Reconstruction of catastrophic outburst floods of the Diexi ancient landslide-dammed lake in the Upper Minjiang River, Eastern Tibetan Plateau

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Abstract
Landslide-dammed lake outburst floods (LLOFs) may pose serious safety threats to nearby residents and their livelihoods, as well as cause major damages to the downstream areas in mountainous regions. This study presents the Diexi ancient landslide-dammed lake (DALL), located along the Upper Minjiang River, in the eastern margins of the Tibetan Plateau. The DALL is known to have an estimated previous maximal lake area of $1.1 \times 10^7$ m$^2$ and an impounded volume of $2.9 \times 10^9$ m$^3$. At approximately 27 ka BP, the ancient landslide dam failed, and catastrophic LLOFs occurred. It was determined that the peak discharge of the Diexi ancient LLOFs could be reconstructed using regression, parametric, and boulder competence approaches. The reconstructed average maximum peak discharge was approximately 79,500 m$^3$/s, with an estimated uncertainty bound of 70,000 to 90,000 m$^3$/s. This indicated that the Diexi ancient LLOFs were the largest outburst floods to have occurred in the Upper Minjiang River Valley since the Late Pleistocene Period. The differences in the widths and slopes within the former and latter reaches of the dam indicated that the geomorphic influences on the river channel resulting from the DALL and its LLOFs have been present for tens of thousands of years. These findings were of major significance in deepening the understanding of the existence and disappearances of important river knickpoints on a time scale of tens of thousands of years.

Keywords Landslide dam · Ancient dammed lake · Landslide-dammed lake outburst floods (LLOFs) · Peak discharge · Uncertainty assessment

List of symbols

$Q_p$ The peak flood discharge (m$^3$/s)
$H$ Height of the water behind the dam (m)
$H_d$ Height of dam (m)
$H_w$ Depth of water above breach invert at time of failure (m)
$d$ Lake level drop (m)
$V$ Volume of water behind the dam (m$^3$)
1 Introduction

Natural processes, such as tectonic movements, climate changes, volcanic activities, biological forces, and chemical processes, can form different types of natural dams and dammed lakes. These include landslide-dammed lakes, glacier lakes, moraine-dammed lakes, volcanic lakes, and organic lakes (Evans 1986; Costa and Schuster 1988; Clague and Evans 2000; Dai et al. 2005; Korup and Montgomery 2008; Pierce et al. 2010; Chen et al. 2013; van Gorp et al. 2013; Delaney and Evans 2015; Emmer 2017; Kataoka et al. 2018). In the category of natural dammed lakes, landslide-dammed lakes are widely found to exist in various parts of the world (Ermini and Casagli 2003; Korup 2004; Dai et al. 2005; Dong et al. 2009, 2011; Butt et al. 2013; Zhou et al. 2013; Stefanelli et al. 2018; Chen et al. 2018; Fan et al. 2020). Landslide dams and dammed lakes are common geomorphic phenomena found in the eastern and southern margins of the Tibetan Plateau in southwestern
China (Dai et al. 2005; Korup and Montgomery 2008; Cui et al. 2009; Chen et al. 2013; Wang et al. 2014a). Among the aforementioned landslides, many large-scaled ancient landslides had blocked rivers, thereby forming ancient landslide-dammed lakes, as illustrated in Table 1.

The longevity of landslide-dammed lakes may vary from several minutes to millennia (Costa and Schuster 1988; Korup 2002; Ermini and Casagli 2003; Butt et al. 2013; Delaney and Evans 2015; Chen et al. 2018). A stable dammed lake may exist for thousands of years and be utilized for hydroelectric generation or tourist attractions. However, unstable dams may fail and generate landslide-dammed lake outburst floods (LLOFs), in turn causing destructive hazards. It is essential to assess the mechanism and processes related to the triggers and breaches of landslides and dammed lakes, and these are of major significance in the reconstructions of previous events, as well as effective hazard mitigation.

China’s Diexi ancient landslide-dammed lake (DALL) is a well-known case and is located the Upper Minjiang River at the eastern margin of the Tibetan Plateau. This lake initially received widespread attention in the research studies which were conducted regarding the Diexi earthquake of 1933. A large number of in-depth examinations of the lacustrine sediment in the upstream area of the landslide dam were completed in the decades following the aforementioned earthquake event (Wang et al. 2011, 2014b; Wei et al. 2015). However, few research reports have presented data regarding the LLOFs and the outburst deposits in the downstream areas. In our previous field research studies, several outburst deposit bars were discovered to be distributed in the downstream areas of the relict ancient landslide dam and were subsequently examined and analyzed (Ma et al. 2018; Chen et al. 2019). In this study, a summarization of the characteristics of the outburst floods of the DALL was presented, and the maximum peak discharge of the LLOFs was reconstructed based on geomorphic and sedimentary characteristics. Furthermore, this study discussed the failure mode of the DALL, along with the geomorphological effects of the DALL and its outburst flooding actions.

2 Regional geological settings

The Minjiang River is considered to be an important tributary of the Yangtze River and originates from the southern Minshan Mountains in Songpan County. The Diexi Reach (31.5 to 32.5°N; 103.5 to 104.5°E) belongs to the middle section of the Upper Minjiang River. It is located between Songpan County and Maoxian County, at the eastern margin of the Tibetan Plateau (Fig. 1a). The river deeply incises the high mountains, where the valleys form deep U- or V-shaped gorges, with elevations of 1500 m in the valleys and 3000 m along the ridges. In addition, the river current is fast, with an average water surface gradient of approximately 10.3%. Narrow valleys can be found in this region, with widths ranging between 100 and 200 m. Meanwhile, the broader rivers range between 200 and 350 m in width.

A well-known ‘North–South Seismic Belt’ of abrupt topographic changes is located in this area (Wang et al. 2011). Two groups of major active fault zones were observed to be developed in the study area, which are referred to as the Minjiang Fault Zone (F8, Fig. 1b) and the Huya Fault Zone (F9, Fig. 1b). The regional crustal stability in the study area has been determined to be largely controlled by the activities of Longmenshan–Minshan Fault Zone, which is characterized by frequent fault activities, frequent earthquakes, and
Table 1  Study cases of ancient landslide-dammed lakes in the Upper Yangtze River on the eastern Tibetan Plateau

