

Chao Ma · Jiayong Deng · Rui Wang

## Analysis of the triggering conditions and erosion of a runoff-triggered debris flow in Miyun County, Beijing, China

**Abstract** The occurrence of debris flow from channel-bed failure is occasionally noted in small and steeply sloping watersheds where channelized water flow dominates debris flow initiation. On August 12, 2016, a debris flow from channel-bed failures occurred in the Caozhuangzi Watershed of the Longtan Basin, Miyun, Beijing. Rainfall records over 10-min intervals and field investigations including channel morphology measurements were used to study the triggering conditions and erosion process. The results indicated that the occurrence of this event lagged the peak 10-min rainfall interval and that the cumulative rainfall prior to the occurrence time played an important role in its formation. A mean 10-min rainfall intensity–duration expression in the form of  $I_{10} = 5.0 \times D^{-0.21}$ , where  $I_{10}$  denotes the mean 10-min rainfall intensity and  $D$  is the rainfall duration ranging from 10 to 60 h, was proposed. The debris flows have low proportions of grain size fractions < 0.1 mm and higher fractions of grains 0.1–2 mm in size, indicating that the flow had low viscosity and was coarse-grain dominated. Channel morphology analysis revealed that abrupt changes in topography in the study area, including a steep section, a concave stream bank area, and a partial concave stream section were eroded more extensively than other sites. The maximum sediment erosion volume and erosion depth were not proportional to the variation in stream gradient. Consideration of the degree of erosion in the channel at sites with abrupt morphology changes, the maximum sediment erosion volume, and the erosion depth and volume at the initial channel site and downstream region of forest area together showed that the prime factor controlling erosion was entrained sediment volume. This work, thus, provides a case study regarding the triggering conditions of runoff-triggered debris flows and the topographical changes by debris flow erosion.

**Keywords** Debris flow · Runoff-triggered debris flows · Channel-bed failures · Rocky mountain, Beijing

### Introduction

Debris flows have the potential to be extremely destructive, primarily because of their abilities to entrain sediment (Iverson 1997; Hungri et al. 2005; Hu et al. 2011; Takahashi 2014). The initiation of a debris flow can result from shallow landsliding due to high pore pressures within the shearing zone (Wang and Sassa 2003; Gabet and Mudd 2006) or may follow sediment entrainment by runoff erosion (Godt and Coe 2007). Debris flows initiated by the latter initiation process are commonly referred to as “runoff-triggered debris flows” and are closely associated with intensive water flow. The initiation mechanics of debris flows are attributable to channel-bed failure, progressive bulking, or generation of surface overland flow (Marchi et al. 2002; Gregoretti and Fontana 2008; McCoy et al. 2012; Kean et al. 2013; Navratil et al. 2013; Comiti et al.

2014). As debris flows are typically low-frequency events, studies about the triggering rainfall process and channel morphology changes are limited, yet these types of studies have the utmost importance for understanding the processes governing debris flow formation.

Generally, water flow during peak rainfall intervals is considered to be the main cause of debris flow initiation. Thus, to analyze the occurrence of debris flow associated with short duration rainfall events, rainfall thresholds have been proposed for regions of the Italian Alps, burn-scar regions in the USA, strong earthquake-affected regions, and some areas in northern China (Tognacca et al. 2000; Cannon et al. 2008; Coe et al. 2008; Zhou and Tang 2014; Guo et al. 2016; Ma et al. 2017). These rainfall thresholds are generally expressed in the form of  $I = \alpha D^{-\beta}$ , where  $I$  denotes the mean rainfall intensity (mm/h),  $D$  is the rainfall duration (h), and  $\alpha$  and  $\beta$  are empirical coefficients. Typically, the peak rainfall interval in a heavy rainstorm has short duration, and except for the role of antecedent precipitation (Wieczorek and Glade 2005; Guo et al. 2013), water flow intensity is also more closely related to shorter duration rainfall (Egashira et al. 2001; Cui et al. 2014). If the mean rainfall intensity is calculated on an hourly basis, the derived mean rainfall intensity–duration threshold merely represents the triggering conditions. Considering the short duration of such events and their close relationship with water flow intensity, rainfall thresholds derived from higher frequency records (such as 10-min rainfall intervals) should improve the reliability of forecasting.

The initiation process of runoff triggered debris flows can be characterized as a process of sediment entrainment. Such debris flow initiation mechanics are relative to the amount of runoff, and it is important to attribute their characteristics to the water flow (Iverson et al. 2011; Iverson and Ouyang 2015). Breien et al. (2008) found that the volume of eroded sediment varied with the channel gradient for a debris flow caused by a glacial lake outburst flood in western Norway. Using cases of debris flow in the Manival torrent of southeastern France, Theule et al. (2015) found that debris flow volumes were dependent on channel scouring. Debris flow scouring increases with slope, which is not the case for bedload transport. Although some authors have highlighted the correlations of flow discharge and channel gradient with particle diameter in the initiation of such flows (Papa et al. 2004; Berti and Simoni 2005) and have estimated the entrainment rate from ground vibrations (Kean et al. 2015), few reports have considered the change of flow volume along the channel length, which has considerable importance in understanding the evolution process of debris flows.

The mountainous regions surrounding Beijing, the capital of the People’s Republic of China (PRC), are susceptible to debris flows, and many debris flows have been documented in these regions in the last few decades. Recent studies have found that some of these were triggered by runoff erosion (Ma et al. 2016; Li

et al. 2017b). On August 12, 2016, a runoff-triggered debris flow occurred in the Caozhuangzi Watershed of the Longtan Basin, Miyun, Beijing. This debris flow traveled across the Longtan River, raised its water level, and caused flood damage to the road along river. About 785 residents downstream of the flow were forced to evacuate during this event. In this study, rainfall records of 10-min interval duration, field investigations, and channel morphology measurements were used to analyze the triggering rainfall conditions and erosion process of this event. The goals of this study were to (i) document the triggering rainfall conditions of this debris flow, (ii) examine the morphological changes of the stream, and (iii) analyze the erosion process. The results of this study provide a case study illustrating rainfall debris flow triggering conditions and their evolution, which is useful for hazard mitigation.

