Recurrent dammed-lake outburst superfloods in the Yigong river, southeastern margin of the Tibet

Kaiheng Hu (✉ khhu@imde.ac.cn)

Institute of Mountain Hazards and Environment

Chaohua Wu

Institute of Mountain Hazards and Environment

Li Wei

Institute of Mountain Hazards and Environment

Xiaopeng Zhang

Institute of Mountain Hazards and Environment

Qiyuan Zhang

Institute of Mountain Hazards and Environment

Weiming Liu

Institute of Mountain Hazards and Environment

Brian J. Yanites

Indiana University Bloomington

Research Article

Keywords: Landslide dammed lake, Paleoflood sediment, Outburst flood, Yigong, Landscape evolution

Posted Date: May 6th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-483952/v1>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Scientific Reports on August 2nd, 2021. See the published version at <https://doi.org/10.1038/s41598-021-95194-1>.

Abstract

Landslide dam outburst floods have a significant impact on landform evolution in high mountainous areas. Historic landslide dams on Yigong River, southeastern Tibet, generated two outburst superfloods of $> 10^5 \text{ m}^3/\text{s}$ in 1902 and 2000 AD. One of the slackwater deposits, newly found immediately downstream of historic dams, has been dated to 7 ka BP. One-dimensional backwater stepwise method gives an estimate of $225,000 \text{ m}^3/\text{s}$ for the peak flow related to the paleo-stage indicator of 7 ka BP. The recurrence of at least three huge landslide dam impoundments and super-outburst floods at the exit of the Yigong lake during the Holocene greatly changes the morphology of the Yigong river. Recent reports of giant landslides elsewhere on the southeastern Tibetan Plateau indicate repeated landslide dams at the same location, which counters the traditional viewpoint that landslide damming is spatially random, unlike glacial damming that persists at the same location. Repeated landslide damming may be a persistent source of outburst floods as well as impede the upstream migration of river knickpoints in the southeastern margin.

1 Introduction

Large landslide or glacier dams and associated outburst floods have profound impacts on alpine landscape evolution around the Tibetan plateau^{1–5}. The impacts have two side effects. On the one hand, natural long-lived dams as stable knickpoints protect upstream channels from river incision and hence retard headward erosion into the plateau interior. On the other hand, the dammed lake outburst floods may control long-term valley evolution such as erosion of bedrock canyons in the Himalaya. Among them, the so-called superfloods play a key role in bedrock plucking, boulder mobilization, coarse grain comminution that moderate flows have poor competence in^{6–9}. However, superflood events are infrequent and rare direct observations are made. Most information of superflooding process comes from sedimentary records of outburst flood deposits at the downstream of breached dams^{10,11}. Records of modern and ancient superflood events in a river are useful for verification of the flood geomorphic effects and hydraulic hypothesis.

The Yigong River, a tributary of Yarlung Tsangpo River, southeastern Tibetan Plateau, experienced two well documented modern superfloods of $> 10^5 \text{ m}^3/\text{s}$ in 1902 and 2000 AD^{12–15} (Fig. 1). Both events were generated by failure of landslide dams at the same location, the Zhamu Creek confluence (Fig. 1B). In this study, we report the findings of old lacustrine and slack water deposits (SWDs) downstream of the Zhamu landslide during the recent field survey (Fig. 1C). Age of the deposits is estimated with radiocarbon and optically stimulated luminescence (OSL) dating methods. We calculate the paleoflood peak discharge related to these deposits by using 1-D step-backwater method and discuss the impact of the three flood events on the Yigong river's evolution. Such rare direct observations and records of repeated outburst floods at the same river reach are very valuable in verifying paleoflood hydraulic reconstruction and better understanding the role of landslide dam outburst floods in the landscape evolution of the Tibet plateau's eastern margin.

2 Study Area

The study area is at downstream of Yigong river, a tributary of Parlung Tsangpo which is flow into Yarlung Tsangpo river through the Grant Tsangpo Gorge in the southeastern margin of Tibetan plateau (Fig. 1). It is surrounded by numerous summits > 6000 m a.s.l. in Nyaiqentanglha range on the north and Himalayan range on the south. Local topographic relief is up to 6 km in the gorge between Namche Barwa (7782 m) and Gyala Peri (7294 m) massifs. Warm and humid Indian monsoon reaches further to upstream of Yigong river through the deep gorge. The average annual rainfall descends from ~ 3000 mm at the town of Medog to ~ 1100 mm at the town of Yigong. Abundant precipitation and high relief make it the most active region for monsoonal temperate glaciers with the total area of 2490 km² in China.