| Drainage basin | Lake name                          | Dating method | Sampling site                                      | Age (ka)  | References          |
|----------------|------------------------------------|---------------|---------------------------------------------------|-----------|---------------------|
| Jinsha River   | Benzilan ancient landslide-dammed lake | U-series dating | Upper part of the lacustrine clay bed on the right bank | 55.4 ± 3.5 | Zhang et al. (2011) |
|                |                                    |               | Lower part of the lacustrine clay bed on the right bank | 82.1 ± 6.6 |                     |
|                |                                    |               | Lacustrine clay bed on the left bank               | 122.0 ± 12.4 |                     |
|                | Wangdalong paleo-dammed lake       | OSL           | Top of lacustrine sediments                        | 1.2 ± 0.1 | Chen et al. (2013)  |
|                |                                    | 14C           | Landslide debris                                   | 1.9 ± 0.06 |                     |
|                | Suwalong paleo-dammed lake         | 14C           | Downstream relict landslide dams                   | 1.175 ± 0.025 | Wang et al. (2014a) |
|                |                                    | OSL           | Lacustrine sediments                               | 1.3 ± 0.14 |                     |
|                |                                    |               |                                                    | 1.8 ± 0.1 |                     |
|                | Xuelongnang paleolandslide-dammed  | 14C           | Bottom of the relict landslide dam                 | 2.1 ± 0.025 | Chen et al. (2018)  |
| Upper Minjiang River | Maoxian paleolake                | 14C           | Bottom of the lacustrine sediments                 | 22.5 ± 0.55 | Wang et al. (2007)  |
|                | Wenzhen paleolake, Maoxian          | 14C           | Middle part of the lacustrine sediments            | 20.76 ± 0.225 |                     |
|                | Gu’ergou paleolake                  | 14C           | Lower-center part of the lacustrine sediments      | 18.84 ± 0.34 |                     |
|                | Lixian paleolake                    | 14C           | Lower-center part of the lacustrine sediments      | 18.94 ± 0.12 |                     |
| Dadu River     | Jiajun paleolake                    | 14C           | Bottom of the lacustrine sediments                 | 19.36 ± 0.42 | Wu et al. (2018)    |
poor stability. Several ancient dammed lakes (Wang et al. 2011), including the DALL, are located in the upper reaches of the Minjiang River, as detailed in Table 1.

The lithologies of the exposed bedrock in the area mainly include the Xinduqiao (T3x), Jurassic (T3zh), Zagu’nao (T2), and Bocigou (T1b) groups of the Triassic and Carboniferous-Permian Periods, and the Weiguan group (Dwg2) of the Devonian Period. These include (fine) sandstone, phyllite, (sandy) limestone, and griotte, as shown in Fig. 1c. In addition, layers of the Quaternary Holocene–Pleistocene (Q1–4) are widely distributed on both sides of the river, including residual, alluvial, debris flow, and lacustrine deposits.

Fig. 1 Study area. a Location map, b Outline of the active tectonics in the East Tibetan Plateau. c The lithologies of the exposed bedrocks in the study area, and the distribution of the DALL. The Diexi Haizi lakes are modern barrier lakes induced by the Ms. 7.5 Diexi earthquake which occurred in 1933.
The climate in the study area has the characteristics of a subtropical plateau-continent monsoon climate. The average annual temperature is approximately 12 °C. It has been observed that more than 80% of the annual rainfall is concentrated within the period ranging from May to October, with an average annual rainfall of 420 mm. The hydrographic system of the Minjiang River is a perennial river with an annual flow of 21.178 billion m³. Meanwhile, the average annual flow of the Diexi Reach area is approximately 700 m³/s.

Based on the findings of previous studies of relict ancient landslide dams, it was noted that an abundance of lacustrine deposits existed in the upstream areas, and several well-preserved band-, fan-, or terrace-shaped outburst deposits could be observed downstream of the Minjiang River (Fig. 1c) (Ma et al. 2018). This study selected a large relict ancient landslide dam located in the Diexi Valley, on the left bank of Minjiang River. The dam was approximately 3 km in length along the river and 1 km in width crossing the river, with the highest elevation observed to be 2316 m (Figs. 2b and 3). The lake sediment sections were preserved on the slope of the relict landslide dam and both sides of

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Fig. 2  a Longitudinal profile of the DALL and the relict ancient landslide dam on the left bank of the Minjiang River. The line of previous ancient landslide dam is schematic. b Geomorphological features of the relict Diexi ancient landslide dam (modified from Ma et al. 2018). Dam D-I is the main relict body of the Diexi ancient landslide dam. Dam D-II is the residue of dam body originated from the left bank slopes, which is located in Xiahaizi Lake. c Geomorphological and sedimentary features of the lacustrine deposits near Zhenping Village, which was inferred the end of DALL.

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the Minjiang River within the upstream areas of the relict landslide dam, which measured approximately 30 km in length (Figs. 1c and 2). In addition, approximately 5 km of outburst deposits were found to be spread on both riverbanks at the downstream reach of the Diexi ancient landslide dam (Fig. 1c).

3 Data sources and methods

3.1 Field investigations and dataset

Detailed field investigations were conducted, including topographic reconnaissance and geomorphologic investigations, along with the determination of the extent and distribution of the deposits from the ancient lake, in order to clarify the formation and evolution of the gigantic DALL, as well as the ancient LLOFs induced by the dam failure. Several dozens of sections distributed over more than 50 km (from Zhenjiangguan to Shidaguan) were investigated along the Minjiang River and the Songping Valley, for the purpose of obtaining sedimentary and geomorphologic evidence related to the DALL and its outburst floods. Then, the topographic reconnaissance and geomorphologic data, including the locations, elevations, lengths, heights, and thicknesses of the profiles, were accurately measured in situ.

The elevations and coordinates (longitude and latitude data) were measured using a portable Trimble GeoExplorer 6000 Series global positioning system (GPS), with an accuracy of ±10 cm. Meanwhile, the data related to the angles, distances, heights, and thicknesses were obtained using Newcon-OPTIK LRM 2200SI hand-held laser rangefinders (range 10–2200 m; accuracy: ±1 m), along with Nikon COOLSSHOT 40i devices (range 7.5–590 m; accuracy: ±20 cm). Along with the characteristics of the landslide dam, this study also required a high-quality digital elevation model (DEM) in order to accurately reconstruct the dam’s previous reservoir. A 10 m DEM generated from the Advanced Shuttle Radar Topography Mission (ASTER) digital elevation model on August 6th of 2013.
with a spatial reference of Krasovsky_1940_Albers, was used in this study. The platform of ArcGIS v10.2 was used for the topographic data analysis.

The powerful “spatial analysis” function of the ArcGIS can be used to calculate the water surface area and capacity of a reservoir, as well as the elevation of the water surface. In the present study, the extent of the previous barrier lake could be inferred from the distribution and sedimentary characteristics of the lacustrine deposits. According to the field investigation results, the section of the lacustrine deposits near Zhenping Village, located approximately 30 km upstream from the Diexi landslide dam, was observed to be coarser, and fluvial sediment had emerged (Fig. 2c). These changes in the sedimentary facies inferred that this site may have been the end boundary of the DALL. The top of the sediment was determined to have an elevation of 2355 m (Fig. 2c). These findings confirmed that the water surface elevation of the previous DALL was not lower than 2355 m. Therefore, it was assumed in this study that the original elevation of the previous lake surface was approximately 2355 m. Using this acquired information, a topographic map based on the 10 m DEM data was drawn in ArcGIS software. Subsequently, the maximal water surface area and volume of the DALL before draining occurred were successfully reconstructed (Fig. 4).

