Magnitude amplification of flash floods caused by large woody in Keze gully in Jiuzhaigou National Park, China

Jiangang Chen, Wenrun Liu, Wanyu Zhao, Tianhai Jiang, Zhongfu Zhu and Xiaoqing Chen

Key Laboratory of Mountain Hazards and Earth Surface Process, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences (CAS), Chengdu, China; CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing, China; University of Chinese Academy Sciences, Beijing, China; Administration Bureau of Jiuzhaigou Valley, Sichuan, China

ABSTRACT
Wood is an important component of flash floods and debris flows in forested mountainous areas. To better understand the characteristics of large wood (LW) movement and its destructive effects on check dams, bridges, and buildings, we conducted field investigations and theoretical calculations on the flash flood process in Keze gully in Jiuzhaigou National Park (China). Based on the gully characteristics and the calculation method, the magnitude amplification ratio of flash flood peak discharge caused by the clogging and breakage processes associated with LW transport reached 2.83 to 3.03 times the mean peak discharge upstream of check dam No. 1. Moreover, the limit analysis and limiting equilibrium state methods were adopted to analyze the additional impact force of LW on the sidewalls of check dams, which resulted in sidewall breaking and sediment block function loss of the check dam. Furthermore, we analyzed the LW transport pattern and formulated a conceptual model of LW transport, including the LW length, channel width, and standing tree spacing. Through this case study, we put forward that the magnitude amplification ratio and the additional impact force of LW should be considered in the design and construction of mitigation engineering projects in forested mountainous areas.

1. Introduction
Large wood (LW) can be defined as pieces of wood longer than 1 m and greater than 0.1 m in diameter (Wohl and Jaeger 2009; Ravazzolo et al. 2015), and it is an important component of flash floods and debris flows in forested mountainous areas (Kramer et al. 2017; Gasser et al. 2019). The transport of LW is strongly influenced...
by the LW length and diameter and the channel width (Chen et al. 2020b). LW can cause serious damage when it is transported in flash floods or debris flows (Su et al. 2010; Watabe et al. 2013; Schalko et al. 2018; Spreitzer et al. 2019). For example, LW can block check dam spillways or become lodged beneath bridges, thereby creating unstable logjams that reduce the channel’s discharge capacity (Ozaki et al. 1998; Rossi and Armanini 2020; Yan et al. 2020). LW can strongly impact dams (Piton and Recking 2016) and also lead to massive inundation or flooding (Jochner et al. 2015; Comiti et al. 2016; De Cicco et al. 2018); however, methods of estimating the LW impact force against structures have not been clarified. A noticeable case occurred in Jiuzhaigou National Park (China), which has a high forest coverage rate of more than 80%. The large amount of LW transported by flash floods or debris flows not only poses a great threat to the areas of scenic and historic interest in this World Natural Heritage Site but also destroys check dams and bridges, which represent major components of the local infrastructure (Cui et al. 2005; Chen et al. 2006, 2018).

Over the past twenty years, three giant earthquakes with magnitudes of 7.0 or higher occurred in western China (Huayong et al. 2019; Liu et al. 2019) close to Jiuzhaigou National Park. These earthquakes aggravated the fragmentation of material and accumulated masses of loose soil on sloped surfaces in Jiuzhaigou National Park, and global warming and extreme rainfall also exacerbated these phenomena (Shou and Yang 2015; Hu et al. 2020; Luo et al. 2020). Therefore, flash flood or debris flow events have increased dramatically in this area in recent years (Turkington et al. 2016; Hu et al. 2017; Cui et al. 2018). After the 2017 Jiuzhaigou earthquake (M, 7.0), a field investigation showed that thirty-two of the debris flow gullies in Jiuzhaigou National Park endured debris flow disasters, which resulted in scenic location damage, lake silting and road destruction (Chen et al. 2018; Hu et al. 2019; Zhao et al. 2020). In addition, this earthquake caused extensive forest destruction and resulted in a massive amount of damaged trees scattered in gullies and on hillsides (Hirata and Chigira 2019). Therefore, abundant LW in Jiuzhaigou National Park could be transported by flash floods or debris flows.

Large amounts of LW can form unstable logjams and lead to inundation and flooding in forested mountainous regions (Schmocker and Hager 2011; Jochner et al. 2015; Comiti et al. 2016). The ratio of the log length over the channel width, the length of the LW, and the topography of the channel are three factors that affect the type of clogging produced by LW (Braudrick and Grant 2000; Galia et al. 2018). The process of LW accumulation and probability of LW entrapment were studied by Schmocker and Hager (2011) through scale modelling experiments, and this research demonstrated the randomness of the blocking process. The experimental tests of Gschnitzer et al. (2017) with different numbers of logs and the influence of small particles within LW accumulation resulted in closing degrees ranging from 1% to 57%. Furthermore, a method for calculating the hydraulic head loss due to LW accumulation was presented by Piton and Recking (2016). LW not only has a direct impact on mitigation engineering but also magnifies the debris flow peak discharge through clogging and sudden breakage of logjams. The LW clogging and breakage process were also observed in field studies and laboratory experiments (Fox 2011; Ruiz-Villanueva et al. 2016; Kramer and Wohl 2017; Chen et al. 2018; Panici and De
However, these studies did not focus on the magnitude amplification effect of the clogging and breakage process and the integrated impact effect of LW and flash floods or of LW and debris flows on check dams.

Clogging and sudden breakage in gullies may occur if a large amount of LW is transported by a flash flood or debris flow in Jiuzhaigou National Park (Chen et al. 2020a). In addition to the discharge amplification effect of a debris flow in a natural gully (Cui et al. 2013), the clogging and breakage effect of LW can also intensify the damage caused by a flash flood or debris flow. The aim of this study is to (1) disclose the magnitude amplification mechanism of the peak discharge induced by the clogging and breakage process of LW and quantify the magnitude amplification ratio; and (2) further analyze the additional impact force of LW on the sidewalls of check dams. Keze gully is located in the central part of Jiuzhaigou National Park, and it is considered here as an example to investigate the characteristics of the LW movement and examine the process of clogging and breakage.

2. Study area

Jiuzhaigou National Park is located in the Songpan-Ganzi Block, and the outcropping strata are mainly Quaternary and Mesozoic (Gong et al. 2020). The lithology consists mainly of limestone and slate with a small amount of sandstone, which were intensely deformed by folding and thrusting during the Late Triassic and Early Jurassic (Chen et al. 1994; Yin and Harrison 2000). Since the Quaternary, the geological tectonic movements have been intense due to the influence of the Tazang, Minjiang and Huya faults (Ren et al. 2013; Liu et al. 2017; Zhao et al. 2018; Fan et al. 2020). Seismicity has occurred six times on the Minjiang fault and Huya fault from 1960 to 2020 with $6.0 < \text{Ms} < 7.0$. Frequent seismic activity has resulted in fracturing of the rock mass, triggering collapses and landslides, which are helpful to debris flow formation.

