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Scale amplification of natural debris flows caused by cascading landslide dam failures ☆

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ABSTRACT

Debris flows are typically caused by natural terrain landslides triggered by intense rainfalls. If an incoming mountain torrent collapses a series of landslide dams, large debris flows can form in a very short period. Moreover, the torrent can amplify the scale of the debris flow in the flow direction. The catastrophic debris flows that occurred in Zhouqu, China, on 8 August 2010 were caused by intense rainfall and the upstream cascading failure of landslide dams along the gullies. In the wake of the incident, a field study was conducted to better understand the process of cascading landslide dam failures and the formation of debris flows. This paper looks at the geomorphic properties of the debris-flow gullies, estimates the peak flow discharges at different locations using three different methods, and analyzes the key modes (i.e., different landslide dam types and their combinations) of cascading landslide dam failures and their effect on the scale amplification of debris flows. The results show that five key modes in Luojiayu gully and two modes in Sanyanyu gully accounted for the scale amplification of downstream debris flows in the Zhouqu event. This study illustrates how the hazardous process of natural debris flows can begin several kilometers upstream as a complex cascade of geomorphic events (failure of landslide dams and erosion of the sloping bed) can scale to become catastrophic discharges. Neglecting recognition of these hazardous geomorphic and hydrodynamic processes may result in a high cost.

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1. Introduction

Debris flows occur when masses of poorly sorted sediment, agitated and saturated with water, surge down a slope in response to gravitational attraction (Iverson, 1997). Debris flows differ from rock avalanches and sediment-laden water floods in that both solid and fluid forces influence its motion and govern the rheological properties of the debris flow (Iverson, 1997). Indeed, most debris flows mobilize from static sediment that is laden with water and poised on a slope. Usually, a landslide that becomes agitated and disaggregated as it tumbles down a steep slope can transform into a debris flow if it contains or acquires sufficient water for saturation. Some of the largest and most devastating debris flows have originated in this manner (e.g., Plafker and Ericksen, 1978; Scott et al., 1995). When mass movement occurs, the sediment–water mixture transforms into a flowing, liquid-like state, which eventually transforms back into nearly rigid deposits (Iverson, 1997).

In mountainous areas, excessive rainfall or snowmelt usually causes strong flash floods upstream. Abundant granular material deposited along channels in the region can easily cause erosion and entrainment of debris by floods, which allows gradual transformation of a flood into a debris flow. Note that landslides are usually the dominant mechanism for conveying large amounts of debris to river channels (Korup et al., 2004); when a landslide is connected with a channel, landslide debris can be transported to the channel (Schwab et al., 2008). Indeed, several studies indicate that much of the sediment produced in upper basins often does not immediately migrate downstream but is instead deposited in a riverbed, resulting in channel aggradation (Kasai et al., 2004; Koi et al., 2008). Furthermore, other studies have reported that large landslides inundate river valleys and overwhelm channels with large volumes of coarse materials, commonly forming stable landslide dams that trigger extensive and prolonged aggradation upstream (Ouimet et al., 2007). Thus, large debris flows are likely caused by the conjunction of many landslide dams of different scales (from bank slides or collapses), bed erosion, and solid transport (Davies, 1986).

The catastrophic debris flows that occurred at Zhouqu in Gansu Province of China on 8 August 2010, are considered to have been induced by upstream flash floods owing to intense rainfall (Hu et al., 2010; Yu et al., 2010; Zhao and Cui, 2010; Tang et al., 2011). Before the disaster, the sloping channels were blocked by clusters of landslide

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dams (cf. Ma and Qi, 1997) that included almost all of the categories summarized and illustrated by Costa and Schuster (1988) based on their various relationships with the valley floor. When upland floodwaters moved downward at high speed and crushed the obstructing landslide dams, the channel blockage was first gradually broken, then rapidly widened the incision (cf. Costa and Schuster, 1988; Chang and Zhang, 2010). Sediment delivery of the landslide debris by the high speed stream flows was quite large, easily forming debris flows (cf. Scott et al., 1995; Iverson, 1997; Chien and Wan, 1999). The debris flows crossed Zhouqu's urban area, destroying streets, houses, and bridges and causing 1765 deaths. Moreover, the debris flows rushed into the Bailong River and formed a dammed lake about 550 m in length and 70 m in width, which flooded half the city.

After the disaster, landslide dams in varying degrees of collapse were observed along the sloping channel. Thus, we can postulate that incoming streams may have caused cascading landslide dam failures. During the process, the magnitude of the sediment flow is believed to have significantly increased because of these dam failures, as the geography downstream from those landslide dams consists of steep canyons with easily erodible granular materials that can be entrained into the flow and can increase flood peaks. There are many case studies of individual natural-dam failure (e.g., Costa and Schuster, 1988; Korup, 2002; Cleary and Prakash, 2004; Korup et al., 2004), but an integrated view of the cascading failure of clusters of landslide dams falling like dominoes along the slope channels does not exist. The mechanisms underlying such a failure process, and the resulting increase in magnitude of downstream debris flows, are still not clear.

To understand this important natural process, a field study was conducted to systematically investigate the debris flows that occurred in Zhouqu. Specifically, we attempt to estimate the size and distribution of the large landslide dams along the gullies. By complementing the documented post-failure morphodynamic histories of each respective site from upstream to downstream, this paper aims to determine the evolution of cascading landslide dam failures initiated by upland flash floods and the variation in flow discharge during the process. Different combinations of landslide dams along the channel that account for the occurrence of flood peaks are then discussed to determine the key modes underlying cascading landslide dam failure.

2. Background of the Zhouqu debris flows

The Zhouqu debris flows occurred in two large gullies, Sanyanyu and Luojiayu, located in the Gannan Tibetan Autonomous Prefecture, Gansu Province of China. The Sanyanyu gully is usually further divided into two large gullies, Dayu and Xiaoyu, which converge at point 'OO' in Fig. 1A, B, and C. The urban area of Zhouqu township is located on the deposited fan (see Fig. 1A and D), and was seriously destroyed by large-scale debris flows from the gullies starting at about 23:40, 7 August 2010 (see Fig. 2A). The debris flows thrust through the urban area, destroying all buildings along the flow as shown in Fig. 2B, then rushed into the Bailong River and formed a dammed lake. The makeshift lake flooded half of the urban area for over 20 days (see Fig. 2C), interrupting electric power, communications, and water supply.

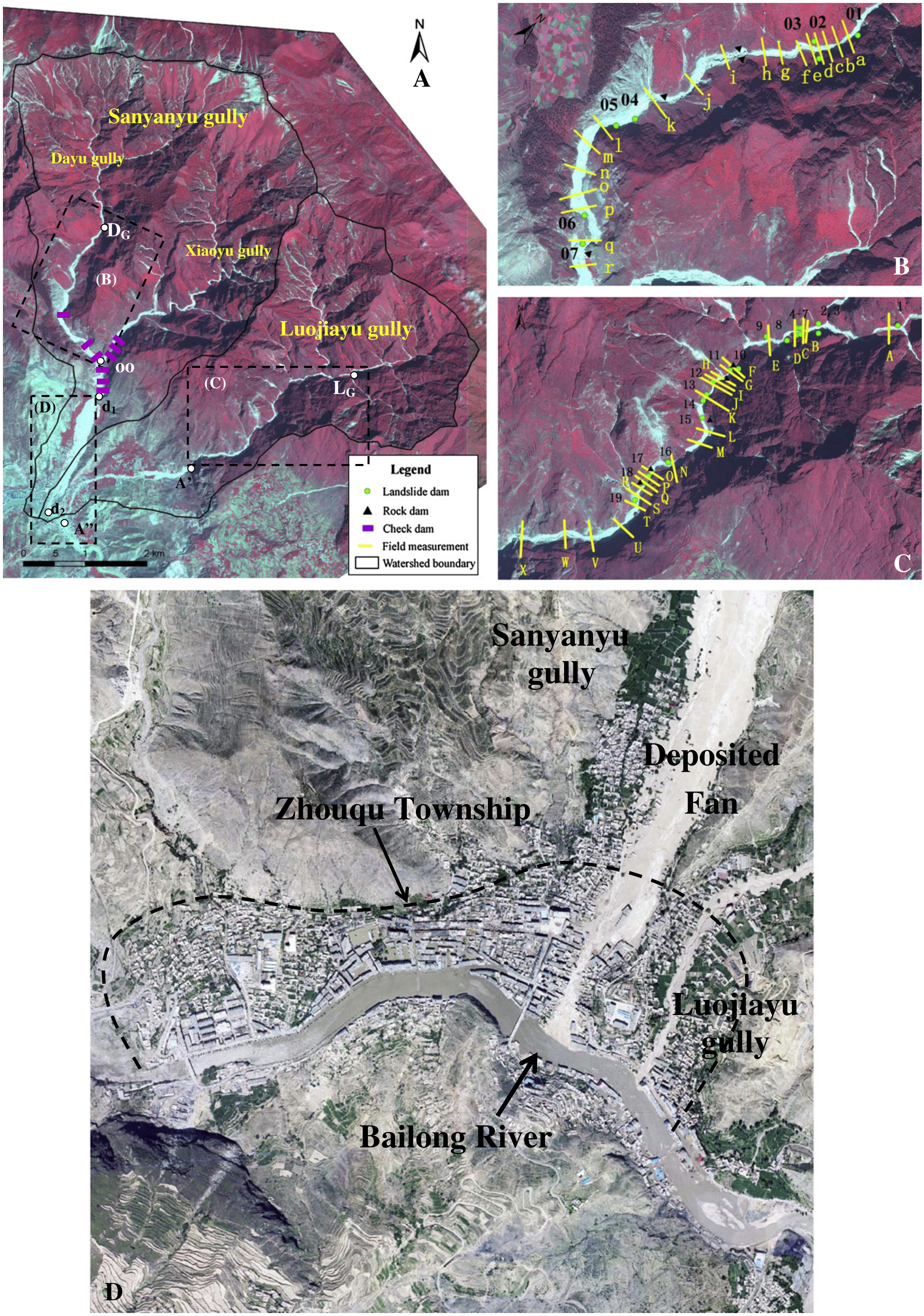
2.1. Geomorphic and geological properties

As a part of the southern area of Gansu Province (which is located in the northern section of the Chinese north–south seismic belt), Zhouqu is located in the west tectonic zone of the Qinling Mountains and is significantly influenced by the Indo-China orogeny and Yanshan movements. New tectonic movements in the area are frequent: hills strongly uplift, gullies rapidly incise, and mountainous areas of high relief are usually formed. The tectonic activities in the late Quaternary period were quite intensive in this region, inducing developed faults and frequent earthquakes. All of the recorded, closely correlated earthquakes—e.g., the Wudu earthquake (M_S 7) in B.C. 186, the Tianshui earthquake (M_S 8) in 1654, and the Wenxian–Wudu earthquake (M_S 8) in 1879—caused serious losses in Chinese history. All three of the above-mentioned earthquakes occurred near Zhouqu (see Fig. 3A), triggering large collapses and landslides that were instrumental in depositing loose solid materials in the gullies of the area. As illustrated by Keefer (1999), high magnitude earthquakes play an important role as preparatory and triggering variables for landslides, reducing slope stability through rock shattering, fault zone weakening, slope tilting, and topographic amplification of ground shaking (cf. Hancox et al., 1997; Korup, 2005). Those landslides usually accumulated in sloping channels, gradually forming the multiple landslide dams as shown in Fig. 1B and C. Those landslide dams are natural barriers, blocking the granular material of upstream debris flows and causing a large volume of solids to accumulate at these points.