**Fig. 4** Map showing the reconstructed original lake surface area and responding volume of the DALL with a water surface elevation of 2355 m
Table 2  Summary of conventional methods and equations developed to determine the peak discharge ($Q_p$) for outburst floods

| Method categories | Equation | Number of case studies | Coefficient of determination ($R^2$) | Accuracy | References |
|-------------------|----------|------------------------|-----------------------------------|----------|------------|
| **Regression equations** | | | | | |
| Water height (depth) | $Q_p = 1.268(H_w + 0.3)^{2.5}$ | 38 | 0.790 | Best fit | Kirkpatrick (1977) |
| | $Q_p = 13.4(H_d)^{1.89}$ | 38 | 0.488 | Best fit | Singh and Snorrason (1982) |
| | $Q_p = 6.7(d)^{1.73}$ | 22 | 0.530 | Best fit | ^Walder and O’Connor (1997) |
| | $Q_p = 0.784(H)^{2.663}$ | 72 | 0.633 | Best fit | Pierce et al., (2010) (linear) |
| | $Q_p = 2.325 \ln(H)^{0.405}$ | 72 | 0.640 | Best fit | Pierce et al. (2010) (curvilinear) |
| | $Q_p = 24(d)^{1.73}$ | 19 | 0.530 | Best fit | ^Cenderelli (2000) |
| Water storage (volume) | $Q_p = 1.776(S_w)^{0.47}$ | 35 | 0.918 | Best fit | Singh and Snorrason (1984) |
| | $Q_p = 0.72(V_w)^{0.53}$ | 39 | 0.836 | Best fit | ^Evans (1986) |
| | $Q_p = 1.6(V_0)^{0.46}$ | 22 | 0.730 | Best fit | ^Walder and O’Connor (1997) |
| | $Q_p = 0.00919(V)^{0.745}$ | 87 | 0.805 | Best fit | Pierce et al. (2010) |
| | $Q_p = 3.4(V)^{0.46}$ | 19 | 0.730 | Best fit | ^Cenderelli (2000) |
| | $Q_p = 1.122(S_w)^{0.57}$ | 35 | – | Best fit | Costa (1985) |
| Water height and storage | $Q_p = 0.54(S_w \cdot H_d)^{0.5}$ | 31 | – | Envelope | Hagen (1982) |
| | $Q_p = 1.154(V_w \cdot H)^{0.412}$ | 37 | 0.788 | Best fit | MacDonald and Langridge-Monopolis (1984) |
| | $Q_p = 0.0176(V \cdot H)^{0.606}$ | 87 | 0.844 | Best fit | Pierce et al. (2010) |
| | $Q_p = 0.038(V^{0.475} \cdot H_w^{1.09})$ | 87 | 0.850 | Best fit | |
| | $Q_p = 0.607(V_w^{0.295} \cdot H_w^{1.24})$ | 32 | 0.934 | Best fit | Froehlich (1995) |
| | $Q_p = 0.99(d \cdot V_0)^{0.4}$ | 22 | 0.760 | Best fit | ^Walder and O’Connor (1997) |
| | $Q_p = 1.9(V \cdot d)^{0.4}$ | 19 | 0.760 | Best fit | ^Cenderelli (2000) |
| | $Q_p = 0.0158PE^{0.41}$ | 12 | 0.810 | Best fit | ^Costa and Schuster (1988) |
| **Parametric equations** | | | | | |

Table 2 (continued)

| Method categories                        | Equation                                                                 | Number of case studies | Coefficient of determination ($R^2$) | Accuracy | References                           |
|------------------------------------------|--------------------------------------------------------------------------|------------------------|--------------------------------------|----------|---------------------------------------|
|                                          | $Q_p = g^{0.5}(2/3)^{1.5}W_t d^{1.5}$                                    | 2<sup>e</sup>         | –                                    |          | Envelope <sup>b</sup>O’Connor and Beebee (2009) |
|                                          | $Q_p = 8/27[(0.4W_b)+(0.6W_t)]g^{0.15}H_b^{1.5}$                         | 2<sup>e</sup>         | –                                    |          | Envelope <sup>c</sup>Manville (2001)            |
|                                          | $Q_p = 0.591C_d \cdot H_b^{1.5}(5W_b + 4z \cdot H_b)$                   | 2<sup>e</sup>         | –                                    |          | Envelope <sup>d</sup>Haeberli (1983) (nontunnel events) |
|                                          | $Q_p = 2V/t_w$                                                           | 5<sup>e</sup>         | –                                    |          | Envelope <sup>e</sup>                        |
|                                          | $Q_p = 1.51\left(g^{0.5}d^{2.5}\right)^{0.06}(kV_0/d)^{0.94},$           |                        |                                      |          |                                      |
|                                          | if $kV_0(gd)^{-0.5}d^{-3} < 0.6$;                                         |                        |                                      |          |                                      |
|                                          | $Q_p = 1.94g^{0.5}d^{2.5}(D_c/d)^{0.72},$ if $kV_0(gd)^{-0.5}d^{-3} \gg 1$|                        |                                      |          |                                      |
| Boulder competence methods               | $Q = vA$                                                                 | 139<sup>e</sup>       | –                                    |          | Best fit <sup>a</sup>Walder and O’Connor (1997) |
|                                          |                                                                         |                        |                                      |          |                                      |
|                                          |                                                                         |                        |                                      |          |                                      |
|                                          |                                                                         |                        |                                      |          | Best fit O’Connor (1993) and <sup>c</sup>Costa (1983) |

<sup>a</sup>This example has been derived entirely from case studies of landslide-dam failure

<sup>b</sup>This equation is applied to broad-crested weir: rectangular breach

<sup>c</sup>This equation is applied to broad-crested weir: trapezoidal breach. Breach development time: 0.76 h; breach erosion rate 100 m/h

<sup>d</sup>The relation is applied to events termed ‘sudden break’. $t_w$ is a time constant with an approximate range between 1000 and 2000s

<sup>e</sup>These case studies are from the statistics of present literature in this paper
3.2 Approaches for the peak discharge calculations

To summarize the previous related study methods, three main types of methods were generally used to estimate the maximum peak discharge ($Q_p$) of dam-break events. Table 2 shows a summary of conventional methods and equations. The physical meanings and units of symbols lists are included in Section Notation List.

3.2.1 Regression equations

The models relied on a single or series of regression relationships derived from test case studies or observed historical dam failures, which were determined to be related to the observed peak discharge levels in order to accurately measure the impounded water volumes. These included the water heights or depths (Kirkpatrick 1977; Cenderelli 2000; Pierce et al. 2010); water storage levels or volumes (Evans 1986; Walder and Costa 1996; Walder and O’Connor 1997); or combinations of the water height (depths) and storage (volumes) (Macdonald and Langridge-Monopolis 1984; Costa 1985; Costa and Schuster 1988). It was found that such regression relationships were convenient for application purposes, but limited in their suitability. This was due to the fact that they generally neglected the inclusion of the basic hydraulic principles related to the breach initiation and enlargement processes (Westoby et al. 2014) and thereby only provided order-of-magnitude predictions of the probable peak discharge levels (Dai et al. 2005).