## Materials and methods

### The Caozhuangzi Watershed

The Caozhuangzi Watershed is a small, fan-shaped watershed located in the eastern mountainous region of Miyun County, Beijing, China (Fig. 1). Miyun County covers a total land area of 2226.5 km<sup>2</sup>. The eastern, western, and northern regions of the county are surrounded by mountains, and the relative relief in the county is from 45 to 1735 m. The mountains in the northern part of Miyun are underlain by gneiss and granite. In the north-west region, the lithology is mainly volcanic rock and gneiss. In the southeast, most terrains are underlain by sedimentary rock and gneiss (Fig. 2a).

The area of the watershed is 0.51 km<sup>2</sup>, and the mean channel gradient is 26.7‰. The main channel, which has a total length of

1.78 km, drains into the Longtan River. Within the Caozhuangzi Watershed, the highest mountain has an elevation of 865 m, and the relative relief is 476 m (Fig. 2b). The watershed is covered by high-elevation vegetation and is underlain primarily by granite. The mountainous area of Miyun County is located in the transition zone between the North China Plain and the Mongolian Plateau and is included within the Yan Mountain Range. This area is located in a warm-temperate, monsoonal, continental, semi-humid climate zone with an annual mean precipitation of ca. 660 mm. The local climate is characterized by distinctive seasons with most of the precipitation falling during July and August (Li et al. 2007). In addition, heavy rainstorms in this region occur mainly within the last 10 days of July and first 10 days of August, during which some rainfall-induced debris flows and floods have been documented (Zhong et al. 2004). According to the Beijing Hydrology Handbook (Beijing Water Authority 1999), the record maximum hourly rainfall in this area is 77.5 mm.

### Rainfall records

In mountainous regions, measurements of rainfall totals are sparse as the number of deployed rain gauges is limited. In addition, orographic effects may enhance local rainfall amounts. Rainfall gauges installed at the upper boundaries or elevations of a watershed can provide relatively accurate rainfall records for use in analyzing the triggering rainfall processes of debris flow events. Before 2011, the closest rainfall gauge to the Caozhuangzi Watershed was at the Bailongtan station, located approximately 1.43 km from the watershed outlet at an elevation of 268 m above sea level (asl). As the mountainous region of the Caozhuangzi Watershed suffered damage from a heavy rainstorm on July 24, 2011, another rainfall gauge, named the Changzigou station, was installed by the

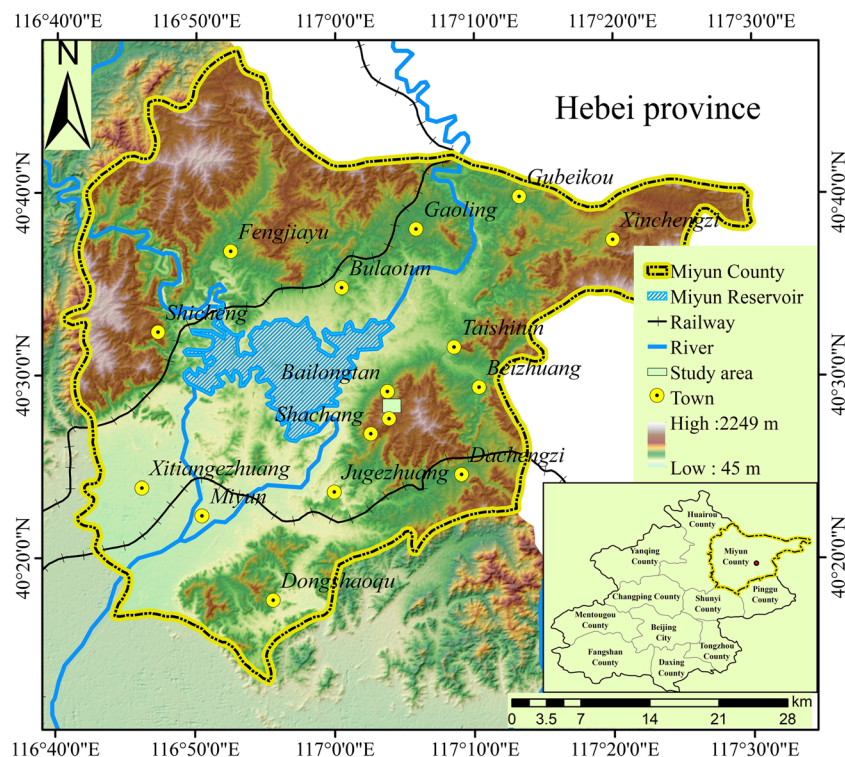
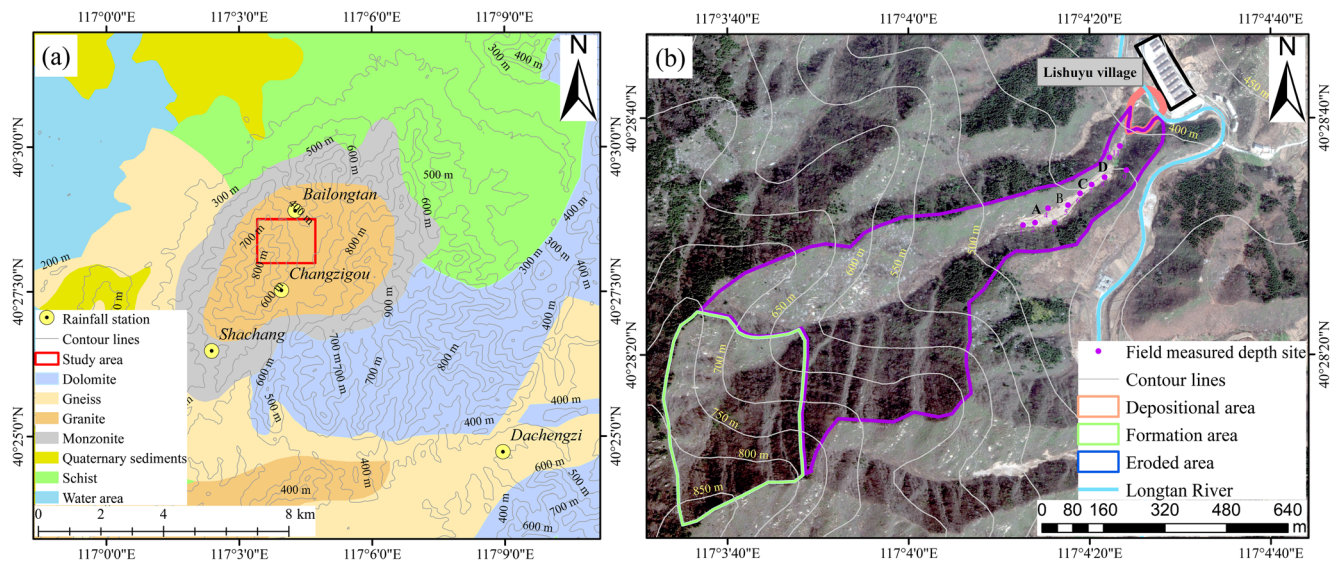


