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REVIEW
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Review of Investigations on Hazard Chains Triggered by River-Blocking Debris Flows and Dam-Break Floods

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The Tibetan Plateau suffers from various types of geohazards (collapses, landslides, and debris flows.) due to abrupt changes in complex topography and weather conditions. Global warming and frequent high-intensity earthquakes in recent years have exacerbated the situation. Collapses and landslides provide vast amount of soil and debris which are conveyed downstream by runoff caused by extreme rainfalls to form large-scale debris flows; then, the debris flows block rivers and finally form dam-break floods, that is, a hazard chain triggered by debris flows. Along the evolution direction of the hazard chain, the affected areas are constantly amplified. This study first summarizes the related research studies on river blockage, debris-flow dam failure, and the hazard chain triggered by debris flows and then points out the drawbacks of existing research studies. Overall, the research (including mechanism, risk assessment, key prevention, and control technologies) on the hazard chain triggered by debris flows is still in its infancy and is disconnected among single hazard types in the hazard chain; meanwhile, the understanding of the mechanism of debris flow blocking the river is not enough; the established model and discriminant have minimal application scope, and there is no empirical model and dynamic model of debris-flow dam failure. Finally, several key scientific issues of this field were raised: 1) it is necessary to elaborate the coupling mechanism of debris-flow dam formation and construct the discriminant and numerical model of debris flow blocking the river with high precision and a wide application range. 2) It is necessary to further study the failure mechanism of a debris-flow dam, construct the numerical model of the failure process of a debris-flow dam, and accurately simulate the outburst flood hydrograph. 3) It is necessary to clarify the critical transformation conditions and dynamic evolution process of the hazard chain caused by debris flows, complete the accurate quantitative simulation of the whole disaster chain process, then establish a complete risk assessment system of the hazard chain, and finally develop some key prevention and control technologies suitable for the hazard chain.

Keywords: debris flow dam, river-blocking mechanism, dam failure, hazard chain, floods

1 INTRODUCTION

In recent years, river blockages induced by debris flows occur more frequently due to the impact of climate change and earthquakes, especially in case of high-intensity earthquakes (Zhou et al., 2022), which are often accompanied by multiple collapses and landslides (Djalante 2019; Haque et al., 2019; Bai et al., 2020). Occurrence of collapses and landslides leads to change of geological and geomorphic conditions and increases the scale of loose materials in gullies, which is prone to large-scale debris flows when there are heavy rainfalls (Liu and Zhao 2016; Domènech et al., 2019; Zhou W. et al., 2019; Ciccarese et al., 2020; Liu et al., 2020; Zhang et al., 2020). River blockage occurs when abundant loose materials of debris flows are brought from tributaries into the main river in a short time, but the main river does not have enough capacity to carry these materials downstream. It often leads to inundation upstream and outburst flood induced by debris-flow dam failure. This is often referred to as the hazard chain induced by debris flows (Guo et al., 2004; Yin et al., 2009; Chang et al., 2011; Cui et al., 2011; Chen C. G. et al., 2012; Zhuang et al., 2012; Cui et al., 2013; Liu and Zhao 2016).

For example, on 9 April 2000, a huge avalanche-landslide-debris flow broke out in the Zhamu gully, a tributary of Tibet's Polongzangbu River Basin, which completely blocked the Yigong Zangpo River. The peak discharge of the dam-break flow reached 124,000 m^3/s when the debris-flow dam failed and smashed nearly a 30-km highway downstream. A total of 2.5 million residents were displaced with 94 casualties (Song 2015). On 7 August 2010, a large-scale debris flow was triggered by heavy rainfall in Luojiayu and Sanyanyu gullies, Zhouqu County, resulting in 1,364 deaths and 401 missing people. After the debris flow passed through the county of Zhouqu, the Bailong River was blocked and inundated half of the county (**Supplementary Figure S1**) (Zhang et al., 2007; Hu et al., 2010; Tang et al., 2011). At around 23:00 on 5 July 2016, a glacier lake (Cirenmacuo Lake) outburst flood transformed into debris flows in Zhangzangbu, Nyalam County. Soon after the river was blocked, dam breach occurred, flooded the Zhangmu port and hydropower facilities, and destructed road and houses in the downstream towns of Kodari and Tatopani in Nepal (Cook et al., 2018; Liu J. K. et al., 2019). On 17 October 2018, a large-scale debris flow broke out in the Sedongpu gully of Milin County, Tibet. The debris flow blocked the Palalung Zangbo River and formed a barrier dam (height 77–106 m, width 3,500 m, and volume 30 × 106 m^3). The reservoir capacity of the barrier lake reached 3260 × 106 m^3, and the flood peak flow reached 18,000 m^3/s after 56 h, which caused important losses to the upstream and downstream (Liu C. z. et al., 2019) (**Supplementary Figure S2**).

The dynamic evolution process of the hazard chain induced by debris flows is shown in **Figure 1**. It mainly includes two kinds of secondary hazards: debris flow blocking the river and debris-flow dam failure.

Based on a brief review of the literature on single mountain hazard types (river blockage and debris-flow dam failure) in the hazard chain triggered by debris flows, this study points out the issues occurred in these studies. Then, research studies on the hazard chain of debris flows blocking the river and dam-break flood are discussed, and some unresolved key issues are put forward.

2 MECHANISM OF RIVER BLOCKAGE INDUCED BY DEBRIS FLOWS

2.1 Influencing Factors

Debris flows are mass movement of viscous and highly concentrated fluid–solid mixture between hyper-concentrated flows and soil mass (Prochaska et al., 2008; Hu et al., 2012; Namgyun et al., 2019). When a debris flow is blocking a river, there is a complicated interaction between the debris flow and the main river, adding difficulty to the identification of related influencing factors. Selecting influencing factors is fairly important to establish a discriminant with accuracy while simplifying the mathematical model. Therefore, multiple research studies are carried out to identify influencing factors in river blockings induced by debris flows (**Table 1**).

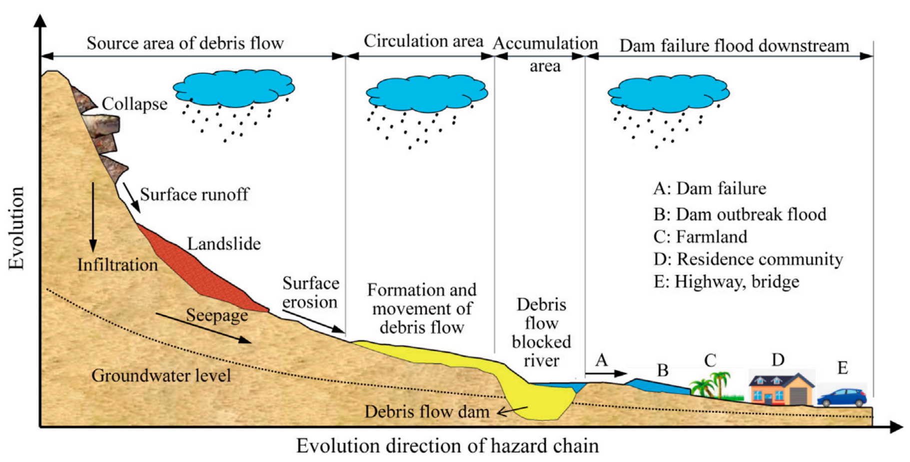

FIGURE 1 | Diagram of the hazard chain evolution.