In the cases where reliable estimates of the time-to-peak flow were unavailable, provided that the geometric characteristics of the dam structure and its lake drainage basin were known, it was considered that the analysis of the empirical relationships could accurately provide an expeditious and simple approach to estimating the peak flows and would be suitable for relatively basic hazard assessments (Morris et al. 2007). Therefore, despite the limitations of the regression equations, they may provide constructive guidance for the general evolution law of the LLOFs’ peak discharge levels. In this study, the equations developed by MacDonald and Langridge-Monopolis (1984), Evans (1986), Cenderelli (2000), and Pierce et al. (2010) were adopted for the reconstruction of the peak flow of Diexi ancient LLOFs, which were described as follows (MacDonald and Langridge-Monopolis 1984; Evans 1986; Cenderelli 2000; Pierce et al. 2010):

$$Q_p = 1.154 (V_w H)^{0.412}$$  \hspace{1cm} (1)  
$$Q_p = 0.72 (V_w)^{0.53}$$  \hspace{1cm} (2)  
$$Q_p = 3.4 (V)^{0.46}$$  \hspace{1cm} (3)  
$$Q_p = 0.038 (V_w^{0.475} \cdot H_w^{1.09})$$  \hspace{1cm} (4)

In this study, the results of the field research revealed that a number of lacustrine deposits directly covered the slope of the relict ancient landslide dam (D–I) located in Jiaochang Village. The thicknesses of these deposits were determined to be between 1 and 3 m with a top elevation of 2302 m a.s.l. (Figs. 2b and 3). It was supposed that the elevation of the ancient lake surface after failure was 2302 m. The water surface elevations of Xiahaizi
Lake and the previous DALL were 2122 m a.s.l. and 2355 m a.s.l., respectively (Fig. 2). Therefore, the previous dam height and the drop in the lake level depth after breaching were determined to be 233 and 53 m, respectively. Finally, the peak discharge ($Q_p$) of Diexi ancient LLOFs was successfully calculated using Eqs. (1–4).

### 3.2.2 Parametric equations

It is noteworthy that these models had considered the semi-physical processes, although they were simplified. Generally, several parameters were taken into consideration, including the lake surface area and volume, lake geometric characteristics, water depth, breach geometric characteristics, flood routing time, and the erosion rate of breach development. The obtained data were applied in the simulations of the dam-break formation, lake drainage characteristics, and maximum peak discharge levels (Fread 1996; Morris et al. 2009; Capart 2013). The models generally required detailed geometric data of the dam structure, as well as its material properties. The hydraulic conditions of the breach flood were also important in order to achieve accurate simulations. However, it has been found to be difficult to obtain all of the aforementioned parameters for ancient dammed lakes, since their failures were rarely recorded in historic literature. Among these previously used models, the physically based predictive equations developed by Walder and O’Connor (1997) were frequently adopted in the assessments of the peak discharge levels of the LLOFs. For example, Dai et al. (2005) estimated the peak flow ($Q_p$) of the LLOFs in southwestern China’s Dadu River using Walder and O’Connor’s predictive equations.

This study also adopted the approach developed by Walder and O’Connor (1997) to estimate the peak flow of the Diexi LLOFs as follows:

\[
Q_p = 1.51 \left(g^{0.5} d^{2.5}\right)^{0.06} \left(kV_0/d\right)^{0.94}, \quad \text{if } \eta < 0.6
\]

(5)

\[
Q_p = 1.94g^{0.5}d^{2.5}(D_c/d)^{0.75}, \quad \text{if } \eta \gg 1
\]

(6)

where $\eta$ and the erosion rate ($k$) at the breach were determined by the following:

\[
\eta = kV_0(gd)^{-0.5}d^{-3}
\]

(7)

\[
k = d/t
\]

(8)

The data collected by Walder and O’Connor (1997) indicate that 10 m/h $< k <$ 100 m/h is typical for most breach cases. The worst-case scenario for hazards assessment would generally involve a breach which erodes rapidly to the base of the dam. In such a case, the dimensionless peak discharge $Q_{p*}$ exhibited weak dependence on all variables except $\eta$. The corresponding value of peak discharge $Q_p$ was then determined based on the following definition:

\[
Q_p = g^{0.5}d^{2.5}Q_{p*}
\]

(9)
3.2.3 Boulder competence methods

In previous research approaches, in accordance with the dynamic characteristics of outburst floods, the relationships between the energy parameters of the flow and the geometric characteristics of the sediment particles being transported by the floods were established in order to estimate the peak flow levels of the outburst floods (Costa 1983; O’Connor 1993). An assumption is generally taken into account in the aforementioned relationships that the largest boulders presented in the outburst deposits can generally represent the maximum transporting energy of the outburst floods. Bradley and Mears (1980) were some of the earliest practitioners of these approaches. They estimated the average velocities and depths of ancient flooding events along Boulder Creek in Boulder, Colorado (USA), using large boulders excavated from the flood plains. In addition, Costa (1983) extended and modified their work, and comprehensively summarized the utilized approaches.

The boulder competence methods can generally be divided into three steps as follows: computations of the average values of the velocity, average depth, and peak discharge levels. In this study, two theoretical relationships and one method were used to reconstruct the average velocity and average depth of the Diexi ancient LLOFs, respectively.

3.3 Step one: reconstruction of the average velocity ($\bar{v}$)

The two theoretical methods used to compute the average velocity were the Helley method (balancing forces using turning moments) (Helley 1969) and the Bradley–Mears method ($F_D + F_L = F_R$) (Bradley and Mears 1980). The Helley method was adopted to calculate the “bed-velocity” ($v_b$), which represented a fluid velocity of approximately 1/3 grain diameter above the mean bed level obtained by equating the turning moments for fluid, drag, and lift with the resisting moments of the submerged particle weights (Costa 1983). The method was simplified by Helley (1969) as follows:

$$v_b = 3.276 \left[ \frac{(\phi_s - 1) d_L (d_L + d_S)^2 MR_L}{C_D d_S d_L M_D} + C_L d_L M_R \right]^{0.5}$$

Then, the average flood velocity was estimated using the following equation:

$$\bar{v} = 1.2 v_b$$

According to Bradley and Mears (1980), at incipient motion, the fluid drag ($F_D$) and the fluid lift forces ($F_L$) are equal the gravitational and frictional forces ($F_R$) acting on a boulder and can be written as follows:

$$F_D + F_L = F_R$$

The fluid drag ($F_D$) and fluid lift forces ($F_L$), along with the gravitational and frictional forces ($F_R$), were determined in this study using the following equations:

$$F_D = C_D A_n (\gamma_f v_b^2)/2$$

$$F_L = C_L A_p (\gamma_f v_b^2)/2$$
The equations were then simplified for solving the $v_b$ as follows:

$$v_b = \left[ \frac{2(\gamma_s - \gamma_f) d g f}{\gamma_f (C_L + C_D)} \right]^{0.5}$$

(16)

Similarly, the bottom velocity was also multiplied by 1.2 in order to obtain the estimated average flood velocity ($\overline{v}$).

