

Article

Numerical Investigation of the Erosive Dynamics of Glacial Lake Outburst Floods: A Case Study of the 2020 Jinwuco Event in Southeastern Tibetan Plateau

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Abstract

Glacial lake outburst floods (GLOFs) represent increasingly common and high-magnitude geohazards across the cryosphere of the Tibetan Plateau, particularly under ongoing climate warming and glacier retreat. This study combines multi-temporal remote sensing imagery and detailed Flo-2D hydrodynamic modeling to investigate the erosive dynamics of the 2020 Jinwuco GLOF in Southeastern Tibetan Plateau. Key conclusions include: (1) The 2.35 km-long flood routing channel exhibits pronounced non-uniformity in horizontal curvature, channel width, and cross-sectional shape, significantly influencing flood propagation; five representative cross-sections divide the channel into six distinct segments. (2) Prominent lateral erosion occurred proximally to the dam, attributable to extreme erosive forces and high sediment transport capacity during peak discharge, with horizontal channel curvature further amplifying local impact and erosion. (3) Erosion rates were highest near the dam and in downstream narrow segments, while mid-reach sections with greater width experienced lower erosion. (4) Maximum flow depths reached 28.12 m in topographically confined reaches, whereas peak velocities occurred in upstream and downstream curved sections. (5) The apparent critical erosive shear stress of bank material is controlled not only by soil strength but also by flood dynamics and pre-existing channel morphology, indicating strong feedback between flow dynamics, channel morphology, and critical erosive shear stress of bank material. This study provides a generalized and transferable framework for analyzing GLOF-related erosion in data-scarce high-altitude regions, offering critical insights for hazard assessment, regional planning, and risk mitigation strategies.

Keywords: glacial lake outburst flood; Tibetan Plateau; valley morphology; lateral bank erosion; critical erosive shear stress of soil



Academic Editor: Achim A. Beylich

Received: 22 August 2025

Revised: 19 September 2025

Accepted: 24 September 2025

Published: 27 September 2025

Citation: Li, S.; Li, C.; Li, P.; Shu, Y.; Li, Z.; Wang, Z. Numerical Investigation of the Erosive Dynamics of Glacial Lake Outburst Floods: A Case Study of the 2020 Jinwuco Event in Southeastern Tibetan Plateau. *Water* **2025**, *17*, 2837. <https://doi.org/10.3390/w17192837>

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1. Introduction

The IPCC Sixth Assessment Report (AR6) pointed out that human activities have already caused an average temperature increase of 1.1 °C [1]. The Tibetan Plateau, known as the “Third Pole,” has the largest number of glaciers outside the polar regions and is also the area most affected by global warming [2,3], with a warming rate twice the global average [4]. Under this trend, large-scale glacier melting on the Tibetan Plateau

is inevitable [5,6]. However, despite the overall shrinkage of glacier area on the Tibetan Plateau, the rate of glacier melting varies significantly across different regions. For example, glaciers around the Karakoram Mountains have shown slight mass gains, while the mass loss rate of glaciers in the southeastern Tibetan Plateau is about three times the average rate for the entire plateau [7]. Among these regions, the Yi'ong Zangbo Basin (In Tibet, large rivers are called Zangbo) is one of the areas where glacier retreat is most pronounced [8]. Between 1971 and 2000, the glaciers in this basin decreased in length at a rate of 48 m a^{-1} , with glacier area reducing at a rate of $0.57\% \text{ a}^{-1}$ [9]. The melting glacier water replenishes terminal glacial lakes, increasing their water volume. Statistics show that over the more than forty years from 1970 to 2016, the number of glacial lakes in the Yi'ong Zangbo Basin increased from 86 to 192, with the total area growing from 44.14 km^2 to 47.07 km^2 [10]. With the increase in the number and volume of glacial lakes, the potential risks and scale of GLOFs also increase exponentially.

GLOFs represent one of Earth's most potent geomorphic agents, capable of instantaneously reshaping high-mountain landscapes while unleashing catastrophic downstream hazards. Previous studies have documented numerous GLOF events. In June 2013, the Kedarnath disaster caused by heavy rainfall led to the death of over 6000 people, most of whom were victims of the GLOF triggered by Chorabari Lake in the Indian Himalayas [11]. On 28 July 2015, Lemthang Tsho in the Hindu Kush Himalaya experienced a breach due to a lateral slope collapse caused by concentrated rainfall. The estimated total flood discharge of this GLOF event was 0.37 million m^3 [12]. On 28 June 2020, Jinwuco in the Nidou Zangbo basin experienced a breach due to high temperatures and continuous rainfall, causing severe damage to downstream infrastructure [13]. Nie et al. mapped the distribution of glacier lakes in the Himalayas over five different periods based on remote sensing imagery and identified 118 rapidly expanding glacier lakes as potential risk lakes [14]. However, most glacier lakes only attract attention after a significant GLOF event occurs. At present, detailed studies on glacier lakes and subsequent GLOFs are scarce due to a lack of cloud-free satellite images and/or safe access to the field.

Unlike precipitation-driven floods, GLOF dynamics are distinguished by their abrupt onset, extraordinary sediment transport capacity, and unparalleled erosive power—attributes that stem from immense potential energy converted into kinetic energy as water plunges through steep, confined valleys. Recent advances integrate multi-scale methodologies to quantify erosional impacts. Satellite differencing and DEM analysis of the 2023 Sikkim GLOF revealed runaway erosion entraining 270 million m^3 of sediment—5.4 times the initial water volume—through 45 secondary landslides along a 67.5 km reach [15]. Similarly, studies of Himalayan cross-border basins using hydrodynamic models (HEC-RAS) show that GLOF peak discharges can reach $38,000 \text{ m}^3/\text{s}$, tenfold higher than seasonal floods, generating shear stresses sufficient to incise bedrock [16]. Cook et al. demonstrated that a single GLOF in Nepal's Bhotekoshi Valley caused more erosion than decades of monsoon rainfall, fundamentally altering river channels and hillslope coupling over tens of kilometers downstream from glacial sources [17].

A significant Glacial Lake Outburst Flood (GLOF) event, named the Jinwuco GLOF event, impacted Tibet, China, on 26 June 2020, coinciding with the early monsoon season characterized by elevated temperatures and heavy precipitation. The resulting floodwaters caused extensive infrastructure destruction and major societal consequences in areas downstream. Previous research has analyzed and reconstructed this disastrous Jinwuco GLOF event comprehensively by integrating numerical modeling with the analysis of remotely sensed data, eye-witness accounts, and media reports [18]. Here, we combine remote sensing imagery and the Flo-2D hydraulic model to numerically investigate of erosive dynamics of glacial lake outburst floods of the 2020 Jinwuco event in Southeastern

Tibetan Plateau. Firstly, we examine the valley morphological characteristics of Jinwuco GLOF using a morphometry method. Then, based on high-resolution satellite images, we investigate the spatial distribution and quantification of valley lateral bank erosion. Finally, based on a GLOF Process simulation with Flo-2D, we attempt to unveil the lateral bank erosion mechanisms of Jinwuco GLOF when propagating downstream. Ultimately, we discuss the influence of oversized boulders on the propagation of GLOF, modeling sensitivity analysis, and limitations of the current research.

2. Study Area

Jinwuco (30.356° N, 93.631° E) is a moraine lake in the upper reaches of the Yi'ong Zangbo basin (30°05'–31°03' N, 92°52'–95°19' E). The Yi'ong Zangbo originates in the Tibetan Plateau Nyainqêntanglha Mountains' southern foothills, with a total length of 286 km. The overall direction of flow is roughly north-west to south-east in a first-class tributary of the Parlung Zangbo and the second-level tributaries of Yarlung Zangbo (Figure 1a,b). It merges into the Parlung Zangbo in Tongmai Village, and then continues to flow southward, merging into the Yarlung Zangbo River near the big bend. The Yi'ong Zangbo Basin covers an area of 13,533 km² and is characterized by steep mountains and deep river valleys. Glaciers in the basin are mainly distributed along the mountain range, with year-round snow cover at elevations above 3500. The Yi'ong Zangbo Basin lies at the intersection of the westerly wind belt, the Indian Ocean monsoon, and the Southeast Asian monsoon, resulting in a warm and humid climate. The average annual temperature is 8.8 °C, the average annual rainfall is 958 mm, influenced by the Indian Ocean monsoon, and the rainfall is concentrated in May–September. Figure 1c depicts the position, pre-GLOF channel, pre- and post-glacial lakes of the Jinwuco glacier lake. The dotted rectangle depicted the studied upstream gentle valley section with an average gradient of 4.67% (marked with OA) in the current research. And the downstream valley section AB is extraordinarily steep with a gradient of 40.95%, which is out of the scope of the current research owing to two main reasons. The first reason is that the initial channel in the steep valley section AB contains several transverse curved sites. The GLOF undergoes significant flow acceleration along the steep slope, leading to intense downcutting and impact erosion. As a result, a new channel was incised by the flood within the original gully, while remnant unconsolidated deposits or bedrock outcrops remained partially eroded (Figure 1c). This process involved abrupt changes in both the flood hydrodynamics and channel morphology, which considerably complicated the subsequent quantitative analysis of lateral erosion mechanisms in this study. The second reason concerns the inherent limitations of the Flo-2D software (Version 6, 2009) when applied to steep terrains such as canyon section AB. Flo-2D simulates flood propagation based on the two-dimensional shallow water equations, which operate under a depth-averaged assumption. While this approach performs well in mild slopes and open plains, it encounters significant challenges in steep, complex topography. In section AB, the high slope gradient leads to rapid flow acceleration, supercritical flow conditions, and highly unsteady hydraulic behaviors. These conditions exacerbate numerical instabilities, such as oscillations in depth and velocity calculations, and may cause convergence issues in the finite difference solution scheme. Furthermore, the model's simplified treatment of vertical flow dynamics and energy loss becomes inadequate under such extreme topography, resulting in potentially large deviations in predicted flow depths, velocities, and erosion patterns. These computational deficiencies pose considerable challenges for accurately simulating lateral erosion and flood evolution in this steep section AB.

