } \rho_s \text{ is the solid density, and } \rho_w \text{ is the}$$

water density. v_s and v_w are the volumes of the solid material and water, respectively. R_u is the solid-water volume ratio.

The instantaneous violent precipitation transforms into powerful surface runoff, generating a fierce hydraulic scouring effect. This triggers instantaneous liquefaction and dynamic instability of the source soil—already near its critical saturation state—thereby inducing large-scale shallow landslides that subsequently transform into debris flows. Based on these scenarios, which couple design frequencies with extreme hyetographs, this study focuses on the dynamic evolution, channel blockage characteristics, and subsequent breaching effects during the landslide-debris flow chain evolution process under various rainfall conditions.

4. Simulation results and risk assessment

4.1 Full-process simulation and analysis

As illustrated in **Fig. 8**, prior to the official breaching, a portion of the debris flow fluid exhibits significant seepage characteristics, continuously discharging into the downstream gully through crevices within the barrier dam. At the blockage point, influenced by the stagnation of early debris flow siltation, the kinetic energy of subsequently arriving fluid dissipates due to the counter-reactive force of the dam body, resulting in a pronounced backwater effect and localized backflow. This complex dynamic mechanism leads to significant heterogeneity in the spatial distribution of flow depth within the blockage zone: the front of the dam body exhibits greater flow depth due to continuous replenishment and compaction, whereas the rear section shows relatively shallower distribution characteristics caused by back-siltation and energy dissipation.

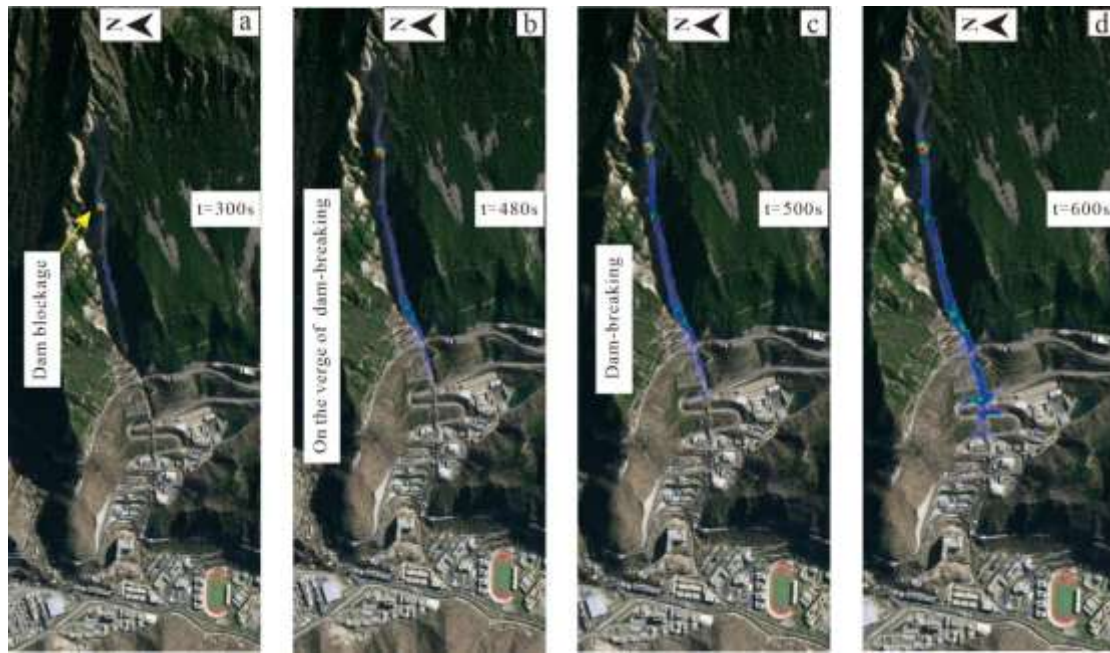


Fig. 8 The breaching process of the debris flow is described as follows: (a) at a simulation time of 300 s, a blockage occurs at a potential blockage point, forming a barrier dam; (b) at 480 s, part of the debris flow fluid seeps through the gaps of the barrier dam and flows into the downstream gully; (c) at 500 s, the barrier dam breaches; and (d) at 600 s, the debris flow rapidly surges into the county urban area.