### 3.4 Step two: estimation of the average depth ($\overline{D}$)

The formula which was used in this study to estimate the average depth was the Manning formula (Williams 1970). The Manning formula reconstructed the depths of the floods from the particle-size data, as follows:

$$\overline{D} = \left( \frac{\overline{v} \cdot n}{\sqrt{S}} \right)^{1.5}$$

(17)

### 3.5 Step three: peak discharge calculations ($Q_p$)

The maximum flood peak discharge level was calculated in this study using the following equation:

$$Q_p = \overline{v} A$$

(18)

At this point in this study’s investigations, the only remaining unknown was the flow surface width, which could be obtained from the cross sections located in the flood valley near the boulder deposits sites. The shapes of the calculated cross sections had major influences on the peak discharge levels. In the current study, for convenience purposes, it was approximately assumed that the calculating cross sections were trapezoidal. Subsequently, the section areas could be calculated using the average depths, slopes of both banks of the valley, and the widths of the riverbed at the cross-sectional sites. It should be noted that due to these approximation treatments of the calculated cross sections, there was a possibility that the maximum peak discharge levels may have produced some errors. Fortunately, for ultra-large-scaled outburst floods, such error effects are considered to be acceptable.

In this study, five cross sections were established to calculate the peak discharge levels of the Diexi ancient LLOFs, as detailed in Fig. 5. In addition, the intermediate and long axis of the largest bounders of the outburst deposits near the cross sections was measured (Table 3). The detailed river parameters and the estimated peak discharge levels are also listed in Table 3.
4 Results

4.1 Characteristics of the outburst deposits induced by the Diexi ancient LLOFs

Several field investigations were conducted in the Diexi Region, and a total eight outburst deposit sections were discovered in the downstream reach areas of the dam. The lithologic
Table 3 Calculating parameters and results of the Diexi ancient LLOFs by the boulder competence methods

| Subjects                                                                 | C.S. 1 | C.S. 2 | C.S. 3 | C.S. 4 | C.S. 5 |
|-------------------------------------------------------------------------|--------|--------|--------|--------|--------|
| Distance from the relict landslide dam (km)                             | 0.45   | 0.90   | 1.95   | 2.80   | 5.00   |
| Statistics of the largest boulders’ geometry                           |        |        |        |        |        |
| Amount of bounders (piece)                                              | 36     | 30     | 30     | 40     | 38     |
| Average long axis/$d_L$ (m)                                             | 4.3    | 3.6    | 2.9    | 1.9    | 1.7    |
| Average intermediate axis/$d_I$ (m)                                     | 3.3    | 2.3    | 1.7    | 1.3    | 1.1    |
| Average short axis/$d_S$ (m)                                            | 2.5    | 1.7    | 1.1    | 0.9    | 0.7    |
| Channel parameters                                                       |        |        |        |        |        |
| $\gamma_s$ (g/cm³)                                                      | 2.85   |        |        |        |        |
| $\gamma_f$ (g/cm³)                                                      | 1.0    |        |        |        |        |
| $G$ (m/s²)                                                              | 9.8    |        |        |        |        |
| $C_L$                                                                   | 0.178  |        |        |        |        |
| $f$                                                                     | 0.7    |        |        |        |        |
| $n$                                                                     | 0.04   |        |        |        |        |
| $S$                                                                     | 0.005  |        |        |        |        |
| $\theta$ (°)                                                           | 35     | 30     | 40     | 30     | 37     |
| Average velocity/$\bar{V}$ (m/s)                                        |        |        |        |        |        |
| Helley’s method                                                         | 20.10  | 15.14  | 13.26  | 11.25  | 10.56  |
| $F_D+F_L=F_R$ method                                                    | 10.40  | 8.14   | 6.46   | 6.00   | 5.69   |
| Average value (m/s)                                                     | 15.25  | 11.64  | 9.86   | 8.63   | 8.13   |
| Manning’s formula                                                       | 25.33  | 16.90  | 13.17  | 10.78  | 9.86   |
| Average depth/$\bar{D}$ (m)                                            | 4,792.26 | 4,283.32 | 3,363.01 | 2,098.93 | 1,773.33 |
| Channel cross-sectional area/$A$ (m²)                                   | 73,070 | 49,871 | 33,155 | 18,107 | 14,410 |
Fig. 6 Distribution and lithological sketches of the outburst deposits sections in the Diexi Region. The OSL dating samples and ages are from Ma et al. (2018)
Table 4 Geomorphological characteristics of the outburst deposits sections

| Section number | Distance from the relict landslide dam (km) | Exposed length (m) | Maximum thickness (m) | Top elevation (m) | Location |
|----------------|---------------------------------------------|--------------------|-----------------------|-------------------|----------|
| I              | 0.45                                        | 120                | 9.3                   | 2024.7            | 32°01′24.86″ 103°41′08.84″ |
| II             | 0.8                                         | 150                | 25                    | 2032.9            | 32°01′20.81″ 103°40′57.71″ |
| III            | 1.2                                         | 78                 | 18                    | 2027.2            | 32°01′11.38″ 103°40′58.11″ |
| IV             | 1.6                                         | 25                 | 4.2                   | 1972.8            | 32°00′57.56″ 103°40′45.00″ |
| V              | 2.0                                         | 110                | 8.5                   | 1964.3            | 32°00′48.91″ 103°40′40.22″ |
| VI             | 2.6                                         | 60                 | 3.4                   | 1949.4            | 32°00′30.36″ 103°40′37.12″ |
| VII            | 3.2                                         | 30                 | 2.2                   | 1929.2            | 32°00′11.77″ 103°40′33.35″ |
| VIII           | 5.0                                         | 62                 | 4.9                   | 1893.5            | 31°59′23.22″ 103°40′25.27″ |

Sections of II, III, and V–VII are from Ma et al. (2018)
Fig. 7 Field photographs showing the sedimentary characteristics of the outburst deposits profiles in the Diexi Region. a Geomorphology and spatial locations of the outburst deposits sections. The base image was captured and modified from Google Earth with a date of January 9th, 2016. b Sedimentary features of the outburst deposits profile near the breaching gate. c Sedimentary features of the outburst deposits profile in the downstream of site b, with a distance of approximately 0.3 km. d Rhythmite interbedded units composed of coarser gravel layers and finer sand and gravel layers in the profile, approximately 5 km from the landslide dam in the lower reach of outburst deposits (modified from Ma et al. 2018). e Gravel diara located in the middle of the Minjiang River formed by well-rounded and well-sorted pebble gravels near the end of outburst deposits.
characteristics of the exposed profiles of the outburst deposit sections are detailed in Fig. 6. In the figure, Sects. 2, 3, and 4 to 6 are obtained from the reports presented by Ma et al. (2018). In our previous research, the three Optically Stimulated Luminescence (OSL) dating samples ages of 20.9 ± 3.1, 27.3 ± 2.8, and 22.7 ± 3.4 ka BP were tested (Fig. 6). The results revealed that the failure time of the DALL occurred no earlier than 27.3 ± 2.8 ka BP, or during the Late Pleistocene Period, as previously explained by Ma et al. (2018). The distribution and geomorphological characteristics of the outburst deposits are detailed in Table 4, in which the calculating parameters for the reconstruction of the outburst floods are provided. In addition, the accuracy of the calculation results was verified using the obtained data.