Table 1 | Researches on the influencing factors of river blocking induced by debris flows

Researcher	Influencing factors of the debris flows						Influencing factors of the main river				Other comprehensive influencing factors		
	Total volume	**Gravity**	**Gully gradient**	**Discharge**	**Particle grading**	**Others**	**Discharge**	**Width of main river**	**Gradient of main river**	**Others**	**Angle of intersection**	**The ratio of main and branch discharges**	**The ratio of main and branch velocities**
Zhang et al. (2007)	○	○	○	○	○	Outbreak frequency, viscosity	○	○	○	—	○	—	—
Zhou (1991)	○	—	○	—	—	—	○	—	—	—	—	○	—
Zhu et al. (2000)	—	○	—	—	—	Duration	—	○	—	Bending radius of river	○	○	—
Liu and Zhou (2015)	—	○	○	○	—	—	○	○	○	—	○	—	—
Xu et al. (2002)	○	○	—	—	—	—	—	—	—	—	○	—	—
Guo et al. (2004)	○	○	—	—	—	—	—	○	○	—	○	○	○
Chen et al. (2002)	—	○	—	—	—	—	—	—	—	Water density	○	○	○
Tang et al. (2006)	—	○	—	○	—	—	○	○	—	—	—	—	—
Wu et al. (2005)	—	—	—	○	○	Nature	○	○	○	Velocity	○	—	—
Wei et al. (2002)	—	○	—	○	○	—	—	—	—	—	○	—	—
Liu and Zhao (2016)	○	○	—	—	—	—	—	○	—	—	—	—	—
Zhu et al. (2016)	○	—	—	—	—	Moisture content	—	—	—	Velocity	○	—	—
Lv et al. (2016)	○	—	—	—	—	Velocity	—	—	—	—	—	—	—
He (2014)	○	—	—	—	—	Moisture content	—	—	—	—	○	○	○
Dang et al. (2009a)	—	—	—	—	—	Impact strength	—	○	○	—	○	○	—
He (2003)	—	○	○	○	○	—	○	—	—	—	—	—	—
Total times	8	10	4	6	4	—	6	8	5	—	11	6	3

The circle "○" in the table indicates that the researcher has considered this influencing factor, and the short line "—" indicates that the researcher has not considered this influencing factor.

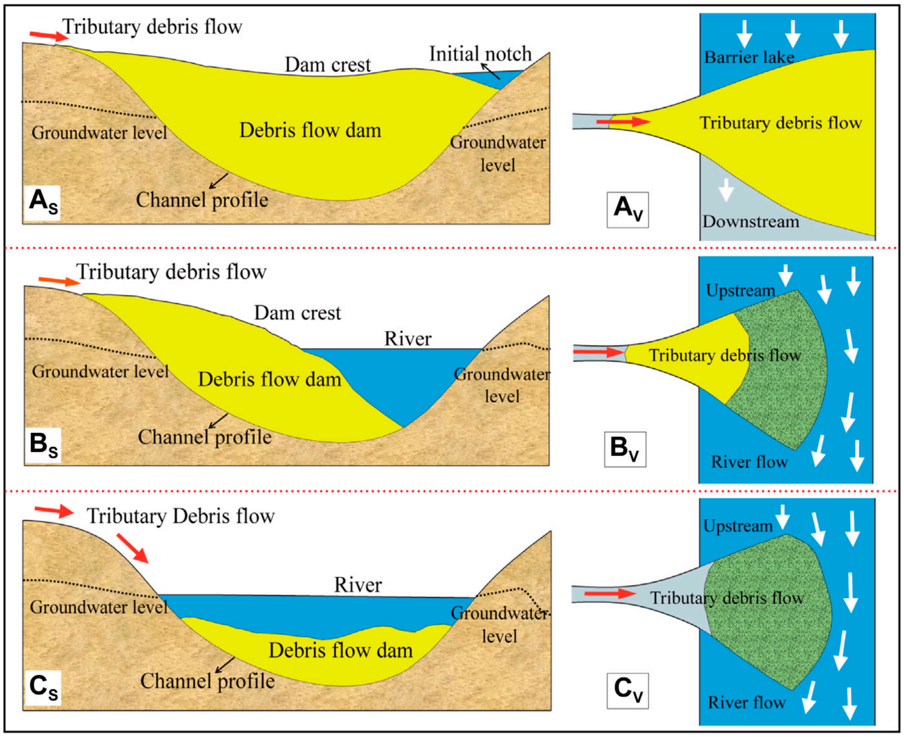

FIGURE 2 | Three river-blocking patterns induced by debris flows: **(A)** Complete blockage, **(B)** partial blockage, and **(C)** submerged dam blockage. The subscript "s" in the figure number represents the "sectional view" and "v" represents the "vertical view."

Table 1 indicates the complexity and diversity of related influencing factors, including the total volume of debris flows, gravity, discharge and width of the main river, ratio of the main river and other discharges, and angle of intersection. The aforementioned influencing factors can be mainly summarized into three categories: main rivers, debris flows, and other comprehensive influencing factors. In addition, although significant progress has been made in studying these related influencing factors, it is worth noting that some of these results are only qualitative descriptions, limiting the applications to other cases. In particular, the process and mechanism of river blockage induced by debris flows under the coupling of multiple factors are not clear, which should be considered by means of experiments and numerical simulation studies in the future.

2.2 Main River Blocking Patterns

There are three river-blocking patterns induced by debris flows: complete blockage, partial blockage, and submerged dam blockage (Chen C. g. et al., 2012; Chen et al., 2013; Liu and Zhao 2016). Complete blockage (**Figure 2A**) refers to a debris flow flowing into the mainstream with vast amount of solid materials. The flow front rapidly reaches the opposite bank and completely blocks the main river. Partial blockage (**Figure 2B**) means that part of the flow front moves forward above the water surface. However, it cannot reach the opposite bank due to insufficient total mass or strong dynamic conditions of the main river. Blockage caused by submerged dam (**Figure 2C**) means that due to the small scale of the debris flows or the depth of the main river, the flow front can only move forward below the water surface and then form a submerged dam that partly blocks the river (Liu and Yao 2012).

Compared with partial blockage and submerged dam blockage, complete blockage can heavily increase the upstream water level and result in serious damage. In order to predict river blockages and take effective hazard mitigation measures, many scholars select key influencing factors based on dimensionless analysis or specific parameter analysis to study the threshold of river blocking induced by debris flows. The judgment formula is shown in **Table 2**. In addition, it should be noted that although the risk of partial blockage patterns is lower than that of complete blockage patterns, it is easy to cause serious erosion of the opposite bank and cause secondary geological disasters, such as landslides and collapses (**Figure 3**). Therefore, all river-blocking patterns should be further deeply studied in the future.

Due to the complexity of the influencing factors and the mechanism in general, it is difficult to establish a discriminant with comprehensive influencing factors. The selection index is simple, and the application scope of the established discriminants is restricted to a certain extent. The main reason behind that is the limited understanding in the mechanism of river blockage. Therefore, the discriminants should be selected cautiously when it is applied, and a discriminant with a larger scope of application should be established considering multiple key influencing factors.

TABLE 2 | Discriminants of river blocking induced by a debris flow.