Fig. 1 Location of the debris flow in the Caozhuangzi Watershed in Miyun County, Beijing (the inset image shows the seven counties of Beijing)





**Fig. 2** Location of the Caozhuangzi Watershed in Miyun County (a map showing the simplified geology of the study area; b full view of the Caozhuangzi Watershed)

Miyun Water Authority (Fig. 2a). This station was installed to obtain more accurate rainfall records to be used in establishing local debris flow hazard emergency responses. The Changzigou station is located 2.74 km from the watershed outlet at an elevation of 475 m asl, and it is parallel to the upper boundary of the downstream area of the watershed. For the 2016 debris flow event, the most accurate data were obtained from the Bailongtan station due to its nearer proximity to the debris flow than the Changzigou station. Rainfall amounts at both rainfall stations were recorded at 10-min intervals.

### Field investigations

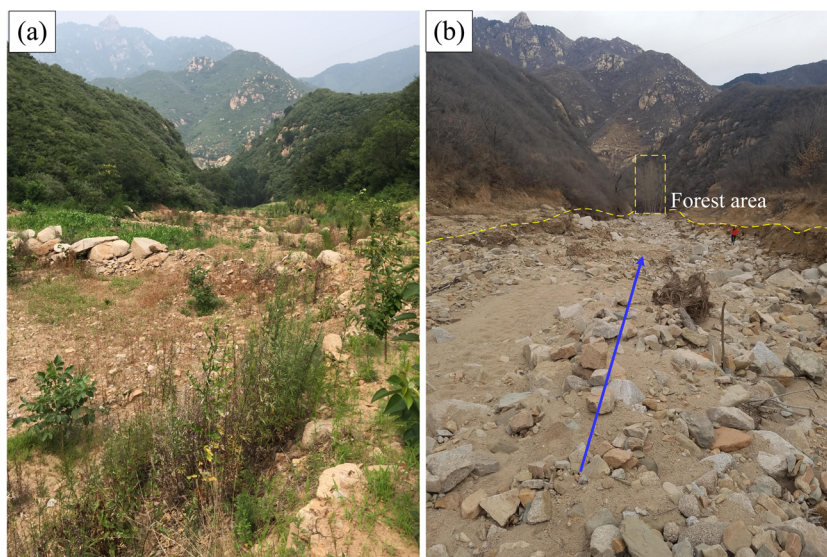
Field reconnaissance and measurements were conducted following the August 12, 2016, heavy rainfall event to:

1. Determine the timing of debris flow initiation

2. Investigate the flow density and particle components
3. Measure the topographic changes of the channel surface following the event

Figure 3 shows photographs of the channel site before and after August 12, 2016. The photograph in Fig. 3a was taken in June 2016, a time when the channel surface was covered by grass. Figure 3b shows that following the debris flow event the channel surface was deeply incised. This incised channel was scanned over a length of about 300 m using a terrestrial laser scanning service. The channel surface upstream of this deeply eroded section was not nearly as denuded and was not scanned.

The surface of the eroded channel was scanned at 1.5-m intervals, after which the dense point cloud data (DPCD) were digitized into geographic information system (GIS) format. The DPCD were used to create a triangulated irregular network (TIN) and then to generate a digital elevation model (DEM) for detection of surface



**Fig. 3** Full view of the channel morphology prior to and after August 12, 2016 (a June 2016; b March 2017)

changes. As the surface relief in the channel may have generated some shadow areas beyond the scanning scope, the total channel surface was scanned from both sides of the channel and from both upstream and downstream perspectives. The distance between two points could have been as short as one fourth of the 1.5-m scanning interval, or 0.375 m. The accuracy of the topography measurements is estimated to be 0.075 m, according to the deviation of the IS-Imaging Station (Topcon, Tokyo, Japan).