The Yigong region is in highly tectonically active mountain belts where the rock uplift rate is as high as 10 mm/yr. The eastern syntax of Himalaya, a northeast protrusion between India and Asia plates is about 30 km to the south. The Jiali fault, a large WNW-ESE trending strike-slip fault extends from the Yigong to the Parlung Tsangpo, traversing the southeast of the Tibetan Plateau. Due to active tectonic movement and high relief, frequent strong earthquakes happened and triggered numerous geological hazards, e.g. the Great Assam earthquake of 8.6 magnitude in 1950, and the Ms 6.9 Milin earthquake in 2017. The Yarlung Tsangpo suture zone is a distinct boundary of Tibetan source and Himalayan source rocks (Fig. 1A). The Tibetan source block completely contains the study area. Primary outcropped rocks in the area are Proterozoic gneiss, Pre-carboniferous schist, and Carboniferous slate and sandstone. Widespread quaternary deposits including laterofrontal moraines, debris fans, and flood deposits distribute along the river's valley.

The Yigong River has a drainage area of 13,500 km² and mean annual discharge of 378 m³/s. Two large-magnitude landslides took place in 1902 and 2000 AD at the Zhamu Creek next to the exit of Yigong lake (Fig. 1). Delaney & Evans¹⁵ reviewed the published literature on the 2000 event and presented a reliable estimate of 115 Mm³ for the landslide volume in 2000. Descriptions of the 1902 event are greatly different because first-hand data are not available and most of records in Chinese literature origin from interviews with local witness in 1960s. Lu et al.¹⁶ calculated the deposition area of 11.6 km² and the final deposition volume of 513 Mm³ from a 1:100,000 topographical map that was measured via airborne survey in 1968. Zhou et al.¹⁷ estimated that the 1902 landslide's volume was 1000 Mm³ (some English literatures report the event emplaced in 1900). The failure of the landslide dams produced two documented modern superfloods of > 10⁵ m³/s in the Yigong river. The floods rushed into the Parlung River at Tongmai junction, traveled into the Tsangpo Gorge on the east flank of the Namche Barwa and Gyala Peri massifs (Fig. 1A). Both of the two landslide dams have not been completely breached and it is argued that the broad Yigong lake was resulted from the 1902 damming¹⁵.

3 Paleoflood Deposits And Peak Flow Reconstruction

3.1 Paleoflood deposits

SWDs are fine-grained sediments carried in suspension in high energy floods that are deposited in areas of low velocity, such as embayments, alcoves, and tributary junctions, and are commonly used as paleo-stage indicators (PSIs) ^{18,19}. One set of SWDs (N30°8'38.67", E95°0'51.15") was found in the lee of a river bend 8.3 km downstream of the 2000 AD dam near Shuangyu village (Fig. 1C, Fig. 2A). The SWDs underly a 1.4 m thick landslide deposit at 52 m above the river level. The sequence is nearly horizontally bedded and comprises four units (Fig. 2B-C): (i) c. 20 cm thick mixture of coarse sand, fine gravel, and diamicton, possibly reworked; (ii) 160 cm of uniform gray oxidized fine sand; (iii) 70 cm thick silt unit; (iv) 50 cm of coarse sand.

Three charcoal samples were collected from the fine sand unit and one from the coarse sand unit. Radiocarbon ages of the charcoal pieces range from 6.7 ka to 7.1 ka BP by radiocarbon dating at the Beta Analytic laboratory, USA (Table 1). Four samples were also collected for OSL dating at the OSL laboratory of the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences. The OSL dating results are shown in Table 2. Additionally, OSL dating of samples from each of the lower three units was performed on a Lexsyg Research automatic TL/OSL instrument at the Institute of Mountain Hazards and Environment, CAS. The sample from the silt unit gave an OSL age of 7.6 ± 0.7 ka, which is consistent with the radiocarbon age. The other two samples gave ages of 18.5 ± 1.7 ka (fine sand) and 15.3 ± 1.4 ka (coarse sand) (Fig. 2D); the difference may be due to their larger grain size, or lack of bleaching in a catastrophic flood event. Combining the OSL and radiocarbon dating results gives a probable age of ~ 7 ka BP for the Shuangyu SWD.