The forest vegetation in Jiuzhaigou National Park is mainly composed of arboreal forests, sparse woodlands, shrubs, etc. There are more than 3,500 native species, and the vegetation coverage rate is 85.5%. Because of the obvious vertical differentiation in regional climate, the vertical distribution characteristics of vegetation are obvious. At elevations from 2,000 m to 2,500 m, the main vegetation includes mingled forest with *Pinus tabuliformis* and *Quercus liaotungensis*, mixed with *Sorbaria sorbifolia*, *Kalopanax septemlobus*, and *Salix babylonica*. Coniferous and broad-leaved mixed forests are distributed from 2,500 m to 2,800 m, including *P. tabuliformis*, *Pinus armandii* Franch, and *Picea asperata*. Coniferous forests dominate from 2,500 m to 2,800 m, and the chief species include *Abies faxoniana* and *P. asperata*. Above 3,500 m, alpine shrub meadows are most common due to the barren soil and the steep slope; thus, vegetation is underdeveloped at these elevations.

Keze gully has a watershed area of 19.89 km² (E: 103°55′; N: 33°7′), a main gully length of 7.07 km, and a mean longitudinal gradient of 24.8% (Figure 1). The gathering area of runoff formed by rainfall or snow melting has an elevation of 2,972 m to 4,442 m, with a relative height difference of 1,470 m. Its coverage is 16.59 km², accounting for 83.7% of the total watershed area. The length of this section is 3.75 km, and the average longitudinal slope is 39.2%. Precipitation, especially
short-duration heavy precipitation, is the major driving factor for the occurrence of flash floods and debris flows in Keze gully. Heavy rainfall cannot rapidly infiltrate in Keze gully within a short amount of time because of the large watershed area and steep slopes with bedrock on both sides. Consequently, it rapidly forms surface runoff, which collects in the channel and scours the gully bed and the solid loose material on both sides, eventually resulting in debris flow.

The section ranging in elevation from 2,710 m to 2,972 m has a length of 2.42 km, a drainage area of 3.19 km² and an average longitudinal slope of 10.8%. In the upstream part of study reach, the cross-section width varies from three to five meters, while in the downstream part, the channel width ranges from 9 m to 13 m. The channel in study reach is straight, with steep slopes on both sides of the banks. There is total of $56.21 \times 10^4$ m³ loose solid material in this study reach, which was assessed using geological radar. Among which, six collapses and two unstable slopes provided $14.38 \times 10^4$ m³ of source material, while other source material was derived from the main and branch gullies. The main processes were the excavation and scouring of the gully bed by the flash flood and the collapse of unstable slopes on both banks into the gully because of the cutting effect of the flash flood and debris flow activity. Under the effect of surface runoff, local loose surface soil was carried away and acted as the main source of fine particles in the flash flood and debris flow. As shown in Figure 1, the convergence of the branch gully and the main gully are taken as the starting point (labelled ‘★’ in Figure 1), the study reach is from the starting point of the measurements to the gully mouth and is 1800 m long, further, the characteristic parameters (such as cross-section size and channel slope) of 11 cross-sections are measured along the channel.

In the section of Keze gully with elevations from 2,578 m to 2,710 m, the mean slope is 9.9% and the hydrodynamic conditions gradually decrease. Thus, the LW carried by the flash flood gradually stopped moving and was scattered in this study.
reach. The river mainly passes along the right side of the depositional fan, and the highway and plank road are at the leading edge of the depositional fan. If a flash flood or debris flow with LW blocks the river, it may silt up Xiajije Lake, a World Natural Heritage Site, and an outburst flood would impact the safety of Zechawa village, which is located 3200 m downstream of Xiajije Lake.

Debris flow mitigation engineering in Keze gully was performed in 1989, and three check dams were built with a design life of 20 years (Cui et al. 2003; Cui et al. 2007). The check dams were constructed from stone blocks with cement mortar, and the foundations of the check dams mainly rest on Quaternary debris flow deposits. Because these deposits are relatively poorly consolidated, highly compressible and highly permeable and feature low strengths and bearing capacities, the check dams can easily experience uneven settlement. The effective height of slit-check dam No. 1 is 2.0 m, and the axis length of the dam crest is 12.5 m. The design aim of this dam is to block huge boulders, and it can work well after flash floods. The sidewall of check dam No. 2 is composed of many sections, and each section is connected with cement mortar. The connectivity of this technique is poor. Consequently, the deterioration of material properties and settlement of the foundation will lead to cracks and failure of the check dam with the extension of its service life. The effective height of check dam No. 3 is 3.0 m, the axis length of the dam crest is 20.4 m, and the deposition slope of the debris flow is 11%. After the flash flood, the downstream of the dam was scoured to a depth of approximately 1.29 m and the right-side wing wall was exposed to the ground, however, check dam No. 3 is still stable.

3. Material and methods

3.1. On-site observations

Both unmanned aerial vehicle (UAV) and remote sensing images were used to interpret the distribution of the landslides and collapses in Keze gully after the 2017 earthquake. This method has been successfully employed to study geohazard problems in other World Natural Heritage Sites (Lollino and Audisio 2006; Niethammer et al. 2012; Margottini et al. 2015; Chen et al. 2018; Tziavou et al. 2018). The UAV (Inspire 2, DJI-Innovations, China) was utilized to take photos of Keze gully, and the images were then used to construct a topographical and geomorphic map for further analysis (Erdelj et al. 2017; Fazio et al. 2019; Imaizumi et al. 2019; Zapico et al. 2020). The check dam conditions were identified using pre-earthquake remote sensing images. The destroyed check dams were interpreted by comparing the pre- and post-earthquake remote sensing images. Landslides were identified by using high-resolution post-event remote sensing images (e.g., TRIPLESAT, with a spatial resolution of 0.8 m; and aerial photographs, with a spatial resolution of 0.2 m). The potential of abundant loose material in gullies was assessed using a geological radar (model No., MALA GEOSCIENCE AB, Sweden), which measured the depth of the loose source material (Ma and Su 2007). Deposit volumes were obtained by multiplying the mean depth times the depositional area. The precision of this approach depends significantly on the accuracy of the onsite investigation and knowledge of the debris flow magnitude (Ma and Chen 2019). Then, maps highlighting the source areas, flow
paths, and flow deposits of the debris flow were compiled. Due to the protection of Jiuzhaigou National Park, the forest coverage rate is high in Keze gully and trees have larger diameters at breast height (DBHs). When the magnitude of a flood and debris flow is large, the forest will dissipate its energy, which will affect the velocity and runout distance. This is similar to the case in forested southeast Alaska (Booth et al. 2020). The roughness coefficient of each cross-section is further determined according to the characteristics of the channel bed and the distribution of particle size from the remote sensing images pre-disaster and the UAV images post-disaster; for details on this method, please see Qian and Wan (2003). The specific determination method is shown in Table 1.