As shown in Fig. 9, throughout stages a-c in Fig. 9a and b, the flow depth of the dam-break debris flow reaches its peak at blockage point b as the gully becomes obstructed. Conversely, the flow velocity drops abruptly to below 4 m/s due to the backwater effect. During the same period (stages a-c), the non-dam-break debris flow remains in the initial stage of initiation, characterized by a gradual increase in velocity, intensified entrainment effects, and a slow increase in flow depth. At point d, the flow velocities for all three scenarios decrease significantly. This is attributed to the location of the monitoring point near the existing check dam engineering, where the debris flow is intercepted, leading to a marked deceleration.

The relationship between flow velocity and travel distance shown in Fig. 9c further illustrates the significant influence of topography on debris flow velocity. During the initial stage of initiation, the flow velocity remains at a low level. However, with the dynamic influx of unstable slope materials and source materials from both sides of the gully, the kinetic energy of the fluid accumulates rapidly, manifested as a continuous surge in velocity. When the debris flow reaches the preset blockage-dam-break point at a horizontal distance of approximately 1,250 m, it encounters strong local topographic confinement, leading to a sudden dissipation of energy. This

results in a sharp drop in flow velocity and the formation of a barrier dam.

The subsequent evolutionary process demonstrates a typical "cascading effect": under the continuous erosion and scouring of surface runoff and subsequent debris flow pulses, the dam structure undergoes instantaneous failure. The accumulated potential energy is rapidly converted into kinetic energy, triggering a catastrophic surge with ultra-high discharge. Under the 0.5% frequency scenario, the instantaneous peak velocity at the moment of breaching exceeds 20 m/s. Although the velocity gradually attenuates as the gully extends, it remains within a high-intensity range sufficient to cause severe damage.

When the fluid reaches a horizontal distance of approximately 1,800 m, corresponding to the location of existing mitigation works above National Highway G214, the simulation curve once again exhibits a "sudden drop and surge" fluctuation. This indicates that while the existing facilities have lost their original protective function, the local topographic changes still induce secondary blockage and breaching processes, posing a severe coupled risk to the highway trunk line and the residential resettlement areas below. In the final stage of debris flow movement, a localized surge in velocity occurs before stopping, caused by the elevation drop created by the ring road structure within Deqin County. This simulation result clearly validates the multi-stage variation characteristics of the Yizhong River debris flow hazard chain under complex topographic constraints.