Table 1
Radiocarbon dating result for samples from shuangyu slackwater deposit

Sample	Material analyzed	Percent modern carbon	Modern carbon fraction	Age (BP)
SC1	Charred material	41.73 +/- 0.16	0.4173 +/- 0.0016	7020 ± 30
SC2	Organic sediment	42.94 +/- 0.16	0.4294 +/- 0.0016	6790 ± 30
SC3	Charred material	43.10 +/- 0.16	0.4310 +/- 0.0016	6760 ± 30
SC4	Charred material	42.89 +/- 0.16	0.4289 +/- 0.0016	6800 ± 30

Table 2

Sample dose rate and optically stimulate luminescence dating results for shuangyu slackwater deposit

Sample	Depth (m)	K (%)	Th (10^{-6})	U (10^{-6})	Dosage rate (Gy/ka)	Number of test pieces	De/Gy	OSL age (ka)
SO1	2.3	3.07 ± 0.04	14.24 ± 0.70	2.44 ± 0.40	3.88 ± 0.28	$8^a + 12^b$	71.6 ± 4.21	18.5 ± 1.7
SO2	-	-	-	-	-	-	-	-
SO3	3.4	3.22 ± 0.04	22.97 ± 0.80	1.74 ± 0.30	4.61 ± 0.34	$8^a + 12^b$	35.1 ± 1.83	7.6 ± 0.7
SO4	3.9	2.36 ± 0.04	25.96 ± 0.80	1.46 ± 0.30	4.16 ± 0.30	$8^a + 12^b$	63.8 ± 3.83	15.3 ± 1.4
^a the number of test pieces using Single Aliquot Regenerative-dose method								
^b the number of test pieces using Standardised Growth Curve method								

In addition, we found lacustrine deposits (N 30°09'05", E 94°59'42") at the mouth of Dayi creek, a Yigong's tributary, 2 km upstream of the Shuangyu SWDs (Fig. 1C). The 2.2m parallel lacustrine lamination with yellow-brown silt is elevated c. 40.0 m above the adjacent floodplain. It is capped by 4.3 m debris-flow accumulation composed of angular and sub-angular gravels and boulders. A 1.5 m no-bedding mixture with sand and gravels is exposed under the lamination (Fig. 3A). Two pieces of charcoal were taken from the silt deposit and radiocarbon dated at Beta Analytic laboratory, USA (Fig. 3B). The ^{14}C ages are determined as 6.3k Bp and 6.6k Bp, which means the Dayi lacustrine deposits are a little later than the Shuangyu SWD. The sediment sequence is located at the mouth of the branch Dayi creek on the right bank of the Yigong river. The bank is a concave bend behind a narrow reach, where the transport capacity of the 7k Bp superflood decreased and large volume of sediment that carried by the superflood stopped here. We speculate the paleoflood deposits jammed the Dayi's outlet, forming a small temporary dammed lake in the creek. Inflow silt had deposited in the dammed lake and produced the lacustrine lamination. The upper debris-flow accumulation on the lacustrine deposits implies that it is very likely a large-scale debris flow happened in Dayi and broke out the dammed lake.

3.2 The modern flood SWDs

Another SWD was found on the opposite bank of Jiazhong village, a hydraulically sheltered area 3.9 km downstream of the 2000AD breached dam (Fig. 1C). The Jiazhong SWD is located within a cove on the river right bank, and its surface is a grassland about 6.0 m higher than the floodplains on the both banks (Fig. 4A). The excavated section is a 1.2 m thick sequence of fine to medium-grained sand capped by a ~ 10 cm thick sandy loam at ~ 21.0 m above the river level. The dark gray fine sand is interbedded with three units of ~ 10 cm thick grey medium sand and mingled with sub-angular gravels (Fig. 4B). The 0–70

cm upper part is nearly parallel laminated, but the lower part inclines to the river at an angle of $\sim 5^\circ$, indicating an original local gradient and flow direction. A piece of charcoal collected in the middle of the SWD section was dated at the Beta Analytic laboratory. The measured percent modern carbon is 100.12 ± 0.37 and the radiocarbon age ranges from 1880 to 1956 AD with 87.3% probability. Monsoon seasonal floods of $\sim 2100 \text{ m}^3/\text{s}$ peak unlikely reach the location of Jiazhong SWD. The upmost sandy loam is very thin, which means it formed in a relatively short period. Moreover, the SWD's elevation is close to the 2000AD flood deposits next to it (Fig. 4A). Therefore, we interpret the Jiazhong SWD as the product of the 2000 outburst flood. The Jiazhong SWD's level can be used as the flood stage indicator of the 2000 event.

3.3 Peak flow reconstruction

The well documented 2000 AD flood can be used as a benchmark to aid reconstruction of historic events. The peak 2000 AD discharge at Tongmai Bridge has been estimated as $126,400 \text{ m}^3/\text{s}$ ¹³, $120,000 \text{ m}^3/\text{s}$ ¹², and $124,000 \text{ m}^3/\text{s}$ ²⁰, with a peak water depth of 52 m. We compare peak discharge calculations for the 2000 AD flood using 15 empirical formulas and know data on breach depth, dam height, volume of released water, and impounded water volume (Table 3)²¹. The MacDonald and Langridge-Monopolis (MLM)²² formula produced the closest estimate to the measured discharge, at $\sim 130,000 \text{ m}^3/\text{s}$. So the MLM formula is used to estimate the peak discharge of the 1902 AD event, using data on breach height and released water volume from Delaney and Evans¹⁵ (Table 4). The resulting discharge of $\sim 168,000 \text{ m}^3/\text{s}$ is more than 50 times that of a large monsoon season flood.

