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Numerical simulation and geomorphic impact of the 2000 Yigong River outburst flood

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Abstract

Currently, there is a shortage of research on modern outburst floods, which hinders our comprehension of the connection between the hydrological features of these events and their geomorphic and sedimentary characteristics. This lack of research also restricts our understanding of the impact of these extreme disasters on the long-term evolution of human survival and living environments. Nevertheless, the 2000 Yigong River outburst flood provides us an opportunity for studying the typical modern outburst floods. The peak discharge of the dammed lake outburst flood was recorded at $1.26 \times 10^5 \text{ m}^3/\text{s}$, leading to significant changes in the riverbed and valley gradient, ultimately causing the riverbed to shift. Moreover, it formed a large amount of gravel bars and slack water deposits downstream of the breach. These sediments are relatively well preserved and provide us with a complete chain of evidence to study modern outburst floods. The dynamics of the flood were simulated using the HEC-RAS 2D unsteady flow model. The relationship between the lateral migration of the channel and the shear stress of the river bed during peak discharge was determined. This reflected the direct control effect of the hydrodynamic conditions of the outburst

flood on the lateral migration of the river bed. The sedimentary morphology, scale, and maximum gravel size of the boulder bar downstream of the breach were found to be closely related to the channel width and local hydrodynamic conditions. The relationship between the hydrological characteristics and sedimentary characteristics of the outburst flood was quantitatively analyzed. The slack water deposit in Jiazhong village was formed during the peak discharge, while the horizontally-bedded laminations containing coarse sand and fine gravel in the tributary valley were mainly formed during the flood decline after the peak discharge. The latest findings in this study provide valuable additions to the research on the devastating floods that have been investigated in the rugged terrain of the Yarlung Tsangpo River basin.

Key words: outburst flood; geomorphology; deposition; bar; dynamics

1. Introduction

As a branch of paleofloods, megafloods have not been documented by modern hydrological tools or reliable human observation methods due to its short duration and large discharge (Baker, 2013). Megafloods are typically large-scale outburst floods, which can be triggered by two main factors: a glacial lake outburst flood resulting from a glacier blockage, or a landslide-dammed lake outburst flood caused by a landslide or debris flow blockage (Cui et al., 2015). Megafloods are not only a global phenomenon but also important runoff that contributes to the formation of continent-scale watershed systems (Uchupi et al., 2001). A large amount of evidence shows that large-scale floods can greatly alter the morphology of river channels and have a significant impact on human life and infrastructure (Korup and Montgomery, 2008; Korup et al., 2010; Lang et al., 2013; Turzewski et al., 2019). However, the relationships between hydrological spatial patterns and geomorphic forms are lacking for some of the devastating historical outburst floods (Korup and Montgomery, 2008; Korup et al., 2010; O' Connor et al., 2013; Liu et al., 2015; Hu et al., 2018; Srivastava et al., 2016; and Borgohain et al., 2020; Hu et al., 2021; Hu et al., 2022) and for many of the ancient outburst megafloods (Montgomery et al., 2004; Lamb et al., 2008; Baynes et al., 2015; Yang et al., 2022). Research on outburst floods and their

geomorphic impact is still insufficient (Cook et al., 2018; Turzewski et al., 2019; Yang et al., 2022). As a result, questions are not well resolved regarding the impact of outburst floods on landscapes, particularly in mountainous settings such as the Tibetan Plateau region. Therefore, improvements in understanding flood hydraulics should enable a better understanding of how outburst floods erode and impact river morphology.

The landslide dam in Yigong River collapsed in June 2000, leading to an outburst flood with a peak discharge of $1.26 \times 10^5 \text{ m}^3/\text{s}$. The flood heavily eroded the riverbed, causing the channel to shift, resulting in the formation of numerous boulder bars and slack water deposits downstream of the breach. This provides us with a complete study of the typical modern case of outburst floods.

The Yigong River outburst flood in 2000 has been well documented regarding the volume and height of the landslide dam, duration of dammed lake impoundment, timing of breach, peak discharge of the outburst flood, and its impact on downstream areas (Yin, 2000; Shang et al., 2003; Evans and Delaney, 2011; Wu et al., 2020). The 2000 outburst flood in Yigong River was previously simulated, focusing mainly on the inversion of the outburst flood to recreate the evolution process of the flood (Xing et al., 2010; Delaney and Evans, 2015; Dai et al., 2019). The analysis of the hydraulics and geomorphic impact of the flood was limited to the 242 km reach of the Siang River from Tuting to Pasighat downstream of the Yarlung Tsangpo Grand Canyon, and the effect of high bed shear stress of the outburst flood on bedrock erosion was analyzed (Turzewski et al., 2019). There is no study on the interaction of flood hydraulics with valley topography immediately downstream of the breach in the Yigong River, where this effect is most complex.

Based on the information above, HEC-RAS was utilized to perform a numerical simulation of the dynamic mechanism of the outburst flood in Yigong River in 2000. Through comparing the simulation results with field investigations, remote sensing observations, discharge estimates, and high-water marks and slackwater deposits, we determine the applicability of the model for hazard assessment and geomorphic investigations in mountainous settings and analyzes the relationships between

hydrological spatial pattern and geomorphic form. It will be helpful to study the ancient catastrophic outburst flood events in the whole Yarlung Tsangpo River basin even in the alpine valley area.

2. Regional setting

The study area is situated in the transitional zone of the Qinghai-Tibet Plateau as it descends towards the eastern mountains, at the intersection of two significant geomorphic regions. To the west lies the interior of the plateau, while to the east is an alpine gorge carved out by river erosion (see Fig. 1). The impact of gravity on the landscape is readily apparent, resulting in a distinctive terrain characterized by mountains and deep canyons with unstable surface features (Ren et al., 2001).

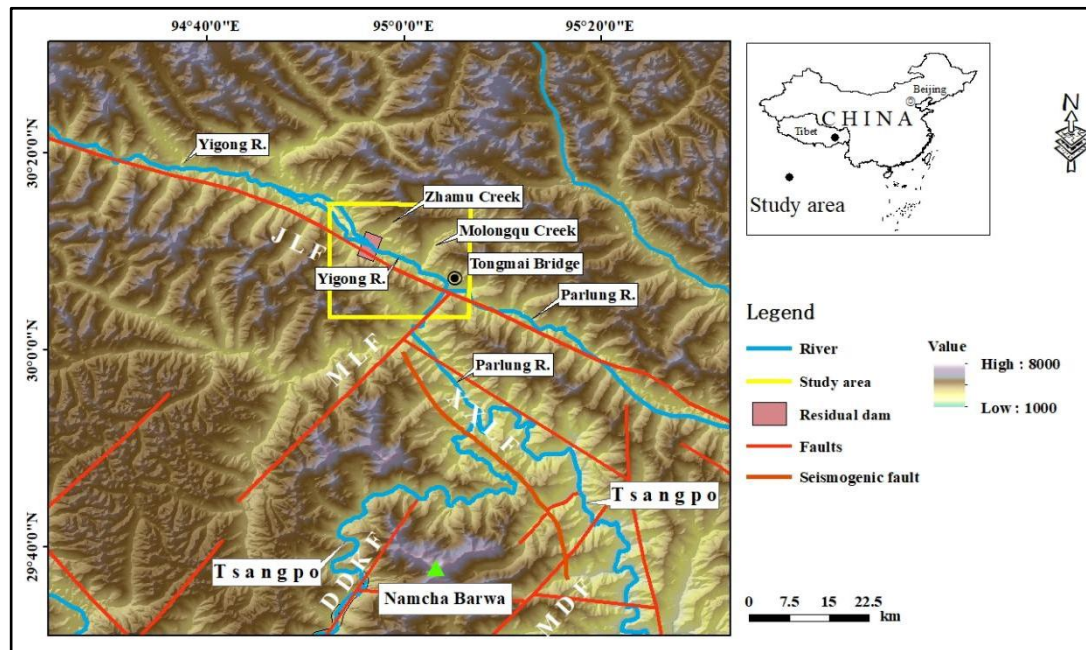


Fig. 1 Location map of study area and main faults.