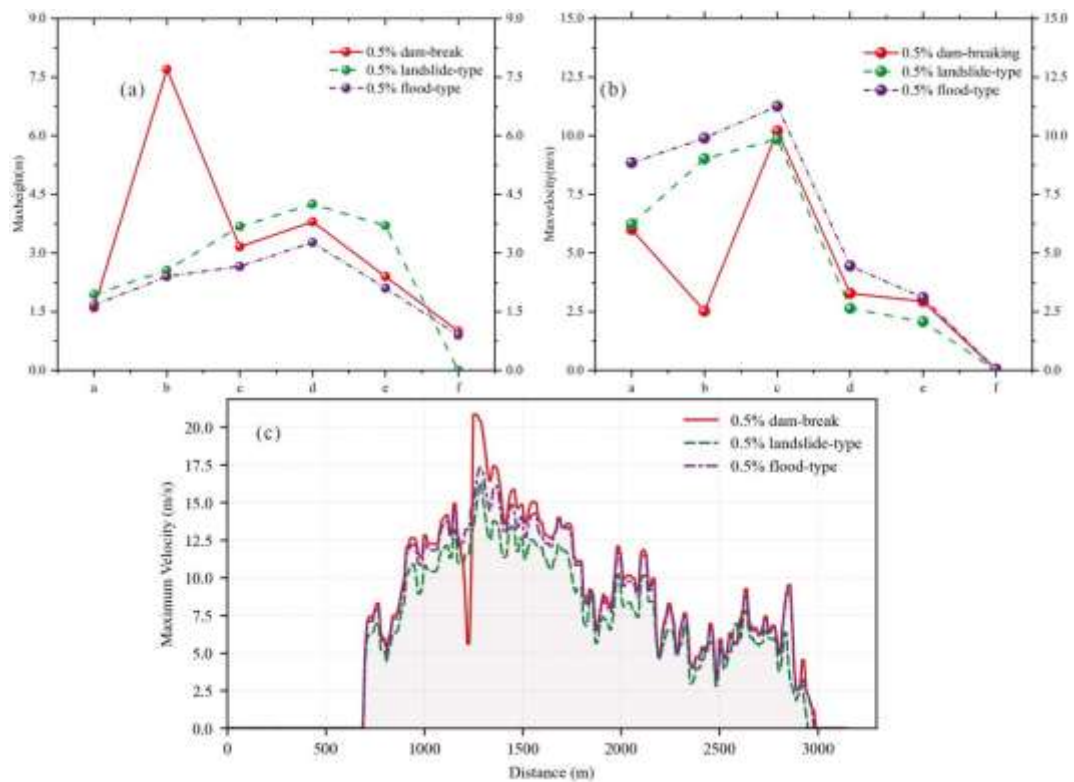


Fig. 9 Comparison curves of debris flow kinematic parameters under three scenarios: (a) maximum flow depths at each monitoring point under the three scenarios; (b) maximum flow velocities at each monitoring point under the three scenarios; and (c) variation curves of the maximum velocity during the entire debris flow process across the three scenarios.

Fig. 10 clearly illustrates the spatial distribution characteristics of debris flow deposition under four simulation scenarios 1,600 s after the initiation of the disaster. In all four scenarios, significant accumulation occurs at the blockage point, validating the extreme susceptibility of this narrow gully section to barrier dam formation and dam-break risks. The comparison between **Fig. 10a, b,** and **c** is particularly striking: despite significantly lower rainfall intensities, the final deposition area and maximum runout distance of the dam-break debris flow are comparable to those of non-dam-break debris flows, demonstrating a potent dynamic amplification effect.

However, the deposition depth of the dam-break debris flow in the upstream channel is significantly lower than that of the landslide-induced debris flow and remains closer to that of torrential debris flows, with depths generally below 2 m except in localized areas. This is primarily because the instantaneous high pressure generated by the breaching enhances the mass transport efficiency of the fluid, exhibiting a formidable dynamic carrying capacity. Consequently, the majority of the solid material is rapidly discharged downstream under the powerful surge

rather than stagnating in the upper and middle reaches of the gully. The localized areas of greater depth still conform to the dynamic deposition characteristics expected under high-discharge and high-velocity impact. Furthermore, under the same 0.5% rainfall frequency, Fig. 10d shows that the deposition area of the dam-break debris flow covers most of the residential areas in the lower reaches of the Yizhong River, indicating that the dam-break hazard chain poses a severe threat to the safety of Deqin County.