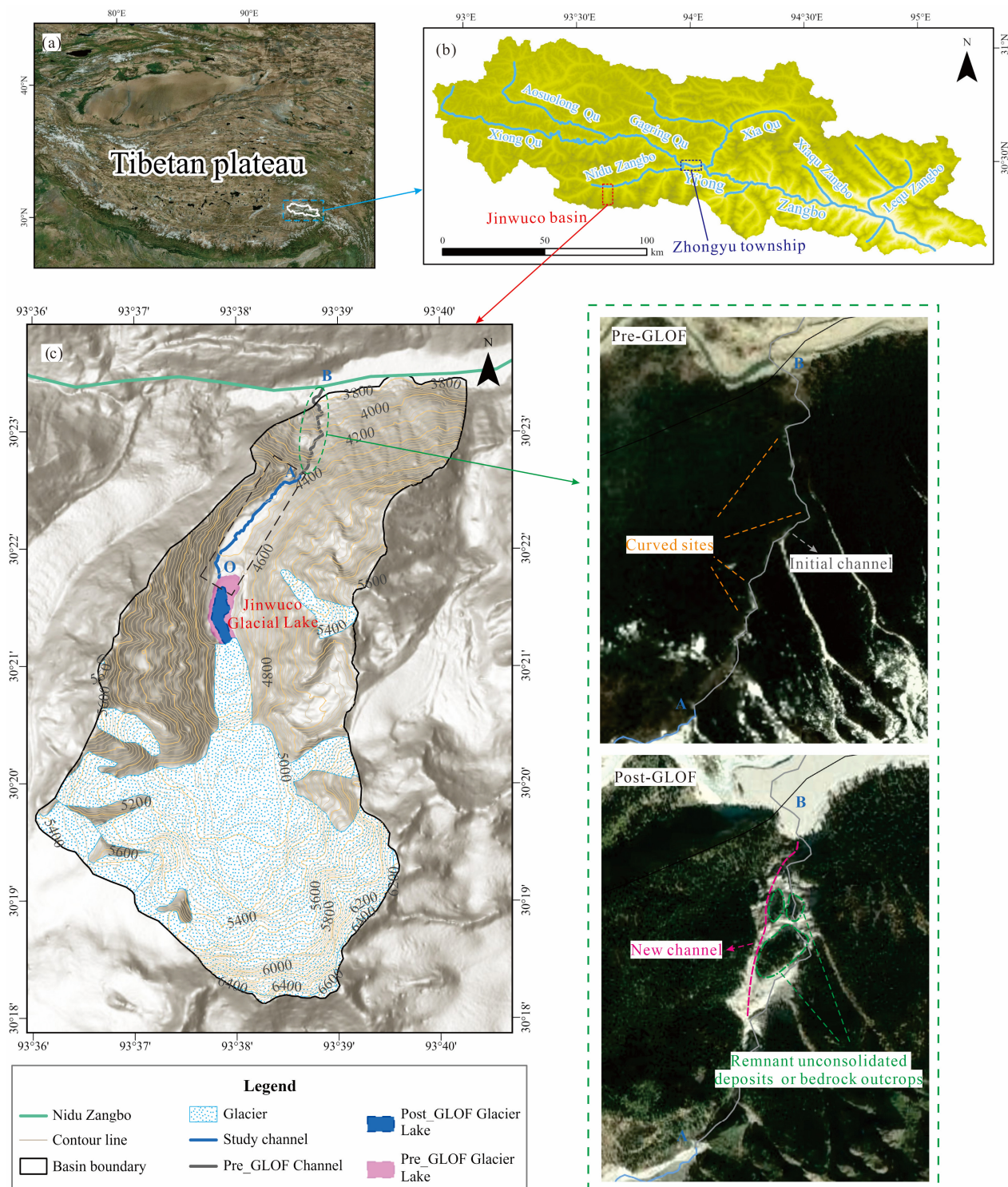


Figure 1. Overview of the study area. (a) Location of the Yi'ong Zangbo Basin. (b) Watershed extent and major tributaries of the Yi'ong Zangbo, and the locations of Jinwuco basin and Zhongyu township are denoted. (c) Jinwuco watershed. The pre-GLOF channel, as well as the pre- and post-glacier lakes, are indicated on the map. The dotted rectangle depicted the studied upstream gentle valley section (marked with OA) in the current research, while the downstream valley section AB is extraordinarily steep with a gradient of 40.95%, which is out of the scope of the current research. The background of figure (a) is the Jilin-1 satellite (2022). The background topography of figures (b,c) was generated from Copernicus DEM GLO-30 (2021). In the lower right corner of this figure, the pre-GLOF remote sensing image was captured on 17 April 2018 as shown in the 2020-11-18 version of the World Imagery map, and the post-GLOF remote sensing image was captured on 17 October 2021 as shown in the 2022-10-12 version of the World Imagery map.

According to the research of Zheng et al. [18], Jinwuco is a proglacial moraine-dammed lake, situated at the terminal of the Jinwuco Glacier with a covering area of 7.9 km². Remote sensing imagery (Maxar WV02 image, <https://livingatlas.arcgis.com/wayback/#mapCenter>, 17 April 2018) indicates that the lake's surface elevation is 4450 m, with an area of 0.56 square kilometers. Glacial mapping and depth measurements, as well as modeling, indicate that Jinwuco has a maximum depth of 54 m, an average depth of 28.5 m, and a total water volume of approximately 13.9×10^6 m³. By examining Maxar WV02 remote sensing images before (Taken on 17 April 2018) and after (Taken on 17 October 2021) the event, we found that the terminus of Jinwuco Glacier extends directly into the lake, with the glacier tongue entering the lake at about 350 m (Figure 2a). The lateral moraines on both sides of the lake have average slopes of approximately 40°. These slopes reach the critical threshold (>30°) for triggering geological disasters such as collapses and landslides, posing a potential risk of disaster chains where mountain hazards could induce GLOFs [19]. Jinwuco's moraine dam lies about 1768 m downstream of the glacier tongue, with a width of approximately 400 m and a height of 10 m. The moraine dam's western side features an outlet channel that sustains a constant surface flow. The GLOF from Jinwuco inflicted significant damage of varying severity on downstream villages and infrastructure lining both riverbanks. Further downstream, at a distance of 45 km from the moraine dam, Figure 2b compares Maxar WV02 remote sensing images of Zhongyu township before (Taken on 12 November 2019) and after (Taken on 18 February 2023) the event. There, the powerful floodwaters swept away roads and bridges, gave rise to channel realignment and hence endangered numerous riverside structures.



Figure 2. (a) A comparison of Maxar WV02 remote sensing images before (Taken on 17 April 2018) and after (Taken on 17 October 2021) the event. (b) Maxar WV02 remote sensing images of Zhongyu township before (Taken on 12 November 2019) and after (Taken on 18 February 2023) the event. The location of Zhongyu township is denoted in Figure 1b.

3. Materials and Methods

3.1. Data Acquisition

The pre-GLOF channel along the routing valley, the pre- and post-GLOF channel boundaries, glacier lakes of the Jinwuco event were obtained based on the Maxar WV02 remote sensing imagery. The pre-GLOF remote sensing image was captured on 17 April

2018 as shown in the 2020-11-18 version of the World Imagery map, and pixels in the source image represent a ground distance of 0.5 m; the post-GLOF remote sensing image was captured on 17 October 2021 as shown in the 2022-10-12 version of the World Imagery map, and pixels in the source image represent a ground distance of 1.2 m. The pre-GLOF channel longitudinal elevation changes and valley morphological features are mainly based on the ALOS 12.5 m DEM dataset (<https://search.asf.alaska.edu/#/>, 22 March 2011), which is derived from elevation data acquired by the Phased Array type L-band Synthetic Aperture Radar (PALSAR) onboard the Advanced Land Observing Satellite (ALOS), launched in 2006. The PALSAR sensor operates in three distinct observational modes: high-resolution, Scan SAR, and polarimetry. This DEM product achieves a horizontal and vertical accuracy of 12.5 m. Between 2006 and 2011, PALSAR generated a substantial volume of observational data, supporting a wide range of geoscientific applications.

The discharge hydrograph at the dam of the Jinwuco GLOF was obtained from the research of Zheng et al. [18]. The total duration of the GLOF was approximately 6965 s. The discharge of the GLOF increased gently in the beginning duration of 3000 s, abruptly reaching the peak value of about 4450 m³/s at the moment of approximately 4075 s, and then declined abruptly in the tailing phase. For simplicity, the valley lateral bank entrainment was assumed to occur mainly within the passage of relatively large flood discharge (exceed 1000 m³/s, as denoted by blue rectangle in Figure 3) with a duration of 2500 s, similar method has been adopted in previous studies regarding the entrainment of dam-outburst flood and abrupt released debris flow surges [20–22]. In the present research, we concentrate on the process of flood propagation 2.35 km downstream from Jinwuco glacier lake, where the GLOF flows into a superior steep valley section AB with a gradient of 40.95% (Figure 1c).