Abbreviations: MLF-Milin fault, JLF-Jiali fault, XXL-Xixingla fault, DDKF-Daduka fault, and MDF-Medog fault. The map was created using a licensed ArcGIS 10.8.1 software (<https://support.esri.com/en/downloads>).

At around 20:00 on April 9, 2000, a large-scale landslide occurred in Zhamu Creek. The debris traveled down the gully and blocked the main channel of the Yigong River, forming a landslide dam with a height of 54 m, a length of about 2.5

km, a reservoir capacity of $2.88 \times 10^{10} \text{ m}^3$ and a volume of $2.8 \times 10^8 \sim 3.0 \times 10^8 \text{ m}^3$ (Yin, 2000; Shang et al., 2003). The dam breached two months after the landslide, following overtopping through a spillway artificially cut for water drainage, resulting in a outburst flood. Peak discharge of the flood reached $1.2 \times 10^5 \text{ m}^3/\text{s}$ and the water level during the peak discharge was 32 m higher than that of Tongmai Bridge, which was equivalent to 36 times of the seasonal flood discharge of Yigong River. The flood dramatically eroded the riverbed , which forced lateral migration of it, and formed a large number of flood accumulation landforms along the edge of the main channel (Lang et al., 2013) (Figure 2).

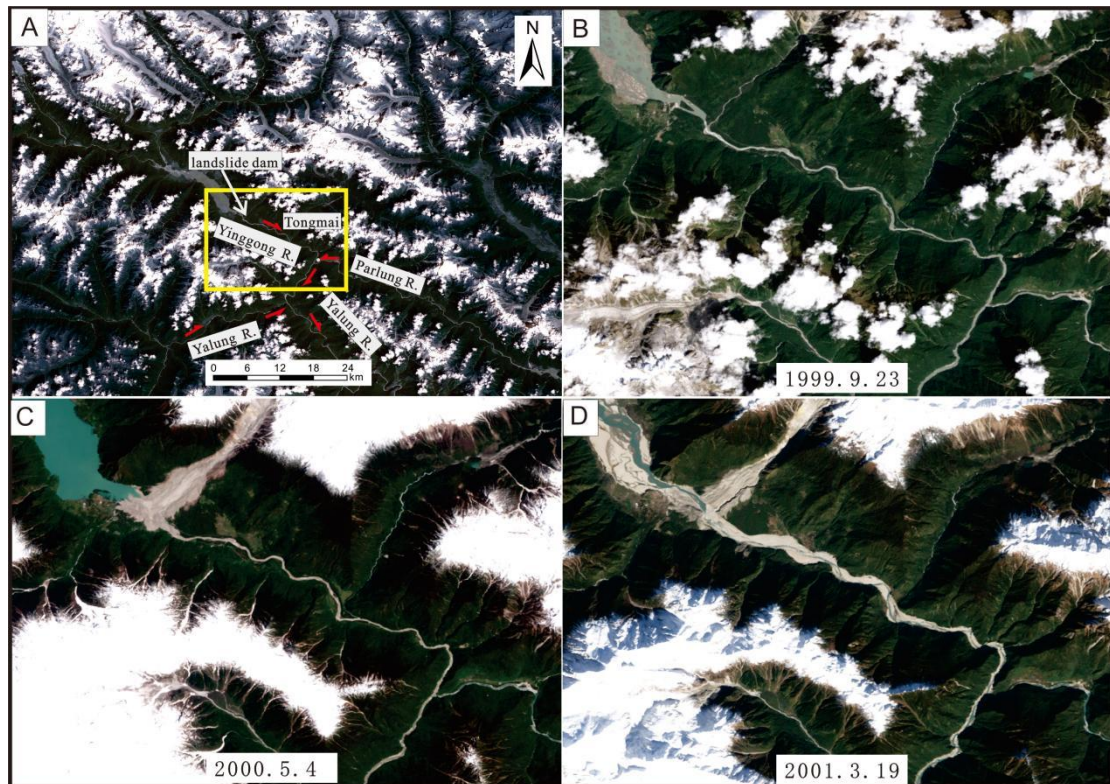


Fig. 2 Comparison of remote sensing images of the Yigong River before and after the June 2000 event

(A) shows the Landsat 7 ETM+ image of the study area on September 23, 1999. The yellow rectangle is the range of the study area soil 2 (B), (C) and (D), which are Landsat 7 ETM+ images on September 23, 1999, May 4, 2000, and March 19, 2001, respectively. The Yigong River's corresponding river morphology is before, during, and after the river blockage.

3. Methods

HEC-RAS is used to simulate the two-dimensional unsteady flow of the 2000 outburst flood in Yigong River. The steps are to build the project, establish geometric data, input boundary conditions, initial conditions and flow process data, and perform calculation and flood hydrological analysis.

3.1. Digital elevation model and hydrologic process

A digital elevation model (DEM) spanning 64 km² from the microwave band imaging data (PALSAR) was obtained by the Earth observation satellite ALOS, numbered ALPSRP148000590 before the 2000 outburst flood in the Yigong River. It was revised and updated on December 3, 2008, with a resolution of 12.5 m (12.5 m both planar and vertical accuracy). The water level markers include slackwater deposits, outburst flood boulder bars, giant bars and flood marks (Fig. 3).

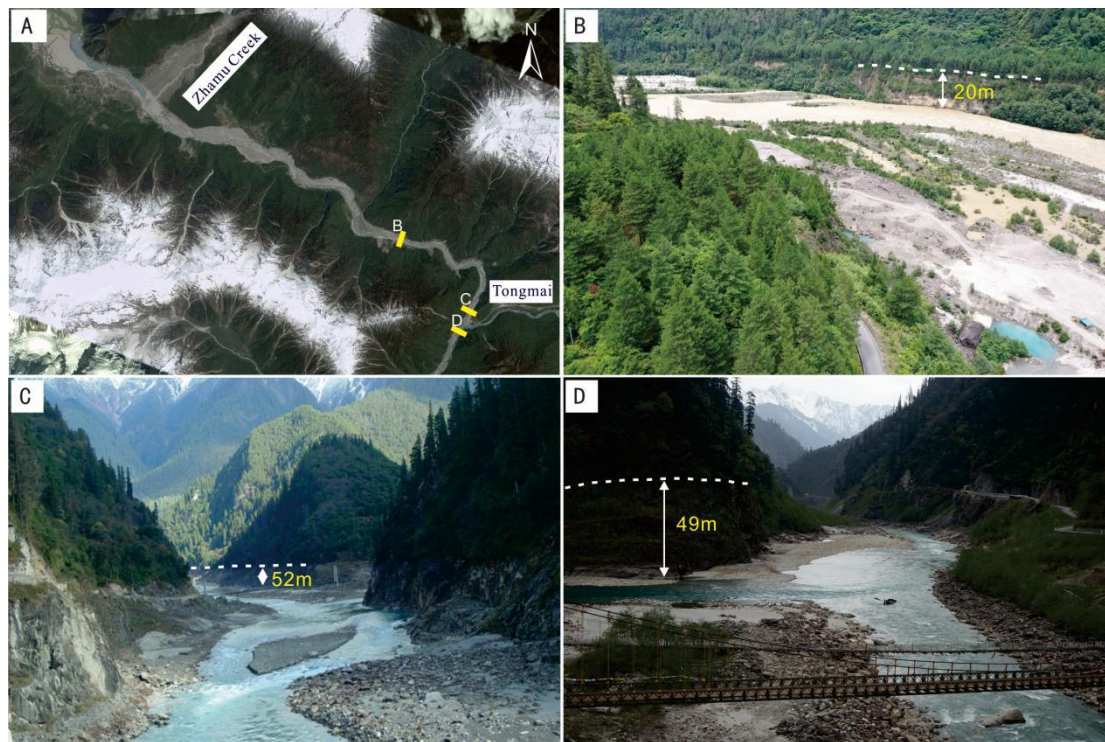


Fig. 3 High-water marks of the 2000 Yigong outburst flood

The water level change monitored by the hydrology station in Yigong indicated that the outburst of the dammed lake lasted for 24 hours from 19:00 on the evening of June 10 to 19:00 on the evening of June 11, with an absolute elevation of 2186.41 m. The hydrologic process line of the outburst flood was calculated using the principle of