Previous investigation by Ma and Qi (1997) illustrated that eight large slope failures (with a total area of 0.88 km^2) had developed in the Sanyanyu gully, with a total sediment volume of 1.30×10^7 m^3. The area had a total of 58 potential collapse areas encompassing 2.83×10^7 m^3 of debris, with additional solids deposited on the channel bed amounting to about 1.03×10^7 m^3. Ma and Qi estimated that 2.51×10^7 m^3 of the total available debris (amounting to 5.16×10^7 m^3) could be entrained and involved in debris flows (Ma and Qi, 1997). The geomorphic properties of Luojiayu gully are quite similar to that of Sanyanyu gully, except for a narrower sloping channel. Although the scale of the landslide dams in Luojiayu gully is relatively smaller, the distribution of the landslide dams along the channel is much denser (cf. Fig. 1B and C). At least two large landslide dams (higher than 10 m) are located in each section with an average 500-m channel length (totally about nineteen landslide dams, as illustrated by Fig. 1C), with lots of sediment accumulation. The landslide dams are usually stable under low rainfall conditions but react quite differently with intense rainfall. Large flash floods induced by these intense rainfalls can mobilize the deposited sediments behind the landslide dams and initiate downstream debris flows.

The fault zone of the Bailong River possesses the major active faults of the basin (see Fig. 3B). Moreover, this fault zone is also composed of a cluster of secondary faults, mainly characterized by reversed faults and left-lateral strike-slip faults. Tectonic activity from the late Quaternary period was quite intensive, leaving obvious changes to the geography of the region. The Bailong River further divides the fault zone into north and south branches (see Fig. 3B). Both branches of the fault zone are fully developed in Zhouqu, and the north branch even penetrates through the downtown area. Fig. 3B shows that the north branch consists of three parallel faults: the Animaqing fault, the Pingding-Huama fault, and the Zhouqu fault, with the Zhouqu fault the most southern of the three. The branch's eastern and middle parts are basically distributed along the valleys of the Bailong River; they twice cut into the river and penetrate into the city from the west, and are the most dangerous to Zhouqu township. The direction of the Zhouqu fault is N.60°W., inclined to the southwest with a steep angle (60–70°). The total penetration length of the fault inside Zhouqu county is about 50 km. Typically, the Zhouqu fault is considered to have been an active fault into the late Pleistocene period. The geomorphic characteristics of the Zhouqu fault are the terraces, whose activities and properties can be described as follows: (i) the morphology terraces are well developed

Fig. 1. Sequential air photography showing massive aggradation on the lower town and Bailong River following the Zhouqu debris flow on 8 Aug. 2010. (A) The satellite image shows the gully morphology where Dayu gully and Xiaoyu gully converge at 'OO'; (B) locations of the landslide dams and sections of field investigation along Dayu gully; (C) locations of the landslide dams and sections of field investigation along Luojiayu gully; (D) Zhouqu township located on the deposited fans (the area bracketed by d_1–d_2 and A′-A″). Image courtesy of the Chinese State Bureau of Surveying and Mapping.



N
A
Sanyanyu gully
Dayu gully
Xiaoyu gully
Luojiayu gully
(B)
(C)
(D)
D_G
OO
d_1
d_2
L_G
A'
A''
Legend
Landslide dam
Rock dam
Check dam
Field measurement
Watershed boundary
0 .5 1 2 km
B
01 02 03 04 05 06 07
a b c d e f g h i j k l m n o p q r
C
1 2, 3 4–7 8 9 10 11 12 13 14 15 16 17 18 19
A B C D E F G H I J K L M N O P Q R S T U V W X
D
Sanyanyu gully
Deposited Fan
Zhouqu Township
Luojiayu gully
Bailong River

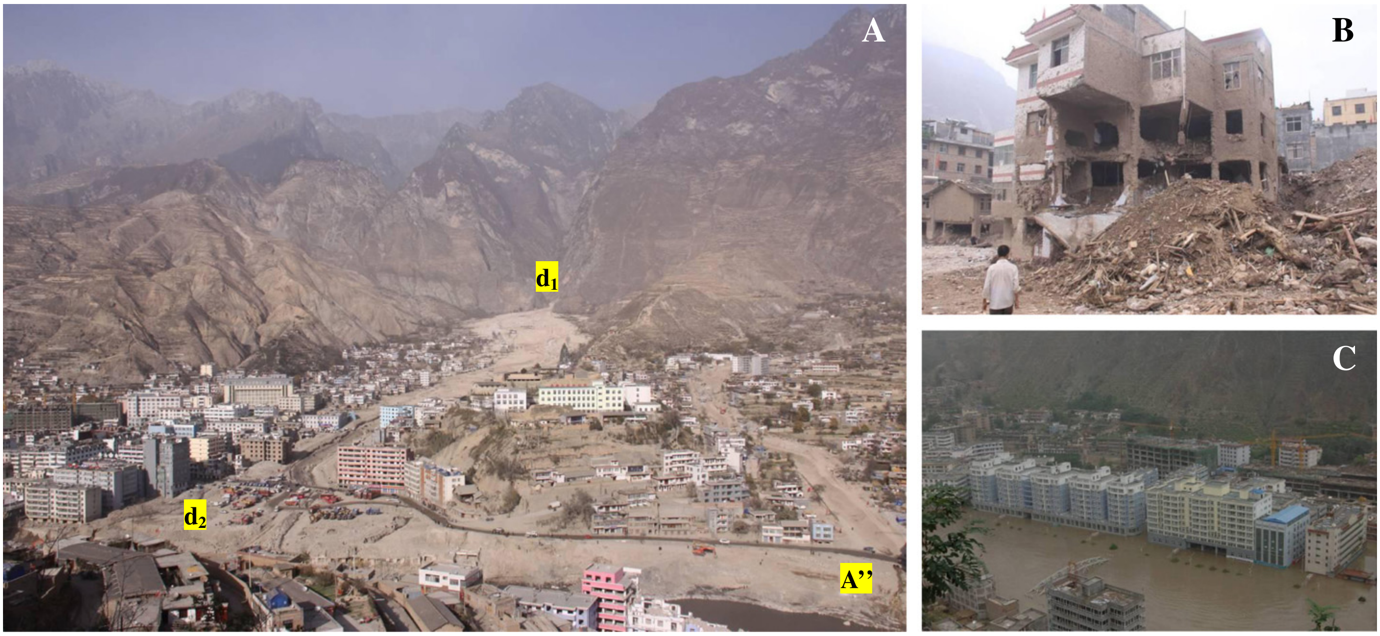


Fig. 2. (A) Image of Zhouqu township destroyed by the debris flow (on the left is Sanyanyu gully and on the right is Luojiayu gully; (B) crushed buildings on the deposition zone (from d_1 to d_2); (C) inundated township upstream of the Bailong River, which was blocked by the debris flows (at the point d_2).

in the fault zone, about 100 m above the bedrock rupture; (ii) the morphology terraces separate the hanging layer, consisting of 30–40 m of redeposited loess and gravels, and the bottom wall, which is composed of carboniferous layers and large gravels; (iii) the morphology terraces break the early diluvial platform; and (iv) the morphology terraces are not completely consistent with the furrow banks of the gullies. The incision of terraces into the main gully at the west point of the Zhouqu township further indicates that formation of the terraces is probably owing to fracture rather than to alluvial–proluvial effects.

Many studies have looked at the backgrounds and reasons behind the large Zhouqu debris flows (e.g., Fang et al., 2010; Hu et al., 2010; Ma, 2010; Yu et al., 2010). Most consider the debris flows that occurred in the Sanyanyu gully before the giant event as nonviscous debris flows. Luojiayu gully possesses a low frequency of debris-flow occurrence, and no debris flows have occurred in recent decades. The watershed of Sanyanyu gully is about 25.75 km^2, stretching from north to south and shaped like a ‘gourd dipper’. The length of the main gully is about 9.7 km, with the highest and lowest elevations being 3828 and 1340 m, respectively, and possessing a mean gradient of 24.1%. The watershed of Luojiayu gully is about 16.60 km^2 and is shaped like a ‘calabash’. The length of the main gully is about 8.5 km, and the elevation changes from 3794 to 1330 m with a mean gradient of 23.9%. Usually no streams can be observed in Luojiayu gully. Because of the intense incision and erosion, most valleys in the gully are V-shaped.

Many landslide dams were found distributed along the narrow gullies before the debris-flow event, impounding an abundance of sediment. Debris flows are mostly triggered by the failure of these landslide dams caused by upland flash floods. Based on the measured thickness and area of the deposition fan, and the sizes of the landslide dams formed in the Bailong River, the runoff of the debris flows for Sanyanyu gully (including Dayu gully and Xiaoyu gully) and Luojiayu gully during the Zhouqu event was about 1.8×10^6 m^3, with a total sediment discharge of over 1.2×10^6 m^3. The landslide dams were also a source for transported debris. The conditions are similar for the narrow Luojiayu gully. The particle size distribution of the debris flows in Sanyanyu gully and Luojiayu gully is illustrated in Fig. 4, which further implies that different debris flows along the two different gullies possess the same mean particle diameter, d_{50}.