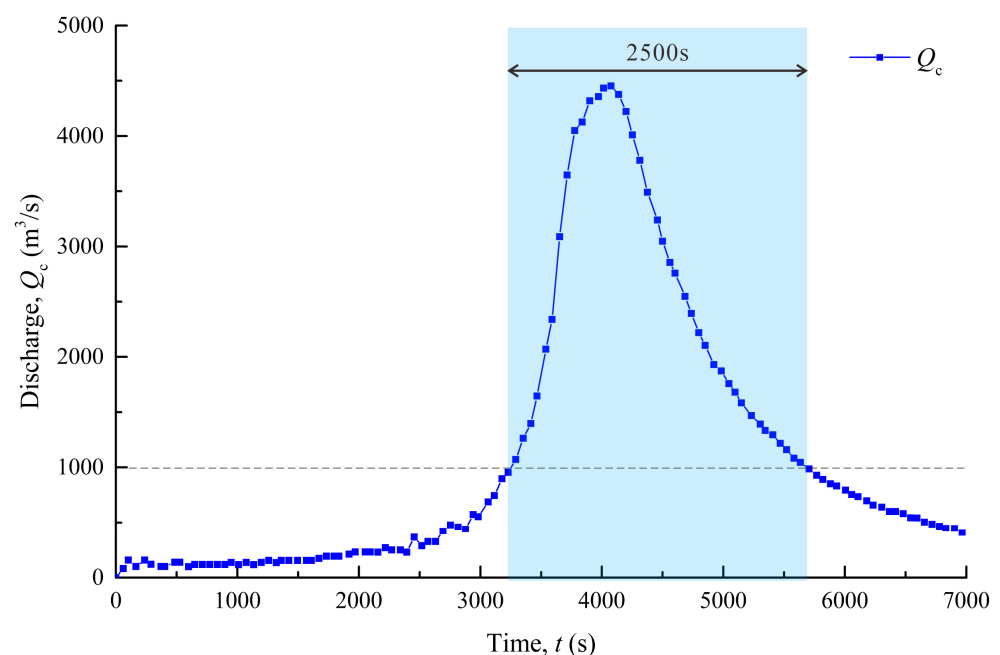


Figure 3. Discharge Hydrograph at the dam of the Jinwuco GLOF.

3.2. Valley Morphometry Analysis

The longitudinal elevation of the routing channel along the valley base is a vital parameter, as it determines the amount of potential energy converted into kinetic energy as the GLOF plunges through steep, confined valleys. Combined with high-resolution Maxar WV02 remote sensing imagery and the ALOS 12.5 m DEM dataset, we obtain the pre-GLOF longitudinal channel elevations H and identify the horizontal bending sites and extents.

The valley cross-sectional form, typically comprising V-shaped and U-shaped forms, can significantly affect the propagation and dynamics of the GLOF, and hence, the concurrent lateral bank erosion process. Here, we refer to a quantitative indicator named V-index proposed by Zimmer and Gabet [23], which quantifies valley cross-sectional shape by relating the area (A_x) between the valley bottom and a specified height (H_s) to the area of an ideal V-shaped profile of identical width and height (A_v). It is defined mathematically as

$$\text{V-index} = (A_x / A_v) - 1 \quad (1)$$

This metric, V-index, measures departure from the theoretical V-form: A precisely V-shaped profile yields V-index = 0; U-shaped profiles exhibit V > 0; and valleys with convex walls produce V-index < 0 (Figure 4).

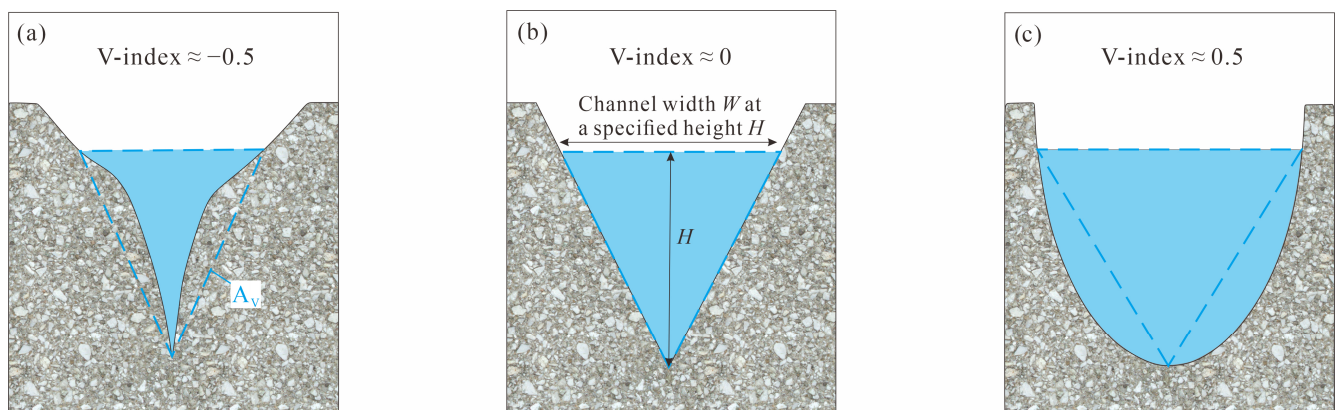


Figure 4. Illustrations showing the V-index spectrum and associated valley profiles. The hatched triangle denotes the ideal V-shape (A_v). (a) Negative V-index values correspond to valleys with convex walls; (b) V-index value equals 0 denotes a precisely V-shaped profile; (c) positive values indicate U-shaped valleys featuring concave walls.

3.3. Jinwuco GLOF Downstream Propagation Modeling

In this section, we use Flo 2D software (Version 6, 2009) to simulate the downstream propagation of Jinwuco GLOF. Flo-2D is a flood routing model that simulates river, alluvial fan, urban, and coastal flooding. Flo-2D can tackle any diverse flooding problem, including river overbank flooding and dam and levee breaches. Flo-2D has been approved as a hydraulic program for flood and debris flow simulation by the Federal Emergency Management Agency of the United States [24]. It is capable of simulating the process of glacier lake dam failure and flood evolution and meets the needs of the full hydrological simulation of the GLOF in the current research [25–27]. The discharge hydrograph depicted in Figure 3 is input as upstream boundary conditions to simulate flood propagation downstream of Jinwuco using Flo 2D. The flood evolution simulation in this study covers 2.35 km of the routing channel downstream of the Jinwuco glacier lake dam. Flo-2D is a grid-based model capable of accommodating varying channel and floodplain geometries. It employs the one-dimensional Saint-Venant equations, solved through a central difference, explicit numerical scheme, enabling detailed simulation of flood wave progression through both channel and overbank areas. The model is better suited to simulations with larger grid cells, as computational demand increases significantly with higher cell densities. For flood routing, the equations of motion are implemented by independently calculating the average flow velocity along each of the eight possible flow directions [24].

$$\frac{\partial h}{\partial t} + \frac{\partial(hv)}{\partial x} = 0 \quad (2)$$

$$\frac{\partial v}{\partial t} + v \frac{\partial(v)}{\partial x} + g \frac{\partial h}{\partial x} = g(S_0 - S_e) \quad (3)$$

where h is the flow depth, v is the depth-averaged velocity in one of the eight flow longitudinal directions, S_0 is the bed slope, and the friction slope S_f can be calculated using Manning's formulas as

$$S_f = \frac{v^2 n^2}{R^{4/3}} \quad (4)$$

in which n is Manning's value, and R is the hydraulic radius of the cross-section. Given that channel width significantly exceeds flow depth, the hydraulic radius R is approximated as flow depth h [28,29]. To obtain the topographic parameters and boundary conditions required for the simulation, we used the ALOS 12.5 m DEM dataset to construct the river grid as the base topography, set the upstream boundary as the modeled GLOF-outflow hydrograph, and defined the downstream condition using a normal depth assumption. Due to the good vegetation cover in the Jinwuco watersheds, the n values for the 2.35 km-long routing channel in the simulation were taken as 0.1, according to the recommendations in the Flo-2D User's Manual [24].

4. Result

4.1. Valley Morphological Characteristics of the Jinwuco GLOF

Initial valley morphological characteristics of the Jinwuco GLOF define the routing path of the flood and largely determine the energy conversion magnitude and hydrodynamic process of the GLOF. To facilitate understanding the effects of valley morphology on lateral bank erosion of the GLOF, 94 cross-sections with an interval distance of 25 m along the pre-GLOF channel are designed (Figure 5). There are two obvious horizontal curved sites at the positions of cross-sections S14 and S81. Figure 6 presents the variations in channel width and cross-sectional V-index at a specified height of 25 m along the 2.35 km-long routing path of the Jinwuco GLOF. The original channel widths comprised several widening and narrowing phases. From the dam of the glacier lake at cross-section S1 to S36, the width of the channel grew abruptly from 14 m to 216 m approximately. Then, the channel width withered rapidly to a width of 81 m at the cross-section of S50 and continued to reduce gently to a value of 11 m at the cross-section of S69. By examining the cross-sectional shape (quantified by a dimensionless parameter V-index in Figure 6b) along the routing path of the Jinwuco GLOF, we find three obvious V-shape sites #1, #2, and #3 (with the value of V-index approaching zero) at an approximate distance of 250 m, 1300 m, and 2100 m downstream the dam of the GLOF. The horizontally alternatively distributed U-shaped and V-shaped Valleys signified the existence of plentiful loose sediment along the routing channel, which can be incorporated by the GLOF.