It was found in this study that the outburst deposits possessed a distinctive sedimentary sequence and presented a transition pattern of unordered to sub-ordered or ordered from the upstream to the middle and lower reaches (Fig. 7). It was found that near the breaching gate, the diamict profiles displayed mixed and disordered sedimentary characteristics, with no distinct bedding and structural characteristics. It was observed that the gravel was mainly angular and poorly arranged in the profile, possessing mixed sizes and containing some isolated boulders (Fig. 7b). Also, at approximately 0.3 km downstream, some sedimentary layers appeared in the profile of the outburst deposits, and clustered boulders formed coarse gravel layers which presented a certain sequence (Fig. 7c). Then, in the middle and lower reaches, the sedimentary layers and bedding became increasingly obvious. These coarser gravel layers and fine sand and gravel layers composed rhythmic units represented various “cycles” in the lower segments (Fig. 7d). There were also gravel diara deposits formed by well-rounded and well-sorted pebble gravel found in the river near the end of outburst deposits, which were found to present imbrication structures (Fig. 7e). These special sedimentary features explained the hydrodynamic changes which had occurred during the propagation of the outburst floods, and were also important indicators for distinguishing the outburst deposits from the other types of sediment in the study area.

### 4.2 Peak discharge levels of the Diexi LLOFs

This study estimated that the original maximal water surface area of the Diexi ancient lake was 1.1 × 10^7 m², with a corresponding volume of 2.9 × 10^9 m³, as shown in Fig. 4. Subsequently, the maximum peak discharge (Q_p) of the Diexi ancient LLOFs was estimated at 86,310 m³/s using Eq. (1); 74,542 m³/s using Eq. (2); 76,592 m³/s using Eq. (3); and 89,925 m³/s using Eq. (4).

It was inferred in this study that the failure incentive of the Diexi ancient landslide dam was triggered by the overtopping actions following the overflow water erosion induced by earthquake-related rock falls or sub-landslides, as detailed in Sect. 5.2. It was indicated that the formation time for the breach was very short. Therefore, Eq. (9) was applied to estimate the peak discharge of the Diexi ancient LLOFs. Walder and O’Connor (1997) suggested simply using the curve in Fig. 4a in their study for r=2.5 to determine the value of Q_p*. In the present study, a value of Q_p*=1.2 was determined. Accordingly, the peak discharge rate at the dam breach was estimated to be 76,822 m³/s.

In regard to the boulder competence methods, the calculated results of the average velocities and average depths obtained using Eqs. (10) to (17) are listed in Table 3. The peak flow rates at the five cross sections were calculated using Eq. (18), as shown in Table 3. It was revealed that the maximum average velocity and peak discharge of the Diexi LLOFs were 15.25 m/s and 73,070 m³/s, respectively. In addition, the water surface
Elevation of the LLOFs as calculated by the Manning formula (Eq. 17) was consistent with the top elevation of the outburst deposits shown in Fig. 8. This shows that the result of the boulder competence methods exhibited high reliability.

It is clear from the results obtained that the peak discharge levels of the Diexi ancient LLOFs were variable when using the three different types of approaches, which were divided into two groups. The values estimated by Eqs. (2), (3), (9), and (18) were approximate, with values of approximately 75,000 m³/s. Equations (1) and (4) obtained larger values, which were close to 90,000 m³/s. The average peak discharge of these three types of approaches was 79,500 m³/s.

According to the “Qiang People’s Autonomous County Annals of Maowen” (Local Chronicle Compilation Committee of the Maowen Qiang Autonomous County and A’ba Tibetan and Qiang Autonomous Prefecture, Sichuan Province 1997), the average annual flow of the Minjiang River is approximately 700 m³/s. In this study, the estimated maximum peak discharge of the Diexi ancient LLOFs was estimated to be more than one hundred times the average annual flow of the Minjiang River. This indicates that these were the largest outburst flooding events in the Upper Minjiang River Valley since the Late Pleistocene Period.