2.2. Triggering mechanisms of the natural debris flows—rainfall conditions

At 23:00 of Aug. 7, 2010, heavy rainfall occurred in the gullies of Zhouqu. Forty minutes later, disastrous debris flows moved downward in the gullies, transporting large boulders. The buildings located on the deposition fan were destroyed by the subsequent debris-flow surges, with the total process lasting about 40 min. According to the investigation, the triggering mechanisms of the debris flows along the two gullies can be summarized as follows:

- The rainfall process of the two gullies can be estimated based on recorded rainfall data from Dongshan station (elevation 2150 m), located 1.5 km away from Luojiayu gully on the left side of the Bailong River (see Fig. 1A). Between 21:00 of Aug. 7 and 04:00 of Aug. 8, 2010, the total amount of rainfall was 96.7 mm for the drainage areas of the two debris-flow gullies; from 23:00 to 24:00 the rainfall intensity reached 77.3 mm/h (see Fig. 5). This rainfall intensity is an amount with a return period of more than 100 yr (Zhao et al., 2010). The recorded rainfall at Daigu Temple, Diebu city (upstream of Zhouqu), was 93.8 mm. However, no intense rainfalls were measured in the other areas of Zhouqu; the rainfall in downtown Zhouqu was only 10 mm. This illustrates that rainfall distribution in Zhouqu is quite nonuniform.
- Large flash floods developed from the uplands of Sanyanyu gully owing to the intense rainfall. The floodwaters descended along the sloping channel at high speed, crushing the debris-filled dams and eroding the loose sediments in the gully. We speculate that upstream, flash floods were easily initiated and turned into debris flows (with high densities) in the downstream areas. Moreover, new instability occurred along both banks of the channel after the event.
- Luojiayu gully originally possessed low-frequency debris flows. The channel is quite narrow, and clusters of landslide dams typically

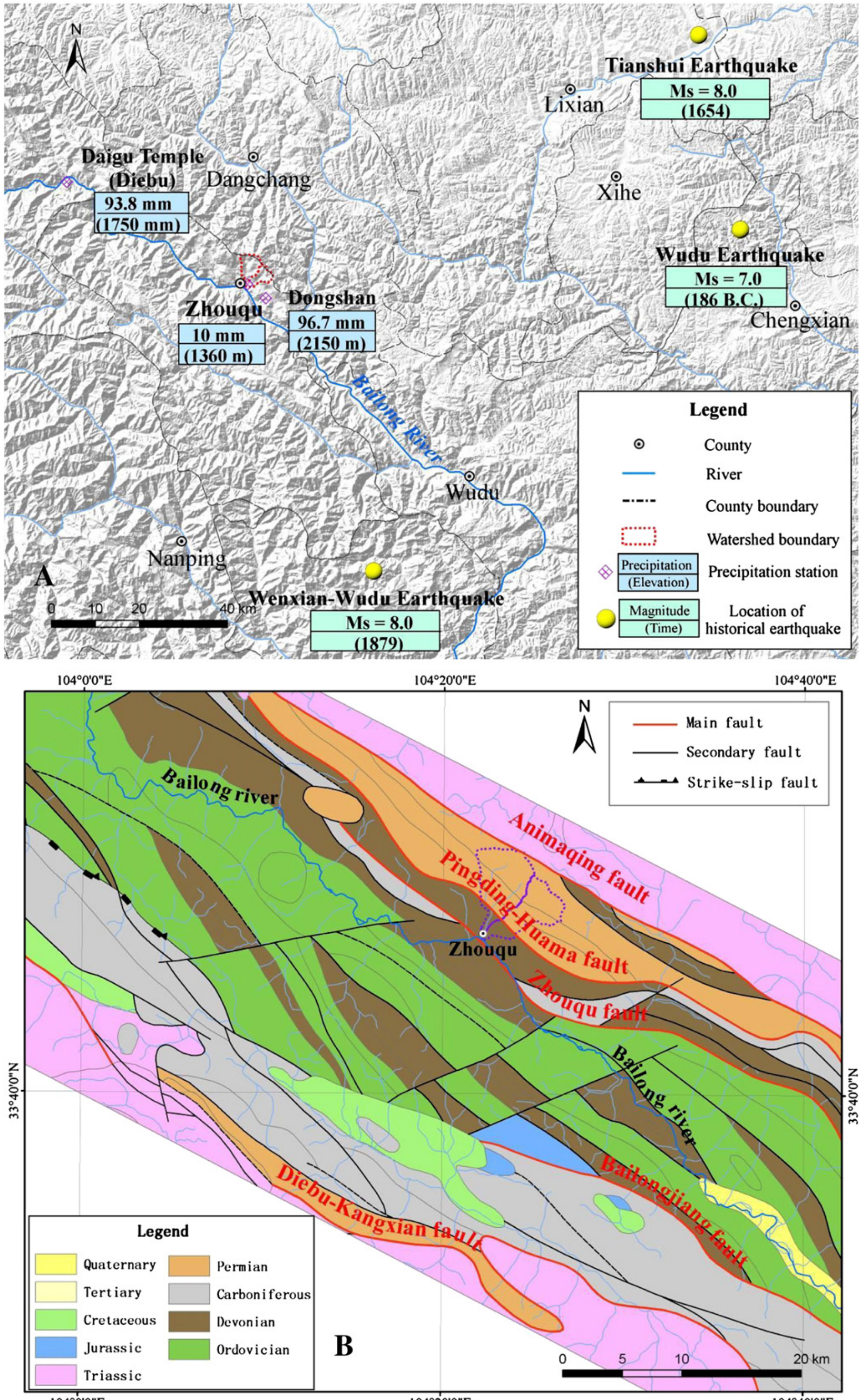


Fig. 3. (A) Location of the three large historical earthquakes near Zhouqu; (B) tectonic map of the active faults in the Bailong River Basin.

formed in the narrowest position and blocked the valley. In general, floods of a normal order of magnitude cannot crush landslide dams in order to induce debris flows (cf., the large flood that occurred in 1946 according to recollections of the local old inhabitants). However, because of the intense rainfall on 7 August, the existing landslide dam clusters were destroyed by upland flash floods, causing sediments to mobilize and entrain and resulting in viscous debris flows forming downstream.

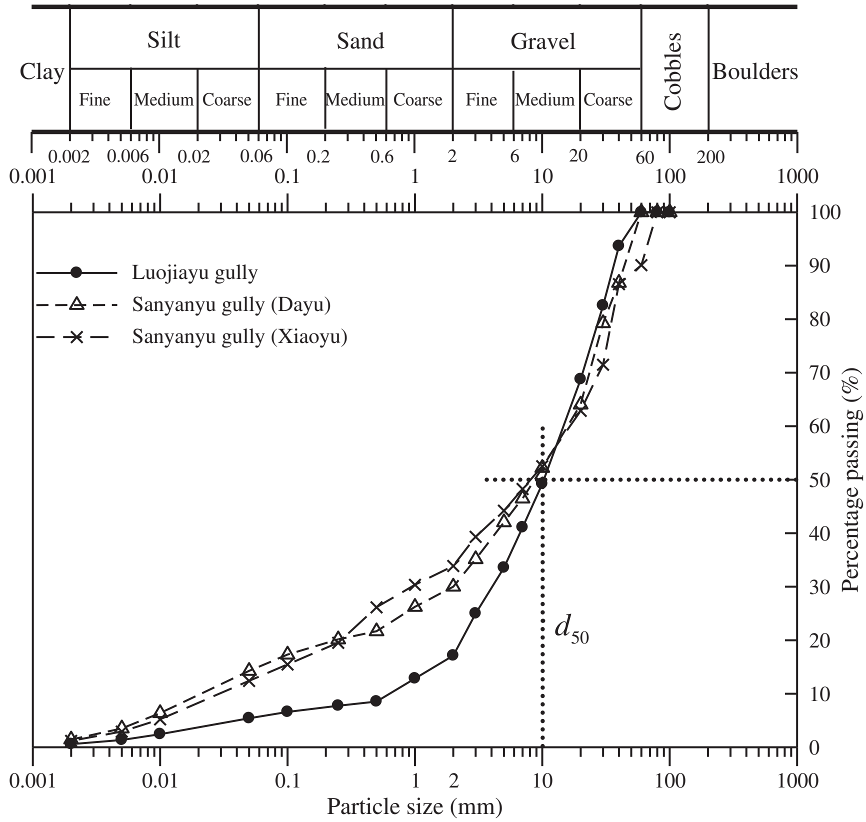


Fig. 4. Particle-size distribution of the debris flows occurred in Zhouqu.

3. Evolution of the Zhouqu debris flows

3.1. Methodologies applied in the field investigation

As discussed by Costa and Schuster (1988), direct measurements of floods or debris flows are nearly impossible; thus, a variety of indirect estimation methods are used, such as drawdown rates (rate of descending ground water levels) or measurements based on post-flood channel surveys and hydraulic formulas. To gather more detail on the initiation, mobilization, erosion, and deposition processes of the Zhouqu debris flows, a field investigation was conducted. The geomorphic settings of Sanyanyu gully and Luojiayu gully were carefully measured and analyzed, including channel width, flow height (judged from the level of mud imprinted on the side walls of the narrow valley or based on the extent of moss and vegetation damage to the gully sidewalls), roughness of the slope bed (i.e. a depth parameter divided by a particle size, which is usually characterized by various bed particle size statistics such as d_{50}, d_{84}, and factors related to particle size distribution) (cf. Jarrett, 1984; Rice et al., 1998; Smart et al., 2002), and landslide dam size and geometry. Furthermore, the locations of the landslide dams along the channels were determined by GPS, allowing analysis of the distribution of clusters of landslide dams in the gullies. The amount of solids sluiced away and incorporated into the flows was estimated based on the incision and breach marks remaining on the post-failure landslide dams. Most attention was focused on the main transportation zones during the field survey: L_G—A′ for Luojiayu gully and D_G—OO for Dayu gully in Fig. 1A. The field traces indicate that the catchment areas above the points L_G and D_G mainly generated fresh floodwaters, and few landslides were found at these points. To estimate the flow discharge and derive debris-flow evolution along the sloping channels, the most widely used hydraulic formula, the Manning equation which considers the open-channel flow velocity to be dependent on the surface materials of the channel's wetted perimeter and the slope inclination (cf. Manning, 1891; Jarrett, 1984; Rice et al., 1998; Munson et al., 2006), was applied. Two widely applied semiempirical formulas for the estimation of discharge and velocity of debris flows were also used for comparison. For more details, Fig. 1B and C illustrates the locations of the chosen cross sections for measurement and the distributions of the landslide dams along the sloping channels for Dayu gully and Luojiayu gully, respectively.

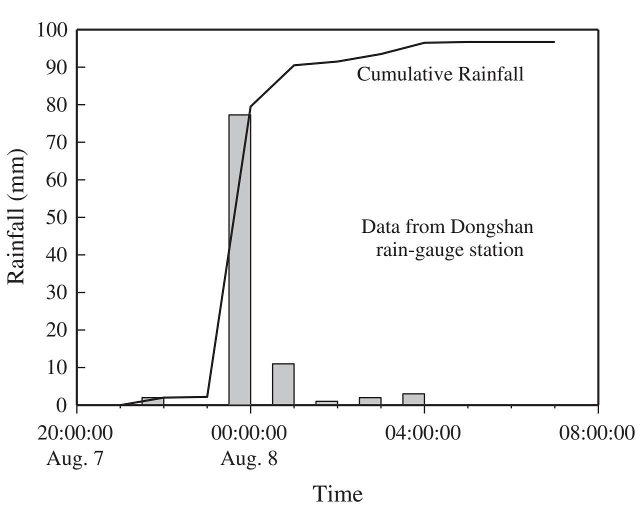


Fig. 5. Rainfall recorded at Dongshan rain-gauge station for the Zhouqu debris-flow event.