the water balance line, taking into account the observation results of the hydrologic station in Yigong. The formula for this calculation is as follows (Chen et al., 2018):

$$(Q_{\text{下}} - Q_{\text{上}})\Delta T = \Delta V$$

The discharge of the Yigong outburst flood in each period was calculated. The peak discharge is $94810.34 \text{ m}^3/\text{s}$, and the total storage capacity of the lake is $2.11 \times 10^9 \text{ m}^3$. A difference coefficient of 1.33 was determined by comparing the peak discharge of the outburst flood at Tongmai Bridge (approximately $1.26 \times 10^5 \text{ m}^3/\text{s}$) with the calculated result based on the measured data from the hydrology station in Yigong. The calculated discharge data for the outburst flood in each period were then adjusted. A process line for the outburst flood flow with a peak discharge of around $1.26 \times 10^5 \text{ m}^3/\text{s}$ was obtained for the two-dimensional unsteady flow model numerical simulation (Fig. 4).

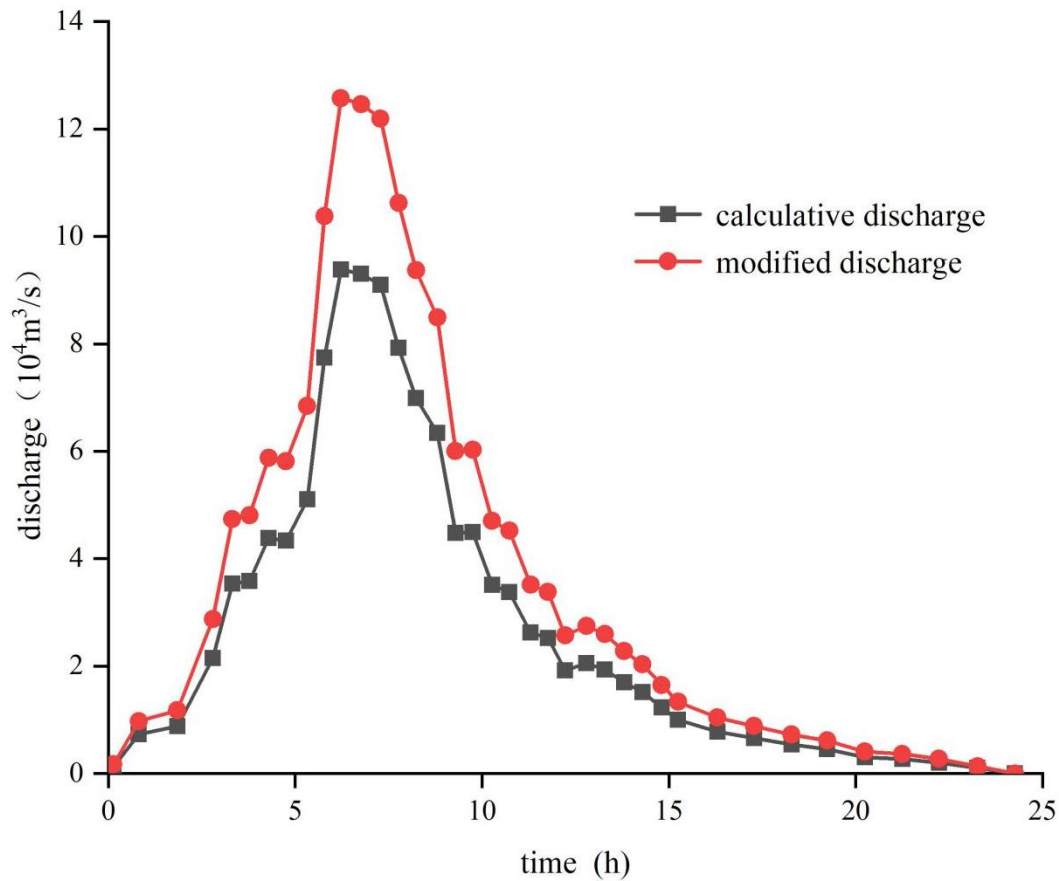


Fig. 4 Flood hydrographs of the 2000 Yigong outburst flood

3.2. The establishment of model and the division of grid

The area covered by the hydrological model of the outburst flood extends from the breach of the dammed lake to 1 km downstream of the confluence of Yigong River and Parlung River. The breach of the dammed lake is situated on the right bank of the river channel at the lake outlet of Zhamu Creek residual dam, which marks the beginning of the flood evolution. The upper reaches of the confluence along the Parlung rivers have a steady water input, which serves as another entry point for flood evolution. 1 km downstream from the confluence is the outlet of flood evolution. The flood evolves along the zigzagging river from the upper wide valley reach to the lower canyon reach. Due to the difference of the width of the river valley, the curvature of the river channel and the local topographic conditions, the flow velocity, flow depth and the shear force of the river bed are different at different locations and times.

Firstly, DEM in the study area is imported into RAS Mapper to generate the terrain. Secondly, the geometric delineation of the two-dimensional simulation area was carried out and the grid was divided. The shape of the Yigong River is very complicated due to its steep slope and curved channel. In this paper, block structure grids were used to discretize the calculation area and divide the grid. The unstructured triangular grids were used in the large terrain slope, and the structured rectangular grids were used in other places. The whole calculation area was divided into 159,989 grids to compute the evolution of the outburst flood. Finally, the inlet and outlet of the simulation range are set according to the instructions provided above.

3.3. Setting of boundary conditions and parameters

The boundary conditions for numerical simulation of the Yigong 2000 outburst flood mainly include inlet flow, outlet flow, energy slope and Manning coefficient.

The discharge of unsteady flow at Inlet 1 is the corrected hydrologic process obtained above. The discharge of flow at inlet 2 is the seasonal flood discharge of the Parlung River before it reaches the confluence. The discharge of approximately constant flow, which is 500 m³/s, was obtained by the hydrology station in Yigong. The energy slope is selected as the outlet, which is approximately replaced by the

longitudinal gradient. The value of the longitudinal gradient is 0.0069, and it is calculated by the following methods:

$$J = \frac{(H_0+H_1)l_1+(H_1+H_2)l_2+\dots+(H_{n-1}+H_n)l_n-2H_0\sum l_i}{(\sum l_i)^2} \quad (1)$$

In the formula, H_i is the elevation of point i ; l_i is the horizontal distance between point i and point $i - 1$; J is the vertical drop value. The formula requires that the turning points of the river profile should be no less than eight. If we set the elevation at the outlet section to be $H_0=0$, then the relative elevations of the other turning points become $h_i=H_i - H_0$, with the distance l_i between each point remaining unchanged, transforming the equation into:

$$J = \frac{h_1l_1+(h_1+h_2)l_2+(h_2+h_3)l_3+\dots+(h_{n-1}+h_n)l_n}{(\sum l_i)^2} \quad (2)$$

The Manning coefficient was determined by dividing the simulated area into three blocks: forest land, flood terrace, and riverbed floodplain, using field observations and high-resolution UAV image analysis (Fig. 5). The roughness coefficients of various types of covered valleys in different areas of the river reach were determined by calculating measured data and establishing empirical values based on the characteristics and conditions of riverbed walls. The calculation formula was Manning-Strickler equation (Larsen and Lamb, 2016). The empirical reference values refer to the Holden roughness table.

$$n = \left(\frac{1}{8.1}\right) \frac{k_s^{\frac{1}{6}}}{g^{\frac{1}{2}}} \quad (3)$$

In the formula: k_s is the roughness coefficient of the riverbed, with values as follows (Johnson, 2014).

$$k_s = r_d r_{br} \sigma_{br} \quad (4)$$

In the formula: r_d and r_{br} represent the hydraulic roughness scale parameter; σ_{br} is the standard deviation of the bedrock elevation.