The eroded depth, equal to the elevation difference of the channel surface, was calculated using the elevation difference between the concave stream surface and the ridge lines of the bank slope. The DPCD of the stream surface beyond the eroded area were used to generate a DEM representing the topography without erosion. The DEM to obtain the elevation change was derived from all DPCD minus those of the stream surface without erosion. Positive values in the new DEM indicated that the topography was eroded, whereas negative values represented an area where debris flow deposition had occurred. To ensure the accuracy of the derived eroded depth, the calculated depths by the DEM were compared with the measured depths (Fig. 4), permitting accurate estimation of the volume of eroded stream sediments.

## Results

### Triggering rainstorm

#### Rainfall process

Daily rainfall before the August 12, 2016, event measured at the Bailongtan and Changzigou recording stations was quite variable. In the preceding 30 days, the cumulative rainfall amounts recorded at the Changzigou and Bailongtan stations were 241.5 mm and 42 mm, respectively (Fig. 5). The cumulative rainfall amounts at these stations from July 26 to August 11 (17 days) were 29.5 mm and 21.5 mm, respectively. The peak 10-min rainfall amounts from Changzigou station on August 12 from 9:20 to 9:50 AM were 16, 17, and 16 mm, whereas those of Bailongtan station recorded at 7:50, 8:20, and 11:50 AM were relatively lower with values closer to 15 mm (Fig. 6).

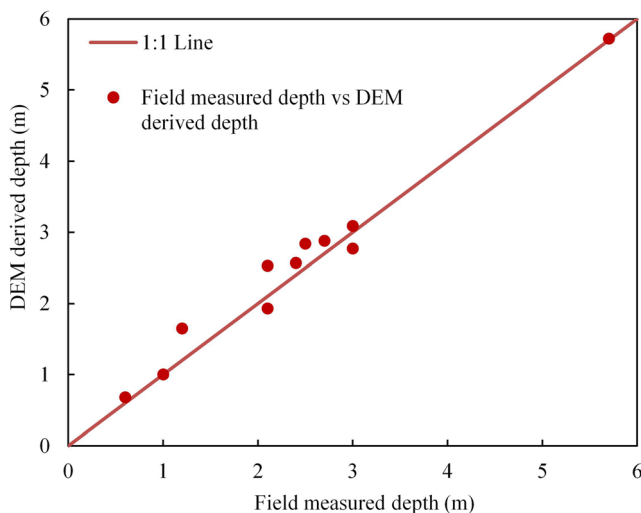


Fig. 4 Estimated eroded depth vs field measured depth

Local inhabitants of the village of Lishuyu across the Caozhuangzi Watershed reported that the rainfall was mainly concentrated in two time intervals: one at dawn (approximately 7:00 AM) and another close to 12:00 AM. Debris flow occurred at approximately 9:00 AM and lasted less than one-half hour. According to rainfall records from the two stations, the cumulative rainfall of Changzigou was merely 25 mm whereas that at Bailongtan was 100 mm (Fig. 6). The first peak rainfall interval at Changzigou station started at 9:00 AM, and the cumulative rainfall amount prior to this time was 15 mm. Therefore, the rainfall records from Bailongtan station were more critical than those from Changzigou station for this analysis because a rainfall total of 15 mm is not considered high enough to saturate the slope terrains.

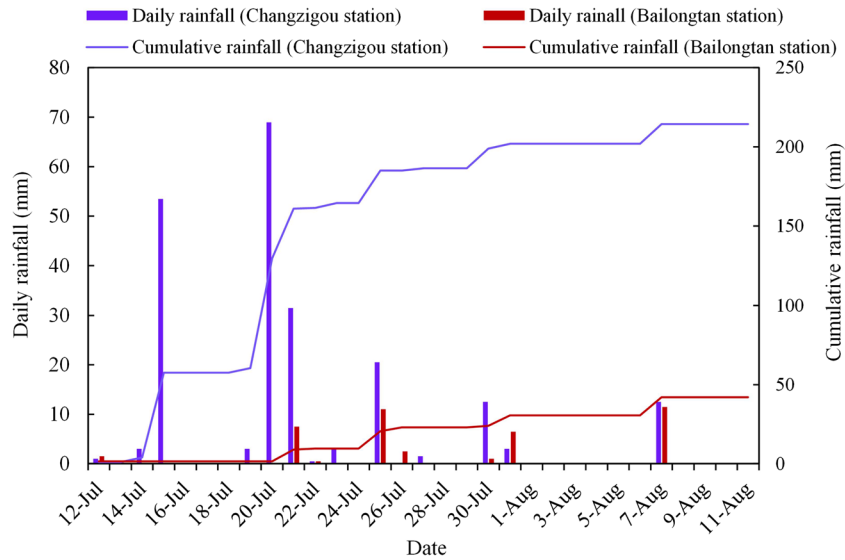
According to the rainfall records of Bailongtan station, the debris flow occurrence lagged the peak rainfall interval. Two maximal 10-min rainfalls of 15 mm were recorded before 9:00 AM: the first from 7:40 to 7:50 AM and the second from 8:10 to 8:20 AM. The maximal 20-min and 30-min rainfalls were 28 mm (7:40–8:00 AM) and 35 mm (7:30–8:00 AM), respectively. Although the antecedent precipitation prior to the day of the debris flow event was insufficient in terms of triggering the debris flow, the heavy rainfall from 7:00 AM to 8:00 AM accumulated as much as 66 mm of precipitation. Local inhabitants documented the debris flow initiation at about 9:00 AM, yet a maximal episode of 15 mm of precipitation occurred during the 8:10–8:20 AM interval and only 9 mm was accumulated from 8:30 AM to 9:00 AM. This indicates that the rainfall amount from the beginning of the storm event up until 8:30 did not play an important role in saturating the slopes and raising the interior water level of stream sediments, but rather produced long-duration and intensified stream flow that mobilized stream sediments into debris flows.