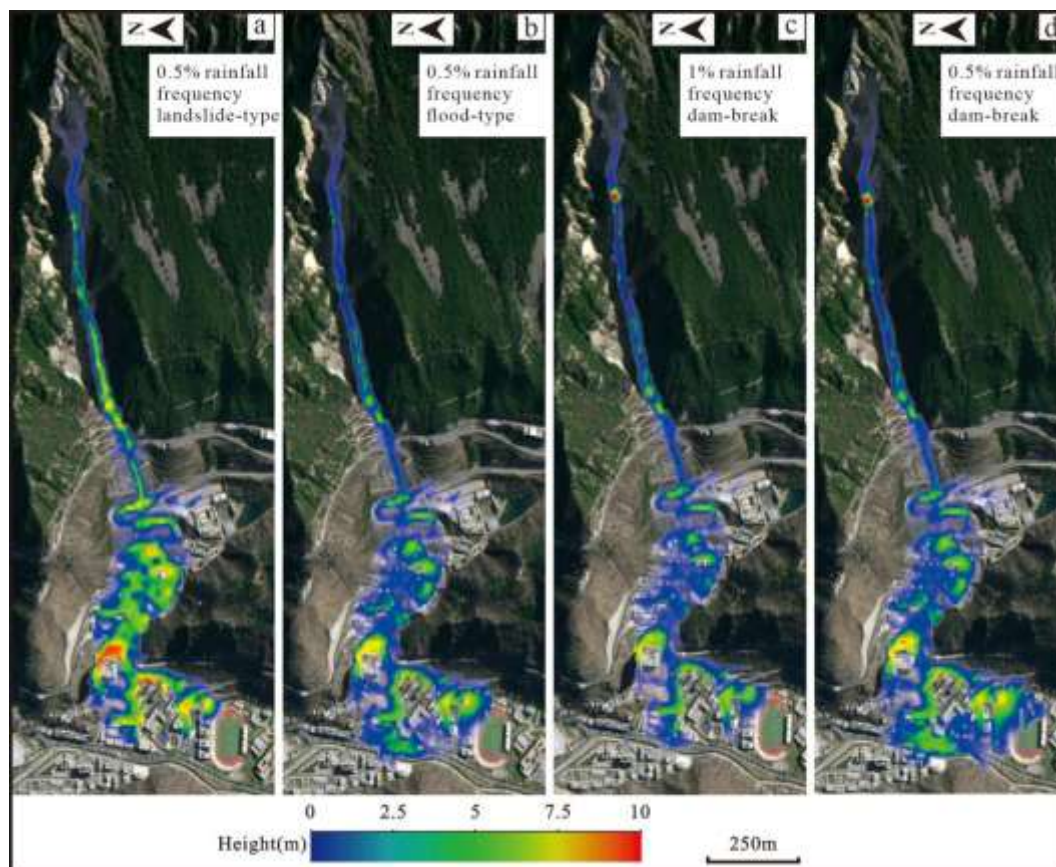


Fig. 10 Simulated deposition depth of debris flows under four scenarios after 1600 seconds of propagation: (a) 0.5% rainfall frequency landslide-type debris flow, (b) 0.5% rainfall frequency flood-type debris flow, (c) 1% rainfall frequency dam-break debris flow, and (d) 0.5% rainfall frequency dam-break debris flow.

Simulations indicate that under the extreme scenario of 0.5% rainfall frequency, a massive surge in discharge occurs during the breaching phases (stages b-c). The maximum instantaneous discharge during the dam-break at the blockage point reaches $927.2\text{m}^3/\text{s}$, which is approximately 15.3% higher than the theoretical value of $804.18\text{m}^3/\text{s}$ calculated using the Hydrological model based on rain-to-runoff transformation and Xie's formula (Fig. 11). We attribute this discrepancy to the fact that theoretical formulas are based on idealized rectangular or trapezoidal cross-sections, whereas the numerical simulation utilizes high-precision topographic data modeled from UAV

aerial photogrammetry. The topographic confinement generated by the typical "V-shaped" glacial trough of the Yizhong River produces constraints that cannot be fully captured by theoretical calculations. Furthermore, under extreme rainfall conditions, the high-intensity surface runoff itself possesses substantial kinetic energy, which exacerbates the entrainment and scouring of source materials in the channel. This results in the simulated fluid exhibiting larger-scale evolutionary characteristics compared to the theoretical static model.

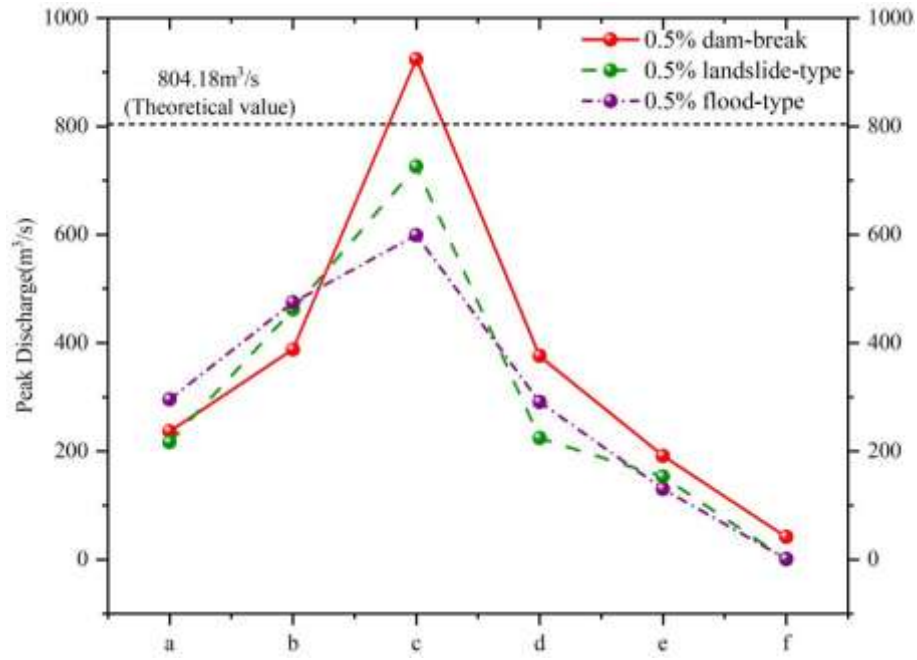


Fig. 11 Comparison of peak discharges between dam-break and non-dam-break debris flows at monitoring cross-sections.