3.2. The process of cascading landslide dam failure and debris-flow scale amplification

According to Costa and Schuster (1988), the highest landslide dams generally form in steep-walled, narrow valleys because there is little area for the landslide mass to spread out. Large-volume slumps and slides of earth and rock, and rock and debris avalanches, are particularly likely to form high dams in narrow valleys because they occur on steep slopes and, in most cases, have high velocities that allow complete stream blockage before the material can be sluiced away. Landslide dams are commonly caused by complex landslides, which start as slumps or slides and transform into rock or debris avalanches. This statement is quite accurate for the conditions in Zhouqu, where landslide dams along the sloping channels are mostly caused by rock or debris avalanches owing to the multiple earthquakes in the region's history (e.g., a historical destructive earthquake occurred in the Wenxian and Zhouqu regions on July 1, 1879 with a magnitude of $M_S = 8.0$).

In Luojiayu gully and Dayu gully, the field investigation measured at least 19 and 7 large landslide dams, respectively (see Fig. 1B and C). Both gullies have clusters of landslide dams along their sloping channels, with a number of dams connected to one another. Potentially, failure of an upstream landslide dam can cause a cascading failure of landslide dams farther downstream. Before the disaster, several constructed concrete dams stood in Sanyanyu gully (Dayu gully and Xiaoyu gully). All of the dams were destroyed to a varying degree by the debris flows. Thus, the magnitude of the debris flows, and their significant impact energy, must have overrun the estimation of the engineers who designed the dams.

Our field investigation measured the dimensions of the landslide dams, and the channel's cross-sectional area and gradient in the Luojiayu and Sanyanyu gullies. Assuming that the debris flows that occurred in Zhouqu were uniform steady flows, the velocity U and discharge Q can be calculated according to Manning's formula

$$Q = \frac{1}{n} A \cdot R_n^{2/3} \cdot \sqrt{J} \tag{1}$$

$$U = Q/A \tag{2}$$

where A is the cross-sectional area, R_n is the hydraulic radius, J is the channel bed gradient, and n is the Manning roughness coefficient. The values of A, R_n, and J were directly measured in the field investigation. However, evaluation of Manning's roughness coefficient for debris flows, while critical to calculate the velocity, is very complex as it includes exterior resistances triggered by the rough boundaries and internal resistances owing to solids collision and contact friction. Therefore, the roughness coefficient is approximately evaluated in this paper according to the research work of Xu and Feng (1979), as the method is highly recommended by Chien and Wan (1999). Assuming a viscous debris flow (cf. Hu et al., 2010; Yu et al., 2010) and a really steep, narrow, and curved channel, the roughness coefficient for the Zhouqu debris flows can be approximately evaluated to be 0.1 according to Table 1. As illustrated by Zhou and Ng (2010), a natural debris flow usually possesses multiple surges and should not be considered as uniform and steady. The limitation of the manning's equation for estimation of debris flow discharges (see Eq. (1)) is obvious. However, it is still the most useful method based on the knowledge available. Note also that Manning's formula and the value of the roughness coefficient (0.1) are recommended by PWRI (1988) for the first pulse of debris flows in Japan.

Table 2
Relationship between the velocity coefficient (Kc) and debris-flow depth (Hc) (from Chen et al., 1983; Du et al., 1987).

H_C (m)	<2.5	2.75	3	3.5	4	4.5	5	>5.5
K_C	10	9.5	9.0	8.0	7.0	6.0	5.0	4.0

Similar to Manning's equation, a new semi-empirical formula for viscous debris flows was developed by Chinese researchers (cf. Kang, 1987):

$$Q = \frac{1}{n_C} A \cdot H_C^{2/3} \cdot \sqrt{J} \tag{3}$$

where H_C is the debris-flow depth, and n_C is the roughness coefficient for viscous debris flows. Based primarily on the field measurements and (back) analysis of viscous debris flows of Huoshao gully in Wudu (near Zhouqu), an empirical equation was developed for the estimation of n_C (Yang, 1985). This further illustrates that the roughness coefficient of debris flows is dependent on the flow depth, in that it decreases with a decrease in flow depth:

$$\frac{1}{n_C} = 18.5 H^{-0.42}. \tag{4}$$

The calculation of debris-flow discharges with Eqs. (3) and (4), and the correlated treatment, are referred to as the Wudu method. Similarities in the lithology of the solids and in flow type between the debris flows that occurred in Wudu and in Zhouqu make the Wudu method highly recommended for estimating the discharge of the Zhouqu debris flows.

Furthermore, a formula for the velocity/discharge estimation of debris flows based on the Chezy model is recommended by Lo (2000) and the China Ministry of Lands and Resources (CMLR; Tang et al., 2011):

$$Q = K_C \cdot A \cdot H_C^{2/3} \cdot J^{1/5} \tag{5}$$

where K_C is a factor that is related to debris-flow depth according to Table 2.

In this study, discharge velocities of the debris flows across different sections are estimated by the three methods (i.e., Manning's equation, Wudu method, and CMLR). The sections where debris-flow scales significantly increased are carefully analyzed. Specially, the modes of landslide dam distribution accounting for flow-scale magnification are carefully determined and summarized in this paper.

3.2.1. Flow velocity and discharge variation along Luojiayu gully

Fig. 6A shows the variation in debris-flow discharge and velocity along Luojiayu gully (using Manning's formula), and the corresponding geomorphic properties (sloping channel gradient) are shown in Fig. 6B. Note that the debris-flow discharge generally changes

Table 1
Roughness of debris flow (data from Xu and Feng, 1979).

Category	Characteristics of debris-flow Channels/valleys	Slope	Values of n for various depth			
			0.5	1.0	2.0	4.0
Nonviscous debris flows	Narrow and steep channel with steps and contractions; bed material is 0.5–2 stones	0.15–0.22	0.20	0.25	0.33	0.50
	Channel with many bends and steps; bed material is 0.3–0.5 stones	0.08–0.15	0.10	0.125	0.167	0.25
	Wide and straight channel, bed material is 0.3 m stones, sand and gravel	0.02–0.08	0.058	0.071	0.10	0.125
Viscous debris flows	Narrow, steep and meandering channel; bed material is big stones, sand and gravel, forming blockage and steps	0.12–0.16	0.056	0.067	0.083	**0.10**
	Comparative straight channel, bed material is stones, sand and gravel	0.08–0.12	0.036	0.042	0.05	0.06
	Wide and straight channel, bed material is stones finer than 0.3 m, sand and gravel	0.04–0.08	0.029	0.036	0.042	0.05

consistently with velocity. Fig. 6C shows that the flow discharge calculations using the three different methods are generally consistent, and the values are quite close to one other. There exists six obvious debris-flow scale amplification phases (i.e., A-B-C, E-F, I-J, K-L-M, Q-R, U-V-W-X) between point L_G and the downstream mouth of Luojiayu gully, as shown in Fig. 6A (the peak points include C, F, J, M, R, and X). The variation in debris-flow discharge along the gully indicates that the enhanced magnitude of the debris flow may have attributed to the cascading failure of landslide dams in the gully. Moreover, five different types of landslide dams composed of rock debris and soils can be refined as basic models to account for cascading landslide dam failure and scale amplification of the debris flows