Researchers	Discriminants	Threshold condition	Notes	Research objects
Zhang and Xie (2008)	$R = \frac{PQ_n J_n}{B_z Q_{zJ}} z.$	R <5, barely blocked; 5< R <10, seriously blocked; R >10, inclined to be blocked	P—outbreak possibility of debris flow, B_Z—width of the main riverway, Q_n—discharge of the debris flow, Q_z—discharge of the mainstream, J_z—gradient of the mainstream, and J_n—gradient of the debris flow gully	Four debris flow gullies in the arid valley area of the upper reaches of the Minjiang River in China
Zhu et al. (2000)	$K = (1 - \cos\theta)\left(\frac{b}{R} + 0.2\frac{Q_b}{Q_m} + \ln\gamma_c + 0.01t\right).$	K <1, never blocked; 1< K <2, temporarily blocked or partially blocked; K >2, completely blocked	θ—confluence angle, b—width of the main riverway, R—bending radius of the river, Q_b—peak discharge of the tributary debris flow, Q_m—mainstream discharge of the tributary debris flow, γ_c—density of the debris flow, and t—duration of the debris flow	Peilong gully, Sichuan–Tibet Highway, Tibet, China
Chen et al. (2002)	$\frac{\gamma_d Q_d v_d \sin\alpha}{\gamma_m Q_m v_m} \geq C_r.$	C_r >1.44, blockage formed	γ_d—volume-weight of the debris flow, γ_m—volume-weight of the water flow, v_d—average flow velocity of the debris flow, v_m—average flow velocity of the mainstream, α—confluence angle, Q_d—discharge of the debris flow, and Q_m—discharge of the mainstream	The formula is based on the flume test.
Tang et al. (2006)	$Z = \frac{2KQ_c\gamma_c\beta}{Q_m B}.$	Z <0.5, never blocked; 0.5 <Z <1.0, partially blocked; Z >1.0, completely blocked	B—width of main riverway, Q_m—discharge of mainstream, Q_C—discharge of debris flow, β—confluence angle, K—correction coefficient, ranging from 1.0 to 1.5	Some debris flow gullies in the upper reaches of the Minjiang River and the Xiaojiang River of Yunnan province, China
Dang et al. (2009a)	$C = \left(\frac{r}{\tan\varphi}\right)^{1/2}\left(\frac{\tau}{\rho g w}\right)^{1/3}\tan\left(\frac{D}{2}\right).$ $r^{\frac{1}{2}} < 1.0$ and $\left(\frac{\tau}{\rho g w}\right)^{\frac{1}{3}}\tan\left(\frac{D}{2}\right)/(\tan\varphi)^{\frac{1}{2}} < 0.4.$	C ≥ 0.87, blockage occurs; When the second discriminant is satisfied, the river is barely blocked.	w—width of the main riverway, $tan\psi$—gradient of the mainstream, r—flow ratio of the debris flow to mainstream, D—confluence angle, $\tau/(\rho gw)$—comprehensive parameter considering the scour resistance of the debris flow and the width of the mainstream	The formula is based on the flume test.
Cheng et al. (2007)	$r = \frac{Q_b v_b \gamma_c \tau_b}{Q_m v_m \gamma_w H \rho g}.$	r > 1001.16, blockage occurs	B—confluence angle, Q_m—discharge of the mainstream, Q_b—discharge of the debris flow, v_b—flow velocity of the debris flow, v_m—flow velocity of the mainstream, γ_c—volume-weight of the debris flow, γ_w—volume-weight of the water flow, ρ—density of water, τ_b—initial shear force of the debris flow, H—upstream banked-up water level, R_M—momentum ratio of the branch to mainstream	Some debris flow gullies in the southeast of Tibet, China
Du et al. (2012)	$R = \frac{(\gamma_s - \gamma_w) g c_{du} \cos\theta \cdot n}{(\gamma_s - \gamma_w) c_{du} + \gamma_w} - g\sin\theta.$	R ≥ 1, the main riverway may be fully blocked; 0.5< Z <1.0, the main riverway may be partially blocked	γ_s, γ_w —density of the debris flow and water flow, respectively, C_{du}—concentration of the debris flow, θ—downstream slope of the gully, g—gravitational acceleration	The formula is derived from the theory.
Liu and Zhou (2015)	$D = 21.18\frac{Q_n}{Q_s} + 0.54\frac{J_n}{J_s} + 0.08\beta + 1.39\gamma_n - 0.06K_z - 9.69.$	D <3, barely blocked; 3 <D <6, partially blocked; D >6, completely blocked	β—angle of intersection, K_z—width of the main riverway, Q_n—discharge of the debris flow, Q_s—discharge of the mainstream, J_s—gradient of the mainstream, J_n—gradient of the debris flow gully, γ_n—volume-weight of the debris flow	Six debris flow gullies in the Wenchuan earthquake area of China

2.3 River Blocking Mechanism

2.3.1 Experimental Study of River Blocking

The process of river blocking induced by debris flows is essentially a complex process of interactions between Newtonian fluid (water) and non-Newtonian fluid (debris flows) (Chen et al., 2011; Maria et al., 2014; Stancanelli et al., 2015). Through flume experiments, we can have an intuitive preliminary understanding of the process of debris flows blocking the river. When the debris flows enter into the main river, most coarse particles such as boulders and cobbles deposit at the gully mouth, which changes

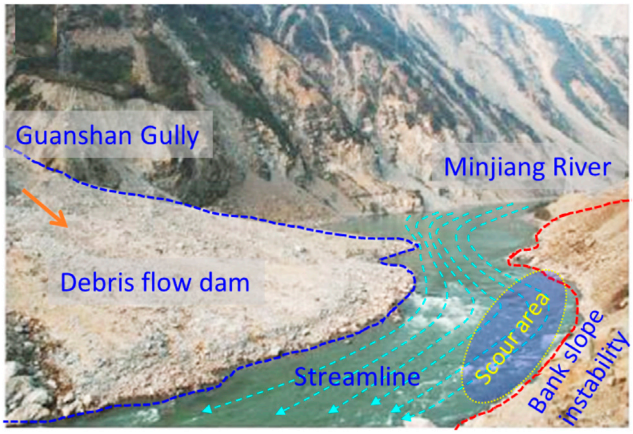

FIGURE 3 | Partial blockage pattern of debris flow causes serious scouring on the opposite bank (In 2008, a debris flow occurred in Guanshan gully, Sichuan province, China, partially blocking the Minjiang River. After the sharp deflection of the river flow streamline, the bank slope was scoured, resulting in the instability and failure of the opposite bank slope).

the local boundary conditions of the confluence area (Maria et al., 2014). The debris flow head, driven by the high momentum, continues to advance to the opposite bank of the main river (Wang et al., 2017). Under the strong hydraulic condition of the main river, the fine particles from debris flows are carried away by the water flow. The sediment concentration and velocity distribution of the solid–liquid two-phase flow at the confluence are characterized as "small and fast in the upper part and large and slow in the lower part" (Chen et al., 2013). When the head of the debris flows reaches the opposite bank and a large volume continues to flow into the river, the main river can be completely blocked; thus, a dam is formed (Wang et al., 2017). In case of a confluence, viscous debris flows are prone to move and accumulate as a whole, while the dilute ones are easier to be carried away in the way of suspended and bed loads, respectively (Chen et al., 2013).

In addition, Chen et al. (2004b)carried out experiments to study the confluence process of the debris flows and water flows. It was found that the inflow angle and the velocity ratio of the main river and tributaries have a great impact on the position and shape of sediment accumulation. Based on the theory of density flow, the motion equation of the debris flow front in the main river was deduced, and the calculation formula of its movement distance was given by (Liu C. R. et al. 2013; Liu C. R. et al. 2014; Liu and Zhao 2016), but these results have not been verified by examples. Chen (2016) studied the intersection process of debris flows and the main river using the flume model test and calculated the width of the debris-flow dam plug by momentum conservation theory; however, these results also have not been verified by examples. At the same time, flume experiments are likely to mask many important experimental phenomena in the prototype. Therefore, it is necessary to further strengthen the verification of experimental results and fully consider the similarity between the model and the prototype, including geometric similarity, kinematic similarity, and dynamic similarity, so that the results of small-scale model experiments can be directly applied to the prototype. Furthermore, based on macroscale analysis of the basin, Lv et al. (2016) pointed out that the two-phase debris flows blocked the Nujiang River, forming a large number of dam Nick points, changing the river flow pattern, causing a large amount of sediment deposition in the lake, and limiting riverbed undercutting. Although the results of this study are qualitative, it can inspire us: in the study of the debris flow blocking the river process, in addition to the intersection process and mechanism of debris flows and the main river, we should also pay attention to the influence of the intersection process on the upstream and downstream of the intersection area, including the upstream and downstream hydraulic characteristics and sediment transport characteristics.