To better quantify this discrepancy, a dynamic amplification factor α is proposed in this study:

$$\alpha = \frac{Q_s}{Q_t} \quad (4-1)$$

Q_s is the peak Dam-break discharge derived from Massflow simulations (m³/s); Q_t is the peak dam-break discharge calculated using theoretical formulas (m³/s).

Calculations reveal that under the 1% rainfall frequency, the dynamic amplification factor α is 1.03, indicating that the theoretical value is largely consistent with the simulation results. However, when the rainfall frequency increases to 0.5%, the dynamic amplification factor α reaches 1.15. We contend that the high-precision DEM in numerical simulations effectively captures the concentration of potential energy within the debris flow, particularly at the narrow cross-sections where breaching occurs.

4.2 Risk Assessment

The numerical simulation study in this paper was conducted based on several simplified assumptions and did not fully account for complex factors such as actual channel vegetation cover, variations in riverbed roughness, and the specific rheological properties of the debris flow. Furthermore, simulation results from single scenarios struggle to comprehensively reflect the overall hazard risk level of regional debris flows. To scientifically evaluate the debris flow hazard risk in the urban area of Deqin County, it is essential to integrate basin characteristics with simulation results. Therefore, we employed the single-channel debris flow risk assessment model proposed by Liu and Mo (Table 6 and Fig. 12) to calculate the potential risk of debris flows in the Yizhong River basin (Liu and Mo 2002; Liu and Mo 2003).

This model classifies single-channel debris flow risk into five levels: very low risk ($0 \leq R < 0.04$), low risk ($0.04 \leq R < 0.16$), moderate risk ($0.16 \leq R < 0.36$), high risk ($0.36 \leq R < 0.64$), and very high risk ($0.64 \leq R < 1$). Comprehensive simulation results indicate that dam-break debris flows under both 1% and 0.5% rainfall recurrence periods exhibit very high risk, representing a significant potential hazard.

Table 6 Debris flow risk assessment under four operational scenarios

Classification	Affected area(m ²)	H	V	Risk Assessment ^b
0.5% Landslide-type	13.9×10 ⁴	0.6735	0.9619	0.6478
0.5% Flood-type	15.6×10 ⁴	0.6514	0.9626	0.6270
1% Dam-break	14.0×10 ⁴	0.6706	0.9622	0.6452
0.5% Dam-break	18.8×10 ⁴	0.6740	0.9643	0.6499

^b The single-channel debris flow risk (R) is defined as the product of hazard (H) and vulnerability (V): $R = H \times V$