5 Discussion

5.1 Uncertainty assessment of the maximum peak discharge of the Diexi ancient LLOFs

The uncertainty of the peak discharge was determined by a variety of factors. In the present study, the uncertainty of regression and parametric equations were mainly determined by the factors of dam height or water height behind the dam, lake level drop, and water volume behind the dam or drained from the lake. In addition, the boulders’ geometry, roughness coefficient (Manning’s n), and channel slope controlled the uncertainty of the boulder
| Approach                      | Factor input       | Original value $(m^3)$ | Increment or decrement | Uncertainty of the peak discharge |
|-------------------------------|--------------------|------------------------|------------------------|----------------------------------|
|                               |                    |                        |                        | Original value $(m^3/s)$ | Computed value $(m^3/s)$ | Absolute changes $(m^3/s)$ | Relative error          |
| Regression equations          | Equation (1) (MacDonald and Langridge-Monopolis 1984) | Lake volume/$V_w$     | $2.9 \times 10^9$ m$^3$ | +10%                           | 86,310 | 89,767 | +3457 | +4.01% |
|                               |                    |                        |                        | –10%                           | 82,644 | –3666  |          | –4.25% |
|                               |                    |                        |                        | +20%                           | 93,044 | +6734  |          | +7.80% |
|                               |                    |                        |                        | –20%                           | 78,730 | –7580  |          | –8.78% |
|                               |                    | Dam height/$H$         | 233 m                  | +25 m                         | 90,012 | +3702  |          | +4.29% |
|                               |                    |                        |                        | –25 m                          | 82,367 | –3943  |          | –4.57% |
|                               |                    |                        |                        | +50 m                          | 93,508 | +7198  |          | +8.34% |
|                               | Equation (2) (Evans, 1986) | Lake volume/$V_w$     | $2.9 \times 10^9$ m$^3$ | +10%                           | 74,542 | 78,405 | +3863 | +5.32% |
|                               |                    |                        |                        | –10%                           | 70,494 | –4048  |          | –5.16% |
|                               |                    |                        |                        | +20%                           | 82,105 | +7563  |          | +10.73%|
|                               |                    |                        |                        | –20%                           | 66,228 | –8314  |          | –10.13%|
|                               | Equation (3) (Cenderelli 2000) | Lake volume/$V$       | $2.9 \times 10^9$ m$^3$ | +10%                           | 76,592 | 80,024 | +3,433 | +4.59% |
|                               |                    |                        |                        | –10%                           | 72,968 | –3624  |          | –4.53% |
|                               |                    |                        |                        | +20%                           | 83,292 | +6701  |          | +9.18% |
|                               |                    |                        |                        | –20%                           | 69,120 | –7472  |          | –8.97% |
|                               | Equation (4) (Pierce et al. 2010) | Lake volume/$V_w$     | $2.9 \times 10^9$ m$^3$ | +10%                           | 89,925 | 94,090 | +4,165 | +4.63% |
|                               |                    |                        |                        | –10%                           | 85,536 | –4389  |          | –4.88% |
|                               |                    | Water depth above breach invert/$H_w$ | 53 m                  | +3 m                           | 95,488 | +5563  |          | +6.19% |
|                               |                    |                        |                        | –3 m                           | 84,392 | –5533  |          | –6.15% |
|                               |                    |                        |                        | +5 m                           | 99,211 | +9286  |          | +10.33%|
|                               |                    |                        |                        | –5 m                           | 80,719 | –9206  |          | –10.24%|
| Approach | Factor input | Original value | Increment or decrement | Original value (m$^3$/s) | Computed value (m$^3$/s) | Absolute changes (m$^3$/s) | Relative error |
|----------|--------------|----------------|------------------------|--------------------------|--------------------------|---------------------------|----------------|
|           | Lake level drop/\(d\) | 53 m | +3 m | 76,822 | 88,159 | +11,337 | +14.76% |
|           | | | −3 m | 66,408 | −10,414 | −13.56% |
|           | | | +5 m | 96,242 | +19,420 | +25.28% |
|           | | | −5 m | 59,965 | −16,857 | −21.94% |
|           | Bounders’ geometric size/ \((d_L, d_T, d_S)\) | (4.3, 3.3, 2.5) | +0.2 m | 73,070 | 85,213 | +12,143 | +16.62% |
|           | | | −0.2 m | 62,201 | −10,868 | −14.87% |
|           | | | +0.3 m | 92,535 | +19,465 | +26.64% |
|           | | | −0.3 m | 56,373 | −16,696 | −22.85% |
|           | Manning’s \(n\) | 0.04 | +0.005 | 87,190 | +14,120 | +19.32% |
|           | | | −0.005 | 59,807 | −13,263 | −15.21% |
|           | | | +0.01 | 102,118 | +29,048 | +48.57% |
|           | | | −0.01 | 47,460 | −25,610 | −52.08% |
|           | Channel slope/\(S\) | 0.005 m/m | +0.0005 | 68,029 | −5041 | −6.90% |
|           | | | −0.0005 | 79,078 | +6008 | +8.83% |
|           | | | +0.001 | 63,731 | −9339 | −11.81% |
|           | | | −0.001 | 86,382 | +13,312 | +20.89% |
competence methods. The uncertainty analysis results for each factor were within a variable value range, according to the required calculation accuracy or previous research results. In most cases, it is possible to assess a rather large range of variation to obtain a comparable error. Then, a new value of peak discharge will be calculated by the modified model for comparison with the original result. In the present work, two groups of symmetrical modification of uncertainty assessment were conducted for each factor. The first group of symmetrical modification represented the ideal uncertainty bound, and the second group was the maximum acceptable uncertainty bound. For instance, the modification of ±10% of the parameter of lake volume was the ideal uncertainty bound, while the set of symmetrical modification of ±20% was the maximum acceptable uncertainty bound, and the same applies for the other parameters. The detail uncertainty assessment results of the maximum peak discharge of the Diexi ancient LLOFs are shown in Table 5.

In order to provide a comprehensive uncertainty bound of the maximum peak discharge of the Diexi ancient LLOFs, the analysis results are illustrated in a manner similar to a box-plot, as shown in Fig. 9. The gray-shaded area in the figure represents the estimated uncertainty bound of the maximum peak discharge of the Diexi ancient LLOFs covered in this study, which ranged from 70,000 to 90,000 m³/s, with a median value of 80,000 m³/s. It can be seen that this was very close to the average value (79,500 m³/s) of the three types of approaches.

As shown in Table 5, the errors of the peak discharge estimated by the regression equations (Eqs. 1–4) were smaller than that determined by the parametric and boulder competence methods, at appropriately 5% and 10%, respectively. This was a result of the two groups of symmetrical modification of each factor. However, the relative errors of the peak discharge, respectively, increased to 15% and 25% when using the parametric method (Eq. 9). The boulder competence methods were sensitive to the modification of input factors, in particular Manning’s n. In the present study, modifications of +0.005 and +0.01 of Manning’s n had caused errors of appropriately +19% and +48% on the estimated peak discharge. This was consistent with the results of previous studies. The Manning’s n is a major contributor to the error of peak discharge due to its high uncertainty (Lenhart et al. 2002). However, the value of Manning’s n for an ancient LLOFs is difficult to determine precisely. In most cases, it still depends on the user’s experience or designated values shown in the previous literature. In addition, some other factors, such as the erosion and accretion of river channel, along with transportation and deposition of sediment, were not taken into account in the present study, since the uncertainty analyses of these indexes were too difficult to quantify, and the significance appeared to not be very great to a catastrophic ancient LLOFs. Ruiz-Bellet et al. (2017) gave a short discussion of other studies’ findings regarding these indexes; thus, here we have not performed an in-depth analysis thereof.

It is clear that the influential extents on peak discharge results of the input factors were determined by the complexity of various methods. A complex operating process will result in a high sensitive uncertainty on peak discharge to the modification of input factors. In the present study, although the peak discharge value of the boulder competence methods exhibited high uncertainty, and appeared to be conservative, its ideal uncertainty bound was within the estimated uncertainty bound (Fig. 9). Moreover, it appears that the calculation process of the boulder competence methods was more reasonable than the other equations. Therefore, the peak discharge of the boulder competence methods could be considered to be more reliable. This method can be used to estimate the peak discharges of LLOFs without accurate data.
5.2 Failure mode of the Diexi ancient landslide dam