#### Rainfall threshold development

The occurrence of runoff-triggered debris flows may lag or coincide with a peak rainfall interval. For example, some debris flows in the Wenchuan earthquake zone were triggered by runoff from heavy rainstorms and their occurrence coincided with the peak rainfall interval (Zhou and Tang 2014; Guo et al. 2016; Ma et al. 2017). However, debris flows in watersheds in earthquake-struck regions contain great amounts of material from landslides and avalanches (Tang et al. 2009, 2011, 2012). The Caozhuangzi Watershed has high vegetation coverage, and the debris flow was initiated from sediment mobilization from runoff erosion. This event can be taken as the typical case of debris flow in mountainous sites in the Beijing region. Although some authors have proposed a rainfall intensity–duration (*I–D*) relationship in Miyun and other counties of Beijing (Ma et al. 2016; Tu et al. 2017), more accurate parameters representing the mean rainfall intensity for the rainfall intervals of 10, 20, 30, 40, 50, and 60 min or some expressions combining these should be considered, because the rainfall amounts at gauges in the study area are recorded at 10-min intervals.

In the 2016 rainfall event, debris flows also occurred in other small watersheds in the Changzigou Basin and around Dachengzi, which is located in the same mountain region as the study area. The triggering rainfall process was recorded by the Bailongtan, Changzigou, and Dachengzi stations. As the water flow during the heavy rainstorm in the study area served as the main factor leading to debris flows, its intensity was closely related to the mean rainfall intensity in a shorter duration. Therefore, the 10-





**Fig. 5** Antecedent rainfall and cumulative rainfall prior to the day of August 12, 2016, for the Bailongtan and Changzigou stations

min rainfall records were used to develop a mean 10-min rainfall intensity–duration relationship:

$$I_{10} = \alpha \times D^{-\beta}, \quad (1)$$

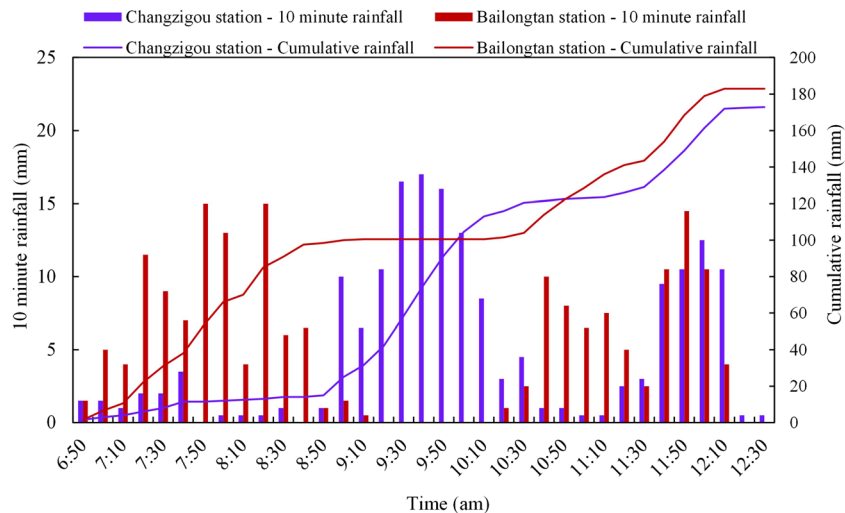
where  $I_{10}$  is the mean 10-min rainfall intensity (mm) in  $D$  duration (one to six 10-min intervals), and  $\alpha$  and  $\beta$  are constants that can be derived from the 10-min basis records from the three rainfall stations.

In the  $I$ - $D$  equations,  $\alpha$  indicates the required hourly rainfall that might trigger a debris flow in a particular region, but few analyses have focused on  $\beta$ . Generally, the constant value of  $\alpha$  indicates the average rainfall intensity, and  $\beta$  represents the relative change in the hourly rainfall amount. The larger the value of  $\alpha$ , the more intense the rainstorm. If  $\beta$  approaches zero, the hourly intensity of the rainstorm does not change much with time. To a certain extent, the value of

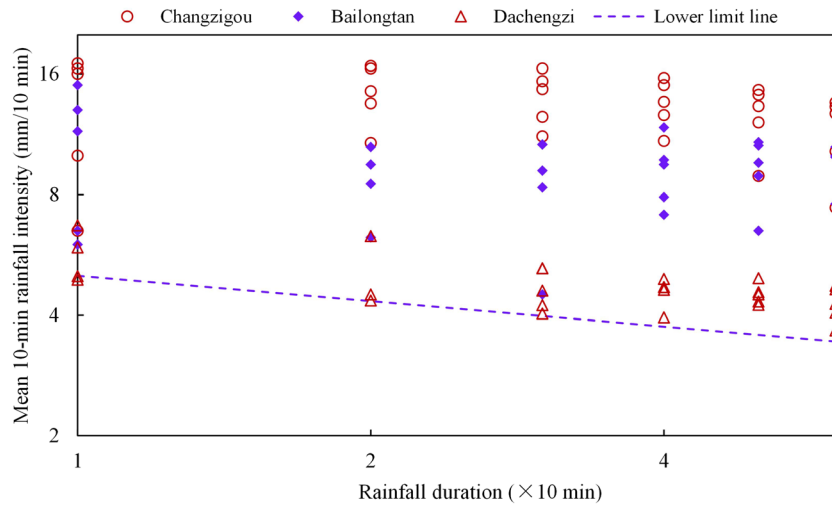
$\beta$  depends on the rainfall duration of the triggering rainstorm. The expression can be obtained by fitting the lowest mean 10-min rainfall intensity with a given 10-min duration. For the relationship shown in Fig. 7,  $\alpha$  and  $\beta$  are 5.0 and 0.21 respectively.