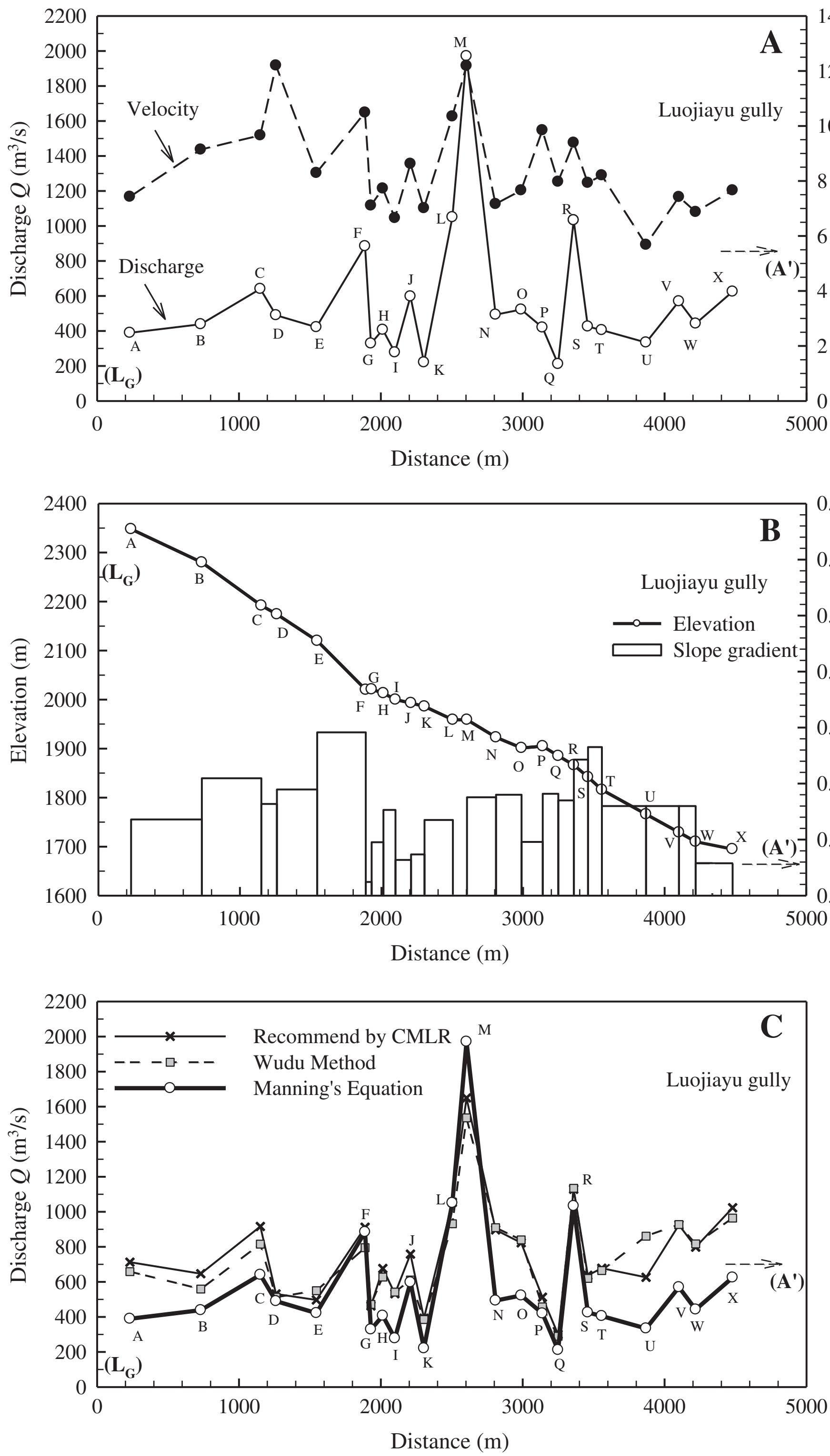
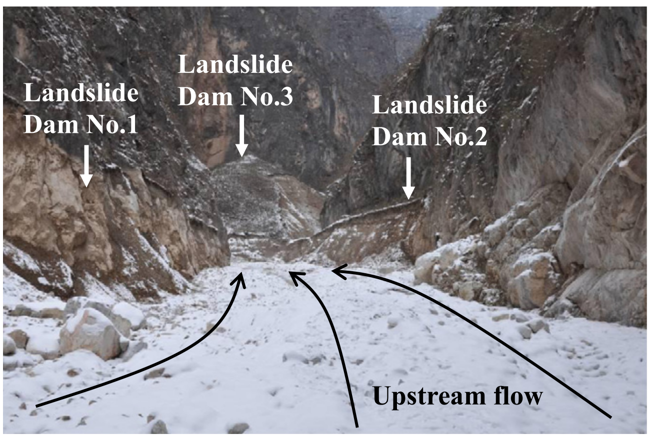
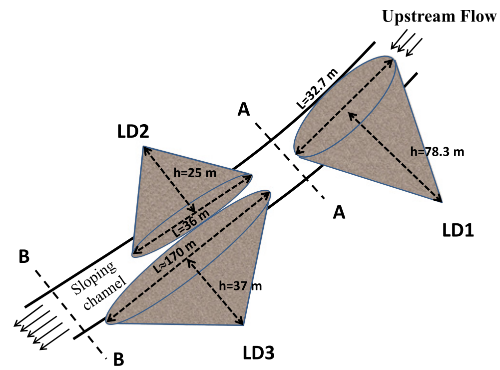
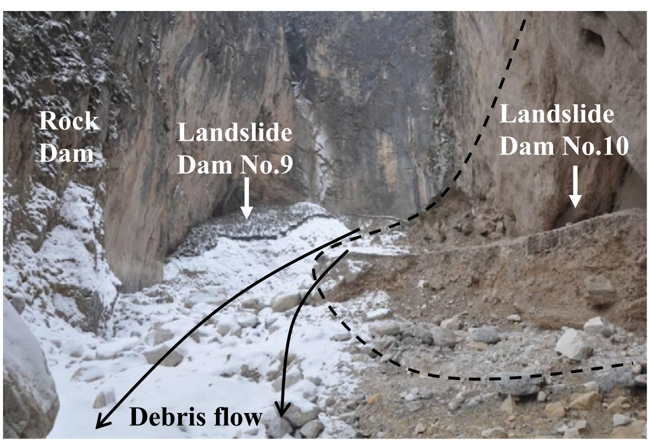
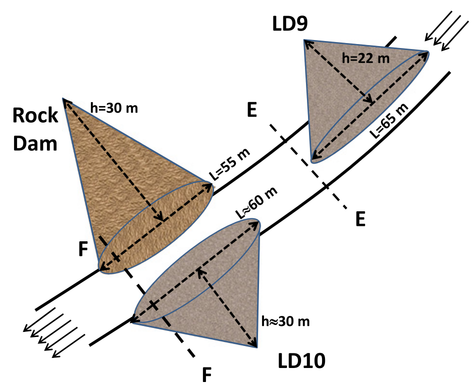
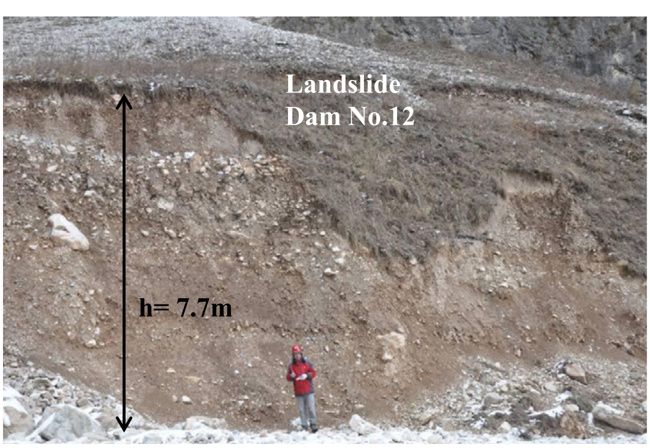
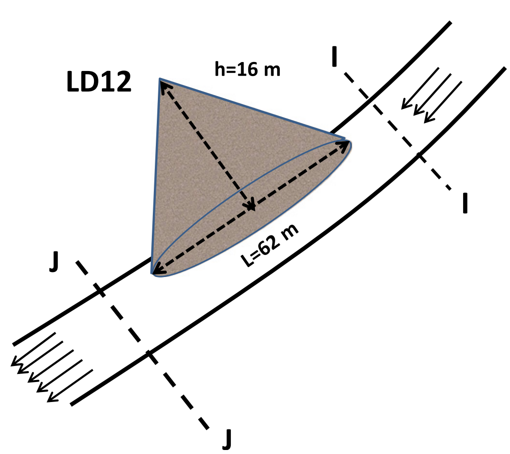


Fig. 6. Evolution of the debris flow along Luojiayu gully: (A) discharge and flow velocity (according to Manning's equation); (B) geomorphology of Luojiayu gully (slope gradient); and (C) comparison of the flow discharge computed using three different methods.

(see Table 3). The phase U-V-W-X represents the scale increase of the debris flow owing to erosion of the channel bed. At this point, the channel is narrowing and the debris-flow speed significantly increases, which easily erodes sediments on the bed that become entrained by the upstream flows. Channel bed degradation with armoring was also observed, with an estimated erosion depth of 2–3 m.

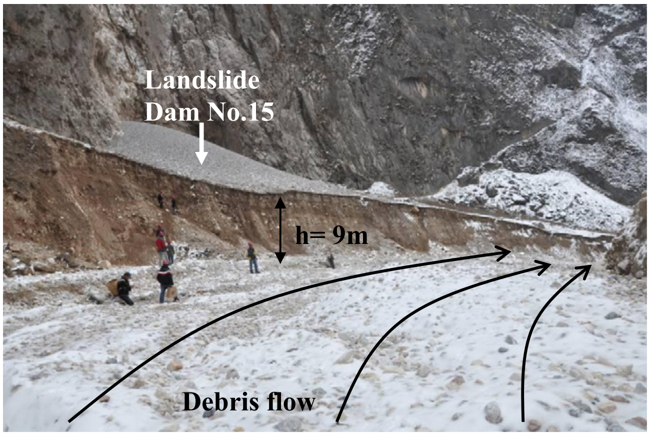
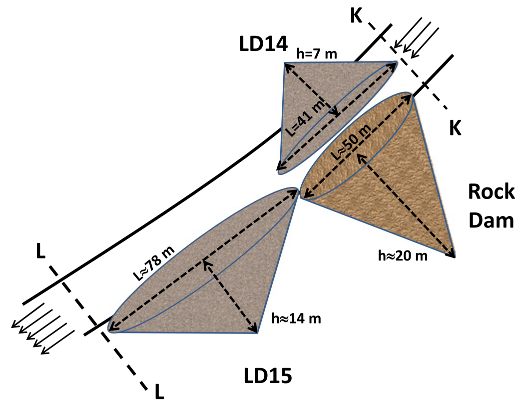
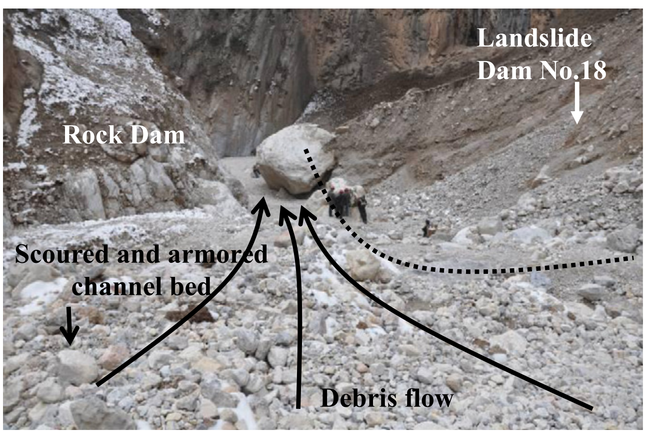
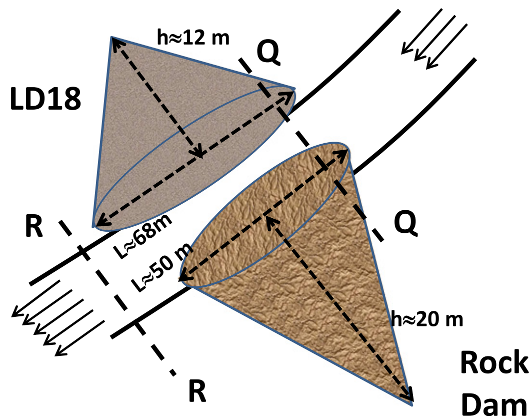
However, the magnitude of the debris flow decreases when the channel morphology widens or curves because the reduced flow velocity induces large amounts of sediment to deposit on the channel

Table 3
Key landslide dam cluster modes in Luojiayu gully.