In summary, the morphology of the 2.35 km-long routing valleys of the Jinwuco GLOF is non-uniform, characterized by varied horizontal curvature, channel depth, and cross-sectional shapes. Changes in channel curvatures and widths will significantly affect the propagation of the GLOF. The profound flow redirection, deceleration, and turbulence of the GLOF when passing over these sites will result in a lot of energy dissipation and hence affect its erosive potential. Based on the morphological analysis above, five representative cross-sections, namely, S14, S36, S50, S69, and S81, are discerned, which cut the 2.35 km-long channel into six segments. This classification will aid in the subsequent investigation on the erosion characteristics of Jinwuco GLOF.

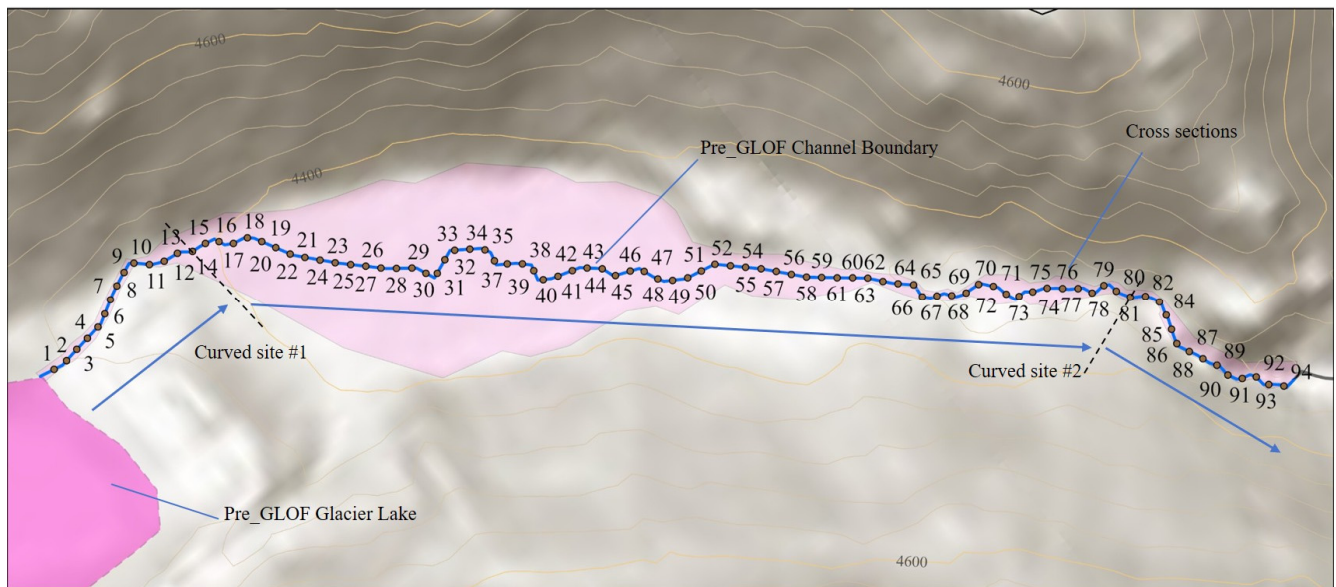


Figure 5. Distribution of 94 cross-sections with an interval distance of 25 m along the pre-GLOF 2.35 km-long channel. Two horizontal curved sites are denoted.

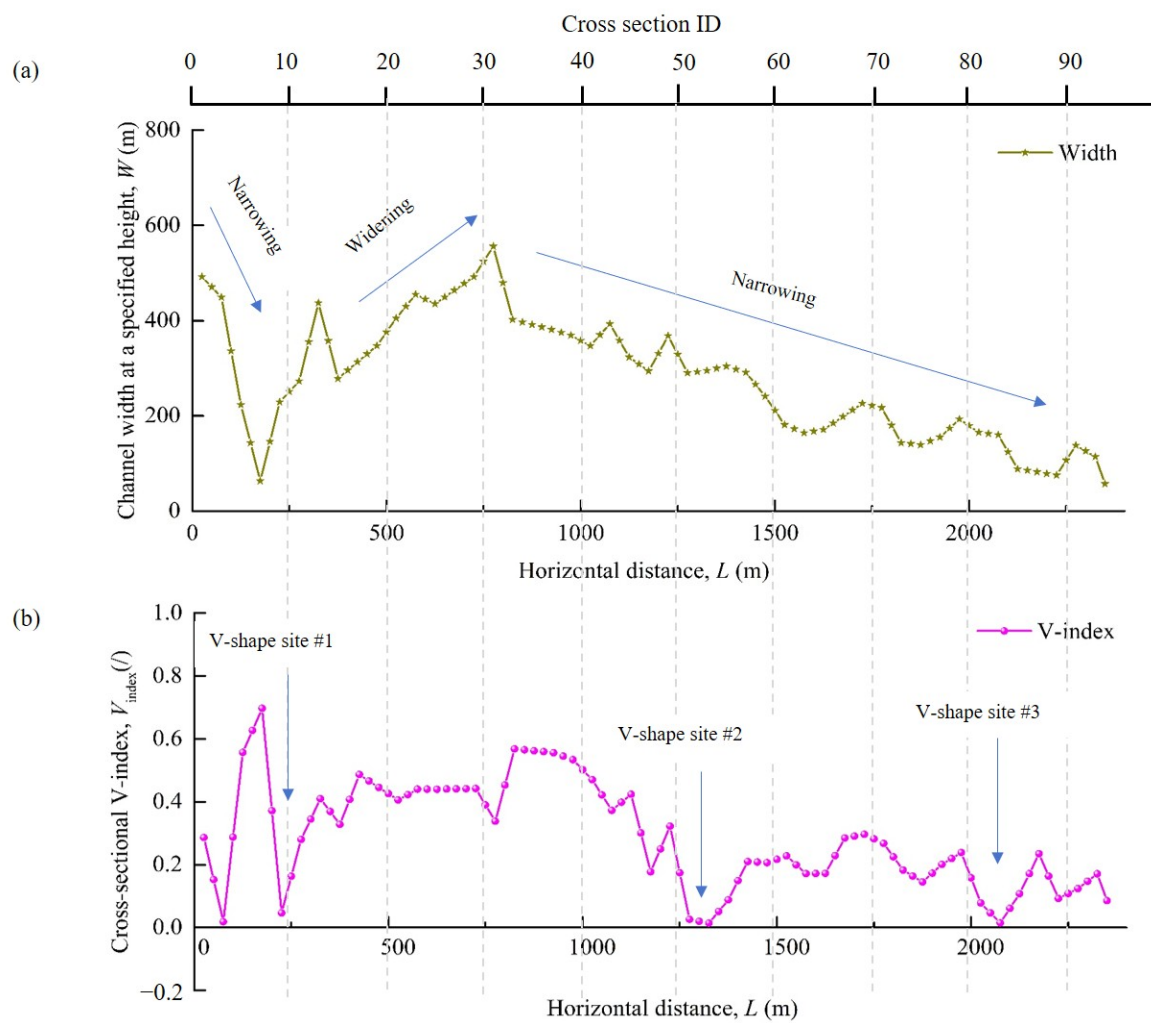


Figure 6. Variations in channel width (a) and cross-sectional V-index (b) at a specified height of 25 m along the 2.35 km-long routing path of the Jinwuco GLOF.

4.2. Spatial Distribution and Quantification of Valley Lateral Bank Erosion

According to the pre- and post-GLOF Maxar WV02 remote sensing images, with a resolution of 0.5 m and 1.2 m, respectively, we obtain the pre- and post-routing channel boundaries for Jinwuco GLOF. A comparison between the pre- and post-GLOF routing channel boundaries is shown in Figure 7 for comparison. Due to the lack of available or reliable reference data, the discrepancies between the pre- and post-GLOF routing channel boundaries can be approximately estimated as the amount of valley lateral bank erosion. Generally, the post-GLOF routing channel boundary expanded significantly on both sides owing to the erosion of GLOF, compared to that of the pre-GLOF boundary. The snapshots in Figure 7c–e present three prominent erosion areas, including upstream erosion area A (with cross-sections ranging approximately from S1 to S22), middle erosion area B (with cross-sections ranging approximately from S35 to S63), and downstream erosion area C (with cross-sections ranging approximately from S70 to S94). The lateral bank erosion was significant on both sides at the upstream half of erosion area A (S1–S10 in Figure 7), with significant bank erosion occurring near the dam of the glacier lake. This may be attributed to the routing channel immediately downstream of the dam breach being quite narrow, while the peak discharge of the GLOF being as large as 4450 m³/s. The huge amount of water released from the glacier lake at the moment of peak discharge indicates superior flow depths and velocities of the GLOF and, hence, extremely high erosive power and sediment transport capacity.

In comparison, the lateral bank on the left side (along the propagation direction of GLOF) was severely eroded in the downstream half (S11–S22) in area A, while the right bank is negligible. This can be ascribed to the right-handed curve of the routing channels in this area. The right-handed curved channel changed the direction of the GLOF, signifying severe frontal collision and impact between the flood and the sediment on the left side. This can be proved by a discernible local small landslide or avalanche (denoted by the blue line in Figure 7c). Similarly, lateral bank erosion mostly takes place on the left side of erosion area B (Figure 7d), owing to the curved path of the outburst floods propagated from upstream erosion area A. As for the erosion area C, severe erosion was detected on both sides of the upstream half routing channel (S69–S81). This can be possibly attributed to that as the GLOF passed over the narrowing site S69 (Figure 7e), significant erosions in the proximity of this cross-section occurred on both sides and rapidly propagated downstream. In comparison, the majority of the lateral bank erosion was found on the right side of the downstream half routing channel of erosion area C (S82–S94). Local small-scale landslide or avalanche (denoted by blue line Figure 7e) indicates a potential head-to-head collision has occurred between the flood in motion and the static sediment on the right lateral slope after the horizontal curved sits #2 (S81). Figure 8 depicts the lateral bank erosion rates (E) along the routing channel of Jinwuco GLOF, calculated by dividing the erosion amount by the erosion duration (2500 s, as depicted in Figure 3). Generally, the bank erosion rate was relatively low at the middle with large channel width, while reaching quite high values at the beginning near the dam of the glacier lake and at the tailing with shrunk channel width.