#### Debris flow properties and deposition characteristics

Four debris flow samplings were used to analyze particle diameter curves. Among these, two samplings were located at the left bank area 20 m downstream of the forest area (Fig. 8a) and the two others were at the depositional area of the watershed outlet (Fig. 8b). As the debris flow deposits at the two sampling sites include large boulders and gravels, focus was placed on grains < 100 mm in size. Particle distributions were analyzed with respect to four natural debris flows from the Dongchuan debris observation station in Jiangjia Ravine, Yunnan Province, southern China (Kang et al. 2006).



**Fig. 6** Ten-minute interval and cumulative rainfall amounts recorded by Bailongtan station and Changzigou station on August 12, 2016



**Fig. 7** The lower limit line expressing the relationship between mean 10-min rainfall intensity (mm) and duration (10 min)

#### Particle distributions

As shown in Fig. 9, the similar particle curves of deposits 1 and 2 reveal that they contain a lower proportion of fine-grained material (< 0.1 mm) and higher proportions of grains in the 0.1–2 mm size range (20.1% on average). For deposits 3 and 4, the fractions of grains < 0.1 mm do not differ significantly from those of sites 1 and 2, but the fractions of grains of 0.1–1 mm and 1–20 mm are 38.6 and 32.4%, respectively. The four samplings in the Caozhuangzi Watershed have similar low volume fractions of silt and clay. In comparison, the debris flows in Jiangjia Ravine have higher fractions of silt and clay content. There is a corresponding relationship between density and the percentage of grains < 2.0 mm in size; that is, the highest density flow contains the highest percentage of grains in this range and the percentage value decreases with decreasing density of the debris flows sampled. For the debris flows from the Dongchuan debris observation station in Jiangjia Ravine, the volume fractions of silt and clay content of the continuous flows in Jiangjia Ravine are higher yet. This indicates that the debris flows in the Caozhuangzi Watershed had lower viscosity and belonged to a continuous flow.

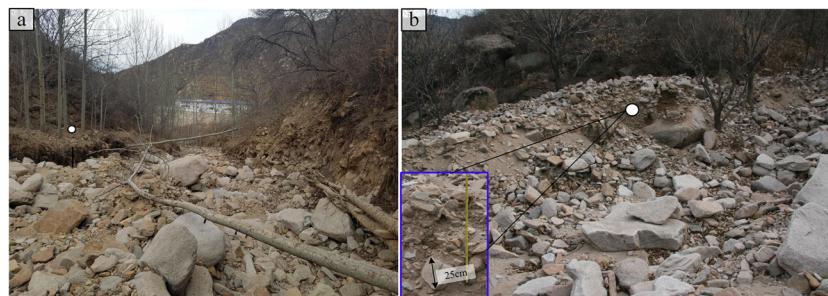
Note that the four debris flow samplings in the Caozhuangzi Watershed have a density range of 1.7–1.8 g/cm<sup>3</sup>. This indicates that the volume fractions of grains are lower than 0.5 based on a solid density of 2.6 g/cm<sup>3</sup>. According to results of Fei and Su (2004), the

main driving forces of debris flows with grain volume fractions less than 0.5 are derived from water; otherwise, the forces are related to solid grains, such as in the high-density debris flows in Jiangjia Ravine. For the debris flows in the Caozhuangzi Watershed, the volume fraction of grains is < 0.5 and the volume fractions of finer particles are low, indicating that water is the main driving force.

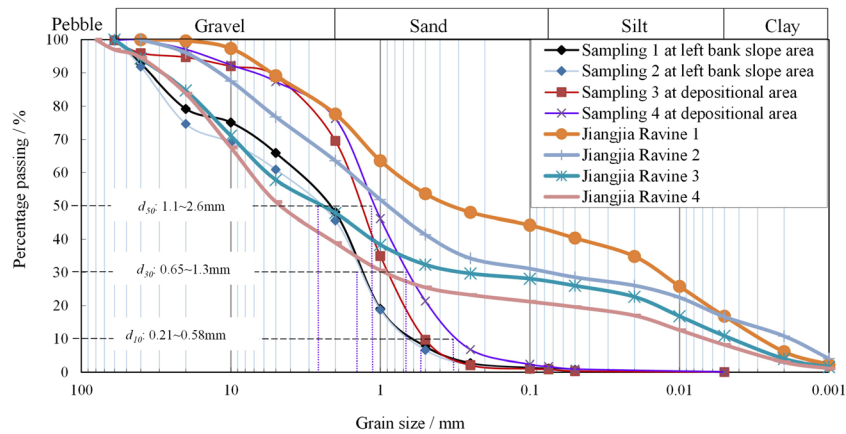
#### Deposition

Hungr et al. (1984) found that debris flow deposition begins at a point where the gradient diminishes to 10°–14° for unconfined flows and 8°–12° for confined flows. A study of debris flows originating from moraine dam breaches in the Cascades (O'Connor et al. 2001) concluded that erosion occurred on gradients steeper than 8°, while deposition was restricted to gradients lower than 18°. In this event, the surface gradient at the bank slope area and depositional area was about 8°.

Debris flow deposition close to the outlet exhibits distinctive characteristics relative to the bank downstream of the forest area. Deposits downstream of the forest area exhibit a fully mixed texture, with no boulders or fractured blocks on the surface and outside of the flow track. This reflects the ability of the forest to stop the advance of large cobbles or boulders in and around the forest area. However, at the side bank near the outlet, the debris



**Fig. 8** The locations of the two debris flow sampling sites (a samplings 1 and 2 on the left channel bank 20 m downstream of the forest area, b samplings 3 and 4 at the depositional area of the watershed outlet)



**Fig. 9** Comparison of particle curves of the four debris flows samplings with four debris flows with density values of 1.7 (Jiangjia Ravine 1), 1.8 (Jiangjia Ravine 2), 1.9 (Jiangjia Ravine 3), and 2.0 kg/m<sup>3</sup> (Jiangjia Ravine 3) from the Dongchuan debris observation station, Jiangjia Ravine, Yunnan Province, southern China (Kang et al. 2006). The site of samplings 1 and 2 is shown in Fig. 8a, and that of samplings 3 and 4 is shown in Fig. 8b

flow deposit exhibits inverse grading, with a coarse layer on the surface to a depth of about 30–40 cm and finer particles restricted to the subsurface (Fig. 8b). Generally, an inverse-graded stratification is characterized by decreasing grain diameter from the deposition surface downward, which reflects specific features where a debris flow will start to deposit onto a flattened fan.