Table 3

Estimates of peak discharge for the outburst flood generated by the 2000 ad yigong dam failure using 15 empirical models listed in Liu et al.²¹

Author	Model*	Publication date	Peak discharge (m ³ /s)
Kirkpatrick	$Q_p = 1.268(H_w + 0.3)^{2.5}$	1977	28835
SCS	$Q_p = 16.6H_w^{1.85}$	1981	27528
USBR	$Q_p = 19.1H_w^{1.85}$	1988	31674
USBR	$Q_p = 48H_w^{1.85}$	1988	32963
Hagen	$Q_p = 0.54(V_s - H_d)^{0.5}$	1982	24239
Singh and Snorrason	$Q_p = 13.4H_d^{1.89}$	1984	26084
Singh and Snorrason	$Q_p = 1.776V_s^{0.47}$	1984	41922
MacDonald and Langridge-Monopolis	$Q_p = 3.85(H_w V_w)^{0.41}$	1984	129944
Costa	$Q_p = 1.122V_s^{0.57}$		225643
Costa	$Q_p = 0.981(V_s H_d)^{0.42}$	1985	42698
Costa	$Q_p = 2.634(V_s H_d)^{0.44}$	1988	2998208
Evens	$Q_p = 0.72V_w^{0.53}$	1986	61459
Froechlich	$Q_p = 0.607H_w^{1.24}V_w^{0.295}$	1995	48528
Webby	$Q_p = 0.0443g^{0.5}V_w^{0.365}H_d^{1.4}$	1996	94314
* Where Q_p is outburst flood peak discharge, V_w is the water released (m ³), V_s is barrier lake volume, H_w is breach depth, and H_d is dam height. In this study, we only considered complete dam breach, thus, V_w is the same as V_s and H_w is the same as H_d .			

Table 4
Basic parameters of the yigong barrier lakes in 1900 ad and 2000 AD

Year	Water depth (m)	Lake area (km ²)	Lake volume* (Gm ³)	Peak discharge† (m ³ /s)
2000	55	48.93	2.015	129,944
1900	73	54.08	2.838	167,943
*Volume was calculated using $V = A^{3.424} * 3304.5$ (Delaney and Evans, 2015), where A is the area of impounded water				
†Peak discharge was calculated using $Q_p = 3.85 * (H * V)^{0.41}$ (MacDonald and Langridge-Monopolis, 1984), where H is barrier lake water depth and V is lake volume.				

SWD surface elevation is widely used in paleoflood hydraulic reconstruction as a PSI^{18,23}. The most commonly used paleoflood peak discharge estimation technique is the 1-D step-backwater method^{18,24}. We applied the method to the 2000AD and 7 ka BP events using HEC-RAS 5.0.7 software²⁵, assuming a subcritical flow regime. Contour lines interpolated from the ALOS DEM (in 2009 with 12.5×12.5 m spatial resolution) correspond well with channel shape and location in the ETM + image for 1999, so provide an acceptable record of pre-2000 AD topography. The starting cross section for the step-backwater calculation was set at the Tongmai Bridge bedrock section. A total of 97 cross sections were extracted along the 19.2 km reach with an average spacing of 200 m using the RAS Mapper of HEC-RAS 5.0.7 (Fig. 5A).

Expansion and contraction coefficients of 0.1 and 0.3 were specified, based on channel width. Manning's n roughness coefficient was calibrated using the peak discharge (126,000 m³/s) and water depth (52 m) of the 2000 AD flood. Computed water surface elevation at the Tongmai and Jiazhong cross sections corresponded well with the 2000 AD flood level when Manning's n was set as 0.03 and 0.035 for river channel and floodplain, respectively. Sensitivity tests in the model show that a 25% variation in Manning's n results in a maximum difference of 0.13% in the discharge result. Using these values of the coefficients, a discharge of 225,000 m³/s provides the best approximation for the Shuangyu deposits (Fig. 5B). The calculated values of the velocity and the flow area of the 2000AD flood at Tongmai bridge are 15.7 m/s and 8350 m², closed to those estimated by Delaney and Evans¹⁵. For the 7 ka BP flood, the velocity and the flow area at Tongmai bridge are 19.5 m/s and 12360 m². The paleo-flood with such a magnitude can yield a bed shear stress of 5 kPa, and move large boulders up to 5 ~ 6 m in diameter⁸.