Region	Prototype	Idealized model
A-B-C		
E-F		
I-J		

(continued on next page)

Table 3 (*continued*)

<table>
<tr><th>Region</th><th>Prototype</th><th>Idealized model</th></tr>
<tr><td>K-L-M</td><td>
</td><td>
</td></tr>
<tr><td>Q-R</td><td>
</td><td>
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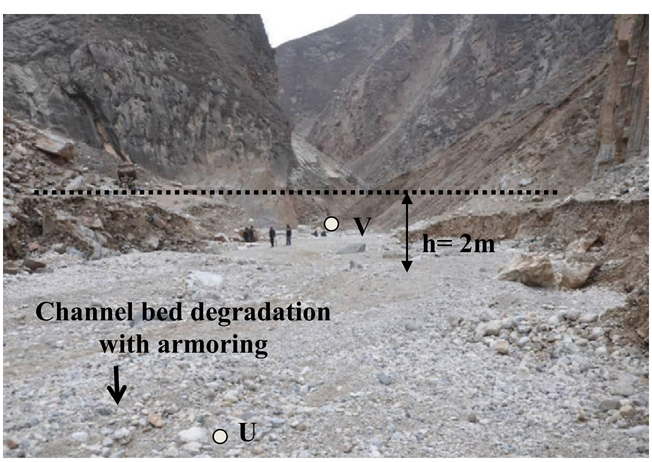
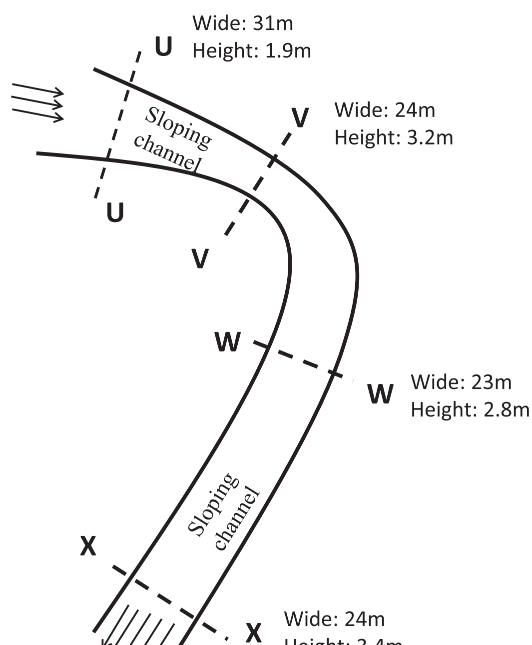
<tr><td>U-V-W-X</td><td>
</td><td>

The channel is narrowing in this process and the flow speed is increased. Sediments on the bed are easily eroded and entrained by the upstream flows.</td></tr>
</table>

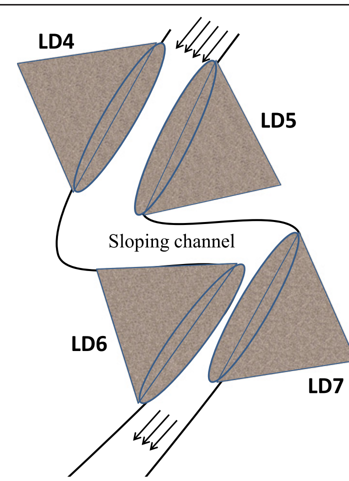
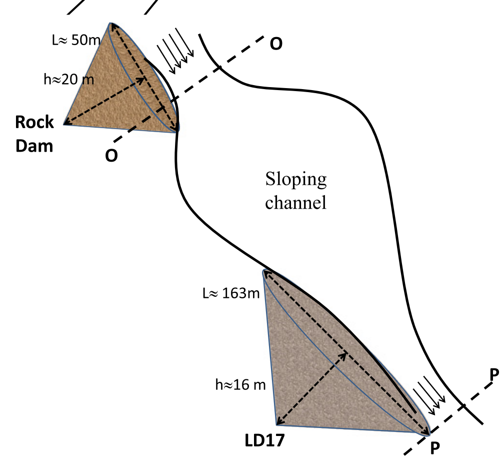
bed. There are two phases (C-D and O-P) where discharge of the debris flow in Luojiayu gully decreases (see Table 4). The C-D phase represents the cascading failure of four landslide dams under debris-flow impact, which was originally seen as a case of debris-flow magnitude amplification. However, what actually occurred is quite different because of the two big bends in the curved sloping channel. As explained by Blanckaert and De Vriend (2003), this is a characteristic and dominant feature of curved flows, which redistribute velocity, boundary shear stress, and sediment transport, shape bed topography, and mix dissolved and suspended matter. Given the depth-averaged velocity, the bed shear stress in a curved flow is higher than in an equivalent straight uniform flow. Moreover, the slope inclination θ at the section C-D is gradually reduced (cf. Fig. 6B). Thus the gravitational component, $g\cdot\sin\theta$, which leads the debris flow movement, is reduced; while the resistance on the slope bed, $g\cdot\cos\theta\tan\phi'$, is also greatly increased (ϕ' is the contact friction angle between debris flow and the sloping bed). Thus, the debris flows mostly moved through the curved channel with gradually reduced velocities. A large amount of sediment in the flow deposited around the bends, reducing the scale of the debris flow. The O-P phase represents when the debris flow moved through a gradually broadening section, depositing a large volume of sediment. This resulted in a decrease in debris-flow scale. What's more, the channel bed was obviously elevated (3–5 m) by aggradation of the debris flow.

3.2.2. Variation in flow velocity and discharge along Dayu gully

Fig. 7A shows the variation in discharge and velocity of the debris flow along Sanyanyu gully (using Manning's formula), while Fig. 7B shows the corresponding channel gradient at different locations. The discharge and velocity evolution of the debris flow shown in Fig. 7A are consistent; i.e. as the velocity of the debris flow increases, the discharge increases accordingly. By analyzing the variation in the discharge of the debris flow, combined with the variation in channel gradient in Sanyanyu gully, four stages of debris-flow scale amplification can be seen in Fig. 7A (i.e., d-e + f-g, g-h-i-j, l-m, o-p-q-r). Obviously, the channel morphology is quite distinct—the two large steep inclines at g-h-i-j and o-p-q-r (see Fig. 7B) are particularly evident—and huge amplifications in the scale of the debris flow appear at these points (cf. Fig. 7A).

Cascading landslide dam failures also occurred in Dayu gully (see Fig. 1B), even though the number of landslide dams along the gully are not as numerable as those found in Luojiayu gully. Consistent with the conditions of Luojiayu gully, the scale of the debris flow is larger owing to the cascading failure of no. 02 and no. 03 landslide dams (see the stage of d-e in Fig. 7A), and the flow discharge decreases (see the stage of e-f in Fig. 7A) in a fashion similar to the reduction seen in debris flows transporting through a curved sloping channel (stage C-D in Table 4). Next along the gully is a relatively straight channel with a large amount of bed erosion. The channel's

Table 4
Landslide dam clusters causing debris-flow discharge reduction in Luojiayu gully.

<table>
<tr><th>Region</th><th>Prototype</th><th>Idealized model</th></tr>
<tr><td>C-D</td><td>
</td><td>
</td></tr>
<tr><td>O-P</td><td>
</td><td>
</td></tr>
</table>

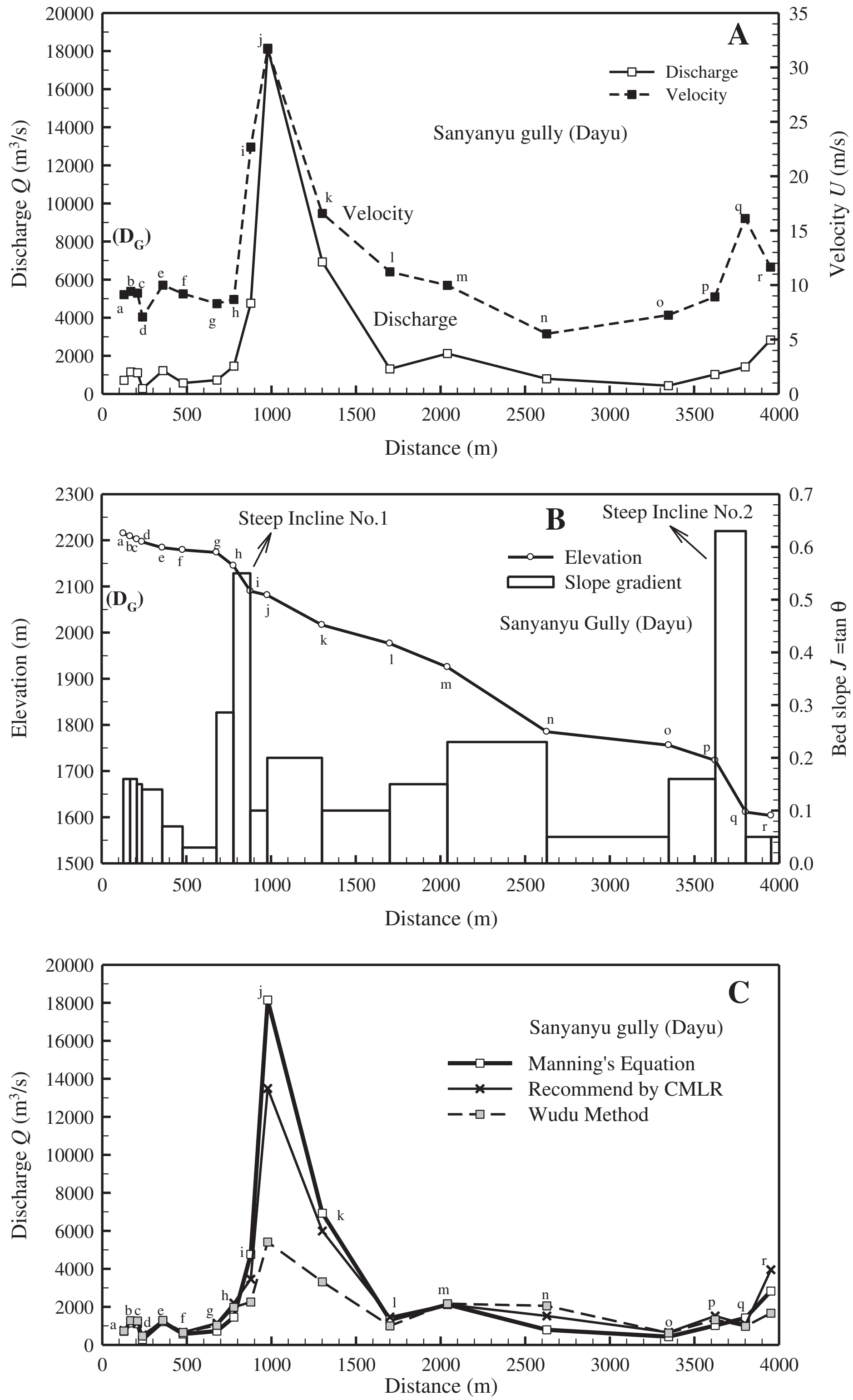


Fig. 7. Evolution of the debris flow along Dayu gully: (A) discharge and flow velocity (using Manning's equation); (B) geomorphology of Luojiayu gully (slope gradient); (C) comparison of flow discharge computed using three different methods.

dimensions are 25 m wide and about 200 m long, with an erosion depth of about 3.5 m. The sediment volume entrained in the debris is estimated to be 1.75×10^4 m^3. The entire cascading landslide dam failure and resulting erosion of the channel bed process is given in Table 5 (the first item d-e-f-g).

As illustrated by Fig. 7B, the vertical change of steep incline no. 1 (g-h-i-j) is 93 m, with a horizontal top-to-toe distance of 300 m (see Table 5). A rectangular passage 35 m in width and 10 m in depth was scoured out at the surface of steep incline no. 1 by the debris flow. Based on these dimensions, about 1.05×10^5 m^3 of solid material

Table 5
Landslide dam cluster modes and two large inclines in Dayu gully.