The riverbed roughness coefficient was calculated to be $k_s=1$ m. The Manning coefficient in the valley bottom area was calculated to be 0.04, which was basically consistent with the empirical reference value based on field observations. The forest

land was at a higher altitude, with many tall trees and few dwarf trees, and the vegetation was lush. The reference experience value of the Manning coefficient was 0.12. The flood terrace consists of the ancient outburst flood terrace and the high river terrace area, which is dominated by shrubs and overgrown weeds. The reference experience value of the Manning coefficient was 0.07. To further confirm the sensitivity of the roughness coefficient of the lower reaches of the Yigong River in the simulation calculation, we calculated the roughness coefficient $\pm 30\%$ for different covered river valleys. The results showed consistency with the calculated results. When the roughness coefficient changed by 30%, the calculated results of the peak discharge were less than 5% different, and the sensitivity of the roughness coefficient to the calculated results was poor.

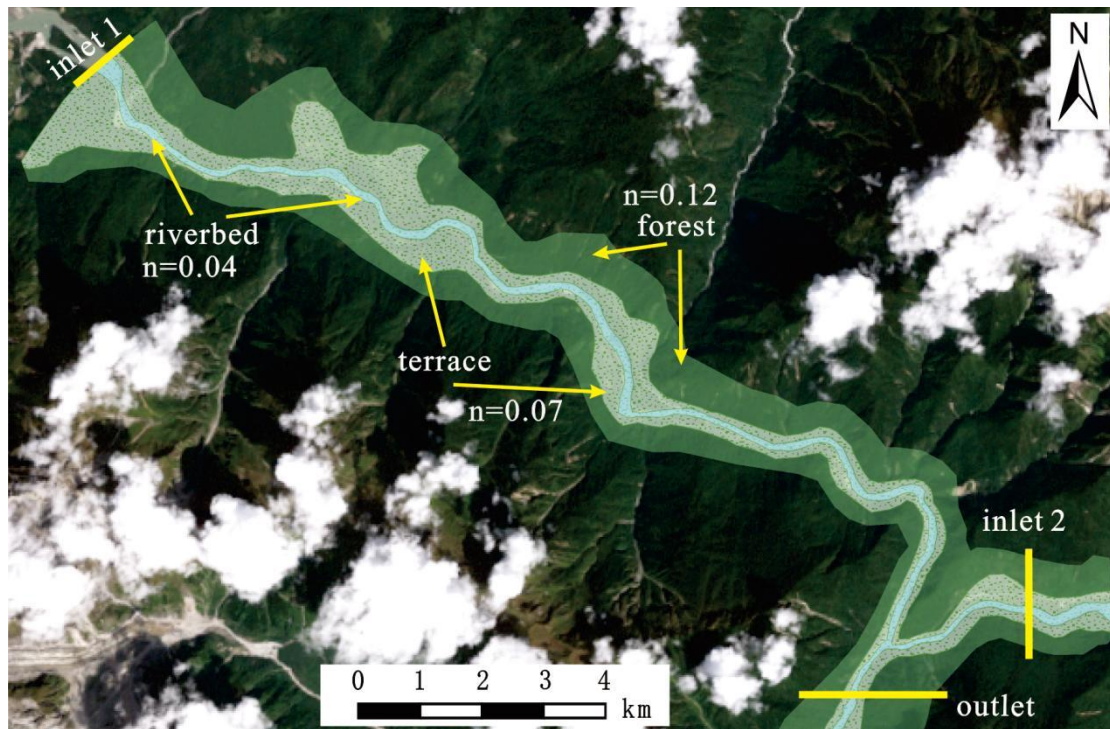


Fig. 5 Different value of manning roughness coefficient in different area

3.4. Hydrodynamic calculation of transport and sedimentation

The following formula is used to calculate the mobilize gravel size of fluid bed shear stress (Lamb et al., 2008) :

$$D = \frac{\tau_b}{\tau_{c*} g (\rho_s - \rho)} \quad (5)$$

In the formula: D is the critical bed shear stress mobilize the gravel particle size; τ_b is the simulated calculated bed shear stress; g is the gravitational acceleration; ρ_s is the gravel density (taken as 2700 kg/m³ for granite); ρ is the water density; τ_c^* is the dimensionless critical shear stress, which can be calculated as follows:

$$\tau_c^* = 0.15S^{0.25} \quad (6)$$

In the formula: S is for river channel gradient (longitudinal slope).

To calculate the critical bed shear stress for fluid-suspended particles of a certain diameter, we use the following formula (Bagnold et al., 1966):

$$\tau_b = \rho(0.8w_s)^2 \quad (7)$$

In the formula: w_s is the particle settling velocity, which can be calculated using the following equation (Ferguson and Church, 2004):

$$w_s = \frac{RgD^2}{C_1v + (0.75C_2RgD^3)^{0.5}} \quad (8)$$

$$R = \frac{\rho_s - \rho}{\rho} \quad (9)$$

In the formula: C_1 is the particle shape and C_2 is the roughness with empirical values of 20 and 1.1, respectively; the viscosity coefficient $v = 10^{-6}$ m²/s; ρ_s is the density of gravel (granite taken as 2700 kg/m³); ρ is the density of water; D is the particle diameter.

3.5. Results

The results indicate that the simulated flood depth, velocity, and bed shear stress during the peak discharge of the Yigong 2000 outburst flood align closely with the actual water level and water level marks. However, there are discrepancies in the simulation results for three outburst flood sediment marks, which are not accurately represented (Fig. 6). These three locations are situated in a river reach characterized by significant changes in the river. The upper two locations are situated within the convex bank of the former river channel, remaining unscathed by inundation resulting from the diversion of the channel due to an outburst flood that directly intersects the convex bank of the previous channel. However, the lower point near the convex bank

of the previous channel is struggling to maintain adequate coverage, as it is being heavily eroded by the outburst flood and the concave bank of the channel is receding. Therefore, the three uncovered points are all caused by the channel change. The simulation process cannot realize the dynamic change of the river channel, and the scope of the uncovered area is small. As a result, the overall outcome is minimally affected.

The results of flow depth show that the maximum flow depth of the entire river reaches 70 m, mainly concentrated in the gorge section of the upper reaches of the confluence of Tongmai Bridge. The flow depth of the lower gorge reach is higher than that of the upper broad valley, and the river reach with the lowest flow depth is located at the inlet of Jiazhong Village in the lower reaches of the breach (Fig. 6B). The upper ancient sedimentary terraces, including the confluence of Dagong Creek, Molong Creek, and the local areas of the confluence of Yigong River and Parlung River, are the main accumulation areas of bed load of the outburst flood in these open areas.

The results of flow velocity analysis indicate that the maximum flow velocity in this reach is 45 m/s, with high flow velocity areas primarily located from the breach to Jiazhong Village. Downstream, the flow velocity decreases and then gradually increases at the canyon reach (Fig. 6C). Overall, the flow velocity at the breach nearby is the highest, which is in contrast to the flow depth results. However, the flow velocity in the canyon reach is higher than that in the wide valley reach, which aligns with the flow depth findings. In the local areas, especially the lower reach of the concave bank, high flow velocity appears, while the lower reach of the convex bank shows a significant difference in flow velocity. The flow velocity of the middle line of the channel is obviously higher than that of the edge area.

The results of simulated bed shear stress show that the maximum bed shear stress reaches 10 kPa (Fig. 6D). The maximum shear stress on the riverbed is located in certain areas from the breach to Jiazhong Village, decreasing downstream, and rising in the lower canyon area. The high bed shear stress is evident in certain sections of the canyon, which roughly correlates with the velocity. The lower reach of the most

concave bank experiences high shear stress on the riverbed, while the lower reach of the convex bank is an area where shear stress is concentrated at a lower value. This difference reflects the varying erosion and sedimentation processes occurring on the convex and concave banks of the channel.