4 Discussions

The landslide dams and outburst floods greatly changed the landscape of the Yigong river. Delaney and Evans¹⁵ plotted a speculative pre-existing profile derived from SRTM-3 data. They proposed it could be

the river valley profile before 1900 event (i.e. 1902 event in this paper). The intersect point of the pre-existing channel with the present is about 5.8 km downstream of the breached dam (Fig. 6). The channel slope from the dam to the intersect point is 16.5‰, double of the pre-channel slope. This reach filled up by quick deposits of the landslides and the outburst floods. The sediment supply from the landslides keeps the bed stable under such a steep slope. From the intersect point to the Tongmai bridge, the channel slope is 8‰ which is probably a natural slope without the disturbance of landslide damming.

It is observed that the lake and braided stream system had developed as early as in 1973 from the KeyHole-9 satellite image (Fig. 7A). The lake's level and fluvial deposits show little change even after 23 years (Fig. 7B). We estimate the trapped sediment in the lake is about 0.26 billion m^3 with 1 km of the lake's average width. Considering the low sediment concentration of the Yigong river, it should take more than thousand-year span to trap such a huge volume of sediment. It is reasonable concluded that the Yigong lake likely formed as early as 7ka ago and the 1902 landslide accumulation overlapped on the previous residual dam. The height of the dam associated with the 7 ka Bp event was at least 170 m based on the peak discharge of 225,000 m^3/s (Fig. 6). The stable knickpoint induces backwater aggradation and protects upstream river channel from incision. We conjecture that the 7 ka Bp dam may be caused by an ancient landslide at Jiazhong village or debris flows in Zhamu or Bailong catchments from the remained site-specific alluvial fan or landslide terrace (Fig. 8).

Glacial and landslide dams in Tibetan-Himalayan rivers contribute greatly to the long-term stability of river knickpoints in the Himalayan syntaxes and, hence, impede incision into the interior of the Tibetan Plateau^{3,4}. Previous research suggests that landslide damming is spatially random, unlike glacial damming repeatedly formed at the same location because of periodic advance of glaciers^{4,26}. However, recent large-scale landslides triggered by earthquakes or ice-rock avalanches at the entrance of the Tsangpo Gorge and on the Parlung River demonstrate that repeated blockage of the rivers by landslide dams at the same location may be common near the eastern syntax of Himalaya^{27,28}. Our findings provide a real case of landslide negative feedback to river incision over geological timescale. The Yigong's three large damming events near Zhamu creek demonstrate that recurrent landslide dammings played a primary role on the stability of some knickpoints when glacial or moraine dams cannot reach to the river trunk.

5 Conclusions

Dammed lake outburst floods are common in the margin of the Tibetan Plateau. In this paper, two slack water and one lacustrine deposits near the 1902 and 2000 AD Yigong landslide dams are reported in detail. From these sediment records, a paleoflood event of ~ 7 ka BP is identified by the radiocarbon and OSL dating tests. The 1-D backwater stepwise method gives a 225,000 m^3/s of peak flow for the paleoflood. The peak discharge of the 1902 AD flood is about 168,000 m^3/s by comparing 15 empirical models with the 2000 AD flood. The river profile was strongly influenced by the dams and associated outburst floods. It is roughly estimated that a volume of 0.26 billion m^3 sediment or even more has been

aggraded upstream of the 2000 AD dam. The slope of the channel immediately after the dam is twice of that before the 7 ka BP event due to rapid settling of the flood sediments. Moreover, at least three superfloods of $> 10^5 \text{ m}^3/\text{s}$ happened on the Yigong since 7 ka BP indicate that the recurrence interval of Holocene outburst floods on the southeastern margin of the Tibetan Plateau is much shorter than that of monsoon floods with the same magnitude. The dominant effect of outburst floods should be accounted for in long-term landscape evolution models of the southeastern margin.

Declarations

Acknowledgments

This research was funded by the Second Tibetan Plateau Scientific Expedition and Research Program (2019QZKK0902), and the National Natural Science Foundation of China (91747207, 41790434).

Authors' contributions:

K.H., the corresponding author, led the study and wrote the manuscript. C.W. performed the field survey and edited the sample data. L.W. calculated outburst flood magnitude using 1-D Step-Backwater Method. X. Z. estimated outburst flood magnitude using empirical method. Q. Z. measured topographical data and plotted the cross-section profiles. W.L. aided the field survey. B.Y. improved the highlights. All authors listed in the manuscript agree with this submission of the manuscript.

Competing interests:

The authors declare no competing interests.

Availability of data and material:

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.