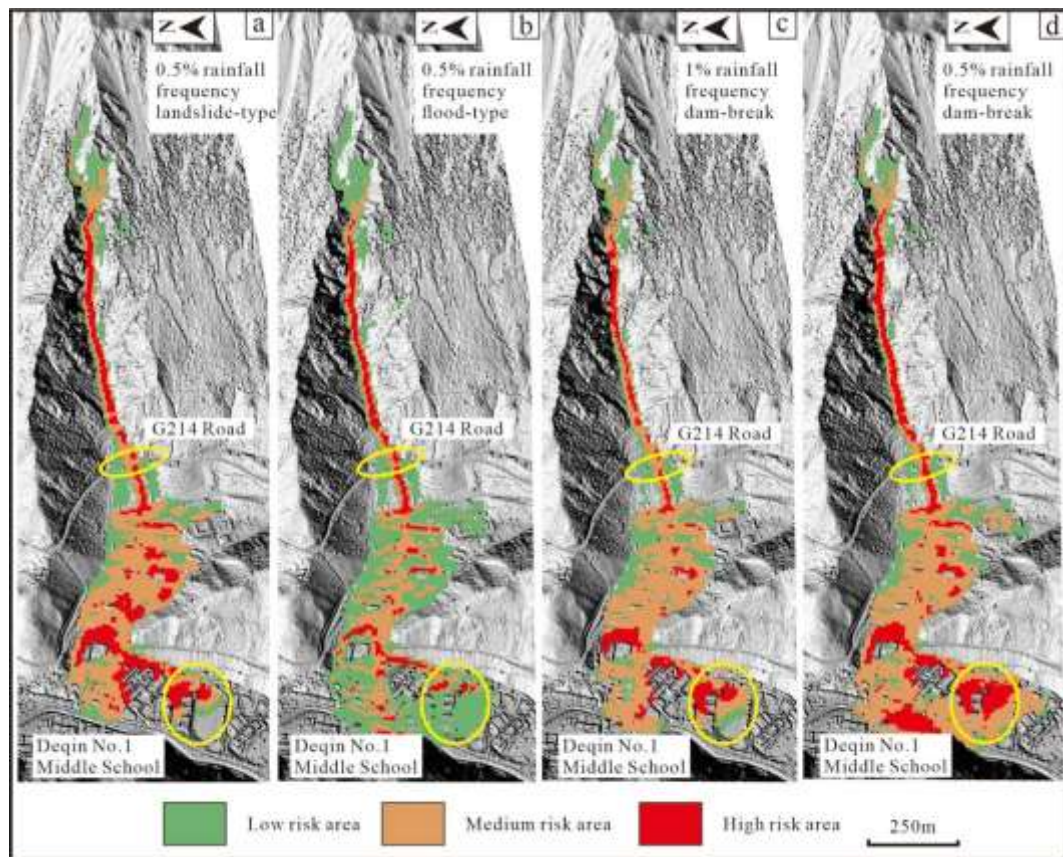


Fig. 12 Risk assessment of debris flows under four scenarios after 1600 seconds of evolution: (a) 0.5% rainfall frequency landslide-type debris flow, (b) 0.5% rainfall frequency flood-type debris flow, (c) 1% rainfall frequency dam-break debris flow, and (d) 0.5% rainfall frequency dam-break debris flow.

5. Discussion

The Yizhong River debris flow exhibits significant evolutionary differences under varying rainfall frequencies, with the core dynamic characteristic being the intense dynamic amplification effect triggered by the "blockage-dam-break" process. Numerical simulation results indicate that although the static storage capacity formed by the barrier dam is relatively limited (approximately 2,000 m³), the instantaneous discharge increment generated during breaching creates an extremely high kinetic energy impact on the downstream area. Furthermore, the Yizhong River is characterized by a typical narrow and deep "V-shaped" cross-section. This topographic configuration induces a "funnel effect" that severely restricts the lateral diffusion of the debris flow fluid. When the lateral flow cross-section is confined, the kinetic energy of the fluid becomes highly focused on longitudinal scouring, thereby intensifying shear erosion of the gully bed. This

synergy between topographic confinement and breaching is the physical essence behind a dynamic amplification factor greater than 1.0.

Analysis of the coupling relationship between flow velocity and depth reveals that under the 0.5% frequency scenario, the energy stored by the barrier dam is released in an extremely short duration, transforming into massive downstream kinetic energy. This dynamic amplification effect is consistent in its mechanical evolutionary logic with several well-known domestic and international cases. For instance: (i) the Chamoli disaster in India, where an ice and rock avalanche formed a barrier dam that subsequently breached, leading to a catastrophic flash flood (Yin et al. 2021); (ii) the Kezilesai debris flow in Yining, Xinjiang, where continuous rainfall triggered a loess landslide-dam-break (Shao et al. 2018); and (iii) the Meilong Gully in Danba, Sichuan, where short-duration intense rainfall initiated bank collapse that transformed into a debris flow, subsequently forming a cascading blockage-dam-break effect that continuously amplified the discharge (Wen et al. 2022). In these cases, the instantaneous peak discharge far exceeds the initial flow, subsequently eroding the gully bank slopes and entraining large volumes of source material, resulting in a significant chain-like amplification effect. Comparative analysis shows that the dynamic amplification magnitude of the Yizhong River is constrained by the narrowness and gradient of its gully topography. This mode of concentrated energy release under topographic confinement is the dominant factor driving the surge in downstream destructive power (Shi et al. 2022).