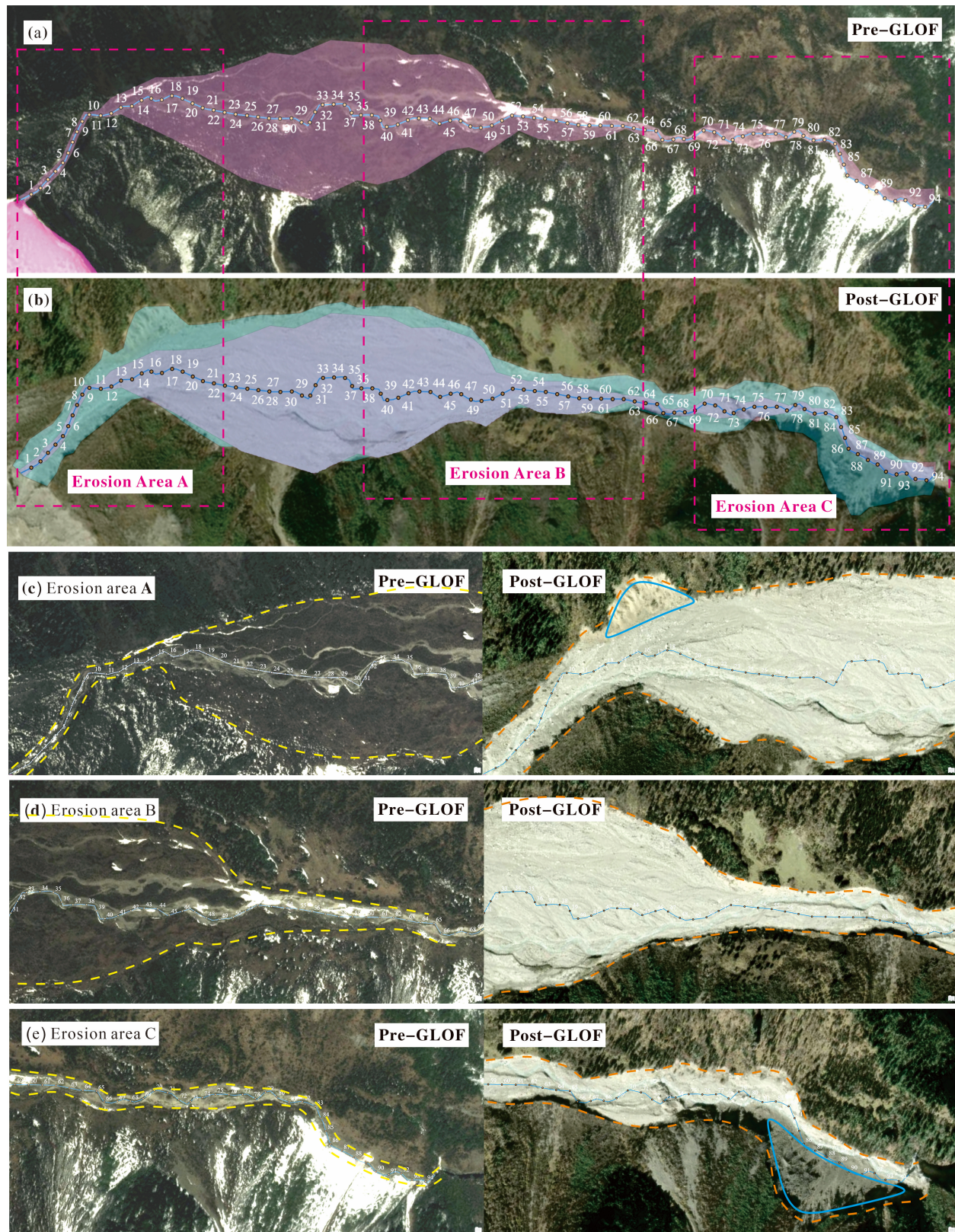


Figure 7. Three obvious erosion areas, A, B, and C, observed based on high-resolution pre- (a) and post-GLOF (b) satellite images. (c–e) Enhanced satellite images that locally present the erosion distributions at these three sites, respectively. The yellow, and orange dotted lines signify the pre-and post-GLOF routing channel boundaries. The blue solid lines with symbols denote the pre-GLOF 2.35 km-long channel with 94 cross-sections, at an interval distance of 25 m. The blue lines that resemble triangles correspond to discernible local small landslides or avalanches.

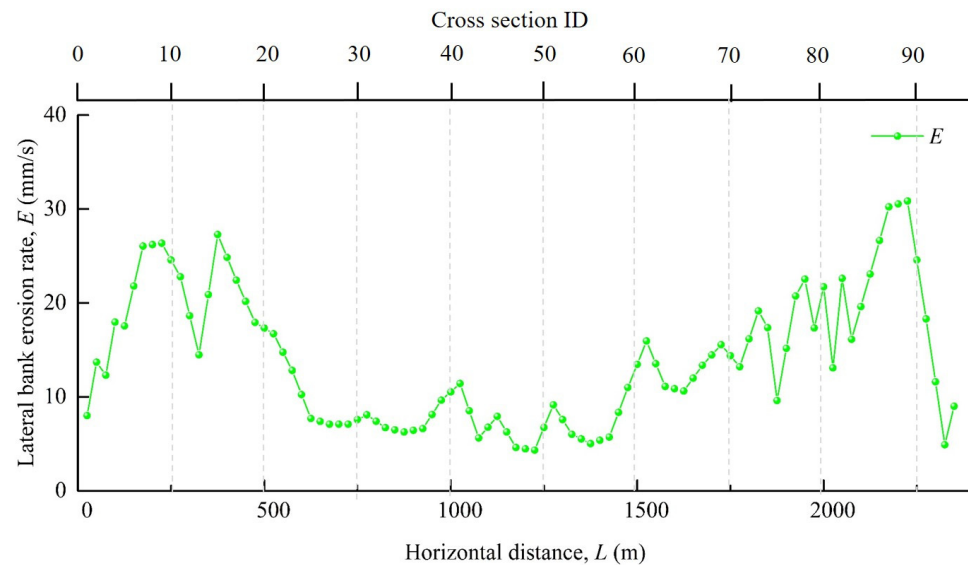


Figure 8. Lateral bank erosion rates (E) along the routing channel of Jinwuco GLOF.

4.3. Lateral Bank Erosion Mechanisms of Jinwuco GLOF

To unveil the internal mechanism of lateral bank erosion along the routing channel of Jinwuco GLOF, we first obtain the spatial distribution of flow depths and velocities of the GLOF. Based on the simulation tool Floc-2D, the maximum flow depth and velocity at each grid node during the whole duration of GLOF propagation are determined, as depicted in Figure 9. The floodwaters primarily concentrate in the pre-GLOF channel but also extend into residential areas on both sides of the channel banks. Backwater effects occur near the glacier lake as the maximum flow depth at cross-section S4 is 13.2 m, relatively higher than adjacent grid nodes. The highest values of maximum flow depths concentrate in downstream narrow channels, with the peak value of 28.12 m occurring near cross-section S93 (Figure 9a). In contrast, the highest values of maximum flow velocity appear in relatively horizontal curved channel sections in the vicinity of S14 and S87 (Figure 9b), which exhibit an inverse distribution pattern compared to maximum flow depth, reflecting the intense kinetic energy of water cascading down from the breach.

The lateral bank evolution along the routing channel is primarily controlled by the flow-induced shear stress and the soil's critical resistance to erosion. To quantify bank erosion rates concerning these factors, this study utilizes data from 94 cross-sectional sites spaced 25 m apart. For simplification, the outburst flood is treated as uniform flow along each cross-section, following previous studies [30–32]. The flow shear stress acting on the lateral bank at each site is calculated using the formula [33]:

$$\tau = \rho_w g n^2 v^2 R^{-1/3} \quad (5)$$

where ρ_w represents water density (1000 kg/m³). A Manning's n value of 0.06 is applied, consistent with earlier Flo-2D simulations. Flow depth h at each section is derived by multiplying the section-averaged maximum flow depth (across all grid nodes in the cross-sectional direction) by a factor of 0.5. For instance, at section S43 (Figure 9a), h is obtained by reducing the averaged maximum depth from the grid nodes (within the blue dotted rectangle) by half. A similar approach is used to estimate flow velocity v . Erosion rate E is then correlated graphically with computed shear stress τ . Based on prior valley morphological analysis (Section 4.1), five representative cross-sections (S14, S36, S50, S69, S81) divide the 2.35 km-long channel into six segments: S1–S14, S15–S36, S37–S50, S51–

S69, S70–S81, and S82–S94. For each segment, linear relationships between E and τ are presented for these six channel segments (Figure 10), expressed as

$$E = k_d(\tau - \tau_c) \quad (6)$$

where the coefficient k_d refers to soil erodibility and is influenced by local lithology [30]. The fitted parameters, including the erodibility coefficient k_d and the soil's critical resistance to erosion τ_c , are shown in Table 1.