References

1. Montgomery, D. R. et al. Evidence for Holocene megafloods down the Tsangpo River gorge, southeastern Tibet. *Quaternary Research*. **62**, 201–207 (2004). <https://doi.org/10.1016/j.yqres.2004.06.008>
2. Ouimet, W. B., Kelin, X. W., Leigh, H. R., Sun, Z.M. & Chen, Z. L. The Influence of Large Landslides on River Incision in a Transient Landscape: Eastern Margin of the Tibetan Plateau (Sichuan, China). *Geological Society of America Bulletin*. **119**, 1462–76 (2007).

3. Korup, O. & Montgomery, D. R. Tibetan plateau river incision inhibited by glacial stabilization of the Tsangpo gorge. *Nature*. **455**, 786–789 (2008).
4. Korup, O., Montgomery, D. R. & Hewitt, K. Glacier and landslide feedbacks to topographic relief in the Himalayan syntaxes. *Proceedings of the National Academy of Sciences***107**, 5317–5322 (2010).
5. Cook, K. L., Andermann, C., Gimbert, F., Adhikari, B. R. & Hovius, N. Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya. *Science*. **362**, 53–57 (2018).
6. Baker, V. R. The Study of Superfloods. *Science*. **295**(5564), 2379–80 (2002).
7. Lamb, M. P., Fonstad, M. A. Rapid Formation of a Modern Bedrock Canyon by a Single Flood Event. *Nature Geoscience*. **3**(7), 477–81 (2010).
8. Lang, K. A., Huntington, K. W. & Montgomery, D. R. Erosion of the Tsangpo Gorge by megafloods, Eastern Himalaya. *Geology*. **41**, 1003–1006 (2013).
9. Carling, P. A., Fan, X. M. Particle Comminution Defines Megaflood and Superflood Energetics. *Earth-Science Reviews***204**, 103087 (2020).
10. Srivastava, P. et al. Paleofloods records in Himalaya. *Geomorphology*. **284**, 17–30 (2016). <https://doi.org/10.1016/j.geomorph.2016.12.011>
11. Turzewski, M. D., Huntington, K. W., Licht, A. & Lang, K. A. Provenance and erosional impact of Quaternary megafloods through the Yarlung-Tsangpo Gorge from zircon U-Pb geochronology of flood deposits, eastern Himalaya. *Earth and Planetary Science Letters*. **535**, 116113 (2020).
12. Shang, Y. J., Yang, Z. F., Li, L. H., Liu, D. A., Liao, Q. L. & Wang, Y. C. A super-large landslide in Tibet in 2000: background, occurrence, disaster, and origin. *Geomorphology*. **54**, 225–243 (2003).
13. Zhu, P. Y., Wang, C. H. & Wang, Y. C. Large-scale landslide-debris avalanche in Tibet, China; 2, Formation of an exceptionally serious outburst flood from a landslide dam in Tibet. *Landslide News***14**, 23–25 (2003).
14. Evans, S. G., Delaney, K. B. Characterization of the 2000 Yigong Zangbo River (Tibet) landslide dam and impoundment by remote sensing in *Natural and artificial rockslide dams* (ed. Evans, S. G., Hermanns, R. L., Strom, A., & Scarascia-Mugnozza, G.). **133**, 543–559 (Berlin, Heidelberg, Springer, 2011). <https://doi.org/10.1007/978-3-642-04764-0-22>
15. Delaney, K. B., Evans, S. G. The 2000 Yigong landslide (Tibetan Plateau), rockslide-dammed lake and outburst flood: Review, remote sensing analysis, and process modelling. *Geomorphology*. **246**, 377–393 (2015). <https://doi.org/10.1016/j.geomorph.2015.06.020>
16. Lu, R. R., Tang, B. X. & Zhu, P. Y. Debris Flows and Environment in Tibet. 32–40 (Chengdu Science and Technology University Press, Chengdu, 1999) (in Chinese)
17. Zhou, C. H., Yue, Z. Q., Lee, C. F., Zhu, B. Q. & Wang, Z. H. Satellite image analysis of a huge landslide at Yi Gong, Tibet, China. *Quarterly Journal of Engineering Geology and Hydrogeology*. **34**(4), 325–332 (2001). <https://doi:10.1144/qjegh.34.4.325>
18. Benito, G., O'Connor, J. E. Quantitative Paleoflood Hydrology in *Treatise on Geomorphology* (ed. Shroder, J.F.). 459–474 (Amsterdam Elsevier 9, 2013).