Both a hand-held global positioning system (GPS; Garmin GPSMAP, Taiwan, China) and laser rangefinder (Contour XLRic, Contour Company, USA) were used to determine the locations and extents in the field investigation. The laser rangefinder had a maximum range of 1,850 m and a measurement accuracy of 0.10 m (Chen et al. 2015).

### Table 1. Roughness of a nonviscous debris flow and flash flood.

| Characteristics of channels/valleys                                                                 | Slope  | 0.5   | 1.0   | 2.0   | 4.0   |
|--------------------------------------------------------------------------------------------------|--------|-------|-------|-------|-------|
| Narrow and steep channel with steps and contractions; bed material is composed of 0.5–2.0 m stones | 0.15–0.22 | 0.20  | 0.25  | 0.33  | 0.50  |
| Channel with many bends and steps; bed material is composed of 0.3–0.5 m stones                   | 0.08–0.15 | 0.10  | 0.125 | 0.167 | 0.25  |
| Wide and straight channel, bed material is composed of 0.3 m stones, sand and gravel               | 0.02–0.08 | 0.058 | 0.071 | 0.10  | 0.125 |

Figure 2. The measurement method of the length and diameters of the LW pieces.
The geomorphological conditions suggested that the accuracy of the deposit volume measured by using the ground penetrating radar system with a measuring error of 1 m was sufficient for the purpose of our work (Tang et al. 2012). Whether the LW moves or not can be determined by two ways: (1) according to the relative distance between the LW centre and a fixed position on the banks and (2) comparing the UAV images from different periods. We measured the length and diameters of the LW pieces scattered in the gully with tapeline (as shown in Figure 2), and the space between standing trees as also measured by tapeline. The average length was obtained by measuring the length of the LW at its three positions: the top and the surface towards and away from the stream. The circumference of the LW was measured at both ends and in the middle, and then the average diameter was obtained through the formula $C = \pi D$, where $C$ is the circumference, $D$ is the diameter and $\pi$ is the circular constant. A camera was utilized to photograph the driftwood distribution state.

### 3.2. Method for the stability analysis of side walls

The limit analysis method is widely used in evaluating the performance of masonry structures (Milani et al. 2006), especially the response of walls under transverse forces (D’Ayala and Speranza 2003; Giuriani and Marini 2008). Therefore, we adopt this method to check the stability of the sidewall of the check dam. Assuming a very small angle $\theta$ (i.e. $\sin \theta \approx \theta$ and $\tan \theta \approx \theta$), the virtual displacement ($\delta$) of the centre of gravity can be calculated as follows

$$\delta = \frac{t}{2} \theta$$

where $t$ is the thickness of the damaged part. The power of gravity, $L^+$, can be calculated as follows

$$L^+ = W \cdot \frac{t}{2} \theta$$

where $W$ is the stabilizing force of gravity. The power exerted by the overturning force can be calculated by the following expression:

$$L^- = \int_0^h p(z)lz\theta dz$$

where $l$ is the length of the damaged part. $p(z)$ is the distribution of hydrostatic pressure that can be expressed as follows

$$p(z) = \rho g(h-z)$$

Substituting Eq. (4) into Eq. (3), we obtain the following:

$$L^- = \int_0^h p(z)lz\theta dz = \int_0^h \rho g(h-z)lz\theta dz = \frac{1}{6} h^3 \rho g l \theta$$
According to the vulnerability assessment model (Milanesi et al. 2018), an object will overturn when the magnitude of the stabilizing force \(L^+\) is smaller than the magnitude of the overturning force \(L^-\).

4. Results and analysis

4.1. Characteristics of the magnitude amplification ratio

The blockage and breakage of LW can result in a sudden magnitude amplification of the discharge of flash flood or debris flows. Therefore, this section takes the flash flood and the debris flow that occurred in Keze gully on June 25, 2018 as an example to analyze the characteristics of the blockage and breakage process. The channel in Keze gully becomes relatively gentle and straight after the branch gullies merge into the main gully.

Assuming that the flash flood and the debris flows that occurred in Keze gully are uniform steady flows, the discharge \(Q\) and velocity \(V\) can be obtained basing on Manning’s formula as follows

\[
Q = \frac{1}{n} AR^{2/3} J^{1/2} \tag{6}
\]

\[
V = \frac{Q}{A} \tag{7}
\]

where \(A\) is the cross-sectional area, \(R\) is the hydraulic radius, \(J\) is the channel bed gradient, and \(n\) is the Manning roughness coefficient. Similar to Manning’s equation, as shown in Eq. (6), Kang (1987) developed a new semi-empirical formula based on the results of continuous observations in Jiangjia gully, Yunnan Province, China.

\[
Q = \frac{1}{n} A \cdot H^{2/3} J^{1/2} \tag{8}
\]

where \(H\) is the debris flow depth, which can be obtained by measuring debris flow marks on the bank or standing trees. The top and base widths, depth, and channel slope were measured by the laser rangefinder and re-checked by the tape line. Then, those parameters were used to calculate the \(A\) and \(R\). Because the natural debris flows display multiple surges, an assumption of uniform and steady flow is not appropriate, which means that Manning’s formula showed an obvious limitation in the present study. However, this formula is still the most useful method (Rickenmann 1999). For example, Manning’s formula was used to calculate the discharge of flash flood and debris flow that occurred in Zhouqu, China, on August 8, 2010 (Cui et al. 2013).