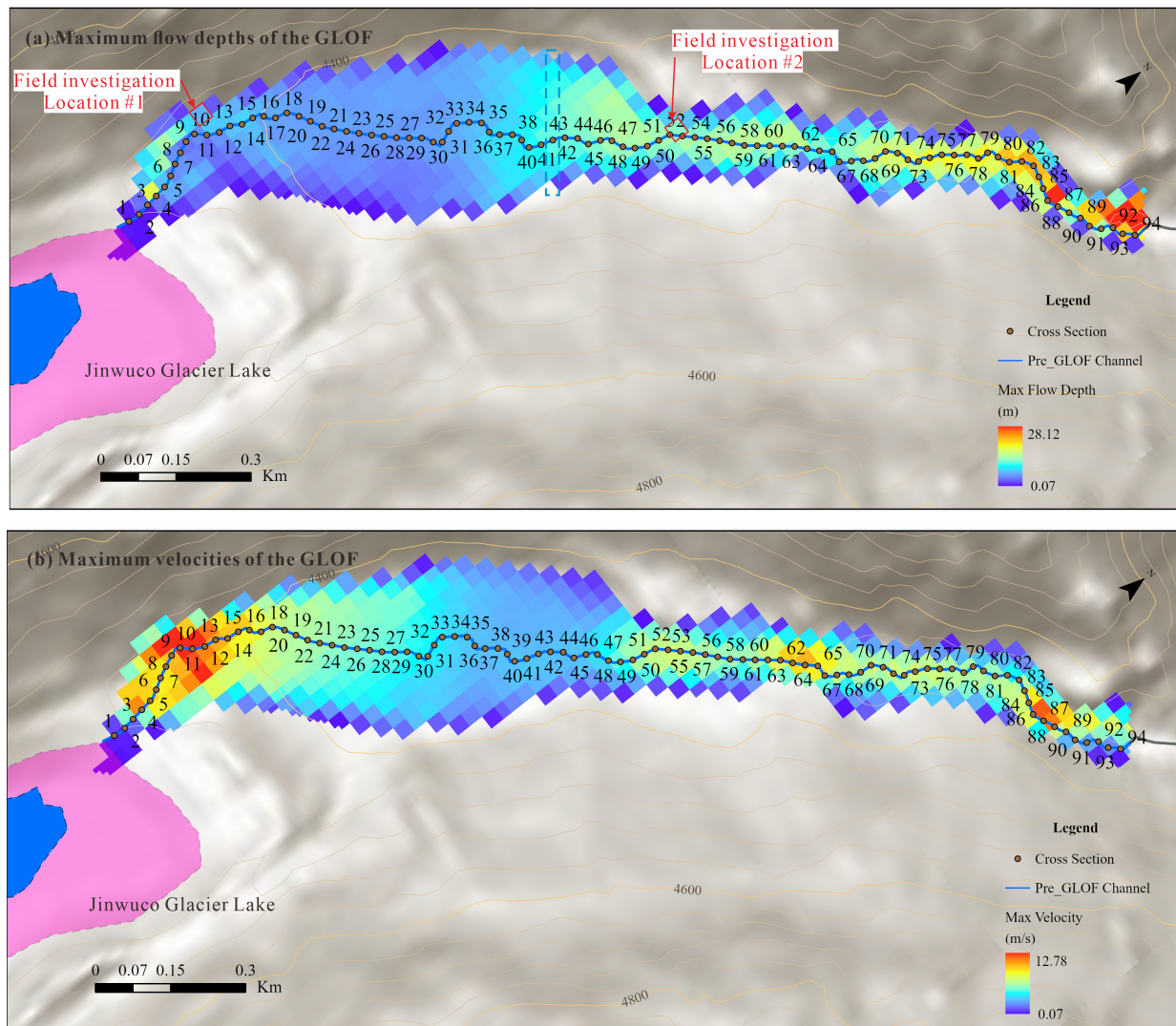


Figure 9. Distribution of maximum flow depth (a) and velocity (b) along the 2.35 km-long routing channel downstream of the dam of Jinwuco glacier lake. Two field investigation locations (#1 and #2) of the peak flow depths of the GLOF are denoted, respectively.

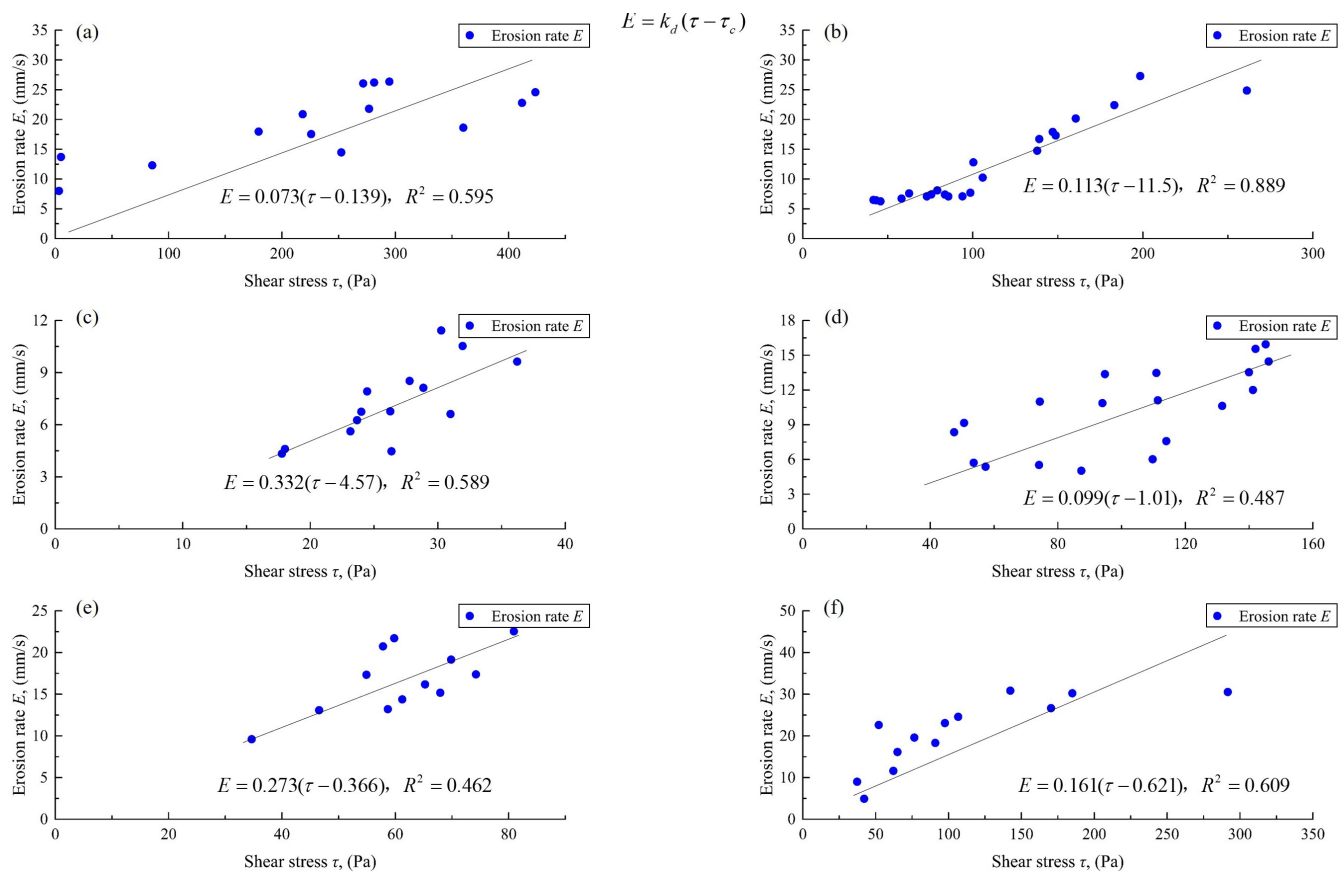


Figure 10. Linear relationships between E and τ are presented for six channel segments: (a) S1–S14; (b) S15–S36; (c) S37–S50; (d) S51–S69; (e) S70–S81; (f) S82–S94.

Table 1. The erodibility coefficient k_d and the soil's critical resistance to erosion τ_c for six channel segments.

Segments	S1–S14	S15–S36	S37–S50	S51–S69	S70–S81	S82–S94
Erodibility coefficient k_d ($10^6 \text{ mm}^3/\text{N-s}$)	0.073	0.113	0.332	0.099	0.273	0.161
Critical resistance to erosion τ_c (Pa)	0.139	11.5	4.57	1.01	0.366	0.621

The erosion resistance of soils is characterized by two key parameters: the critical erosive shear stress and the coefficient of erodibility, as expressed in Equation (6). Consequently, the erodibility of the six channel segments can be classified according to these two quantities. Hanson and Simon established a categorical system for soil erodibility based on these same parameters [34]. Alternatively, Briaud et al. introduced an alternative classification using a graphical approach that relates critical erosive shear stress to erosion rate, derived from more than 15 years of experimental data involving bridge foundations, river meanders, cliffs, and levees [35]. Given the non-constant nature of erosion rates during outburst GLOF events, the present study adopts the categorization framework proposed by Hanson and Simon [34].