19. Carling, P. A. Freshwater megaflood sedimentation: What can we learn about generic processes?. *Earth-Science Reviews*. **125**, 87–113 (2013).
20. Ma, D. T. Study on influences of mountain hazards in Yigong Zangbu River Basin to mitigation and reconstruction of Sichuan-Tibetan Highway Line [Ph.D. thesis]: Chengdu, Graduate School of Chinese Academy of Sciences 54 (2006).
21. Liu, N., Cheng, Z., Cui, P., Chen, N. S. Dammed Lake and Risk Management. 141 (Science Press, Beijing, 2013) (in Chinese)
22. MacDonald, T. C. & Langridge-Monopolis, J. Breaching characteristics of dam failures. *Journal of Hydraulic Engineering*. **110**, 567–586 (1984).
23. Thorndycraft, V., Benito, G., Rico, M., Sopen~a, A., Sa´nchez-Moya, Y. & Casas, M. A long-term flood discharge record derived from slack water flood deposits of the Llobregat River, NE Spain. *Journal of Hydrology*. **313**, 16–31 (2005).
24. Webb, R. H. & Jarrett, R.D. One-dimensional estimation techniques for discharges of paleofloods and historical floods in *Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology Water Science and Application Series 5* (ed. House, P. K., Webb, R. H., Baker, V. R. & Levish, D. R.) 111–126 (2002).
25. Hydrologic Engineering Center. HEC-RAS, River Analysis System, Hydraulics Reference Manual, Version. 5.0. Davis, California, U.S. Army Corps of Engineers 25 (2016)
26. Korup, O., Strom, A. L. & Weidinger, J. T. Fluvial response to large rock-slope failures: Examples from the Himalayas, the Tien Shan, and the Southern Alps in New Zealand. *Geomorphology***78**, 3–21 (2006).
27. Deng, M., Chen, N. & Liu, M. Meteorological factors driving glacial till variation and the associated periglacial debris flows in Tianmo Valley, south-eastern Tibetan Plateau. *Natural Hazards and Earth System Sciences*. **17**, 345–356 (2017).
28. Hu, K. H., Zhang, X. P., You, Y., Hu, X. D., Liu, W. M., Li, Y. Landslides and dammed lakes triggered by the 2017 Ms6. 9 Milin earthquake in the Tsangpo gorge. *Landslides*. **16**, 993–1001 (2019).

Tables

Table 1. Radiocarbon dating result for samples from shuangyu slackwater deposit

Sample	Material analyzed	Percent modern carbon	Modern carbon fraction	Age (BP)
SC1	Charred material	41.73 +/- 0.16	0.4173 +/- 0.0016	7020±30
SC2	Organic sediment	42.94 +/- 0.16	0.4294 +/- 0.0016	6790±30
SC3	Charred material	43.10 +/- 0.16	0.4310 +/- 0.0016	6760±30
SC4	Charred material	42.89 +/- 0.16	0.4289 +/- 0.0016	6800±30

Table 2. Sample dose rate and optically stimulate luminescence dating results for shuangyu slackwater deposit

Sample	Depth (m)	K (%)	Th (10^{-6})	U (10^{-6})	Dosage rate (Gy/ka)	Number of test pieces	De/Gy	OSL age (ka)
SO1	2.3	3.07 ± 0.04	14.24 ± 0.70	2.44 ± 0.40	3.88 ± 0.28	$8^a + 12^b$	71.6 ± 4.21	18.5 ± 1.7
SO2	-	-	-	-	-	-	-	-
SO3	3.4	3.22 ± 0.04	22.97 ± 0.80	1.74 ± 0.30	4.61 ± 0.34	$8^a + 12^b$	35.1 ± 1.83	7.6 ± 0.7
SO4	3.9	2.36 ± 0.04	25.96 ± 0.80	1.46 ± 0.30	4.16 ± 0.30	$8^a + 12^b$	63.8 ± 3.83	15.3 ± 1.4

^a the number of test pieces using Single Aliquot Regenerative-dose method

^b the number of test pieces using Standardised Growth Curve method

Table 3. Estimates of peak discharge for the outburst flood generated by the 2000 ad yigong dam failure using 15 empirical models listed in Liu et al. ²¹

Author	Model*	Publication date	Peak discharge (m^3/s)
Kirkpatrick	$Q_p = 1.268(H_w + 0.3)^{2.5}$	1977	28835
SCS	$Q_p = 16.6H_w^{1.85}$	1981	27528
USBR	$Q_p = 19.1H_w^{1.85}$	1988	31674
USBR	$Q_p = 48H_w^{1.85}$	1988	32963
Hagen	$Q_p = 0.54(V_s - H_d)^{0.5}$	1982	24239
Singh and Snorrason	$Q_p = 13.4H_d^{1.89}$	1984	26084
Singh and Snorrason	$Q_p = 1.776V_s^{0.47}$	1984	41922
MacDonald and Langridge-Monopolis	$Q_p = 3.85(H_w V_w)^{0.41}$	1984	129944
Costa	$Q_p = 1.122V_s^{0.57}$		225643
Costa	$Q_p = 0.981(V_s H_d)^{0.42}$	1985	42698
Costa	$Q_p = 2.634(V_s H_d)^{0.44}$	1988	2998208
Evens	$Q_p = 0.72V_w^{0.53}$	1986	61459
Froechlich	$Q_p = 0.607H_w^{1.24}V_w^{0.295}$	1995	48528
Webby	$Q_p = 0.0443g^{0.5}V_w^{0.365}H_d^{1.4}$	1996	94314