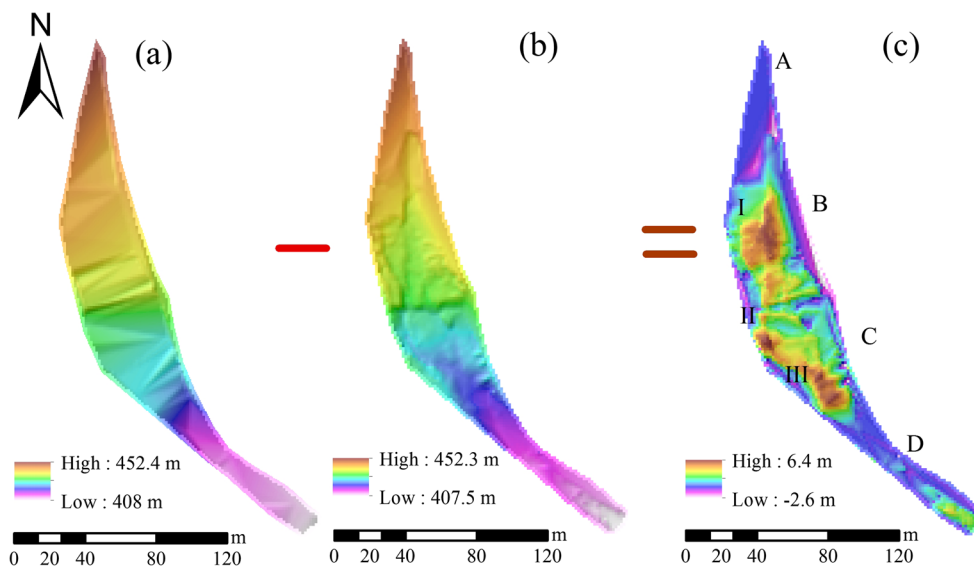
#### Channel morphology change and eroded sediments

##### Topographic effect and effect of forest area on erosion

Figure 10 shows the elevation derived from the channel ridge line (Fig. 10a), channel surface (Fig. 10b), and the eroded depth as the channel descends to lower elevation (Fig. 10c). As the upstream region of the scanned section is covered by large boulders with cobbles embedded in the larger gaps, the local stream surface does not erode easily (Fig. 11a). At the middle and downstream regions of the channel (the scanned channel in this study), the streambed

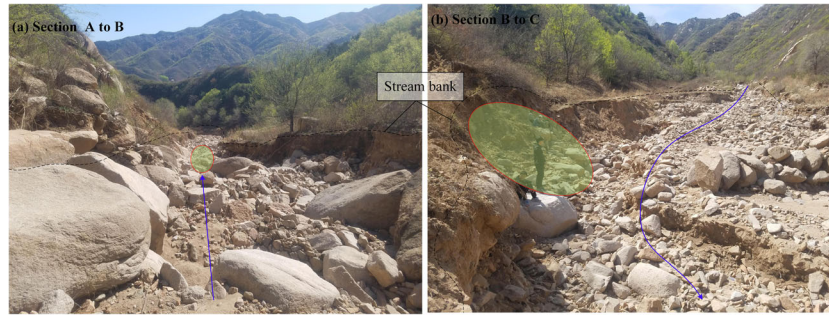
surfaces are covered by relatively finer particles derived from upstream and are clearly seen in several dike terraces (Fig. 3b).

By considering the erosion depth, as shown in Fig. 10c, the channel surface from section B to C is seen to be eroded more substantially than other areas. The eroded depths over section B–C (marked I and II in Fig. 10c) and the convex bank are 3 m, 4.74 m, and 6.5 m and the channel gradients are 13.6°, 9.1°, and 9.8°, respectively. The cross section C is located downstream of the 28.8° steep section, where debris flows may accelerate to obtain high speed and momentum, cause serious erosion from collision, and scour at the concave channel between the steep section and soft streambed. The reason why site II with a stream gradient of 9.1° was significantly eroded is that it is located at the convex side of the channel where the debris flow accelerated due to centrifugal force (Fig. 11b). The stream bank at the convex channel is also seriously eroded, and the eroded depth at the corresponding concave bank is not comparable to that of the convex bank. Note



**Fig. 10** Derived channel morphology based on terrestrial laser scanning service (a the channel bank DEM; b the channel surface DEM; c the eroded depth derived by a and b, the four letters A, B, C, and D indicate the cross section)





**Fig. 11** a and b Maps showing the channel morphology change from section A to B and B to C, respectively. The channel section from C to D and that at the downstream region of forest area can be seen in Figs. 3b and 8a

that the three sites marked I, II, and III in Fig. 10 represent the typical topography and abrupt morphology in the channel. This indicates that steep channel or abrupt channel profile sites tend to be eroded to greater extents.