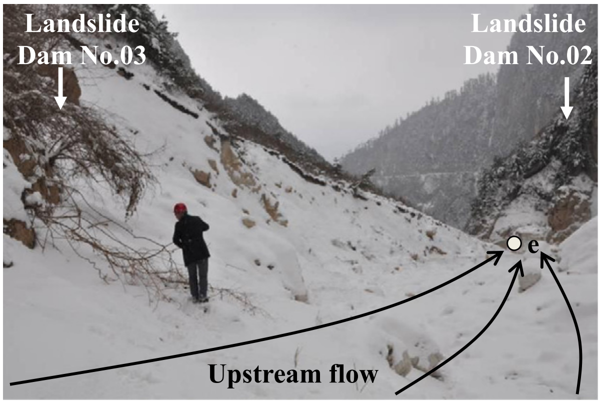
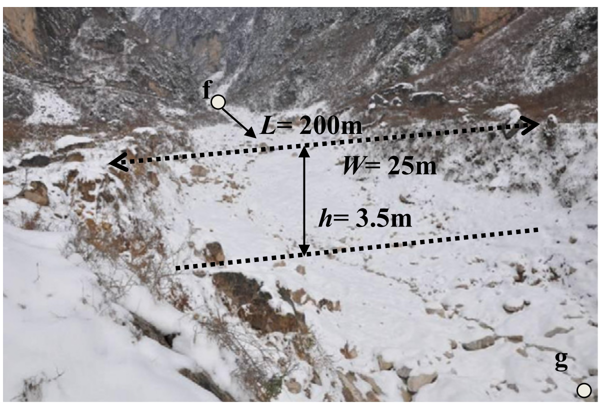
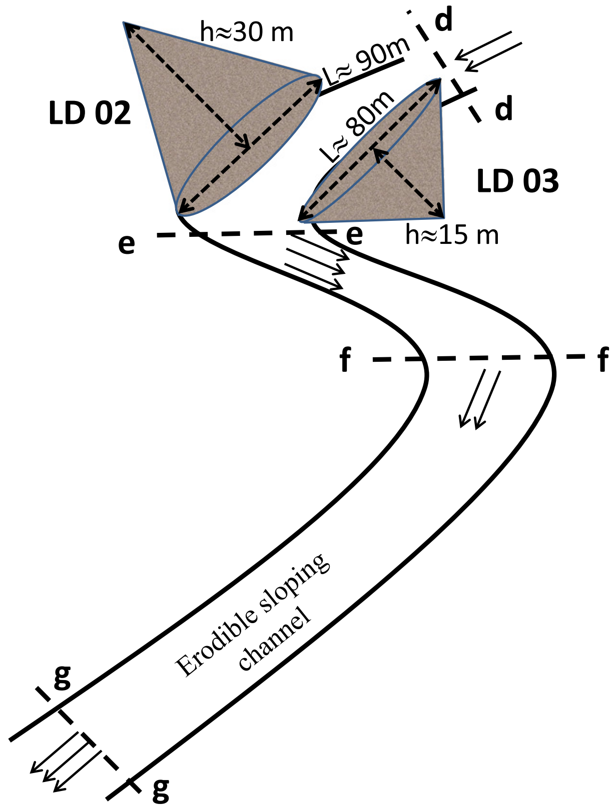
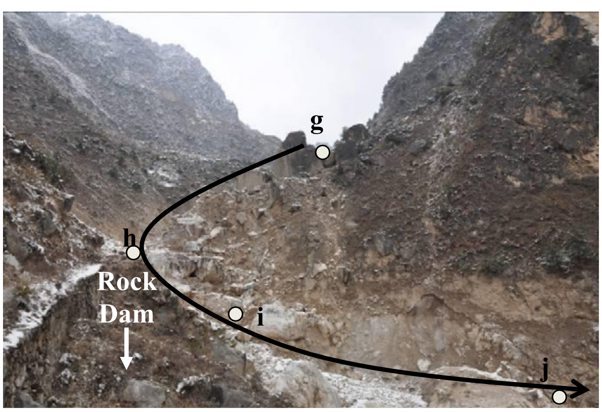
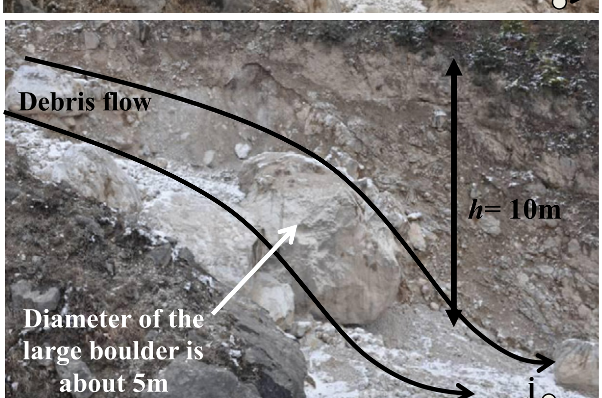
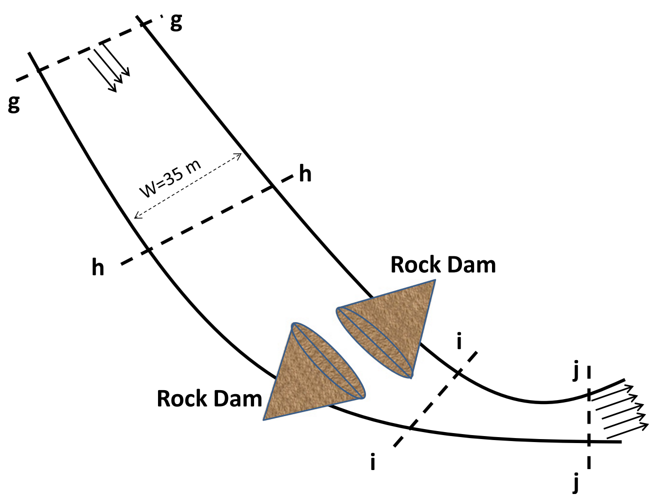
Item	Prototype	Idealized model
Cascade landslide dams (d-e) and erodible straight channel (f-g)		
Steep incline no. 1 (g-h-i-j)		

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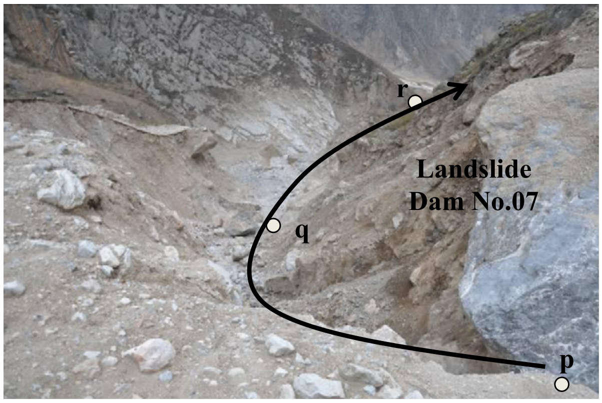
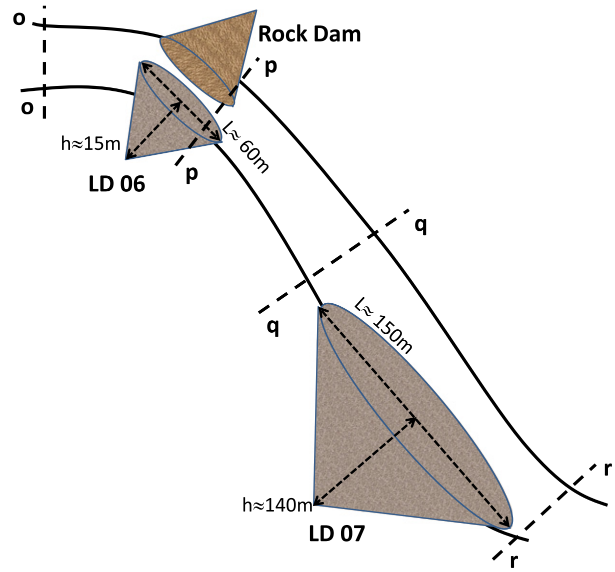
Table 5 (*continued*)

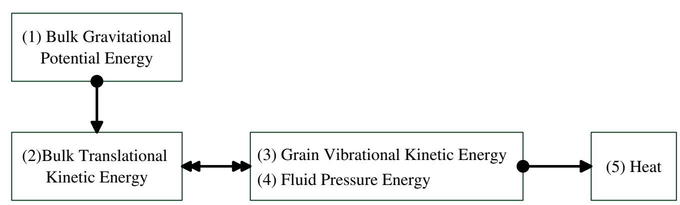
Item	Prototype	Idealized model
Steep incline no. 2 (o-p-q-r)		

was scoured away. Likewise, the change in elevation of steep incline no. 2 (o-p-q-r) is 153 m, and the horizontal top-to-toe distance is 604 m (Fig. 7B and Table 5). The cross section of the trapezoidal passage at the surface of steep incline no. 2 is 5 m in height, with a median width of 25 m. Based on these dimensions, steep incline no. 2 provided about 0.78×10^5 m^3 of solid materials to the debris flow. The debris flow then transported through a narrow canyon composed of a rock dam and two landslide dams, similar to the cascading failures of landslide dams nos. 14 and 15 in Luojiayu gully (region of K-L-M in Table 3). This geomorphology usually provides significant scale amplification to the debris flow (see region o-p-q-r in Fig. 7B and steep incline no. 2 in Table 5). When debris flows run through these steep inclines, the potential energy is rapidly converted into kinetic energy, boosting the sediment transport capability of the flood or debris flow. Therefore, flows are able to mobilize large boulders and scour channel beds, then entrain and mix the solid materials together to form a viscous debris flow.

Next, the flow discharges through the gully were calculated using the three different methods and are compared in Fig. 7C. Flow discharge variation is quite consistent between the three results, with similar values except for the peak values in the two steep inclines. Note that the three methods for debris-flow discharge estimation are all more or less based on fluid dynamic assumptions for steady, uniform flow in shallow channels. Usually, these equations are also applicable for approximating the discharge/velocities of debris flows, which can be unsteady, nonuniform, and occur in steep channels (Prochaska et al., 2008.). However, using these methods for debris-flow analysis along steep inclines—which possess huge inclinations that can significantly influence the flow regimes of the debris flow—needs further verification and will perhaps require significant modifications to the model.