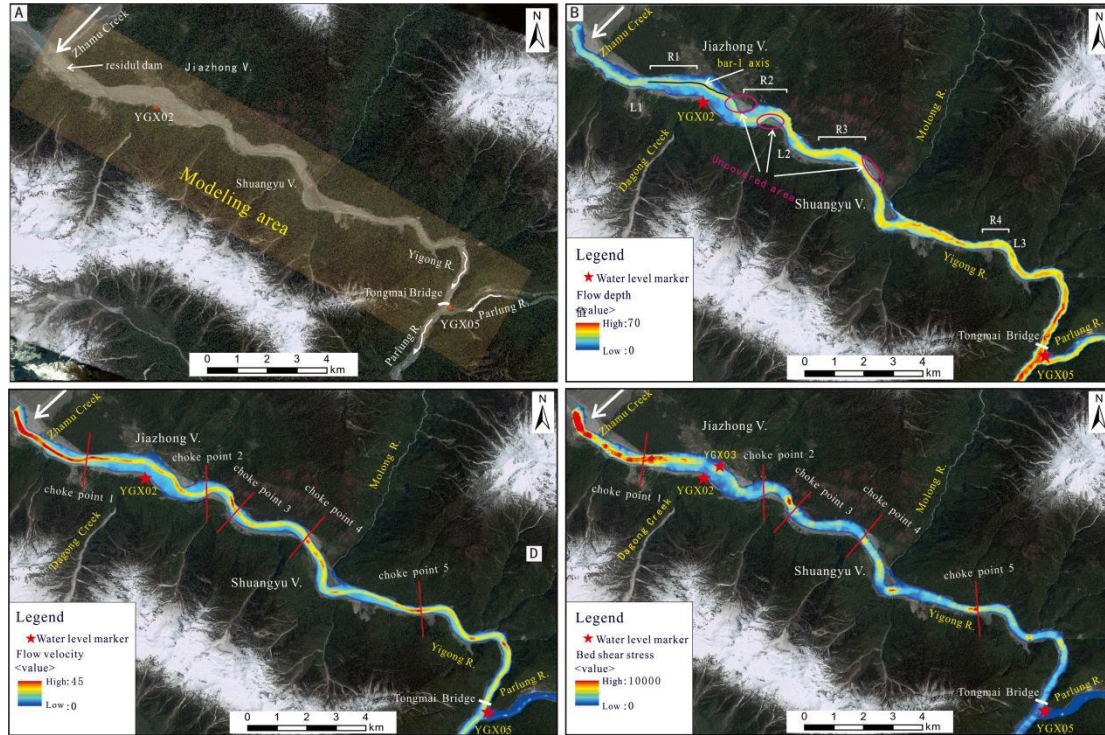


Fig. 6 Numerical simulation results of Yigong 2000 outburst flood

4. Discussion

4.1. Lateral channel migration

There is a large amount of evidence that high-energy outburst flood can dramatically alter landscapes, resulting in large-scale river diversion (Cook et al., 2018; Turzewski et al., 2019; Zhang et al., 2022). The outburst flood strongly erodes the concave bank of the channel, resulting in lateral migration of the concave bank. A large amount of gravel and coarse sand carried by the flow gradually deposits at the tail of the convex bank where the local hydrodynamic conditions are weak. The 2000 outburst flood in Yigong River caused a large-scale migration of four local river reaches, namely reaches R1-R4, in the wide valley river downstream of the breach (Fig. 7). The maximum lateral migration was reached at R1, with a value of 341 m,

followed by R2 at a distance of 205 m, R3 at a distance of 311 m, and R4 at a distance of 118 m.

It has been found that the topographic choke points of the channel are located at 1-5 (refer to Fig. 7) (see Fig. 6CD). These locations exhibit high values of flow velocity and bed shear stress throughout the entire reach, with longer durations, especially during peak discharge. The flow velocity exceeds 30 m/s. The bed shear stress of the local reach is higher than 2.5 kPa, which is sufficient to mobilize 3 m blocks.

The lateral migration of the river channel due to the Yigong 2000 outburst flood is directly linked to local flow velocity and bed shear stress. This relationship is evident when comparing the velocity and bed shear stress of the main stream line at different locations before and after the flood (refer to Fig. 7). The colored curves in the figure illustrate the variations in dynamic parameters over time at specific locations. It is worth noting that reaches R1-R4, which experienced significant changes, are located in areas with high flow velocity and bed shear stress. The choke point of the R1 exhibits a maximum flow velocity of 40 m/s and a maximum bed shear stress of 4.5 kPa, with the bed shear stress exceeding 4 kPa for more than three hours. The starting points of the two drastic changes in the R2 reach are choke point 2 and choke point 3, corresponding to maximum flow velocities of 33 m/s and 37 m/s, respectively, and maximum bed shear stresses of 2.5 kPa and 3.6 kPa. The bed shear stress near choke point 3 exceeds 3 kPa for more than four hours. The starting point of the R3 reach is choke point 4, corresponding to a maximum flow velocity of 37 m/s, a maximum bed shear stress of 3.0 kPa, and a bed shear stress above 2.5 kPa for more than four hours. The starting point of R4 is choke point 5, corresponding to a maximum flow velocity of 41 m/s, a maximum bed shear stress of 5.0 kPa, and a bed shear stress above 4.5 kPa for more than seven hours. Among them, the R1-R3 reaches are wide valleys with high bed shear stress and velocity, leading to large lateral migration of the channel. In contrast, the R4 reach is situated in a bedrock canyon. It has been observed that there are local maximum bed shear stress and velocity at the choke point in this reach, although the channel variation is smaller than in the

previous reaches. This suggests that the lateral migration of the channel due to outburst floods is not solely determined by the shear stress and velocity of the bed in the local reach, but also influenced by the width of the valley in certain reaches.