The distributions of discharge and velocity at each cross-section and the operation state of the check dams after the flood are shown in Figure 3. It can be seen that the discharge suddenly increased when the flood reached check dam No. 2 and then gradually decreased to 41.1 m\(^3\)/s at the location with \(L = 1,232\) m. The mean peak discharge of the three cross-sections upstream of check dam No. 1 is taken as the basic peak discharge, i.e. \(Q_{\text{Basic}} = 47.8\) m\(^3\)/s. The maximum discharge is \(Q_{\text{Peak}} = 135.2\) m\(^3\)/s at \(L = 812\) m, which is 64 m upstream of check dam No. 2. According to the
definition, the magnitude amplification ratio is obtained as follows: $\beta = \frac{Q_{\text{Peak}}}{Q_{\text{Basic}}} = 2.83$. According to Eq. (8), the basic peak discharge is $Q_{\text{Basic}} = 48.8 \text{ m}^3/\text{s}$, the maximum discharge is $Q_{\text{Peak}} = 147.9 \text{ m}^3/\text{s}$, and the corresponding magnitude amplification ratio is $\beta = \frac{Q_{\text{Peak}}}{Q_{\text{Basic}}} = 3.03$. Therefore, the variation range of the magnitude amplification ratio $\beta$ ranges from 2.83 to 3.03. The reason for the sudden increase in discharge is that the LW formed an unstable dam during transport in the flood, and this dam then failed and discharged a large amount of water into the channel. When the failed dam released all of the backed-up water, the downstream flow gradually returned to the original level.

### 4.2. Analysis of the check dam failure

A flash flood in Keze gully was triggered under the influence of heavy rainfall on June 25, 2018, which caused damage to the sidewall of check dam No. 2 as shown in Figure 4. The onsite investigation revealed the following. (1) Numerous logs were deposited behind the check dam, and both the discharge orifice and spillway were blocked by small LW. (2) A long log with a mean length of 11.2 m and a mean diameter of 0.4 m was found at the failure position of the sidewall as shown in Figure 4(c). (3) Six logs were observed leaning against the dam downstream of the check dam. (4) No obvious scour or silting on the gully was found from the upstream and downstream of the destroyed side wall. The flash flood did not cause scouring damage because the elevation of the side wall was higher than the spillway of the dam.
When the check dam becomes blocked, the flood waters will start to accumulate in the reservoir area and the flow velocity will gradually decrease. When the water depth reaches the spillway, the flood will overtop the spillway and flow downstream. At this time, the flow velocity near the side wall becomes small and the hydrodynamic pressure on the side wall can be ignored. Whether the sidewall was damaged by hydrostatic pressure or the combined effect of the hydrostatic pressure and the impact of LW carried by the flood remains unclear. Thus, we used the obtained results to analyze the reason for the side-wall damage in the next section.

4.2.1. Stability analysis of the sidewall without the LW impact

Many slender cracks occur parallel to the fracture surface in the left bank sidewall of the dam, and they can be attributed to the decreased strength of the masonry dam and the uneven settlement of the dam foundation with the extension of its service life. During the failure process of sidewall, the collapsed part experienced overall
overturning failure and both ends did not reach the force limit. The damaged part of the sidewall can be regarded as a cuboid shape. Because a small LW blocked the discharge orifices and the spillway of the check dam, debris accumulated upstream of the check dam. Considering the low velocity along the sidewall, the hydrodynamic pressure was not considered in the calculation. The force acting on the sidewall is shown in Figure 5(a). The top elevation of the sidewall is higher than that of the dam crest. Because of the angle between the sidewall and the horizontal plane is 3°, the values of sine and cosine do not differ greatly from those associated with an angle of 0°. The construction material of the sidewall is cement mortar masonry with a density of 2,400 kg/m³. The damaged sidewall can be simplified as a cuboid, with dimensions of 12.7 m long, 4.3 m high and 1 m thick as shown in Figure 5(c). The acceleration of gravity is 9.8 m/s². According to Eq. (2), the power is $L^+ = 64.2 \times 10^4 \theta J$. 

![Figure 5. Schematic diagram of the forces acting on the sidewall.](image)
According to Figure 5, the water depth varies along the damaged block. Thus, Eq. (5) can be expressed as follows

\[
L^{-} = \int_{0}^{12.7} \frac{1}{6} h(x)^3 \rho g \theta dx
\]  

(9)

where \( \rho \) is the density of the flood accumulated behind the check dam; in this event, \( \rho = 1200 \text{ kg/m}^3 \). Thus, the power exerted by the overturning force is \( L^- = 47.1 \times 10^4 \text{ J} \).

Therefore, \( L^+ > L^- \) in this flood event, which means that the sidewall remained stable until the dam was full according to the vulnerability assessment model (Milanesi et al. 2018).

4.2.2. Stability analysis of the sidewall with the LW impact

LW has many ways to impact the sidewalls, and the worst-case scenario is a vertical impact from the long axis of the LW on the wall. In this situation, the stabilizing force is still only gravity whereas the overturning force includes a combination of the LW impact force and the hydrostatic pressure (see Figure 5(b)). According to Haehnel and Daly (2004), the maximum impact force of LW is as follows

\[
F_{\text{max}} = U \sqrt{km}
\]  

(10)

where \( U \) is the collision velocity; \( k \) is the effective contact stiffness in the case of collision, with \( k = 2.4 \text{ MN/m} \) under the LW impact; and \( m \) is the LW mass.

When the impact angle of LW is not vertical, the calculation method based on the conservation of angular momentum proposed by Ikeno et al. (2016) is as follows

\[
F_{\alpha} = \lambda F_{\text{max}}
\]  

(11)

where \( \lambda \) is a reduction coefficient affected by the impact angle and LW shape. This parameter is calculated as follows

\[
\lambda = \sqrt{\frac{1 + (L_T/I)^2 \sin^2 \alpha}{1 + (L_T/I)^2}}
\]  

(12)

where \( L_T \) is the distance from the collision point to the centre of gravity of the LW; \( \alpha \) is the impact angle between the long axis of LW and the wall and ranges from \( 0 \sim 90^\circ \) when the log is regarded as a cylinder; and \( I \) is the radius of inertia. When a log is regarded as a cylinder, \( I \) is determined as follows

\[
I = \sqrt{\frac{(3R^2 + L^2)}{12}}
\]  

(13)

where \( R \) is the mean radius of the LW.

The relation between the collision velocity \( U \) and the flood velocity \( V \) can be expressed as follows
The power of the overturning force is as follows:

\[ U = V \sin \alpha \]  

(14)

The power of the overturning force is as follows:

\[ L^- = F_2 \theta h + \int_0^h p(z)lz \theta dz \]  

(15)

When \( L^+ \) equals \( L^- \), the forces acting on the sidewall reach the limit equilibrium state.

According to the calculations, the average flood velocity was 3.19 m/s at the cross-section 64 m upstream of the check dam. The LW has a mean length of 11.2 m, a mean diameter of 0.4 m, and a density of 765 kg/m³. Additionally, the angle between the flood flow direction and the sidewall was \( \alpha = 40^\circ \), and the water depth \( h \) where the LW hit the sidewall was 2.73 m.

Substituting the impact force of LW and the power exerted by hydrostatic pressure into Eq. (15), the power of the overturning force is \( L^- = 68.4 \times 10^4 \theta J \).