Although research on the threshold of river blocking based on empirical expressions has made some progress, there are few achievements in the quantitative description of its mathematical models by the view point of the hydrodynamic process of water and sediment.

2.3.2 Numerical Simulation of River Blocking

Compared with the traditional flume model test, application of numerical simulation methods to study and analyze the river-blocking mechanism induced by debris flow is more cost-effective, time-saving, and is easier to change parameters (Szczukiewicz et al., 2014; Celis et al., 2017).

Combining with particle-in-cell (PIC) and marker and cell (MAC) algorithms, Chen et al. (2013) proposed a two-field coupling model for the interaction between the debris flow and the main river. The main characteristic of the model is that the rheological parameters and sediment settling velocity in the calculation unit of a confluence may be expressed with the aid of the specific weight of mixed fluids. In addition, based on the weir flow theory, a numerical calculation method to figure out the main river depth and debris flow velocity after river blockage was established by Chen C. G. et al. (2012). However, the shock wave at the initial debris flow intersection was not fully considered in the model. Liu and Yao (2012) applied the finite volume method to simulate and analyze the flow field of the main river under different blocking coefficients of debris flows in the partial blockage pattern; however, in the model, the debris flow blockage body is generalized as circular, which is inconsistent with the actual fan-shaped accumulation body, and under the action of the main river flow, the fan edge will inevitably shift in the water flow direction (**Figure 4**). Some commonly used fluid mechanics simulation software applications have also been used to simulate the debris flow movement and accumulation process. For example, CFX software was used by Han et al. (2016) and Xu et al. (2019) to simulate debris flows in the Mozi gully in Wenchuan County and Shiwulong Gully in Rantang County, respectively; FLO-2D software was used by Wang et al. (2017) to simulate and analyze river blockage patterns of the Guangyuanbao gully debris flows under different rainfall intensities. Although these pieces of software have high accuracy in the simulation of debris flow movement, there are large errors in the simulation of the debris flow accumulation process because these pieces of software do not consider the

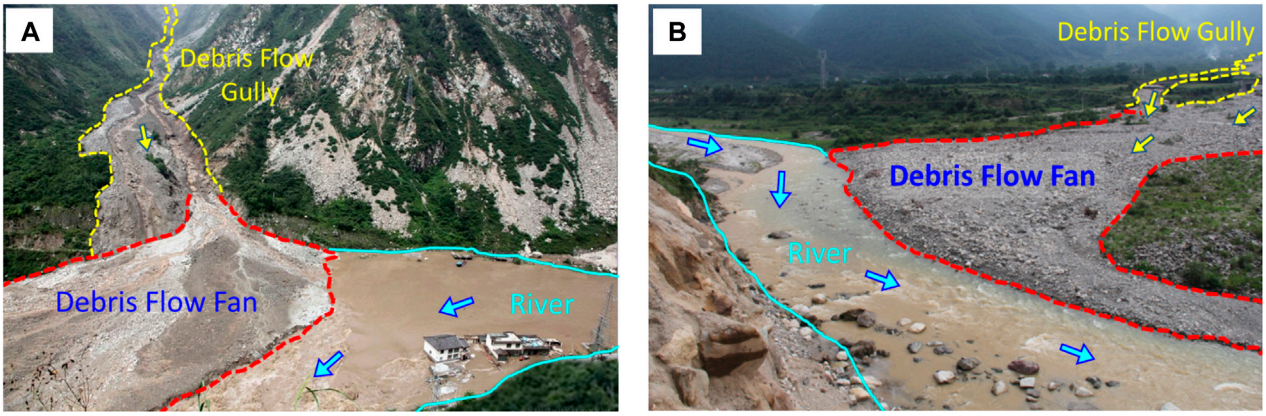

FIGURE 4 | (A) On July 3, 2011, the debris flow in Gaojiagou Gully, Yinxing Township, Wenchuan County, Sichuan Province blocked the Minjiang River. **(B)** On June 26, 2020, a debris flow in Yihai Town, Mianning County, Sichuan Province blocked Caogu River..

TABLE 3 | Some new numerical simulation methods in recent years.

Method	Features
DDA	DDA (discontinuous deformation analysis) is a numerical analysis method for geotechnical engineering, which can be used to simulate discontinuous large deformation problems.
MPM	MPM (material point method) is a new particle numerical method with the advantages of Lagrange description and Euler description, which is especially suitable for the analysis of problems with large deformation and moving interfaces.
PFEM	PFEM (particle finite element method) is also the combination of Euler and Lagrange methods, which can consider free surface, breaking wave, flow separation, etc., and can effectively avoid grid distortion in large deformation.
SPH	Core of the SPH (smoothed particle hydrodynamics) method is the interpolation principle of the kernel function, which strictly meets the mass conservation. Different rheological constitutive relations can be used in the calculation model, which is suitable for dealing with large deformation, movable boundary, free surface tracking, and moving interface problems.
NMM	NMM (numerical manifold method) uses mathematical and physical two sets of independent cover systems, which only need to cover the whole calculation area with regular grids. The cover function can be freely selected, according to the type of solving problems, and can solve continuous and discontinuous problems uniformly.
DEM	DEM (discrete element method) takes particles as the research object and reflects the microscopic dynamic characteristics of a large number of particles by defining the interaction between particles, which is suitable for analyzing the water debris flow and diluted debris flow with a small viscosity of the slurry.
CFD-DEM	CFD-DEM (computational fluid dynamics–discrete element method) is a coupling calculation of the continuous medium and discrete medium, which is suitable for simulating the debris flow with obvious gap flow and solid particle interaction.

interaction between the debris flow and the main river water flow in the simulation.

Therefore, for the complex process involving sediment dynamics, hydrodynamics, and soil dynamics of the debris flow blocking the river, it is necessary to consider using other relatively novel numerical simulation methods, such as DDA (Fu et al., 2020), MPM (Du et al., 2021), and NMM (Yang et al., 2019, 2020; Zheng et al., 2019). **Table 3** lists some new numerical simulation methods in recent years, which can be used to simulate the process of debris flows blocking the river.

All the aforementioned studies are aimed at analyzing river blockage induced by the viscous debris flow. The main reason is that diluted debris flows are accompanied by the sedimentation of large particles during the movement. The internal composition is highly heterogenous, and the related mechanism is far more complicated. Furthermore, the results of numerical simulation are quite different from reality since the numerical simulation parameters of the debris-flow dams are difficult to be calibrated, and the model's boundary conditions and dynamic equations are oversimplified. Hence, numerical simulation studies on the process of river blocked by diluted debris flows are rare at present.

3 MECHANISM OF DEBRIS-FLOW DAM FAILURE

The internal composition of debris flows and the dynamic process of river blockage are complex. There are great differences between the dams induced by debris flows and the ones induced by the landslides (or maimora dam) (Wang et al., 2017; Wu et al., 2020). The former is difficult to maintain long-term stability and often bursts soon, and dam failure often occurs when there is an overtopping flow (Yan et al., 2009). The main differences between different types of barrier dams are shown in **Table 4**. These differences lead to the inevitable differences between the collapse process and the mechanism of the debris-flow dam and

TABLE 4 | Comparing different types of barrier dams.