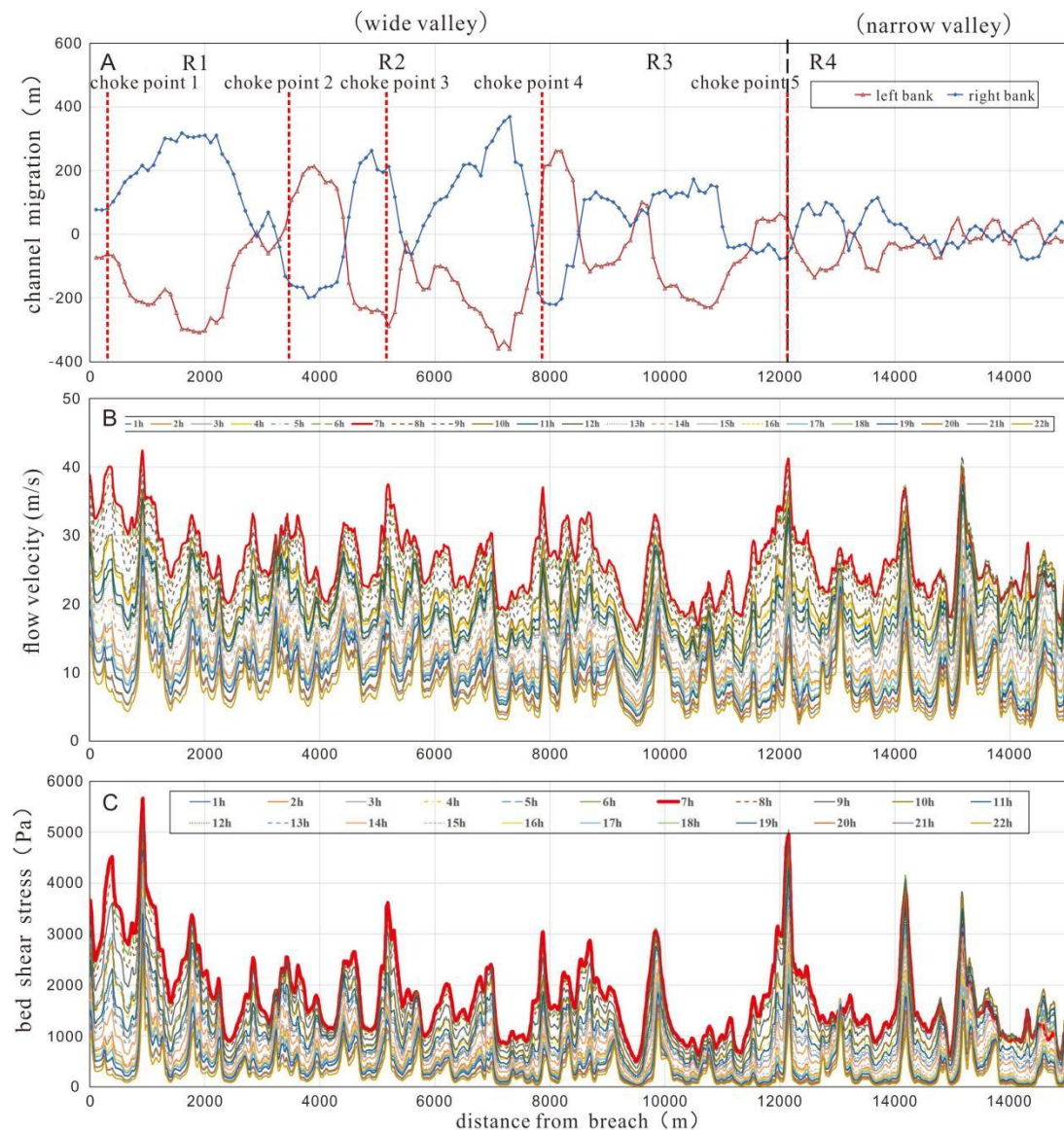


Fig. 7 Comparison of velocity and bed shear stress-channel changes in different time of the outburst flood along the mainstream

The strong erosion of the channel by the outburst flood can also induce a large number of landslides in the valley slopes on both sides of the channel (Larsen and Montgomery, 2012; Turzewski et al., 2019). The simulation results show that the three large landslides (L1-L3 above) near the Tongmai Bridge are located at the largest bend of the concave bank of the river channel, and the local narrow area of the river

valley is the area where the flood strongly erodes the valley slope. L1 landslide is located on the right bank slope at the choke point 1, where the local maximum flow velocity is 40 m/s, the maximum shear stress is 4.5 kPa, and the bed shear stress is above 4 kPa for more than three hours. L2 landslide is on the right bank slope of the choke point 3, where the local maximum flow velocity reaches 37 m/s, the maximum bed shear stress reaches 3.6 kPa, and the shear stress of the bed near the choke point 3 is above 3 kPa for more than four hours. L3 landslide is located in the area with the local maximum flow velocity of 37 m/s and the maximum shear stress of 4.1 kPa, and the bed shear stress is above 4 kPa for more than two hours.

4.2 Hydrodynamic characteristics of the boulder bars

There are certain morphological characteristics of the boulder bars formed during the 2000 Yigong outburst flood. In the upper wide valley reach of 10 km, the ratio of the long axis to the short axis is about 5, with little change, and the shape is mainly convex lens type. In the lower valley reach, the ratio is about 10, with significant changes and various forms, including convex lens type, crescent type, and long strip type (Fig. 8).

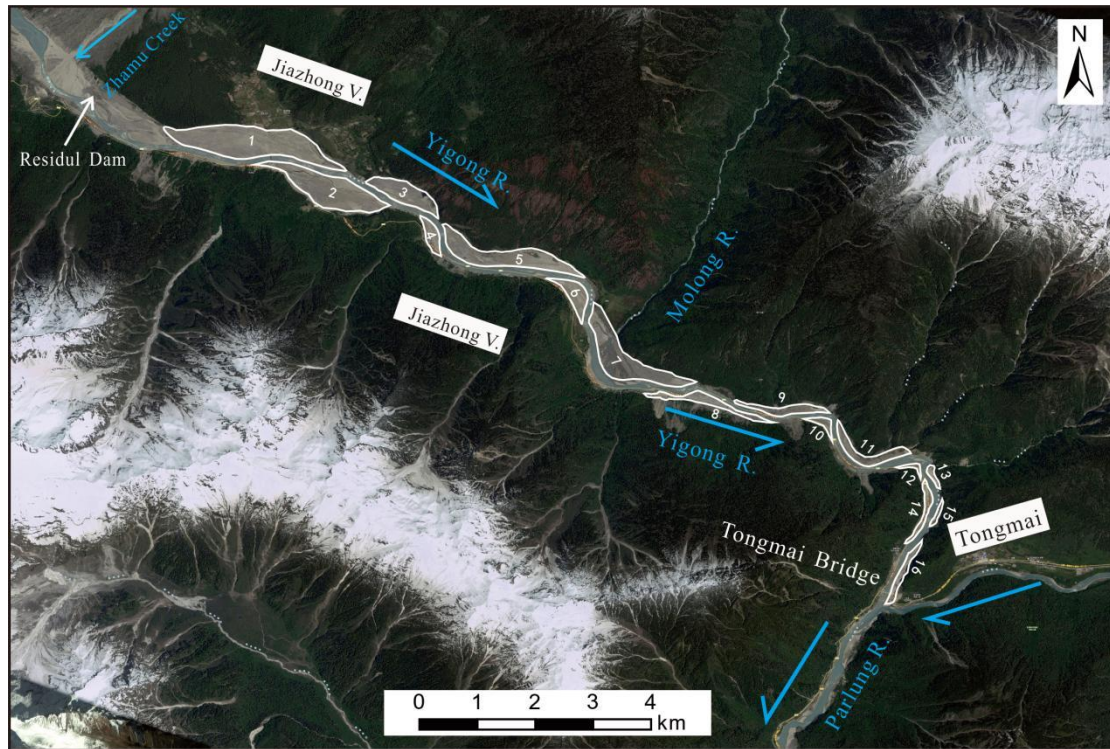


Fig. 8 The distribution of the 2000 Yigong outburst flood boulder bars and sections

The Bar-1, Bar-2, Bar-3 and Bar-4 in the wide valley upstream are convex lens-shaped, primarily situated at the transition zone from the convex bank to the concave bank. A comparison of the image data before and after the flood in this area reveals that Bar-1, Bar-2, Bar-3 and Bar-4 were located on the concave banks prior to the flood. The simulation results indicate that the concave banks were strongly eroded and the bedrock was incised by the outburst flood. Particularly during the flood rise period, high bed shear stress (≥ 3 kPa, enough to pluck boulders with a diameter of 4 m) is focused at the axis of the concave bank. Additionally, the flow velocity is relatively high, with speeds exceeding 20 m/s at the axis. The choke points of Bar-1, Bar-3 and Bar-4 are point 1, 2 and 3 respectively. It can be seen that the erosion intensity before the peak discharge provided a suited local topography for the subsequent sedimentation of bed load. During the peak discharge, the flood cut through the original river terrace of convex bank, causing the river channel to migrate laterally. As a result, the river curvature decreased, the main flow line turned to the outside of the concave bank, and the flow velocity and bed shear stress inside the concave bank decreased rapidly. This led to a large number of boulders and gravel being deposited, forming boulder bars. Due to the large curvature of the original river channel in this reach, the short axis of the boulder bars is relatively long, resulting in a small ratio of the long and short axes and presenting a convex lens shape.