The calculated values show that \( L^+ = 64.2 \times 10^4 \theta J < L^- = 68.4 \times 10^4 \theta J \), indicating that the sidewall experienced an overturn according to the vulnerability assessment model (Milanesi et al. 2018). This result is in agreement with the conditions during the flood event on June 25, 2018. Therefore, the impact force of LW should be considered in the future design of mitigation engineering.

**Figure 6.** Various ways of LW recruitment into the active channel. (a) and (b) LW caused by foundation excavation of the check dam; (c) LW form gully erosion; (d) LW from hillslopes.
5. Discussion

The results of this study demonstrate the magnitude amplification ratio of discharge induced by the logjams and the check dam failure caused by the LW impact force. This is a key issue for mitigation engineering design in forested mountainous gullies. The flood and debris flow induced by strong precipitation can scour both banks and slopes, easily destroying the surrounding forest and bring plenty of wood into the gully (Comiti et al. 2016). Furthermore, the natural replacement of forests also brings a lot of driftwood. Therefore, a quantitative analysis model was proposed by Benda and Sias (2003), which accounts for input, output, and storage parameters at a given time scale and reach scale. LW originates mainly from the hillslopes, banks along the gully, and the toppling of trees caused by the foundation excavation of the check dam, which is shown in Figure 6. Given the protection of Jiuzhaigou National Park, the forest coverage rate is high in Keze gully, and trees have larger DBHs. Moreover, when the flood and debris flow scale is large, the forest will dissipate its energy, which affects the velocity and runout distance. This is similar to the case in forested southeast Alaska (Booth et al. 2020). Figure 7 shows the channel morphology changes downstream of the check dams from 2018 to 2021, the toppling trees were transported downstream by floodwater, and the morphology of the channel cross-section also changed considerably.

In this section, we focus on the LW transport pattern in Keze gully. The distribution of LW in Keze gully was obtained through field investigations after a flash flood. The LW length ranges between 1.0 m and 22.7 m, the LW diameter ranges between 0.18 m and 0.76 m, and the cross-section width ranges from 9 m to 13. The anchoring effect of an intact root system and the blocking effect of the standing trees on the opposite bank make the LW difficult to transport and plays a key role in blockage and energy dissipation; Figure 8(a) shows a single tree across a gully, and Figure 8(b) shows a group of trees staggered across a gully. The trees crossing the channel and the anchoring effect provided by intact roots can block the transport of LW, resulting...
in the formation of a logjam, as shown in Figure 8(c) and (d). This type of LW cannot be moved until it is further broken (Merten et al. 2013; Steeb et al. 2017; Tonon et al. 2018). Once the root system decays and the branches are damaged, the remaining trunk starts to drift away along the channel at different angles under the influence of flash floods and debris flows. In addition, this type of LW has a large amount of kinetic energy during transport and can easily cause damage to check dams (as shown in Figure 4(c)). More importantly, long LW is often involved in the development of the skeleton structure of a logjam and the stability of long LW can control the blockage and breakage process (Davidson et al. 2015; Kang and Kimura 2018; Kang et al. 2021; Welling et al. 2021).

LW can easily be moved in a flash flood or debris flow when its length is less than the channel width (B). However, its movement can also be limited by the spacing of the standing trees in a catchment with abundant vegetation (Wohl 2017). When the LW length is shorter than the channel width and the tree spacing (Bocchiola et al. 2006; Wohl 2020), it can continuously move along the channel (Figure 9(a) and (b)). However, these small LWs also tend to block the discharge orifices of the check dams (Figure 3(c) and (d)), which will affect the discharge capacity and cause sediment deposition behind the dams. A logjam can form when the LW is blocked by standing trees or one tree and a bank (Ruiz-Villanueva et al. 2017; Picco et al. 2021), which leads to sediment and small wood deposition upstream of the logjam (as shown in Figure 8(c) and (d)). Based on the geometric conditions, three scenarios are
considered to analyze LW logjams. (1) The first case involves a LW with a length $L$ equal to or less than the spacing between two standing trees $W (L \leq W)$; Figure 9(a) shows the LW parallel to the connecting line of the two standing trees, and Figure 9(b) shows the LW tilted away from the connecting line of the two standing trees. A
piece of LW with a length at $L \leq W$ cannot be blocked. Generally, this type of LW can naturally pass through or collide through the standing trees. Moreover, the movement direction of the LW may also be changed by the trees. (2) The geometric conditions of the second case with decreasing LW length ($W < L < B$) are shown in Figure 9(c) and (d). The LW length plays a decisive role in the clogging, and regardless of how the other conditions change, the channel will eventually block. However, when the length decreases to a certain threshold, no clogging will occur (Braccia and Batzer 2001; Wohl et al. 2016; Haga et al. 2017). (3) The geometric conditions of the third case with $L \geq B$ are shown in Figure 9(e) and (f). Figure 9(e) shows that the LW can pass through the standing trees under the condition of $L \sin \theta \leq W$ or $W < L \sin \theta < 0.5(B + W)$. Figure 9(f) shows that the LW cannot pass through the standing trees under the condition of $L \sin \theta > 0.5(B + W)$ due to blocking by the standing trees and the limitation of the LW length.

During a flood, mobile LWs are those with lengths shorter than the average channel width and diameters smaller than the average flow depth (Dixon and Sear 2014). Generally, LW is not uniform moving from upstream to downstream (Picco et al. 2021). More wood mobilizing during a short time can lead to congested transport and thus form a logjam, as presented in Kramer and Wohl (2017) for a logjam on a medium river with 25 m channel width and mean wood length of 3.3 m. Chen et al. (2020a) also reported logjams that formed at a slat-check dam and in natural rivers (Ravazzolo et al. 2015). Logjams influence the hydraulic roughness of the gully bed, further influencing the flow velocity and discharge calculations. The LW velocity, which is used to calculate the impact force on the sidewall, is approximately the surface velocity of the flood, which meets the application condition proposed by MacVicar and Piégay (2012). Mobile wood, especially with high velocity, will endanger bridges and increase the flooded area due to clogging (Ruiz-Villanueva et al. 2014; Mazzorana et al. 2018a, 2018b). In Keze gully, the lateral input of larger trees that can entrap floating wood and the favourable specific morphological settings of the channel (Wohl 2017) make it easy to form logjams, resulting in backwater rise upstream of clogged cross-sections (Schalko et al. 2018). If logjams cannot withstand the upstream force, the breakage of logjams will magnify the flow magnitude. Chen et al. (2020a) revealed that the maximum magnitude amplification ratio is 1.60 due to LW clogging and breakage based on laboratory experiments. In this paper, the magnitude amplification ratio is 2.83–3.03 based on calculations and detailed field study. Thus, the effect of the discharge magnitude amplification does exist during the process of logjam clogging and breakage. However, further research is needed.