Category	Debris-flow dams	Landslide dams	Moraine dams	Notes
Formation conditions	It is formed by the debris flow blocking the river (Wang et al., 2017; Zou et al., 2020).	It is formed by landslides blocking the river (Cui et al., 2009; Li et al., 2021).	It is formed by moraine accumulation and contains buried ice (Clague and Evans, 2000; Benn and Owen, 2002.	—
Geometry of the dam	Dam height and upstream and downstream slopes are smaller than those of landslide dams Cheng et al. (2007); Dang et al. (2009b)	Dam height and upstream and downstream slopes are larger than those of other dams Lai et al. (2015); Shen D. et al. (2020).	Dam height and upstream and downstream slopes are smaller than those of landslide dams Evans and Clague (1994).	In most cases
Water content of the dam	Full saturation Cheng et al. (2007); Dang et al. (2009b); Wang et al. (2017)	Natural water content Cui et al. (2009); Li et al. (2011); Zheng et al. (2021)	Natural water content Osti et al. (2011); Herrmann and Bucksch (2014); Begam et al. (2018)	In most cases
Clay content of the dam	High Dang et al. (2009b); Liu J. F. et al. (2014)	Middle Cui et al. (2009); Zhang et al. (2016); Zhang et al. (2019)	Low Osti et al. (2011); Begam et al. (2018); Neupane et al. (2019)	In most cases
Roundness of the dam material particles	High Dang et al. (2009b); Wang et al. (2009)	Middle Li et al. (2011); Zhang et al. (2016); Zhong et al. (2017); Zheng et al. (2021)	Low Herrmann and Bucksch (2014); Begam et al. (2018); Neupane et al. (2019)	In most cases
Structure of dam	Dense and poor particle sorting Dang et al. (2009b); Liu J. F. et al. (2014)	Relatively loose and good particle sorting Zhang et al. (2019); Zheng et al. (2021)	Loose and poor particle sorting Evans and Clague (1994); Neupane et al. (2019)	In most cases
Permeability of the dam	Low Dang et al. (2009b)	Middle Gregoretti et al. (2010); Wang et al. (2017); Zheng et al. (2021)	High Liu J. J. et al. (2013); Neupane et al. (2019)	In most cases

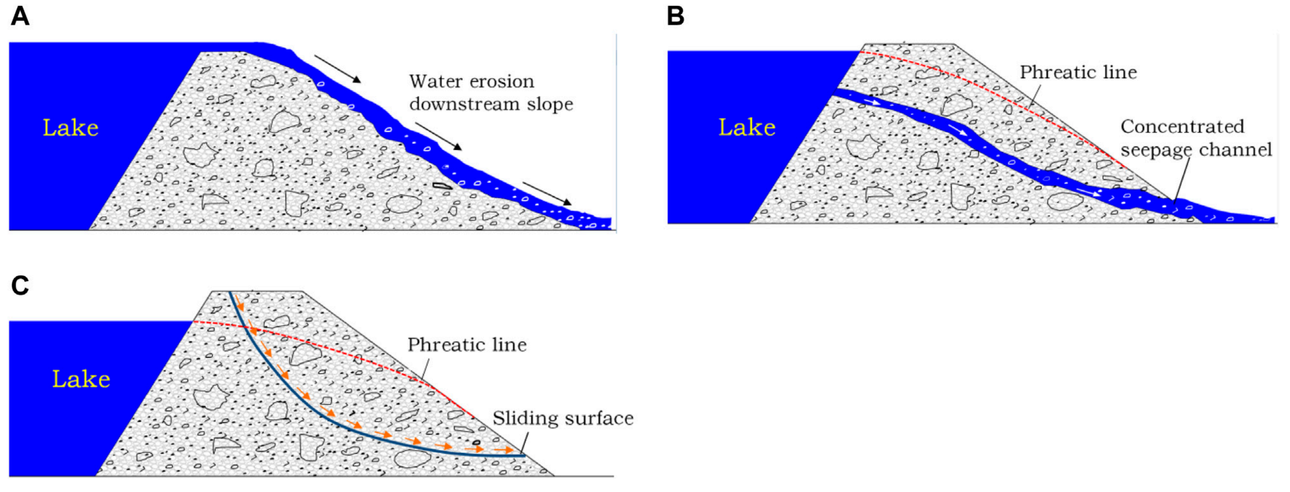

FIGURE 5 | Failure modes of a debris-flow dam: **(A)** Overtopping, **(B)** piping, and **(C)** slope instability.

other dam types. For example, the former is difficult to maintain long-term stability and often bursts soon, and dam failure often occurs when there is an overtopping flow (Yan et al., 2009).

There are three failure modes of a barrier dam: overtopping, piping, and slope instability (**Figure 5**) (Peng and Zhang 2012; Shrestha and Nakagawa 2016; Dhunagan and Wang 2019; Kumar et al., 2019; Jiang et al., 2020; Ruan et al., 2021). However, because the debris-flow dams are mostly saturated, they have high clay content and strong water-retaining property; moreover, the height and slope of debris-flow dams are much smaller than other dams (landslide dam and moraine dam), and the seepage path is longer (Chen et al., 2011; Liao et al., 2012; Pan et al., 2013; Liu et al., 2015; Neupane et al., 2019; Sattar et al., 2019; Zou et al., 2020). Therefore, it is very difficult for the debris-flow dam to have piping or dam slope failure.

In the process of debris-flow dam failure, based on the flume model experiment, Ruan et al. (2021) drew on the idea of dividing landslide dams and divided the failure process of debris-flow dams into three stages according to the longitudinal evolution characteristics of the breach: the formation stage of the retrogressive scarp, the erosion stage of the retrogressive scarp, and the decline stage of the retrogressive scarp (**Figure 6**). Different from landslide dams, the debris-flow dam can form a very obvious retrogressive scarp in the process of failure. In addition, in a recent study, we found that the erosion rate and peak discharge of debris-flow dam failure were significantly higher than those of landslide dams under the same conditions, and the peak time of debris-flow dam failure was slower (**Figure 7**). Therefore, in the future, it is necessary to further compare and study different types of dams (the debris-

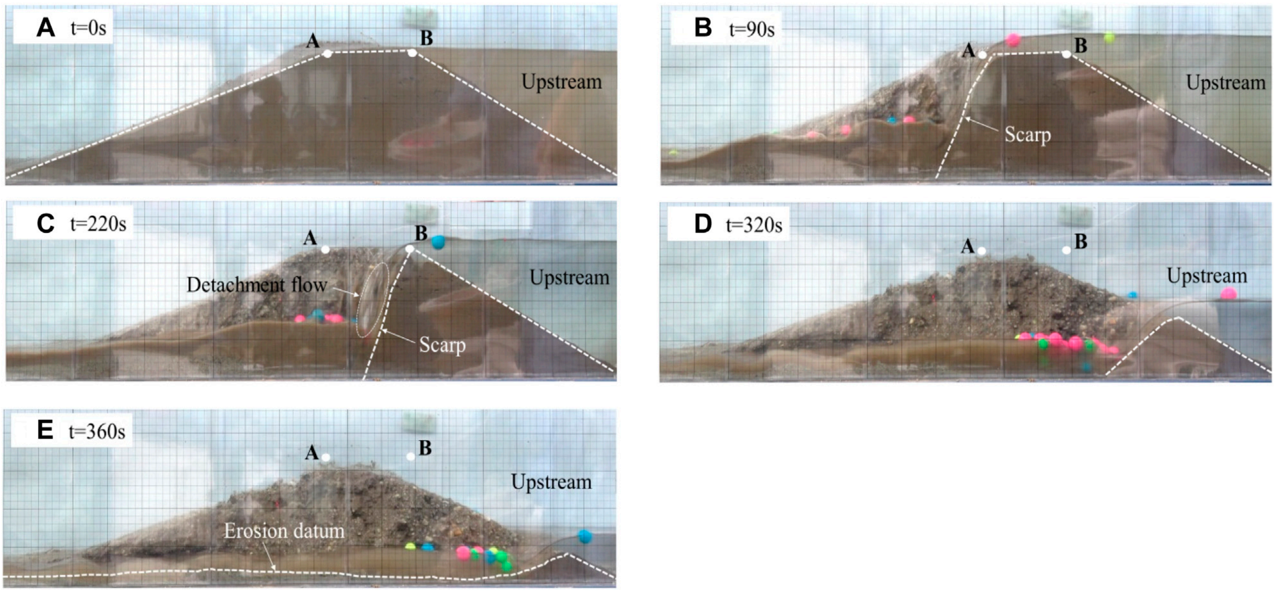

FIGURE 6 | Longitudinal evolution process of the debris-flow dam breach. **(A,B)** Formation stage of the retrogressive scarp (0–90 s); **(B–D)** Erosion stage of the retrogressive scarp (90–320 s); and **(D,E)** Decline stage of the retrogressive scarp (320–360 s) (Ruan et al., 2021).