As the rainfall intensity increases from a 1% to a 0.5% frequency, the simulated peak discharge jumps from 704m³/s to 927.2m³/s. This magnitude increase further translates into heightened dynamic flow pressure during the debris flow movement, exacerbating the threat to downstream areas (Destro et al. 2018). During the downstream propagation after the dam-break, the fluid maintains extremely high kinetic energy, and the dynamic pressure intensifies significantly as flow velocity surges. Particularly upon entering the highway section within the county town, the immense pressure generated by the coupling of flow depth and high velocity can lead to the structural failure of ground-level buildings. Furthermore, the massive influx of solid deposits is likely to block culverts and drainage channels in the urban area, easily triggering fluid avulsion and deviation from the original channel. This lateral expansion effect further broadens the scope and impact area of the disaster.

The aforementioned dynamic amplification factor α suggests that in high-mountain and steep-gorge regions like Deqin County, the rapid evolution of the Yizhong River debris flow makes traditional empirical design values overly conservative. Conventional check dams face a risk of overloading when subjected to impact forces of historical extreme magnitudes. Therefore, it is imperative to introduce dynamic amplification parameters based on topographic correction for engineering mitigation. It is recommended that proactive diversion strategies be adopted at critical sections, such as National Highway G214 and the entry points to the county town. This can be achieved through stepped drainage channels or energy-dissipation structures to reduce the kinetic energy of the fluid (Li et al. 2025). Concurrently, considering the driving roles of different rainfall conditions, the early warning accuracy for sudden disasters like flash floods, landslides, and debris flows depends heavily on rainfall monitoring (Borga et al. 2014). Future efforts should prioritize the establishment of a coupled early warning system based on real-time rainfall intensity monitoring and the prediction of discharge amplification factors.

6. Conclusion

By quantitatively analyzing the entire process of debris flow blockage and dam-break in the Yizhong River, Deqin, this study draws the following primary conclusions:

(i) Pronounced discharge amplification effect. The Yizhong River debris flow exhibits an intense discharge gain under the cascading "blockage-dam-break" evolution. Under 0.5% and 1% rainfall frequencies, the simulated peak discharge reaches 927.2m³/s and 704m³/s, respectively, which are 15.3% and 3% higher than theoretical calculations. This indicates that short-term intense rainfall-induced runoff and material replenishment contribute significantly and nonlinearly to the disaster magnitude after breaching, leading to an ultimate evolutionary scale that far exceeds theoretical expectations.

(ii) Clarified kinetic mechanism. The kinetic energy of the debris flow during dam-break is profoundly influenced by topography and flow velocity. Under extreme scenarios, high-intensity antecedent runoff enhances the entrainment and transport of channel source materials, resulting in simulated discharges that exceed theoretical static values. With the surge in velocity, the dynamic flow pressure increases sharply, further intensifying the erosion capacity and forming a multi-level

composite hazard chain pattern.

(iii) Engineering mitigation strategies based on simulation. Based on Massflow simulation results, under a 0.5% frequency rainfall, the instantaneous peak discharge at the breaching point can reach 927.2m³/s, with peak velocities exceeding 20m/s. Traditional rigid check dams are susceptible to failure due to instantaneous high-pressure impact. Future prevention strategies should shift toward "dynamic energy dissipation." It is recommended to implement stepped or energy-dissipating drainage channels to induce the dissipation of fluid energy and mitigate the dynamic threat to Deqin County. Furthermore, the design depth for drainage channels should be based on the simulated maximum flow depth, with a recommended net depth of no less than 4 m.

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602 Author Contributions

603 All authors contributed to the study conception and design. Material preparation, data collection
604 and analysis were performed by L.C.W., W.P.W., and Y.W.. The first draft of the manuscript was
605 written by L.C.W. and all authors commented on previous versions of the manuscript. All authors
606 read and approved the final manuscript.

607 Data Availability

608 The datasets generated during and/or analyzed during the current study are available from the
609 corresponding author on reasonable request.

610 Ethics Approval

611 Not applicable. (This study does not involve human participants or animals.)

612 Consent to Participate

613 Not applicable.

614 Consent for Publication

615 Not applicable.