6. Conclusions

Understanding the blocking and breakage process of LW logjams in natural gullies is crucial for calculating the possible impact of wood acting on the check dam, which is helpful for designing check dams in forested mountainous area. LW in Keze gully in Jiuzhaigou National Park not only affects this unique World Natural Heritage Site but also impacts its affiliated facilities. In this paper, a flood in Keze gully is taken as an example to study the characteristics of the movement of LW.
During the LW transport process, the blocking and breakage process of unstable LW logjams results in a sudden magnitude amplification, and the magnitude amplification ratio $\beta = Q_{\text{Peak}}/Q_{\text{Basic}}$ in Keze gully, which was calculated by two methods, ranged from 2.83 to 3.03. Moreover, based on the limit analysis method and limiting equilibrium state, the reason for the check dam failure was analyzed. The hydrostatic pressure of the flood retained upstream of the check dam did not cause sidewall collapse; instead, the additional impact effect of the LW played a crucial role in the destruction of the sidewall. Further, we analyzed the LW transport pattern and provided a conceptual model. According to the on-site observations, the transport patterns present three conditions of LW length. LW can be transported easily when the length is shorter than the standing tree spacing, and this type LW tends block the discharge orifices of check dams; a logjam gradually forms by individual or clusters of LW with increasing length, and the stability of such logjams plays a crucial role in the blockage and breakage process. Lastly, we proposed that further experimental studies are required to determine the stability of a check dam by coupling the flood action with various return periods and the LW impact force, and the magnitude amplification ratio needs to be investigated quantitatively due to its importance in the engineering design of mountainous hazard mitigation in forested areas.

**Disclosure statement**

The authors have no conflicts of interest to declare.

**Funding**

This study is supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA23090403), the National Natural Science Foundation of China (Grant No. 41925030), and the CAS ‘Light of West China’ Program.

**ORCID**

Xiaoqing Chen [http://orcid.org/0000-0002-0177-0811](http://orcid.org/0000-0002-0177-0811)

**Data availability statement**

The authors agree to make data supporting the results or analyses presented in this paper available upon reasonable request from the first author and corresponding author.

**References**

Benda LE, Sias JCA. 2003. Quantitative framework for evaluating the mass balance of in-stream organic debris. For Ecol Manage. 172(1):1–16.

Bocchiola D, Rulli MC, Rosso R. 2006. Transport of large woody debris in the present of obstacles. Geomorphology. 76(1-2):166–178.

Booth AM, Sifford C, Vascik B, Siebert C, Buma B. 2020. Large wood inhibits debris flow run-out in forested southeast Alaska. Earth Surf Process Landforms. 45(7):1555–1568.
Braccia A, Batzer DP. 2001. Invertebrates associated with woody debris in a southeastern US forested floodplain wetland. Wetlands. 21(1):18–31.2.0.CO;2

Braudrick CA, Grant GE. 2000. When do logs move in rivers? Water Resour Res. 36(2):571–583.

Chen XQ, Chen JG, Cui P, You Y, Hu KH, Yang ZJ, Zhang WF, Li XP, Wu Y. 2018. Assessment of prospective hazards resulting from the 2017 earthquake at the world heritage site Jiuzhaigou Valley, Sichuan. J Mt Sci. 15(4):779–792.

Chen JG, Chen XQ, Li Y, Wang F. 2015. An experimental study of dilute debris flow characteristics in a drainage channel with an energy dissipation structure. Eng Geol. 193:224–230.

Chen XQ, Cui P, Wei FQ. 2006. Study of control debris flow in high-covered vegetation region. J Mt Sci. 24(3):333–339.

Chen SC, Tfwala SS, Wang CR, Kuo YM, Chao YC. 2020b. Incipient motion of large wood in river channels considering log density and orientation. J Hydraul Res. 58(3):489–502.

Chen JG, Wang DZ, Zhao WY, Chen HY, Wang T, Nepal N, Chen X. 2020a. Laboratory study on the characteristics of large wood and debris flow processes at slit-check dams. Landslides. 17(7):1703–1711.

Chen SF, Wilson CJL, Deng QD, Zhao XL, Zhi LL. 1994. Active faulting and block movement associated with large earthquakes in the Min Shan and Longmen Mountains, Northeastern Tibetan Plateau. J Geophys Res. 99(B12):24025–24038.

Comiti F, Lucia A, Rickenmann D. 2016. Large wood recruitment and transport during large floods: a review. Geomorphology. 269:23–39.

Cui P, Liu SQ, Tang BX, Chen XQ. 2003. Debris flow prevention pattern in national parks: Taking the world natural heritage Jiuzhaigou as an example. Sci China Ser E. 46(7):1–11.

Cui P, Chen X, Liu S, Tang B. 2007. Techniques of debris flow prevention in national parks. Earth Sci Front. 14(6):172–180.

Cui P, Hu K, Chen H, Zou Q. 2018. Risks along the Silk Road Economic Belt owing to natural hazards and construction of major projects. Chin Sci Bull. 63(11):989–997.

Cui P, Liu S, Tang B, Chen X, Zhang X. 2005. Research and prevention of debris flow in national parks. Beijing, China: Science Press.

Cui P, Zhou GGD, Zhu XH, Zhang JQ. 2013. Scale amplification of natural debris flows caused by cascading landslide dam failures. Geomorphology. 182:173–189.

Davidson SL, MacKenzie LG, Eaton BC. 2015. Large wood transport and jam formation in a series of flume experiments. Water Resour Res. 51(12):10065–10077.

D’Ayala D, Speranza E. 2003. Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings. Earthq Spectra. 19(3):479–509.

De Cicco PN, Paris E, Ruiz-Villanueva V, Solari L, Stoffel M. 2018. In-channel wood-related hazards at bridges: a review. River Res Appl. 34(7):617–628.

Dixon SJ, Sear DA. 2014. The influence of geomorphology on large wood dynamics in a low gradient headwater stream. Water Resour Res. 50(12):9194–9210.

Erdelj M, Król M, Natalizio E. 2017. Wireless sensor networks and multi-UAV systems for natural disaster management. Comput Netw. 124:72–86.

Fan J, Wei X, Shi W, Guo Q, Zhang S, Xu H, Song H, Xu C, An W, Jiang H. 2020. Response of tree rings to earthquakes during the past 350 years at Jiuzhaigou in the eastern Tibet. Sci Total Environ. 731:138714.