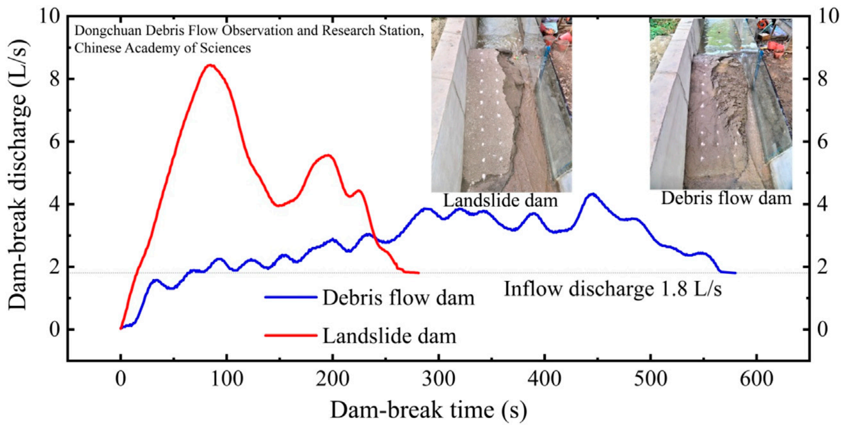

FIGURE 7 | Comparison of the dam-break discharge between a debris-flow dam and a landslide dam.

flow dam, landslide dam, and moraine dam) and construct the theory and model of different types of dams.

A reasonable description of the development process of the breach (the longitudinal downcutting process and cross widening process) is a prerequisite for accurate simulation of the outburst flood. At present, several models of the breach evolution of barrier dams have been proposed (**Figure 8**). The models of Chang and Zhang (2010), Zhong et al., (2017), and Zhou G. G. D. et al. (2019) are only applicable to landslide dams. When Chang and Zhang's (2010) and Zhong et al's., (2017) models are used to simulate the outburst flood, the cross-sectional shape of the breach is assumed to be trapezoidal (**Figures 8A,B**). Zhou G. G. D. et al's. (2019) model does not have a calculation model for the cross widening of the breach and a complete calculation model for the longitudinal evolution of the breach (**Figure 8C**), which cannot be applied to numerical simulation. Ruan et al. (2021)obtained the longitudinal evolution model of a debris-flow dam through flume experiments (**Figure 8D**), but the bottom slope and velocity of the breach in the model are difficult to obtain in advance (**Formula 1**), and there is no cross expansion model of the breach, which cannot be applied to numerical simulation.

$$E = -0.01 \cdot \left(0.0149\frac{\ln(\mu)}{\mu} + 2.72\frac{1}{D_c^2} + 0.301\right) \cdot v \cdot \sin(0.85+\theta)^3, \quad (1)$$

where E is the erosion rate (cm/s); μ and Dc are grain-size distribution parameters (Li et al., 2013; Li et al. 2015; Li et al.

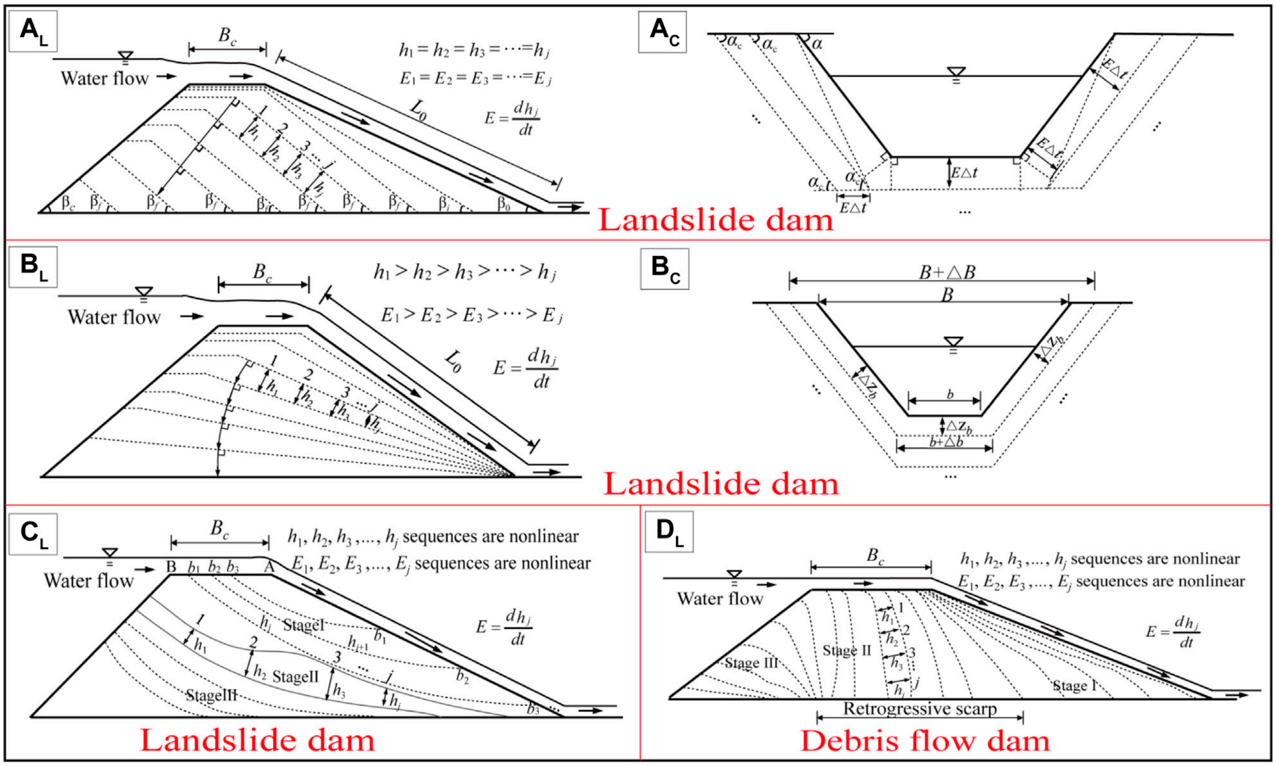

FIGURE 8 | Evolution models of the breach of the barrier dam. **(A)** Evolution model of the breach of the landslide dam proposed by Chang and Zhang (2010) (modified). **(B)** Evolution model of the breach of the landslide dam proposed by Zhong et al. (2017) (modified). **(C)** Evolution model of the breach of the landslide dam proposed by Zhou G. G. D. et al. (2019) (modified). **(D)** Evolution model of the breach of the debris-flow dam proposed by Ruan et al. (2021) (modified). The subscript "L" in the figure number represents the "longitudinal evolution of the breach" and "V" represents the "cross evolution of the breach".

TABLE 5 | Several dam-break models based on dynamics proposed in recent years.