4. Mechanisms of debris-flow scale amplification through cascading landslide dam failures

Debris-flow motion involves a cascading of energy that begins with incipient slope movement and ends with deposition. As described by Iverson (1997), when a debris flow moves downslope, its energy degrades to higher entropy states and undergoes the following conversions:



Here, right pointing arrows (•→) denote conversions that are irreversible, except in special circumstances, whereas the two-way arrow (↔) denotes a conversion that apparently involves significant positive feedback. The details of this energy cascade encompass virtually all the important issues of debris-flow physics. Before pursuing these details, however, it is worthwhile to consider debris-flow energetics from a broader perspective. The trigger and formation of debris flows through cascading landslide dam failures can also be interpreted from an energy perspective:

- Landslide dam failures and the formation of downstream rapid flow waves are a process of energy transformation from reserved water potential energies to bulk kinetic energies. It is widely reported that large landslides inundate river valleys and overwhelm channels with large volumes of coarse materials, commonly forming stable landslide dams that trigger extensive and prolonged aggradation upstream (Ouimet et al., 2007). The water levels of the reserved water behind landslide dams are typically large enough to breach landslide dams. Thus, the potential energy involved is quite large. Once the break in the landslide dam occurs, that huge potential energy can transfer into a large kinetic energy of strong flow waves. In a word, one landslide dam inside a sloping channel represents a certain potential energy that can be reserved and rapidly released once the dam is breached by upstream (debris) flows. The only uncertainties are the release time and the cascading effect on downstream landslide dams, both of which are closely correlated to the scale amplification of descending flows along a sloping channel.

- Following the breach of a landslide dam, the solids of the dam (including the reserved granular particles behind the landslide dam) are fully mobilized and involved in the developed flows. The additionally entrained solids in the water increase the flow density. The most important issue is that the sediment concentration increases as the flow type changes from a pure water flow, to a stream flow with solids transport, then to a hyperconcentrated flow, and finally a debris flow (or even a landslide or debris avalanche) (Coussot and Meunier, 1996). To be a special type of solid-water two-phase flow, the discharge of the debris flow must consist of two components: water and granular particles. However, debris flows differ from sediment-laden water floods where solids are generally dragged by fluids. Solid particles in debris flows possess certain structures and mix with pore fluids to then flow together. Pore fluids are mostly mobilized and dragged by solids, and both solid and fluid forces influence movement of the flow and govern the rheological properties of the debris flow. The entrained solids in debris flows are certainly helpful in increasing the bulk discharge, and the flow energy also accumulates to breach larger downstream landslide dams. It is noted that the debris-flow entrainment of wet bed sediment had been detailed by Iverson et al. (2011): positive feedback and momentum growth during debris-flow entrainment of wet bed sediment. The descending flow usually erodes and entrains more granular materials on the sloping channel bed, further enlarging debris-flow discharge. Some flows also undercut the base of channel banks and trigger more collapses or landslides, thus involving more granular materials in the flow. Large quantities of granular particles, which are initially kept stable along the sloping channel, are fully mobilized, and their potential energy is gradually transformed into bulk kinetic energy. Cascading landslide dam failures and the evolution of debris flows can also be considered a mass exchange process. Finally, the floods resulting from the failure of natural dams are, in most cases, much larger than floods originating directly from snowmelt or rainfall.
- Geomorphology of the sloping channels significantly influences energy release and transformation. Debris flows usually accelerate when passing through shrinking channels (i.e., the cross-sectional area becomes smaller while the discharge remains unchanged). The increased flow velocity can induce more sediment erosion on the channel bed and sidewalls, thus causing the flow discharge to increase accordingly. In contrast, debris flows decelerate through widening channels and aggradation of granular materials on the bed may occur; thus, flow discharge is reduced. As mentioned above, curved sloping channels and steep inclines can greatly affect flow dynamics, which can further influence the energy and mass exchange between debris flows and the sloping channels.

As illustrated by Costa and Schuster (1988), a dam failure is a complex hydrologic, hydraulic, and geologic phenomenon, controlled primarily by the failure mechanism and the characteristics and properties of the dam. One way to compare different kinds of dam failures is to investigate the relationship between the potential energy of the lake water behind the dam prior to failure and the flood peak discharge from the failure of the dam. The potential energy of the lake water behind the dam can be computed as the product of dam height, volume, and specific weight of the fluid. Fig. 8 compares large dam failures and their following peak discharges for a number of historical dam failures (cf. Costa and Schuster, 1988). The results show that the magnitude of potential energy needed to initiate a cascading failure of landslide dams and a resulting debris flow is relatively small ($<10^8$ J). However, the corresponding peak discharge (100–1000 $m^3\ s^{-1}$) is large enough to cause catastrophic events.

5. Discussion and conclusions

Clusters of landslide dams created by intense earthquakes, and which completely or partially block sloping channels before debris-flow events, are quite common in mountainous areas. These clusters can fall like dominoes; once the failure of an upstream landslide dam occurs, a cascading failure of landslide dams farther downstream will likely take place. Often, this hazardous process can begin many tens of kilometers upstream of the deposition fan and, through a complex cascade of geomorphic events, can lead to catastrophic discharge at downstream locations. Our field study of the Zhouqu debris flow analyzed cascading landslide dam failures along sloping channels, and we investigated the mechanisms behind the amplification of debris-flow discharges.

A well-accepted concept is that the failure of a single landslide dam can cause a peak discharge. These peak discharges owing to dam-break floods depend not only on the size of the impounded lake but also on the occurrence of a critical flow at the breach and breach-erosion rate (Walder and O'Connor, 1997). Costa and Schuster (1988) also pointed out that differences in flood-peak discharges caused by natural-dam failures appear to be controlled by dam characteristics and failure mechanisms. Furthermore, the field study in this paper shows that landslide dam distributions and the geomorphology of the sloping channels along the flood route significantly influence the peak discharge and scale amplification of gradually developed debris flows. It is extremely likely that cascading landslide dam failures, as described in this paper, do occur. For Luojiayu gully and Sanyanyu gully in the Zhouqu event, we have determined five and two key modes (or refined idealized models), respectively, which led to cascading landslide dam failures and which are listed in Tables 3 and 5.

The whole process of cascading landslide dam failure and flood scale amplification is a transformation from reserved potential energy to bulk kinetic energy of the flow, together with a mass exchange between granular material on the sloping bed and the debris flow. Depending on the evolution analysis, the peak discharge of the hazardous process can exceed that of infrastructure designed to withstand floods (typically a 50- to 200-year flood return period) by a factor of 2 to 50. Meanwhile, the magnitude of the debris flow observed in the curved sloping channels in Luojiayu gully and in the two steep inclines in Sanyanyu gully show that scouring or aggradation by a nonfluvial process can exceed hydrologically derived estimates by several factors. It is therefore recommended that a geomorphic approach be taken to recognize and quantify the potential for nonfluvial processes and that these findings be integrated into channel-crossing engineering designs. Moreover, a new peak debris-flow discharge model that accounts for cascading landslide dam failure and entrainment of sediment materials (e.g., channel scouring and degradation) needs to be developed. This is vital and fundamental for natural hazards analysis. Therefore, it is highly recommended that both geomorphic and hydrodynamic approaches be used to recognize and quantify the potential for nonfluvial processes.

This phenomenon of cascading landslide dam failure and resulting flow scale amplification is quite complicated and certainly not yet fully understood. Our research at this stage was a preliminarily study to determine the key landslide dam distribution modes, which most likely account for cascading failures, and to investigate the mechanisms for discharge amplification of downstream debris flows. Based on this study, new physical and numerical models can be designed for detailed parametric studies to determine the controlling parameters of peak discharges. Moreover, a new method for calculating debris-flow discharge that takes into account the hydrodynamic approach toward cascading landslide dam failures, as well as the geomorphic properties of sloping channels, can be developed for engineering design.

Note that the longevity of a landslide dam depends on numerous factors such as rate of inflow into the impoundment, the size and shape of the dam, and its geotechnical characteristics. Floods caused by the failure of natural and constructed dams constitute a widespread hazard to people and property, in part owing to the suddenness and unpredictability of dam failures of all types (Walder and O'Connor, 1997). The formation and failure of landslide dams is a series of complex processes that occur at the interface between hill-slopes and alluvial plain or valley-floor systems. As elaborated by Iverson and Denlinger (2001),

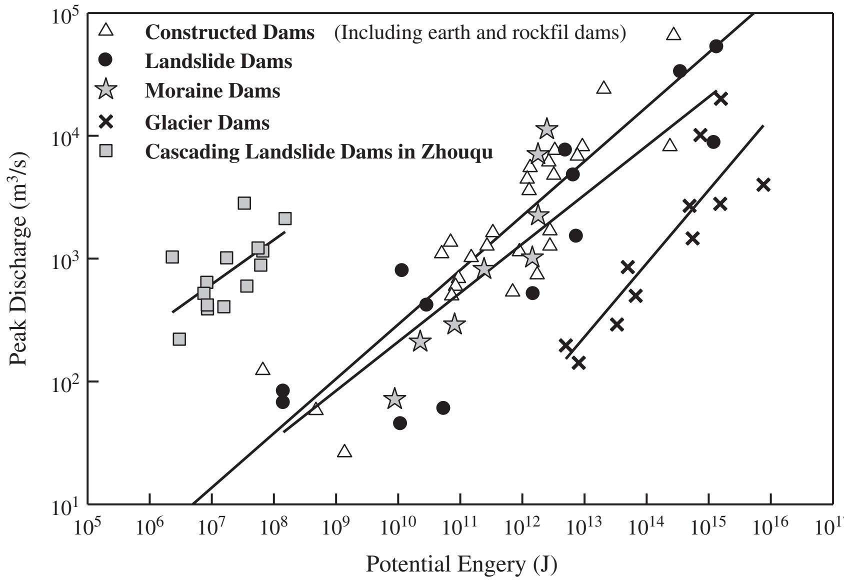


Fig. 8. Relationship between the potential energy of lake water and triggered peak discharge for various types of dam failures.

the normalization of the depth-averaged Coulomb mixture equations yields dimensionless scaling parameters that can aid in the design and interpretation of experiments aimed at simulating geophysical flows. When flow size increases, the opposing change in the dimensionless scaling parameters indicates that viscous stresses may diminish in their importance and pore fluid pressure effects may grow more pronounced. This means insurmountable difficulties may plague miniature experiments that aim to mimic the behavior of geophysical flows in which fluid effects are significant (Iverson and Denlinger, 2001; Iverson et al., 2004). Thus, a raw conclusion can be drawn that model scale plays a significant role in flow mechanisms, and thus influences debris-flow simulation. This means that most of the existing physical model tests, which have generally been conducted at limited scales, cannot reflect the essence of real large debris flows. In future, physically based studies of the complicated hydrodynamic process of cascading landslide dam failures owing to upstream (debris) flows should be modeled in large flumes to correctly capture the key modes of cascading landslide dam failure. The geomorphic effects of sloping channels (curvature, steep inclination, and channel confinement) should also be appropriately incorporated.

Acknowledgments

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