Fazio NL, Perrotti M, Andriani GF, Mancini F, Rossi P, Castagnetti C, Lollino P. 2019. A new methodological approach to assess the stability of discontinuous rocky cliffs using in-situ surveys supported by UAV-based techniques and 3-D finite element model: a case study. Eng Geol. 260:105205.

Fox DM. 2011. Evaluation of the efficiency of some sediment trapping methods after a Mediterranean forest fire. J Environ Manag. 92(2):258–265.

Galia T, Tichavský R, Škarpich V, Silhán K. 2018. Characteristics of large wood in a headwater channel after an extraordinary event: the roles of transport agents and check dams. CATENA. 165:537–550.
Gasser E, Schwarz M, Simon A, Perona P, Phillips C, Hübl J, Dorren L. 2019. A review of modelling the effects of vegetation on large wood recruitment processes in mountain catchments. Earth Sci Rev. 194:350–373.

Giuriani E, Marini A. 2008. Experiences from the Northern Italy 2004 earthquake: vulnerability assessment and strengthening of historic churches. In: D’Ayala D, Fodde E, editors. Structural analysis of historic construction: preserving safety and significance. Boca Raton, FL: CRC Press; p. 13–24.

Gong XL, Chen KT, Chen XQ, You Y, Chen JG, Zhao WY, Lang J. 2020. Characteristics of a debris flow disaster and its mitigation countermeasures in Zechawa Gully, Jiuzhaigou Valley, China. Water. 12(5):1256.

Gschnitzer T, Gems B, Mazzorana B, Aufleger M. 2017. Towards a robust assessment of bridge clogging processes in flood risk management. Geomorphology. 279:128–140.

Haehnel RB, Daly SF. 2004. Maximum impact force of woody debris on floodplain structures. J Hydraul Eng. 130(2):112–120.

Haga H, Morishida T, Morishita N, Fujimoto T. 2017. Properties of small instream wood as a logjam clogging agent: Implications for clogging dynamics based on wood density, water content, and depositional environment. Geomorphology. 296:1–10.

Hirata Y, Chigira M. 2019. Landslides associated with spheroidally weathered mantle of granite porphyry induced by 2011 Typhoon Talas in the Kii Peninsula. Japan. Eng Geol. 260:105217.

Hu X, Hu K, Tang J, You Y, Wu C. 2019. Assessment of debris-flow potential dangers in the Jiuzhaigou Valley following the August 8, 2017, Jiuzhaigou Earthquake, Western China. Eng Geol. 256:57–66.

Hu T, Sun Y, Zhang X. 2017. Temperature and precipitation projection at 1.5 and 2 °C increase in global mean temperature. Chin Sci Bull. 62(26):3098–3111.

Hu G, Tian S, Chen N, Liu M, Somos-Valenzuela M. 2020. An effectiveness evaluation method for debris flow control engineering for cascading hydropower stations along the Jinsha River. China. Eng Geol. 266:105472.

Huayong N, Hua G, Yanchao G, Blumetti AM, Comerci V, Manna PD, Guerrieri L, Vittori E. 2019. Comparison of Earthquake Environmental Effects and ESI intensities for recent seismic events in different tectonic settings: Sichuan (SW China) and Central Apennines (Italy). Eng. Geol. 258:105149.

Ikeno M, Takabatake D, Kihara N, Kaida H, Miyagawa Y, Shibayama A. 2016. Improvement of collision force formula for woody debris by airborne and hydraulic experiments. Coast Eng J. 58(4):1640022.

Imaizumi F, Masui T, Yokota Y, Tsunetaka H, Hayakawa YS, Hotta N. 2019. Initiation and runout characteristics of debris flow surges in Ohya landslide scar, Japan. Geomorphology. 339:58–69.

Jochner M, Turowski JM, Badoux A, Stoffel M, Rickli C. 2015. The role of log jams and exceptional flood events in mobilizing coarse particulate organic matter in a steep headwater stream. Earth Surf Dynam. 3(3):311–320.

Kang ZC. 1987. A velocity research of debris flow and its calculating method in China. Mountain Res. 5 (4):247–259. (in Chinese).

Kang T, Kimura I. 2018. Computational modelling for large wood dynamics with root wad and anisotropic bed friction in shallow flows. Adv. Water Res. 121:419–431.

Kang T, Kimura I, Onda S. 2021. Application of computational modelling for large wood dynamics with collisions on moveable channel beds. Adv. Water Res. 152:103912.

Kramer N, Wohl E. 2017. Rules of the road: a qualitative and quantitative synthesis of large wood transport through drainage networks. Geomorphology. 279:74–97.

Kramer N, Wohl E, Hess-Homeier B, Leisz S. 2017. The pulse of driftwood export from a very large forested river basin over multiple time scales, Slave River, Canada. Water Resour Res. 53(3):1928–1947.
Liu Z, Tian X, Gao R, Wang G, Wu Z, Zhou B, Tan P, Nie S, Yu G, Zhu G, et al. 2017. New images of the crustal structure beneath eastern Tibet from a high-density seismic array. Earth Planet Sci Lett. 480:33–41.

Liu G, Xiong W, Wang Q, Qiao X, Ding K, Li X, Yang S. 2019. Source characteristics of the 2017 Ms 7.0 Jiuzhaigou, China, Earthquake and implications for recent seismicity in Eastern Tibet. J Geophys Res Solid Earth. 124(5):4895–4915.

Lollino G, Audisio C. 2006. UNESCO World Heritage sites in Italy affected by geological problems, specifically landslide and flood hazard. Landslides. 3(4):311–321.

Luo HY, Fan RL, Wang HJ, Zhang LM. 2020. Physics of building vulnerability to debris flows, floods and earth flows. Eng Geol. 271(105611):105611.

Ma CH, Su HQ. 2007. S/N ratio of 4-channel A/D geological radar non-uniform sampling signals. J China Univ Min Technol. 17(4):534–536.

MacVicar B, Piégay H. 2012. Implementation and validation of video monitoring for wood budgeting in a wandering piedmont river, the Ain River (France). Earth Surf Process Landforms. 37(12):1272–1289.

Margottini C, Antidze N, Corominas J, Crosta GB, Frattini P, Gigli G, Giordan D, Iwasaky I, Lollino G, Manconi A, et al. 2015. Landslide hazard, monitoring and conservation strategy for the safeguard of Vardzia Byzantine monastery complex, Georgia. Landslides. 12(1):193–204.

Mazzorana B, Ruiz-Villanueva V, Marchi L, Cavalli M, Gems B, Gschnitzer T, Mao L, Iroumé A, Valdebenito G. 2018a. Assessing and mitigating large wood-related hazards in mountain streams: recent approaches. J Flood Risk Manage. 11(2):207–222.