Figure 11 displays the erodibility classifications of the six channel segments under this system, with erodibility values of landslide deposits [36] also provided for reference. The critical erosive shear stress falls within a comparatively narrow range, from 0.139 Pa to 11.5 Pa, while the coefficient of erodibility spans two orders of magnitude. Six channel segments all fall into the very erodible category, while the landslide deposits fall into the

categories ranging from the resistant to the erodible category. This may be ascribed to that the research of Chang et al. was based on small-scale field jetting tests [36], while here we concentrate on the natural-scale GLOF. The large scale of GLOF and its superior erosive potential contribute to the extremely rapid erosion of lateral bank soil, and hence high values of the coefficient of erodibility k_d . The critical erosive shear stress τ_c reflects the ease of initiation of erosion in the soil. Li et al. [22] pointed out that the ‘apparent’ critical erosive shear stress of soil is not only a function of its mechanical strength, but also other factors, including the dynamics of upper erosive flood and initial channel morphology, etc. As shown in Figure 11, the critical erosive shear stress τ_c is quite high at channel segments S37–S50 (4.57 Pa) and S15–36 (11.5 Pa). This may be ascribed to GLOF passing these channel segments with relatively large widths or within a widening phase (Figure 5). The flow depth, velocity, and erosive power of the GLOF reduced, corresponding to a higher ‘apparent’ critical erosive shear stress of lateral bank soil. In contrast, for the channel segments S70–S81, S82–S94, and S51–S69, the narrowed or horizontally curved channels enhance the flow depth, velocity, and erosive power of the GLOF, and therefore result in lower ‘apparent’ critical erosive shear stress of lateral bank soil, with a value of 0.366 Pa, 0.621 Pa, and 0.101 Pa, respectively. Especially for the channel segment S1–S14 downstream of the dam of the glacier lake, the unstable nature of the outburst flood at the dam breach and the accompanying strong turbulence renders the soil particles on lateral banks into rolling and saltation motions, and more easily carried by the flood. Hence, the ‘apparent’ critical erosive shear stress of lateral bank soil at channel segment S1–S14 is as low as 0.139 Pa. Conclusively, the non-uniform channel morphology can alter the flow dynamics, the initiation of lateral bank soil, and thus, affect its ‘apparent’ critical erosive shear stress. These related processes or stresses hinder the complete and comprehensive understanding of the GLOF erosion mechanism, and further studies are warranted.

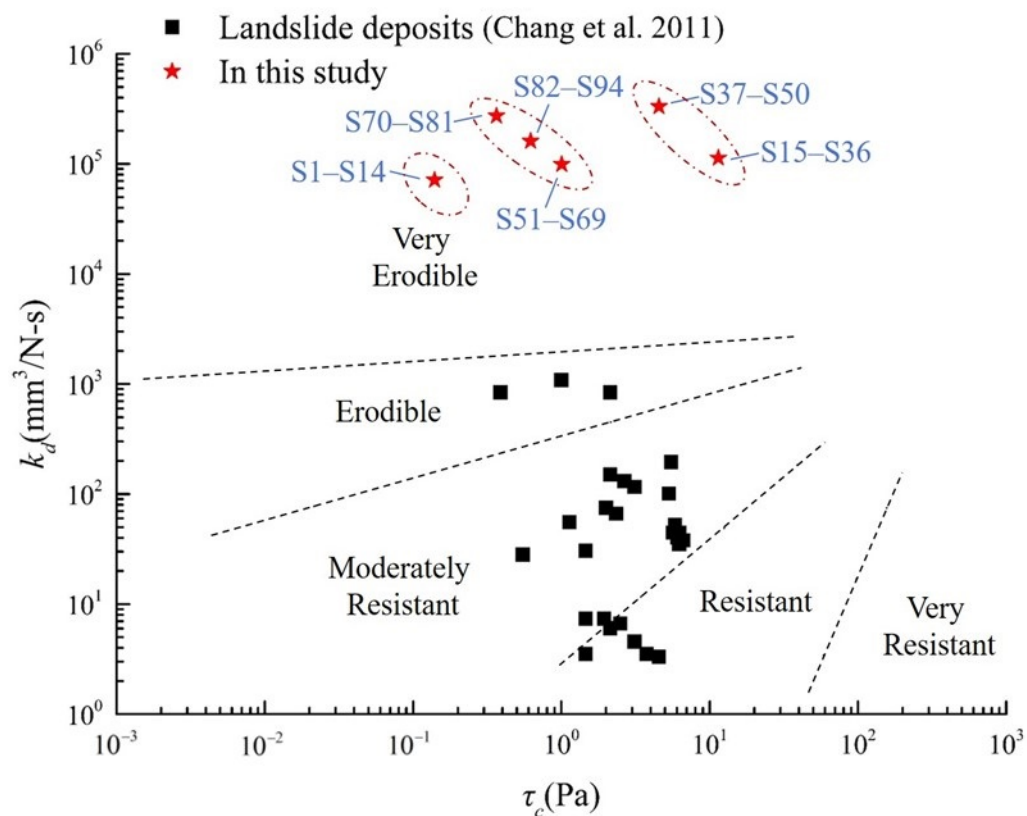


Figure 11. Erodibility categories for six channel segments according to Hanson and Simon’s classification. The erodibility of landslide deposits [36] is shown for comparison.

5. Discussion

5.1. Influence of Oversized Boulders on the Propagation of GLOF

The true destructive power of GLOFs emerges not merely from water discharge but from their unrivaled sediment entrainment capacity. As the flood propagates downstream, it mobilizes massive boulders and incises channel beds—processes that fundamentally alter its fluid composition from clearwater flow to hyper-concentrated slurry. Huber et al. [37] suggest that discharges between 10^3 and 10^5 m³/s are required to entrain boulders of the estimated sizes, based on assumed flow density and hydraulic regime. In this study, the recorded peak discharge of the outburst flood reached 4450 m³/s (Figure 3), indicating that such flows were capable of transporting these oversized boulders along the channel, ultimately depositing them in zones where the canyon narrows or the gradient decreases. The current study focuses on the processes and mechanisms of progressive erosion during GLOFs along the channel, without addressing deposition—particularly the influence of oversized boulder transport and deposition on flood dynamics. Boulder deposition is controlled by multiple factors, including topography, hydrodynamic conditions, and boulder shape. GLOFs generally exhibit lower transport capacity than debris flows; thus, when flowing through irregular channels with variable widths, boulders tend to deposit in wider sections or narrow constrictions. These deposited boulders can form temporary obstructions, trapping finer sediments and creating in-channel dams, as well as inducing concave or convex profile breaks, thereby altering subsequent flood propagation and discharge hydrographs. Moreover, the breaching of such boulder-induced blockages modifies local hydrodynamic conditions and can significantly increase transient sediment transport rates. Transported boulders may also impact the channel bed and bank toes, potentially triggering further gravitational erosion such as collapses or landslides.

The research of Morey et al. [38] demonstrated that, under specific conditions of boulder delivery dynamics and size distributions, megaflood deposited boulders can initiate over 100 knickpoints with up to 3.5 m of relief each. Meanwhile, the size and spatial distribution of pre-existing oversized boulders within the erodible channel layer influence bed erodibility, leading to localized scouring or blockage under GLOF conditions. In addition, the presence and irregular distribution of large boulders along banks play a critical role in forming localized constrictions, expansions, and changes in channel alignment. Therefore, utilizing remote sensing interpretation and feasible geophysical methods to determine the spatial distribution of oversized boulders near the breach and along the channel, quantify boulder supply during GLOF propagation, and characterize boulder transport and deposition patterns can substantially support the study of erosion and deposition processes of GLOFs. Future research should focus on these aspects to improve the mechanistic understanding of GLOF-induced erosion and channel evolution, thereby supporting risk assessment and disaster mitigation efforts.

5.2. Modeling Sensitivity Analysis and Limitations

A sensitivity analysis was conducted to evaluate the influence of key input parameters on the simulated Jinwucuo GLOF dynamics, with particular focus on changes in the maximum flow velocity and maximum flow depth. The baseline values were set at 0.1 for Manning's n , 4450 m³/s for peak discharge, and 7000 s for the total hydrograph duration. The results indicate that the model is most sensitive to variations in Manning's roughness coefficient. Reducing the coefficient by 25% to 0.075 resulted in a 12.36% increase in maximum velocity and a 2.62% decrease in maximum depth. Conversely, increasing Manning's n by 25% to 0.125 led to a 12.36% decrease in maximum velocity and a 2.62% increase in maximum depth. Our conclusion is similar to that of Zhang et al. [39] and Wang et al. [40], who found that changes in the Manning value significantly alter the simulation results. The

model exhibited moderate sensitivity to changes in peak discharge. A 20% reduction in peak discharge to $3560 \text{ m}^3/\text{s}$ caused a 5.71% decrease in maximum velocity and a 4.83% decrease in maximum depth, while a 20% increase to $5340 \text{ m}^3/\text{s}$ resulted in a 5.71% increase in maximum velocity and a 4.83% increase in maximum depth. In contrast, variations in the hydrograph duration had minimal impact. A 20% reduction in duration to 5600 s changed the maximum velocity by -0.64% and maximum depth by -0.55% , and a 20% increase to 8400 s resulted in changes of $+0.64\%$ and $+0.55\%$, respectively. These findings underscore that flow velocity and depth are predominantly influenced by channel roughness and peak discharge, while the hydrograph duration has negligible effects within realistic ranges. Although additional factors such as digital elevation model uncertainty could influence the results, the present analysis focuses on the most critical hydraulic parameters governing erosion processes during this specific event.