In the middle and lower reaches of the river, Bar-6, Bar-7, Bar-10, Bar-11, and Bar-12 are crescent-shaped and appear on the convex bank curves of the main river. The ratios of their long and short axes are relatively low. By comparing the location of the channel before and after the flood and the simulated results of the bed shear stress, it is shown that the intermediate axis of Bar-6 corresponds to the original main channel, with a maximum bed shear stress of more than 3 kPa. This results in strong denudation of the riverbed, with a flow depth of more than 10 m. On the other hand, Bar-7, Bar-10, Bar-11, and Bar-12 are all situated on the convex banks of the original channel with large curvature. The high bed shear stress and flow velocity extend to

the upstream position of these convex banks. Intense scouring is likely to occur on the outer edges of these convex banks during peak discharge. As a result, these boulder bars also experience significant scouring during peak discharge, leading to the formation of localized concave topography. The simulation results for bed shear stress and flow velocity indicate that after the peak discharge, the main stream shifts towards the outer edge of the convex bank. As the flow velocity decreases and the bed shear stress declines, the edges of these convex banks gradually transition into a sedimentary environment with the deposition of a large number of boulders. The simulation results for flow depth indicate that a shallow depth at the edge of the convex bank is conducive to deposition. The boulder bars in the lower reaches of the river are distributed in a ribbon along the straight channel with small curvature, and the scale decreases with the larger ratio of long and short axis.

The four boulder bars of Bar-1, Bar-2, Bar-5, and Bar-7 have the largest scale. The simulation results show that the head positions of Bar-1, Bar-5, and Bar-7 are exactly where the choke points 1, 3, and 4 are located. The maximum bed shear stress is ≥ 3 kPa, and the local in bar-1 is ≥ 5 kPa. This high bed shear stress is sufficient to pluck and transport a boulder of 6 m diameter (Fig. 7C). During the peak discharge, the intermediate axis of these boulder bars is strongly eroded by outburst flood, which corresponds to the high bed shear stress and flow velocity, leading to channel migration. Comparing the axial position of the boulder bars with the flow depth, it is evident that the flow depth gradually decreases as the flood recedes. Obviously, these local concave areas have been filled or even piled up by a large number of boulders and gravel carried by the flood, which corresponds to the low flow depth.

It is showed that the core of the axis of bar-1 is incised strongly by the flood with the bed shear stress ≥ 2.5 kPa for more than 11 hours (Fig. 9). This is sufficient to plucked 3-meter blocks, so most imbricated boulders covering the top of bar-1 may be formed during the flood decline.

It is shown that the maximum bed shear stress is 4 kPa during the peak discharge at location YGX03 on the edge of the channel in Bar-1. This level of stress is

sufficient to transport a 5.5-m block, which aligns with the largest boulder observed in the field, measuring about 5 m (Fig. 6D, Fig. 10). Therefore, it can be concluded that the block was transported to this location by the flood during the peak discharge. As the flood extends laterally to the edge, the flow velocity decreases and deposits are formed. The simulation results of the intermediate axis at the tail of bar-1 show that it is always under low bed shear stress (< 1 kPa) and flow depth (< 10 m) during the rise stage of the outburst flood (Fig. 6BD, Fig. 11). It is insufficient to start and transport boulders above 1.5 m during the peak discharge. Therefore, a large amount of boulder bed loads (> 1 m) in the upper reaches are gradually transported and deposited here by the flood, which is consistent with the thicker deposit at the tail end of Bar-1.

In conclusion, the morphology, scale, and orientation of the maximum boulder bar are influenced by the original river valley shape, channel width, bed shear stress distribution, flow depth before and after peak discharge, and local hydrodynamic conditions of the flood channel and valley topography.

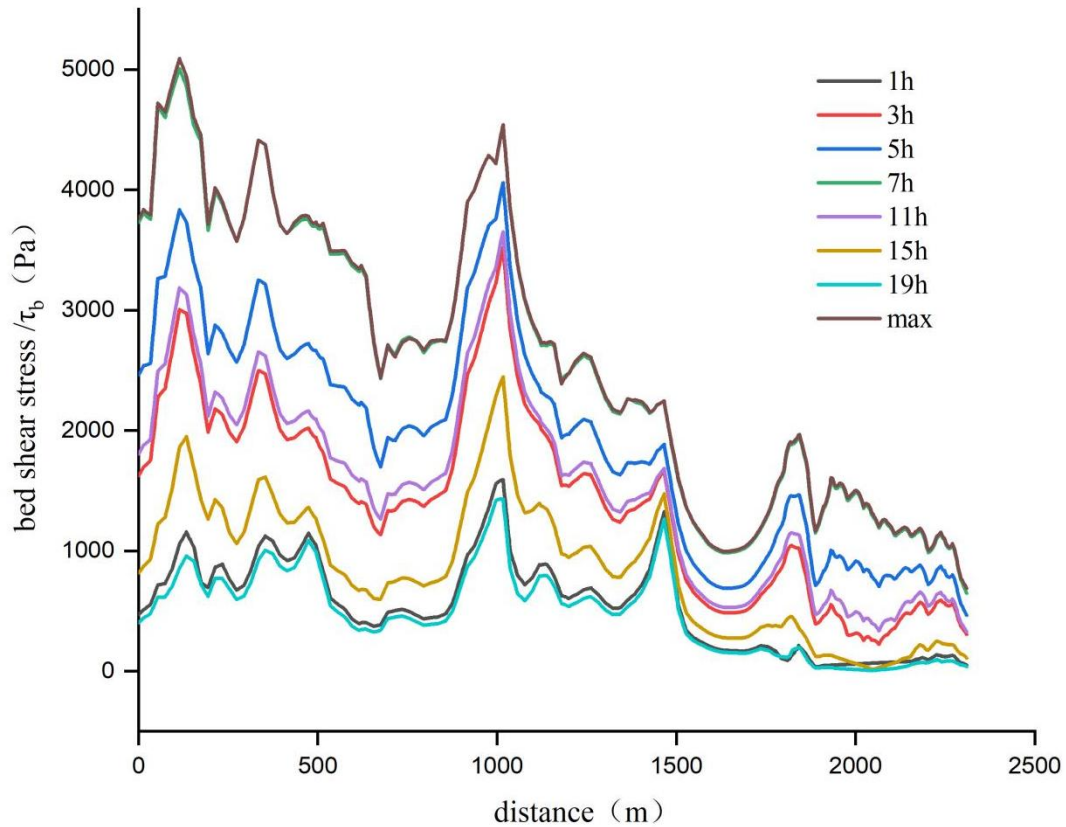


Fig. 9 Variation of shear stress at the intermediate axis of bar-1 in different time (The

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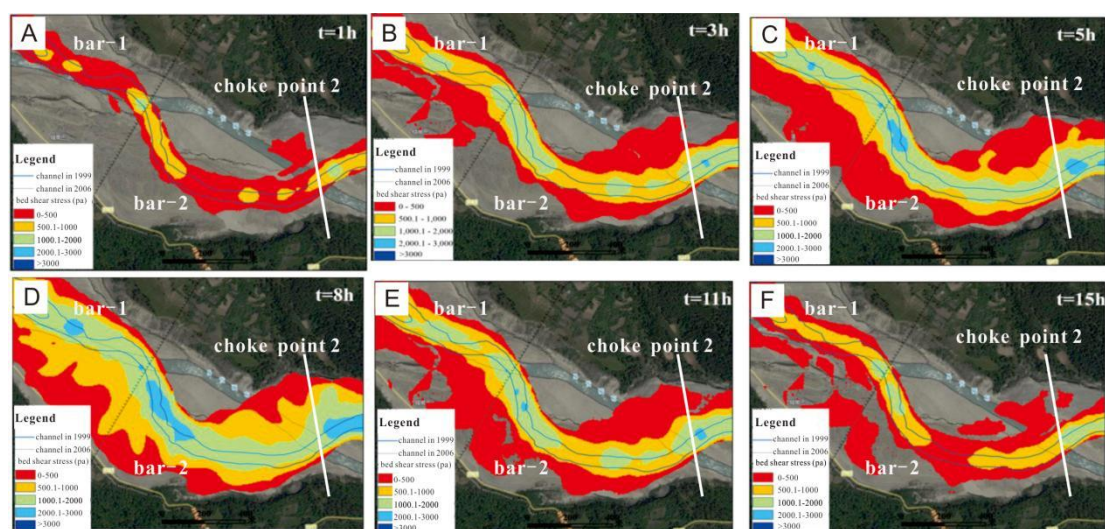
position of the central axis of bar-1 is shown in Fig. 7B)



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Fig. 10 Boulders on the bar-1



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Fig. 11 Variation diagram of the bed shear stress near the choke point 2 on reach R2 in the outburst flood

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442 4.3 Analysis of sedimentary hydrodynamics

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The 2-D simulation results of unsteady flow are in good agreement with the slack water deposit YGX02 and deposit in the eddy bar YGX05. As can be seen from

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the distribution diagram of flow depth during peak discharge in the outburst flood (Fig. 7B), the outburst flood just reaches the location of the YGX02, and the water depth is relatively shallow. The flow velocity simulation results indicate that the velocity is low in this area, promoting the formation of slack water deposits. These deposits are formed during peak discharge and consist mainly of medium-fine sand.