Mazzorana B, Trenkwalder-Platzer H, Heiser M, Hübl J. 2018b. Quantifying the damage susceptibility to extreme events of mountain stream check dams using Rough Set Analysis. J Flood Risk Manage. 11(4):e12333.

Merten EC, Vaz PG, Decker-Fritz JA, Finlay JC, Stefan HG. 2013. Relative importance of breakage and decay as processes depleting large wood from streams. Geomorphology. 190:40–47.

Milanesi L, Pilotti M, Belleri A, Marini A, Fuchs S. 2018. Vulnerability to flash floods: a simplified structural model for masonry buildings. Water Resour Res. 54(10):7177–7197.

Milani G, Lourenço PB, Tralli A. 2006. Homogenised limit analysis of masonry walls, Part II: structural examples. Comput Struct. 84(3–4):181–195.

Niethammer U, James MR, Rothmund S, Travelletti J, Joswig M. 2012. UAV-based remote sensing of the Super-Sauze landslide: evaluation and results. Eng Geol. 128:2–11.

Ozaki Y, Kamogawa Y, Mizuyama T, Kasai S, Shima J. 1998. A debris flow with woody debris trapped by a steel-pipe gridded Sabo dam. J Jpn Soc Eros Control Eng. 51(2):39–44.

Panici D, De Almeida GAM. 2018. Formation, growth, and failure of debris jams at bridge piers. Water Resour Res. 54(9):6226–6241.

Picco L, Scalari C, Iroumé A, Mazzorana B, Andreoli A. 2021. Large wood load fluctuations in an Andean basin. Earth Surf Process Landforms. 46(2):371–384.

Piton G, Recking A. 2016. Design of sediment traps with open check dams. II: woody debris. J Hydraul Eng. 142(2):04015046.
Ruiz-Villanueva V, Bodoque JM, Díez-Herrero A, Bladé E. 2014. Large wood transport as significant influence on flood risk in a mountain village. Nat Hazards. 74(2):967–987.

Ruiz-Villanueva V, Piégay H, Gurnell AM, Marston RA, Stoffel M. 2016. Recent advances quantifying the large wood dynamics in river basins: new methods and remaining challenges. Rev Geophys. 54(3):611–652.

Ruiz-Villanueva V, Wyža B, Miikuś P, Hajdukiewicz M, Stoffel M. 2017. Large wood clogging during floods in a gravel-bed river: the Długopole bridge in the Czarny Dunajec River. Earth Surf Process Landforms. 42(3):516–530.

Schalko I, Schmocker L, Weitbrecht V, Boes RM. 2018. Backwater rise due to large wood accumulations. J Hydraul Eng. 144(9):04018056.

Schmocker L, Hager WH. 2011. Probability of drift blockage at bridge decks. J Hydraul Eng. 137(4):470–479.

Shou KJ, Yang CM. 2015. Predictive analysis of landslide susceptibility under climate change conditions—A study on the Chingshui River Watershed of Taiwan. Eng Geol. 192:46–62.

Spreitzer G, Tunnilcliffe J, Friedrich H. 2019. Using structure from motion photogrammetry to assess large wood (LW) accumulations in the field. Geomorphology. 346:106851.

Steeb N, Rickenmann D, Badoux A, Rickli C, Waldner P. 2017. Large wood recruitment processes and transported volumes in Swiss mountain streams during the extreme flood of August 2005. Geomorphology. 279:112–127.

Su ZM, Xu LR, Ugaik E, Yang QQ, Cai F. 2010. The characteristics of the process of debris flow disaster in 2007 in Nannmoku Village, Gunma Prefecture, Japan and its enlightenment on disaster mitigation. J Mt Sci. 28:367–372.

Tang C, Van Asch TWJ, Chang M, Chen GQ, Zhao XH, Huang XC. 2012. Catastrophic debris flows on 13 August 2010 in the Qingping area, Southwestern China: the combined effects of a strong earthquake and subsequent rainstorms. Geomorphology. 139-140:559–576.

Tonon A, Picco L, Rainato R. 2018. Test of methodology for developing a large wood budget: a 1-year example from a regulated gravel bed river following ordinary floods. CATENA. 165:115–124.

Turkington T, Remaitre A, Ettema J, Hussin H, Van Westen C. 2016. Assessing debris flow activity in a changing climate. Clim Change. 137(1–2):293–305.

Tziavou O, Pytharouli S, Souter J. 2018. Unmanned aerial vehicle (UAV) based mapping in engineering geological surveys: considerations for optimum results. Eng Geol. 232:12–21.

Watabe H, Itoh T, Kaitusuka K, Nishimura S. 2013. Experimental studies on debris flow with logs focusing on specific weight difference of log species. J Mt Sci. 10(2):315–325.

Welling RT, Wilcox AC, Dixon JL. 2021. Large wood and sediment storage in a mixed bedrock-alluvial stream, western Montana, USA. Geomorphology. 384:107703.

Wohl E. 2017. Bridging the gaps: an overview of wood across time and space in diverse rivers. Geomorphology. 279:3–26.

Wohl E. 2020. Wood process domains and wood loads on floodplains. Earth Surf Process Landforms. 45(1):144–156.

Wohl E, Bledsoe BP, Fausch KD, Kramer N, Bestgen KR, Gooseff MN. 2016. Management of large wood in streams: an overview and proposed framework for hazard evaluation. J Am Water Resour Assoc. 52(2):315–335.

Wohl E, Jaeger K. 2009. A conceptual model for the longitudinal distribution of wood in mountain streams. Earth Surf Process Landforms. 34(3):329–344.

Yan S, He S, Deng Y, Liu W, Wang D, Shen F. 2020. A reliability-based approach for the impact vulnerability assessment of bridge piers subjected to debris flows. Eng Geol. 269:105567.

Yin A, Harrison TM. 2000. Geologic evolution of the Himalayan-Tibetan Orogen. Annu Rev Earth Planet Sci. 28(1):211–280.

Zapico I, Molina A, Laronne JB, Sánchez Castillo L, Martín Duque JF. 2020. Stabilization by geomorphic reclamation of a rotational landslide in an abandoned mine next to the Alto Tajo Natural Park. Eng Geol. 264:105321.
Zhao D, Qu C, Shan X, Gong W, Zhang Y, Zhang G. 2018. InSAR and GPS derived coseismic deformation and fault model of the 2017 Ms7.0 Jiuzhaigou earthquake in the Northeast Bayanhar block. Tectonophysics. 726:86–99.
Zhao W, You Y, Chen X, Liu J, Chen J. 2020. Case study on debris-flow hazard mitigation at a world natural heritage site, Jiuzhaigou Valley, Western China. Geomat Nat Hazards Risk. 11(1):1782–1804.