* Where Q_p is outburst flood peak discharge, V_w is the water released (m^3), V_s is barrier lake volume, H_w is breach depth, and H_d is dam height. In this study, we only considered complete dam breach, thus, V_w is the same as V_s and H_w is the same as H_d .

Table 4. Basic parameters of the yigong barrier lakes in 1900 ad and 2000 AD

	Year	Water depth (m)	Lake area (km^2)	Lake volume* (Gm^3)	Peak discharge† (m^3/s)
	2000	55	48.93	2.015	129,944
	1900	73	54.08	2.838	167,943

* Volume was calculated using (Delaney and Evans, 2015), where A is the area of impounded water
†Peak discharge was calculated using (MacDonald and Langridge-Monopolis, 1984), where H is barrier lake water depth and V is lake volume.

Figures

Figure 1

(A) Location of the Yigong river and the Yarlung Tsangpo Gorge. The eastward flowing Yigong River turns southward and flows into the gorge after confluence with the westward flowing Parlung River at Tongmai. The topographic map was extracted from NASA's 90 m Shuttle Radar Topography Mission elevation data. The gray line is the Yarlung Tsangpo suture zone. The yellow lines are the Jiali fault. The black box is the extension of the subfigure B. NB denotes Namche Barwa massif (7782 m), GP denotes Gyala Peri massif (7294 m). (B) Topographic relief of the Yigong's downstream area mapped with the Advanced Land Observing Satellite-1 (ALOS) 12.5 m DEM. The blue and orange outlines denote the ranges of the 1902 AD and 2000 AD landslide dams, respectively. The yellow circles with black crosses denote the location of the sediment records. Tongmai Bridge is in a bedrock reach at the confluence of Yigong and Parlung rivers. (C) ETM+ image from November 15, 2001. The 2000 AD flood greatly changed the river

channel morphology and local topography. A–A' marks the location of cross sections in Fig. 2. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

(A) Location of slackwater deposits (SWDs) at Shuangyu Village. Orthographic image taken on May 11, 2020 by Dajiang unmanned aerial vehicle (UAV); (B) Upper part of sedimentary section; (C) Lower part of sedimentary section. Total thickness of section is 2.6 m. SO1 to SO4 denotes luminescence dating sample and SC1 to SC4 denotes radiocarbon dating sample; (D) Cross section and sedimentary sequence

of Shuangyu SWD. The two cross sections derive from UAV survey on May 11, 2020 (solid line) and the Advanced Land Observing Satellite (ALOS) 12.5 DEM (dashed line). Water level is estimated as c. 3 m, based on the mean discharge of 520 m³/s in May. The ALOS DEM is consistent with the UAV survey for the main channel and floodplain, but differs by up to 25 m on river banks and hillslopes.

Figure 3

(A).The sediment sequence at the outlet of Dayi creek. (B) Section of the lacustrine deposit between the debris-flow accumulation and the mixture layer. The ruler is 50 cm long.

Figure 4

(A) Location of slackwater deposits (SWDs) on the opposite bank of Jiazhong Village. Orthographic image taken on May 11, 2020 by Dajiang unmanned aerial vehicle (UAV). (B) Exposed sedimentary section of the SWDs. The notebook is 14 cm high.

Figure 5

(A) the locations of 97 cross sections used in HEC-RAS Mapper component of HEC-RAS 5.0.7 for the 1D step-backwater computation from the breached dam to the bridge. (B) Longitudinal profiles of water surface and energy grade elevations calculated using the step-backwater method. Peak discharges of 126,000 m³/s and 225,000 m³/s provided the best approximation for the levels of the SWDs at Jiazhong and Shuangyu.

Figure 6

Profile of the Yigong river downstream and probable water level of the 7 ka BP dammed lake according to a peak flow of 225,000 m³/s

Figure 7

(A) KeyHole-9 satellite image of the Yigong lake on March 26, 1973, and (B) TM satellite image of the Yigong lake on December 27, 1996.

Figure 8

The location of Bailong creek and the ancient landslide at Jiazhong village. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.