The eddy bar where YGX05 is located is completely flooded during peak discharge. It is evident in most areas of the bar that the flow depth exceeds 10 m and the flow velocity is greater than 5 m/s. The maximum bed shear stress is about 300 Pa, enough to transport 40-cm gravel. The maximum bed shear stress is above 700 Pa at local area along the outer edge of the main flood channel, which is sufficient to transport a 1-m boulder (Fig. 12AB). The maximum gravel particle size within the horizontally-bedded laminations in the eddy bar is only 10 cm based on field observations. Therefore, it can be inferred that the horizontal lamination of coarse sand and fine gravel in the eddy bar was mainly formed during the flood decline period following the peak discharge.

The average particle size of deposits here is 5 mm according to the test results in the laboratory, corresponding to a critical bed shear stress of 63 Pa. However, the bed shear stress along the outer edge of the bank is about 700 Pa, while in other places it is lower, around 300 Pa, during peak discharge. As a result, these deposits are currently in a suspended state. Therefore, these deposits should be formed after the peak discharge. The flow velocity and the bed shear stress decreased during the flood decline, and the fine gravel and coarse sand gradually deposited in the upper inner edge of the bar.

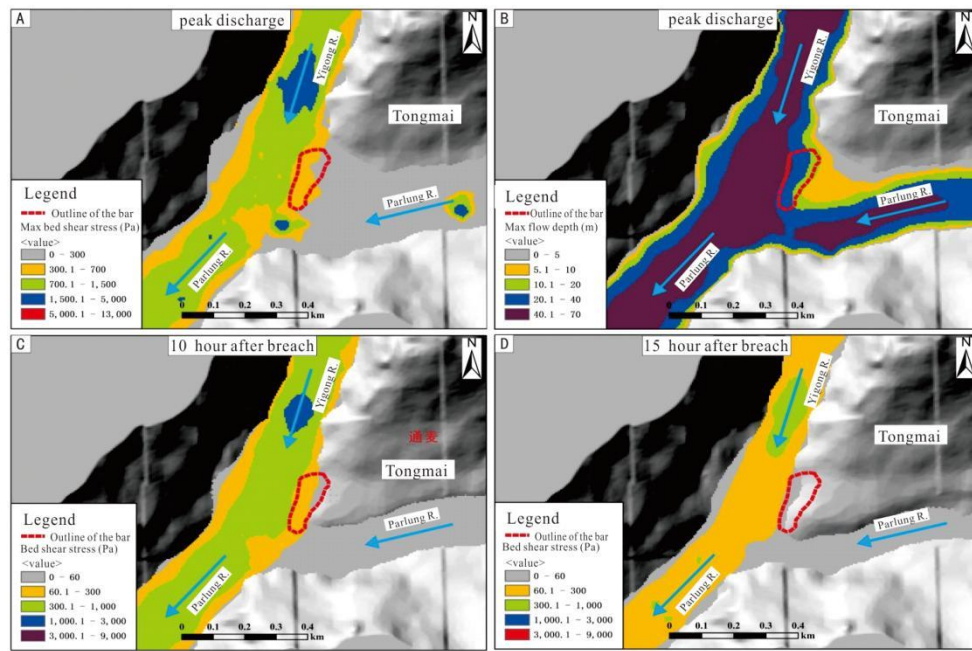


Fig. 12 Numerical simulation results of the eddy bar in confluence

It is shown that the discharge of the flood decreases to less than 4×10^4 m³/s, and the bed shear stress at the inner edge of the bar is less than 60 Pa about 10 hours after the outburst flood occurred. The 5-mm granules suspended in the flood are transformed into bed loads and deposited at the inner edge (Fig. 12C). The flood discharge decreases to less than 2×10^4 m³/s after about 15 hours, causing the flood to separate from the main body of the bar. The horizontally-bedded laminations of the eddy bar finish the deposition process with a thickness of 4 m (Fig. 12D).

The main body of the eddy bar starts to accumulate about 10 hours after the flood outburst, and finishes the deposition around 15 hours later. It only takes 5 hours to create the horizontal laminated coarse sand and fine gravel layer, which represents a rapid deposition of bed loads from the hyper-concentrated flow in the outburst flood.

5. Conclusion

The hydrologic process leading to the 2000 outburst flood in the Yigong River was calculated using the observation results from the hydrology station on Yigong Lake. A 2D unsteady flow model was utilized to simulate the outburst flood. The results indicate that the inundation patterns closely match the water level marks. Only

small areas of three boulder bars were not inundated during peak discharge. The three places are all located near choke points, where the flood strongly erodes the channel. The simulation process cannot realize the dynamic change as erosion of the river channel intensifies. However, the uncovered areas are small and have little effect on the simulation results, so it is feasible to use the 2D unsteady flow model to assist the study of flood reconstruction and geomorphic remodeling in mountainous areas.

Integration of simulated results and remote sensing observations from pre- and post-flood events provide insights into the control of extreme flood hydraulics on erosion. Results show that in the four river reaches with lateral migration of more than 100 m, the maximum flow velocity at the choke point exceeds 30 m/s, the corresponding maximum shear stress is above 2.5 kPa, and the duration is approximately four hours during peak discharge, reflecting the strong lateral erosion of the outburst flood. The choke point gradually transitions into the starting point for large-scale lateral migration of the riverbed, leading to significant changes in the R1, R2, R3, and R4 reaches. The sudden flood event triggered the lateral migration of the riverbed, highlighting the powerful transformative impact of floods on the riverbed. The simulation results indicate that the highest local riverbed shear stress and velocity are found in reach R4 of the gorge. However, the variation range of the channel in this area is smaller compared to the wider valley reaches R1 to R3. This suggests that the lateral migration of the channel due to the outburst flood is influenced not only by riverbed shear stress and flow velocity, but also by the width of the valley. Additionally, the simulation results for landslides in reaches L1 to L3 demonstrate that long-term high riverbed shear stress is a significant factor in inducing valley landslides.

Field survey and remote sensing observations were incorporated to study the depositional landform of the outburst flood, along with numerical simulations. The results indicate that the morphology, scale, and the central axis of maximum boulders of the boulder bars are closely related to the morphology of the original river valley, valley width, and the riverbed shear stress of the outburst flood. The consistency in the range of boulder bars and the flow depth before and after peak discharge of the

main flood channel indicates that the scale of boulder bars is closely related to the local hydrodynamic conditions and valley topography. The variations in riverbed shear stress on the central axis of bar-1 are in good agreement with the computed results of the critical riverbed shear stress mobilizing big boulders at different positions on the top of bar-1. This reflects the reliability of the simulation results. The hydrodynamic analysis of the simulation results of the giant bar near Tongmai Bridge shows that the sedimentary sequence of the 4m thick horizontally-bedded laminations of coarse sand and fine gravel on the giant bar is a rapid bedload deposition from hyper-concentrated flow. The deposition process lasts for 5 hours from 10 to 15 hours after the flood outburst, mainly during the flood decline stage following the peak discharge.

Data availability

All data and material are available in the main text or in cited resources mentioned in the text.

Code availability

All software applications used in this paper are free or open-source and can be found in cited resources mentioned in the text.

Declarations

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

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