Based on field surveys of mudline marks and boulder impact scars on valley slopes, the estimated outburst flood depths at locations #1 and #2 in Figure 9 were 4.4 m and 10.8 m, respectively. The simulated peak water depths from the Jinwuco GLOF modeling in this study were 5.08 m and 10.04 m at these corresponding sites, with relative errors of 15.34% and 7.06%, respectively. These results indicate a good agreement between the simulated values and field measurements. Wang et al. [41] conducted simulation studies on potential GLOF scenarios in the Yi'ong Zangpo basin prior to the 2020 event. Under the parameter settings of a breach width of 120 m, depth of 5 m, and a total outflow duration of 3 h, the simulated outburst released a total water volume of approximately 30 million cubic meters, resulting in a peak discharge of $1570 \text{ m}^3/\text{s}$. In the present study, the simulation of Jinwuco GLOF adopted initial parameters based on the research of Zheng et al. [18], which included a breach width of 80 m, depth of 20 m, and a total outflow duration of 1.2 h. The released water volume was about 10 million cubic meters, while the calculated peak discharge reached $4450 \text{ m}^3/\text{s}$ (Figure 3). A comparison of the two cases indicates that although the total released water volume in the Jinwuco event was significantly smaller (approximately one-third) than that in the Yi'ong Zangpo simulation, the peak discharge was nearly four times greater. This discrepancy is likely attributable to differences in breach dimensions—specifically, breach width and depth—as well as the total duration of the outburst process.

The application of the Flo-2D model in this study is subject to certain limitations. Notably, Flo-2D operates on shallow water equations under a depth-averaged assumption and does not explicitly simulate the dynamic feedback between sediment erosion/deposition and flood hydraulics. This simplification means the model does not account for potential changes in flood bulk density along the flow path, which can alter bedload movement and subsequent erosion processes, a factor particularly important in sediment-rich GLOFs. Furthermore, numerical instabilities can arise when applying the model to steeply sloping terrain. Despite these constraints, Flo-2D was selected for its proven capability in simulating key flood hydrodynamic parameters (inundation extent, depth, and velocity). These outputs provide a critical foundation for assessing spatial patterns of hydraulic force, which serve as a primary proxy for interpreting erosion potential. Given the study's focus on leveraging commonly available data and established methods for a preliminary hazard assessment, and considering the lack of high-resolution sediment data required for more complex multi-phase modeling, Flo-2D was deemed a suitable tool for reconstructing the fundamental flood dynamics. Consequently, this study focuses on the upstream 2.35 km-long channel reach where the model's performance is most robust, and the analysis of valley evolution and erosion processes further downstream is based on remote sensing interpretation paired with the simulated hydraulic patterns. The input discharge process was simplified as an instantaneous event without considering the temporal dynamics of

breaching (e.g., progressive or multi-phase breaches); input parameters and boundary conditions were simplified. These assumptions limit the realism of the model and affect the simulation accuracy [42–44].

Scientific understanding of the GLOF has evolved from treating them as rare hydrological anomalies to recognizing them as primary drivers of landscape evolution in glaciated regions. As climate warming accelerates glacier retreat and expands glacier lakes globally, the frequency and magnitude of GLOFs are projected to rise, necessitating a deeper mechanistic understanding of how these floods sculpt terrain, evolve in fluid composition, and amplify hazards along their flow paths. Future research could be expanded by combining remote sensing change detection with ground-based monitoring, using rainfall observation, earthquake early warning systems, and lake-level gauges to monitor GLOF-inducing factors under climate change, and constructing a threshold-driven dynamic early warning system. Further, using UAVs or LiDAR to obtain higher-resolution terrain data to incorporate more refined inputs for boundary conditions and hazard-specific processes, thereby improving model realism and predictive accuracy.

5.3. Implications for Future GLOF Hazard

Previous studies on GLOFs are mostly concentrate on the formation and breakage of the glacial lake, the propagation of the outburst floods and their destructive consequences on downstream human communities [11–14,32]. While the morphology of the routing channel for the GLOFs are often overlooked. Non-uniform channels are commonly observed in natural routing channel of GLOFs and exert significant effects on the dynamics of the outburst floods, the stability of sediment on channel bed and lateral banks, and hence the erosion processes and overall rates. Similar conclusions have been concluded for high-density debris flows [21]. In the current research, the impacts of channel horizontal curvature, cross-sectional width and shapes on the erosive power of the flood and lateral erosion rate are investigated quantitatively. Innovatively, a term named ‘apparent’ critical erosive shear stress of soil on the lateral bank is proposed. These findings may aid future studies on further investigations on erosion mechanisms in other events elsewhere and contribute to the development of more reliable modeling of GLOF propagation. Especially in the context of globally warming, seasonal freeze–thaw cycles can significantly degrade the strength of moraine deposits on both sides of channels, thereby triggering unstable slope failures that obstruct gullies and alter channel morphology. These processes subsequently influence the depth, flow velocity, and downstream erosion patterns of glacial lake outburst floods (GLOFs). Such mechanisms are widespread across the global cryosphere.

Previous research on glacial lake outburst floods (GLOFs) has largely focused on the processes of lake formation and breaching, the downstream propagation of floods, and the associated impacts on infrastructure and communities. However, the influence of channel morphology on GLOF dynamics has often been overlooked, despite its critical role in controlling flood behavior. Natural drainage channels typically exhibit significant non-uniformity—including variations in curvature, width, and cross-sectional shape—which strongly affects flow velocities, shear stress distributions, and sediment stability. These morphological factors, in turn, influence patterns and rates of erosion along the channel bed and banks, ultimately modulating the flood’s destructive potential. Similar influences of channel geometry have been reported for high-density debris flows [22], highlighting the need to integrate such factors into GLOF studies.

In this study, we quantitatively analyze the effects of channel sinuosity, cross-sectional geometry, and width variability on erosion processes during the 2021 Jinwucuo GLOF event. A key innovation of our work is the proposal of an “apparent critical erosive shear stress” for bank materials, which helps better account for lateral erosion under

complex flow conditions. This concept offers a transferable framework for improving mechanistic erosion models in other high-mountain regions prone to GLOFs. Nevertheless, specific numerical values—such as erosion thresholds and scaling coefficients—should be applied cautiously outside the Tibetan Plateau context, as site-specific factors including material composition, moisture content, and channel geometry may considerably alter local responses. Our findings hold important implications for assessing climate-related GLOF risks. As global temperatures rise, intensified freeze–thaw cycles contribute to permafrost thaw and moraine destabilization, increasing the likelihood of slope failures and channel obstructions. Such changes can alter flow pathways and amplify erosion potential, necessitating predictive models that incorporate channel morphological effects. The approach developed here provides a basis for more reliable flood propagation modeling and hazard mapping in vulnerable cryosphere regions.

When compared to other reported major GLOF events [14,45], the Jinwuco flood shares common initiating mechanisms—particularly moraine destabilization and rapid lake drainage [18]. However, it is distinguished by pronounced channel curvature and its coupling with intense lateral erosion, which collectively enhanced downstream sediment evacuation and flood transformation. Although systematic comparative studies remain limited, the Jinwuco event underscores the need to account for local channel characteristics in flood modeling and risk assessment. Further comparative analysis would help identify regional patterns and improve generalized models under ongoing climate change.

6. Conclusions

Glacier lake outburst floods (GLOFs) are common natural disasters in the cryosphere of the Tibetan Plateau. Due to global warming, glaciers in the region are continuously melting, causing an increase in the overall volume of glacier lakes and a corresponding rise in GLOF risks. This study combines remote sensing imagery and the Flo-2D hydraulic model to investigate the erosive dynamics of the 2020 Jinwuco GLOF in Southeastern Tibetan Plateau. The conclusion can be summarized as follows:

- (1) The morphology of the 2.35 km-long routing valley of the Jinwuco GLOF is non-uniform, characterized by varied horizontal curvature, channel width, and cross-sectional shapes. Changes in channel curvatures and widths will significantly affect the propagation of the GLOF. Based on the morphological analysis, five representative cross-sections are discerned, which cut the 2.35 km-long channel into six segments.
- (2) The lateral bank erosion was significant on both sides near the dam of the glacier lake, which can be attributed to the extremely high erosive power and sediment transport capacity at the moment of peak discharge of the GLOF. The curved channel changed the direction of the GLOF, signifying severe frontal collision and impact between the flood and the sediment on one side, and hence, enhancing lateral bank erosion.
- (3) Generally, the bank erosion rate was relatively low in the middle with a large channel width, while it reached quite high values at the beginning near the dam of the glacier lake and at the tail with a shrunk channel width.
- (4) The highest values of maximum flow depths of Jinwuco GLOF concentrate in the downstream narrow channels, with a peak value of 28.12 m. In contrast, the highest values of maximum flow velocity appear in relatively horizontal curved channel sections.
- (5) The ‘apparent’ critical erosive shear stress of soil on the lateral bank is not only a function of its mechanical strength, but also other factors, including the dynamics of upper erosive flood and initial channel morphology. The non-uniform channel morphology of the Jinwuco GLOF can alter the flow dynamics and the initiation of lateral bank soil, thus affecting the ‘apparent’ critical erosive shear stress of soil.

This study provides an in-depth investigation of the lateral bank erosion of Jinwuco GLOF and establishes a theoretical framework that can be applied to other data-scarce high mountain regions. It will support regional planning, early warning strategies, and GLOF risk assessment, contributing to more effective GLOF risk management for Jinwuco and similar glacier lakes in the region.

Author Contributions: S.L.: methodology, data analysis, manuscript writing. C.L.: funding acquisition, manuscript review and editing. P.L.: data collection. Y.S.: remote sensing analysis. Z.L.: hydrodynamic modeling, result interpretation. Z.W.: field investigation, manuscript revision. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been financially supported by the Foundation of PowerChina Northwest Engineering Corporation Limited (XBY-DKY-2023-02).

Data Availability Statement: All raw data can be provided by the corresponding authors upon request.

Conflicts of Interest: Authors Shuwu Li, Changhu Li, Zhengzheng Li, and Zhang Wang were employed by PowerChina Northwest Engineering Corporation Limited, Xi'an. The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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