Model	Sediment transport	Breach shape	Flow over the dam	Breach mode	Soil erodibility	Reference
DABA	Meyer–Peter and Müller formula	Trapezoidal	Broad-crest weir flow	Overtopping	Varied	Chang and Zhang (2010)
Zhong et al.'s model	Linear shear stress erosion formula	Trapezoidal	Broad-crest weir flow	Overtopping	Constant	Zhong et al. (2017)
DB-IWHR-2018	Hyperbolic shear stress erosion formula	Trapezoidal	Broad-crest weir flow	Overtopping	Constant	Chen et al. (2015)

2017); v is the flow velocity of the breach (m/s); and θ is the longitudinal slope of the breach (°).

The numerical simulation of debris-flow dam failure is still in the preliminary exploration stage. Depending on the gradual breach model (Zhang and Huang 2007; Huang 2008), Zhao et al. (2009) stimulated the flood discharge process and calculated the peak discharge of the debris-flow dam in the Kezi River, Xinjiang. In this model, it is assumed that the cross-sectional shape of the breach is trapezoidal. However, for high viscous debris-flow dams, the failure process is often accompanied by intermittent large-scale collapse of the negative angle breach slope (Ruan et al., 2021). Moreover, Liu Hd et al. (2013) calculated the stability of a debris-flow dam by FLAC3D software, which can be used to determine the failure possibility of the debris-flow dam. However, the stability of a debris-flow dam is not the focus of the study because the length of a debris-flow dam along the river is usually very long, and the upstream and downstream dam slopes are much slower than those of the landslide dam. It is difficult to understand the instability of the dam slope, and the overtopping failure is the focus of the study of the debris-flow dam. **Table 5** summarizes several dam-break models based on dynamics proposed in recent years, which can simulate the evolution process of the break and the dam-break flood hydrograph, but they are only applicable to the simulation calculation of a landslide dam. In the future, these models can be improved according to the characteristics of debris-flow dams, and then, some dam-break models suitable for debris-flow dams can be obtained.

In summary, little research on the failure of debris-flow dams has been conducted until now. The existing research studies mainly focus on the failure mode and process of dam break. Research on the failure mechanism of a landslide dam, especially the evolution law of the debris-flow dam of the breach, including longitudinal

TABLE 6 | Empirical formula for the peak discharge of dam break.

Empirical formula	Parameter	Applicable condition	Reference
$Q_p = 6.3 \cdot (H_d)^{1.59}$.	H_d—dam height (m)	Landslide dam	Costa (1985)
$Q_p = 672 \cdot (V_1)^{0.56}$, $Q_p = 181 \cdot (V_1 H_d)^{0.43}$.	V_1—volume of dammed lake (m^3) and H_d—dam height (m)	Landslide dam	Costa and Schuster (1991)
$Q_p = 0.0158 \cdot (PE)^{0.41}$, $Q_p = 0.99 \cdot (dV_0)^{0.40}$.	PE—potential energy of water, d— lake water-level drop during the flood (m), and V_0—volume of dammed lake (m^3)	Landslide dam	Walder and O'Connor (1997)
$Q_p = g^{0.5} H_d^{2.5} (H_d/H_r)^{-1.417} \cdot (V_1^{1/3}/H_d)^{1.569} \cdot (V_d^{1/3}/H_d)^{-0.471} \cdot (H_d/W_d)^{-0.265} \cdot e^a$.	g—the acceleration of gravity (m/s^2), H_d—dam height (m). $H_r = 1$ m, V_1—volume of dammed lake (m^3). W_d—dam width (m), V_d —dam volume (m^3), and a—erodibility coefficient	Landslide dam	Peng and Zhang (2012)
$Q_p = 1.268 \cdot (H_w + 0.3)^{2.5}$.	H_w—height of water above final breach bottom (m)	Embankment dam	Kirkpatrick (1977)
$Q_p = 1.776 \cdot (S)^{0.47}$.	S— lake area (m^2)	Embankment dam	Singh and Snorrason (1984)
$Q_p = 1.154 \cdot (V_w H_w)^{0.412}$.	V_l—volume of water above the final breach (m^3) and H_w—height of water above final breach bottom (m)	Embankment dam	Macdonald and Langridge-Monopolis (1984)
$Q_p = 0.6971 (H_w)^{1.5} (V_1)^{0.25}$.	H_w—height of water above final breach bottom (m) and V_l—volume of the dammed lake (m^3)	Embankment dam	Hakimzadeh et al. (2014)
$Q_p = 0.038 (V^{0.475} H^{1.09})$.	H —height of water behind the dam (m) and V —volume of water behind the dam (m^3)	Embankment dam	Pierce et al. (2010)
$Q_p = 0.6971 (H_w)^{1.5} (V_1)^{0.25}$.	H_w—height of water above final breach bottom (m). V_l—volume of the dammed lake (m^3)	Embankment dam	Froehlich et al. (1995)
$Q_p = 0.0443 g^{0.5} V_1^{0.367} H_w^{1.40}$.	g—the acceleration of gravity (m/s^2), H_w—height of water above final breach bottom (m), and V_l —volume of the dammed lake (m^3)	Embankment dam	Webby (1996)

and cross evolution laws of the breach, is relatively limited. In addition, there are no numerical models and theoretical calculation methods that can completely and reasonably describe the evolution law of the breach of the debris-flow dam (undercutting erosion and lateral collapse of the breach) and the flow discharge during the dam failure process. The dynamic model of the debris-flow dam break should be constructed in the future. Furthermore, from **Table 6**, it can be found that there is no empirical formula for the peak discharge of dam break that is applicable to debris-flow dams, which is also the focus of future studies.

4 HAZARD CHAIN TRIGGERED BY RIVER-BLOCKING DEBRIS FLOWS

Mountain hazards often include collapses, landslides, debris flows, and glacial lake outburst floods (GLOF). (Zhong et al., 2017; Begam et al., 2018; Bhambri et al., 2019; Medwedeff et al., 2020; Shen P. et al., 2020). However, sometimes due to factors such as limited space, large-scale or extra large-scale mountain hazards often transform from one kind to another, forming hazard chains and causing severe damages (Shulmeister et al., 2009; Xu et al., 2014). There are many variants of mountain hazard chains, with different combinations of disaster types (Zhong et al., 2013). "The debris-flow river-blocking debris-flow dammed-lake dam-break flood" is only a common type of the mountain hazard chain. Due to the distinctions in material composition, structure, movement form, and enlargement scale, the dynamic process of river blocking and dam failure caused by debris flows is significantly different from that caused by collapse or landslides.

4.1 Basic Characteristics and Mechanism

Attention was paid to formation, basic characteristics, distribution laws, hazard risk analysis, and prevention measures of debris flows in the last couple of years. However, less attention was paid to the hazard chain caused by debris flows. Cui et al. (2008) pointed out that Wenchuan earthquake-induced debris flows→dammed lakes→burst floods and secondary disasters were distributed intensively along the fracture zone and its two sides from the perspective of regional spatial analysis, and it did not involve the transformation process and mechanism of disasters. Xu et al. (2012) analyzed the formation conditions and chain formation mechanism of four types of disasters chains and found that in all these disaster chains, each episode was caused by the previous episode. Moreover, the amount of mass movement decreased along the disaster chains. Zou et al. (2013)investigated and analyzed some typical hazard chains after the Wenchuan earthquake and pointed out that a complete hazard chain process includes four key stages: disaster formation, the triggering stage, damage stage, and chain-breaking stage; but these analyses were qualitative. Zhong et al. (2013)analyzed the factors causing a mountain hazard chain and pointed out that the formation of mountain hazard chains is the result of interaction, infiltration, transmission, and transformation of materials and energy of each disaster under specific conditions. The most remarkable characteristic of a disaster chain is the obvious amplification effect in the evolution process of the disaster chain. However, there are very few quantitative research studies on the amplification effect of disaster chains caused by debris flows, which is the focus of future research. He (2014) preliminarily simulated and calculated the river-blocking debris flow and dam-break hazard chains caused by the so-called "8.13 Hongchun gully large-scale debris flow" from three aspects: the impact force of the debris flow, peak discharge of dam breaks, and the evolution process of flood outburst; but these three parts are separated in the analysis process. Fan et al., (2020) first integrated the rock mass stability model (FLAC^{3D} and RocPlane tools), landslide sliding MassFlow program, dam-break DABA program, and dam-break flood HEC-RAS program to simulate