It is generally known that landslide dams commonly fail by overtopping and erosion actions caused by externally triggered overflow channels. These external triggers include snow-ice avalanches or calving, rock falls, and sub-landslides, which become intensified by the lack of channelized spillways or other protected outlets (Costa and Schuster 1988; Clague and Evans 2000; Ermini and Casagli 2003). Costa and Schuster (1988) summarized that, in the majority of the cases examined in previous studies, the dam breaches were triggered by the fluvial erosion of landslide material. In addition, the head-cutting had progressively moved upstream toward the lake. More than 90% of the landslide dams examined in their study had failed under those conditions. Peng and Zhang (2012) documented that 91% (131 cases out of the 144 cases with known failure modes) of the dams failed through overtopping actions. Additional known modes include piping and slope failures. The seepage through the dams potentially led to internal erosion and piping failures if the dam materials were loose and non-compacted, forming seepage channels on the downstream faces of the dams (Costa and Schuster 1988). The mode of slope failure was observed to be rare, since the majority of the natural landslide dams tended to have high width-to-height ratios, and the slope faces of the upstream and downstream areas tended to be gentle. In this study, it was estimated that the Diexi ancient landslide dam had a high width-to-height ratio (more than 10 m/m) which had formed a relatively stable structure. In addition, no leakage traces were found on the downstream side of the relict dam. Therefore, it was deduced that the dam breach in the Diexi Region was not triggered by piping or slope failure. Consequently, it was inferred that overtopping actions, followed by erosion by overflow water induced by earthquake-related rock avalanches, were the failure incentives of the Diexi ancient landslide dam.

5.3 Geomorphological effects of the DALL and LLOFs

Landslide dams which have existed for long periods of time can potentially exert significant influences on the evolution of river systems by controlling the patterns and rates
of intermontane sedimentation, as well as the migration of sediment. As a result, valley landforms may be modified, manifesting in ways such as the creation of local base levels, retreats in the river knickpoints, and the reorganization of river networks (Korup 2005; Korup et al. 2010; Hood et al. 2014; van Gorp et al. 2014, 2016; Yunus et al. 2016; Fan et al. 2020). Moreover, the impacts on fluvial landforms generally persisted for quite some time, potentially even thousands to tens of thousands of years (Burchsted et al. 2014). Korup and Tweed (2007) suggested that even alpine belts with high erosion rates may retain geomorphic and sedimentary evidence of dam-breaking events. One of the most direct consequences of the landslide dams was the imposition of variations in the river incision rates (Costa and Schuster 1988; Korup 2005; Ouimet et al. 2007). Furthermore, the migration of sediment is known to have been significantly controlled by large-scaled landslide dams and their drainage processes (Pratt-Sitaula et al. 2007; Korup 2012).

It was found in previous studies that lacustrine sediment could be commonly observed in the upstream areas of long-term landslide dams in high mountain regions (Montgomery et al. 2004). Furthermore, in the downstream regions of landslide dams, evidence of outburst sediment may also be well preserved for thousands of years (Cutler et al. 2002; Carling 2013; Chen et al. 2018). In the Diexi Region, it was observed that thick lacustrine sediment had extended in the upper reach of the Diexi landslide dam of the Minjiang River for tens of thousands years, with a length of approximately 30 km and a maximum thickness of more than 200 m (Wang et al. 2014b; Ma et al. 2018; Xu et al. 2020). In addition, it has been found that below the dam, the high-energy outburst floods delivered coarse diamict boulders from the landslide dam to the downstream areas. These types of diamict sediment usually formed band- or terrace-shaped outburst deposit bars, among which the largest one had a maximum exposed profile length of approximately 200 m, and ranged up to 25 m in height (Ma et al. 2018). The long-term accumulation of these types of sediment had significant impacts on the evolution of the Minjiang River.

Figure 10 details the average slope values within the 30 km upstream area and the 8 km downstream area of the landslide dam, which were 1.63% and 3.88%, respectively. These findings indicated that the average slope in the downstream was more than twice that of the upstream. Furthermore, the average channel width in the lower reach of the dam was determined to be 263 m, which was smaller than that in the upper reach, in which the average value was 300 m. Therefore, it was clear that the geomorphic influences on the river channel from the DALL and its LLOFs had existed for tens of thousands of years. The lacustrine sediment above the landslide dam had promoted the channel deposition, as well as impeding the erosion action. However, the LLOFs encouraged erosion of the riverbed and riverbanks. A number of other similar studies have also been conducted in southwestern China, in the southeastern section of the Tibetan Plateau (Ouimet et al. 2007; Chen et al. 2013, 2018; Wang et al. 2014a; Liu et al. 2018). It is suggested that well-informed future research studies should be carried out for systematically understanding the implications of ancient landslide-dammed lakes and their potential for flooding.

6 Conclusions

This study selected the Diexi ancient landslide-dammed lake as the study object. This dammed lake is believed to have existed for a long period of time, forming thick lacustrine sediment in the upstream areas of the Upper Minjiang River at the eastern margin of the Tibetan Plateau. It was estimated that the previous maximal lake area was $1.1 \times 10^7$ m$^2$,
with a lake surface elevation of 2355 m, and an impounded volume was $2.9 \times 10^9$ m$^3$. It is believed that at approximately 27 ka BP, during the late Pleistocene Period, the ancient landslide dam failed due to the overtopping actions. The subsequent LLOFs formed large amounts of outburst deposits in the downstream areas of the landslide dam, with an estimated length of approximately 5 km along the Minjiang River. These outburst deposits possessed a distinctive sedimentary sequence which was completely lacking in other sedimentary types. It was observed that a change pattern of unordered to sub-ordered or ordered existed from the upstream to the middle and lower reaches, which indicated the changes in energy and medium during the transport and accumulation processes.

Furthermore, this study systematically summarized the empirical methods for estimating the peak discharge levels of outburst floods. It was found that various approaches, including regression equations, parametric equations, and boulder competence methods, tended to produce disparate values, yet they were consistent in order of magnitude. The average peak discharge of these three types of approaches was 79,500 m$^3$/s. The uncertainty analyses of the calculation results of the peak discharge indicated that the estimated uncertainty bound of the maximum peak discharge of the Diexi ancient LLOFs ranged from 70,000 to 90,000 m$^3$/s. It was also noted that there was a possibility of over- or under-estimating the values of the peak flow due to the extra uncertain or approximated parameters. It was found that the best practice for reconstructing the peak discharge of the ancient LLOFs seemed to be collecting the accurate flood water levels in the downstream areas, followed by re-calculating the peak discharge under unsteady flow conditions (Fread 1996; Dai et al. 2005; Liu et al. 2019).
Large ancient landslide-dammed lakes and their LLOFs can have significant impacts on river evolution. The differences in the widths and slopes within the former and latter reaches of the dam indicated that the geomorphic influences on the river channel from the DALL and its LLOFs had existed for tens of thousands of years. Therefore, it is of major significance to deepen the current understanding of the existence and disappearance of important river knickpoints on a time scale of tens of thousands of years.

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Declarations

Conflict of interest The authors declare no conflict of interest.

Consent to participation and publication All of the authors have consented to participation in and publication of this paper.

Availability of data and materials The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Code availability No, the code is not available. However, the calculation is simple.

Human and animal rights This article does not contain any studies with human participants or animals performed by any of the authors.

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