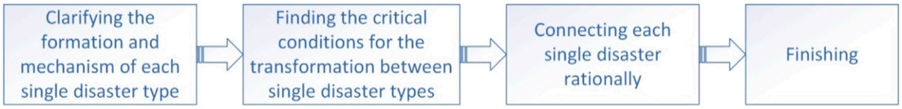

FIGURE 9 | Research ideas of the disaster chain.

the whole process of river blocking and collapse hazard chains which might be caused by three potential landslides in the Baige landslide dam. Although each model has its limitations to some extent, the simulation process has error accumulation; the study only focuses on the river-blocking landslide break hazard chain, and it provides a new idea for the study of river-blocking debris flow-dam break hazard chains and other types of disaster chains (**Figure 9**). In addition to numerical simulation, experimental research can also be used as an important research method for future research on the disaster chain.

The transformation among disaster types is the key in forming a hazard chain, making the critical conditions of the transformation a prerequisite for the formation of a hazard chain. Although achievements have been made in studying critical conditions of river-blocking debris flows and the dam-break model, the two are studied separately. In order to get a better understanding of the transformations in the hazard chain and quantitative descriptions of the whole process, it is necessary to conduct a systematic and in-depth analysis of the whole hazard chain and the evolution process of each knot in the chain.

4.2 Risk Assessment and Key Prevention and Control Technologies

Risk assessment of a single mountain-hazard type has been relatively mature after years of development. Based on empirical methods and numerical simulation methods (Tacconi Stefanelli et al., 2020; Choi et al., 2021), a relatively mature mountain-hazard risk assessment system has been established. However, in the context of global warming, a single mountain-hazard type is often transformed to form a hazard chain with strong destructive power (Fan et al., 2020), which also brings many challenges to the risk assessment of the hazard chain. For example, the specific challenges of the risk assessment of the hazard chain caused by debris flows are as follows. 1) The hazard chain caused by debris flows mainly includes three single types of hazards (the debris flow, weir dam, and outburst flood). The three single types of hazards occur continuously and follow their respective physical laws and transformation mechanisms. Therefore, in the risk assessment, it is necessary to clarify the transformation mechanism of three single types of hazards and systematically evaluate the entire hazard chain. For example, the physical properties of the debris flow in the process of movement are changing at all times, and there are erosion and scale amplification effects along the movement direction (Chen et al., 2020). The characteristics of the dam after debris flow blocking the river and the evolution of the outburst flood need to be fully considered. 2) In the risk assessment, it is necessary to take full account of the hazard-bearing bodies within the impact range of the entire hazard chain, but the impact range is often hundreds of kilometers or even thousands of kilometers. The hazard-bearing bodies involved mainly include roads, railways, bridges, villages, and farmland. The workload of the investigation is very huge. Hence, the traditional risk assessment method of a single hazard type cannot meet the quantitative assessment requirements of many mountain hazard chains. On this basis, it is necessary to further consider the relationship between various single hazards to truly describe the risks brought by the evolution process of the mountain hazard chain.

At present, the key technologies for debris flow prevention and control have been studied in depth. A variety of debris flow prevention and control projects have been proposed, such as check dams (Kim and Kim 2021) and drainage channels (Wang et al., 2021), and have been widely applied to effectively reduce the risk of debris flow hazards. In terms of the debris-flow dam, there is no key technology for the prevention and control of the debris-flow dam, and the related prevention and control technology of the landslide dam can be used for reference in the future. Most importantly, for the large-scale hazard chains occurring in the alpine gorge area, such as the hazard chain caused by debris flows, the conventional key technologies for the prevention and control of single disaster types cannot meet the needs of hazard reduction. Therefore, on the basis of clarifying the evolution mechanism of hazard chains, we need to develop new materials and structural prevention and control projects suitable for strong earthquake, high altitude, extremely cold and large temperature difference working environments, explore new hazard risk prevention and control principles, and regulate the whole process of hazard chain material and energy. In addition, effective engineering measures are needed to control the key links of hazard chain and cut off the critical conditions of disaster chain transformation.

5 CONCLUSION AND PROSPECTS

Although some progress has been made in studying debris flows that block the main river, the investigations on hazard chains of river-blocking debris flows and dam-break floods are still at an initial stage. Some conclusions and several frontier scientific issues on the river-blocking mechanism by debris flows and dam failure hazard chains are drawn as follows:

1) There are three patterns of river-blocking debris flows: complete blockage, partial blockage, and submerged dam blockage. Although the river-blocking factors have already been considered comprehensively and varied discriminants were established, studies on river blocking are mostly restricted at laboratory scales (flume tests), which limit the applications of the established river-blocking discriminants because the characteristics of the debris flows, the shape of the

main river, and its hydrogeological conditions are unique in real-world scenarios. In addition, studies on the mechanism of river blocking by debris flows mainly focus on describing the macro phenomena. There are fewer quantitative achievements in describing the mathematical model of the dynamic process in water–particle interactions, which is also the main reason for low accuracies in the simulation results. In this regard, it is necessary to elaborate on the coupling mechanism of debris-flow dam formation, and then, a discriminant and numerical simulation model of debris flow blocking the river with multiple influencing factors and larger application scope should be established in the future. In the meantime, a large-scale model test is worth considering in future studies.

2) At present, studies on the breach of debris-flow dams mainly focus on the breach mode and dynamic failure process by considering different particle size distribution, bulk density, and clay content of a debris-flow dam, not on the breach mechanism, especially the law of the breach development (undercut and side collapse of the breach). There is no numerical model or theoretical calculation method that can reasonably reflect the evolution law of the breach and the discharge hydrograph of the outburst flood. It is vital to estimate the peak discharges of the outburst flood and erosion rate of dam materials accurately in order to predict the dynamic failure process of the dam with higher precision. Hence, in the future, it is necessary to further strengthen the research on the mechanism of debris-flow dam failure, accurately describe the evolution process of the breach, establish the physical model of debris-flow dam failure based on dynamics, and establish a prediction model of the peak discharge of debris-flow dam failure.
3) The hazard chain of river-blocking debris flows and dam failure is a common type of mountain hazard chain, with continuous evolution and strong destructive power. Although researchers have made some progress in the blockage and breach models, the investigations are designed and conducted separately. Also, related studies are still lingering over the initial stage, mainly focusing on typical case studies of the hazard-inducing environments, inducing factors, basic characteristics, and prevention measures. In addition, the research study on the risk assessment and key prevention and control technology of the disaster chain caused by debris flows is still in the initial stage of exploration. The traditional risk assessment theoretical methods and key prevention and control technology for a single disaster type are no longer applicable to the disaster chain caused by debris flows, especially because the current understanding of the whole dynamic evolution process of the disaster chain is not enough. In this regard, it is worth noticing the critical conditions and dynamic evolution process of hazard type transformation, conducting in-depth and systematic investigations on the hazard chain, and completing a quantitative description of the whole process of the hazard chain. Finally, a complete hazard chain risk assessment system should be established, and some key prevention and control technologies suitable for the hazard chain should be developed as well, including new materials, prevention and control projects, and emergency plan measures.

AUTHOR CONTRIBUTIONS

HC and HR finished the manuscript. XL and YY collected the data and references. JC, HC, and HR modified the manuscript. All authors contributed to the manuscript and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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