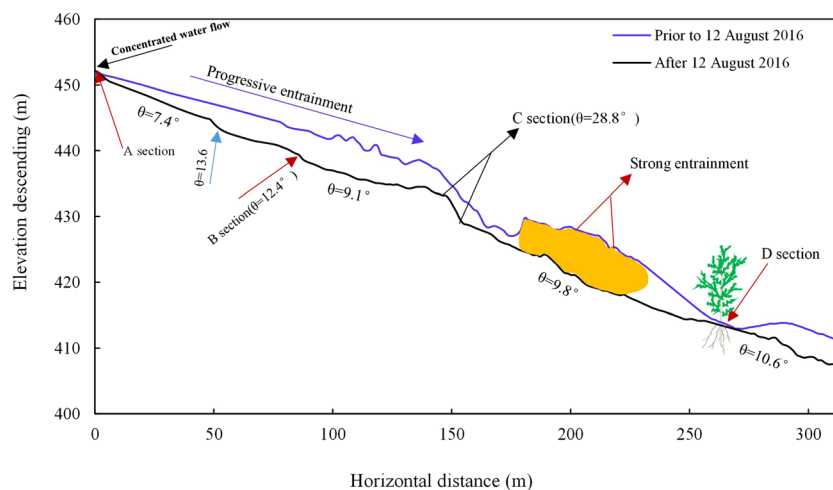
From section C to D, the erosion depth decreases gradually and the post-event stream surface is parallel to the surface before this event. This indicates that the forest area protected the stream surface by offering resistance to erosion and led to partial deposition of grains in and around the site (Fig. 3a). As a result of minor cobble and boulder deposition, a back-siltation of debris flow deposits occurred. However, when debris flows traveled through the forest area, the erosion depth increased gradually (Fig. 10c).

Elevation change and eroded volume with channel descent

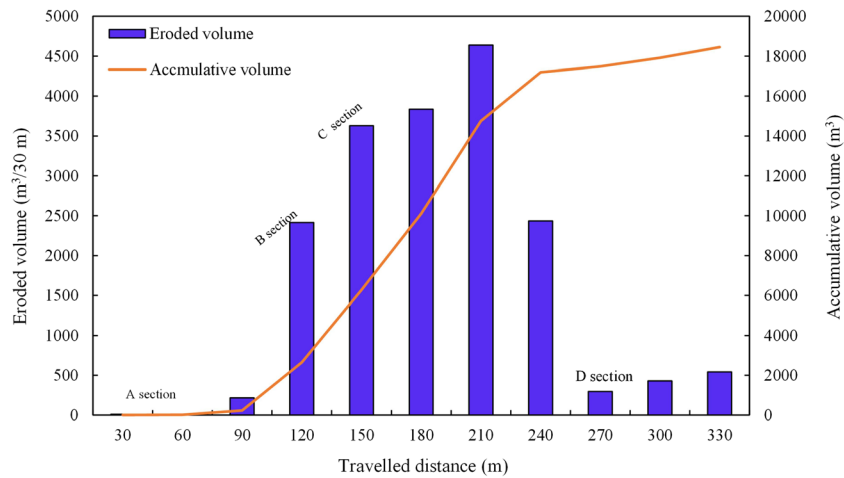
Figure 12 shows the erosion depth with decreasing channel elevation. For the initial 50 m, the erosion depth is about 2.92 m, compared to an erosion depth of 4.73 m at 100 m downstream. This indicates that stream sediment was entrained due to progressive bulking. In comparison, the erosion depth in the channel downstream of the forest area is also increased. However, the erosion depth at that location is only 2.34 m at the channel, with a steep gradient of  $28.8^\circ$ , which is less than the erosion depth at the initial 50-m and 100-m sites. Such a steep channel may lead to acceleration of debris flows, which increases momentum and erosion.

A total of  $1.8 \times 10^4 \text{ m}^3$  of sediments and an average yield rate of about  $60 \text{ m}^3/\text{m}$  were determined for this event (Fig. 13). These values are not comparable to those of some lake outburst and other runoff-triggered debris flows worldwide (Breien et al. 2008; Santi et al. 2008; Mccoy et al. 2012; Theule et al. 2015). This difference may have resulted from limited available sediment volume and the small dimensions of the watershed. According to the distribution of eroded sediment volume per 30 m of channel, the yield rate does not seem proportional to the variation in gradient. For example, the channel section with maximal sediment erosion volume contains the site with maximal erosion depth, while the stream gradient is only  $9.8^\circ$ . At a stream gradient of  $28.8^\circ$ , the volume of eroded sediment is smaller.

At the 100-m site and the downstream area of forest, both the erosion depth and sediment erosion volume increase progressively. This implies that the momentum of the debris flow increased as it traveled downstream and that this high momentum resulted in significant erosion at several sites. Generally, the erosive ability of a debris flow is closely related to its velocity and momentum. Wang et al. (2003) and Iverson et al. (2011) proved that high pore water pressure in nearly saturated sediments can facilitate sediment liquefaction into debris flow movement and increase sediment entrainment ability. If the sediments are relatively dry, the sediments incorporated into a debris flow may increase the density of the debris flow without high pore water pressure within the sediments, causing



**Fig. 12** Channel surface elevation change after the debris flow event on August 12, 2016



**Fig. 13** Volume of eroded stream sediments with distance traveled

higher flow resistance from friction and collision (Tian et al. 2014). However, in the study area, this event lagged the peak rainfall interval, indicating that the stream sediments may have had high moisture content. Also, as the stream gradient was  $7.4^\circ$  at the initial entrainment stage, such a low stream gradient would make it difficult for debris flow to initiate, indicating that this debris flow event was produced by a combination of initial water flow erosion and subsequent progressive entrainment due to the momentum increase of the mixture of water and soil. This can be demonstrated by the smaller erosion depth at the initial 50 m channel site and the maximum erosion depth site downstream at the  $28.8^\circ$  convex channel site, where the corresponding erosion depths are 2.94 m and 6.4 m, respectively.

### Discussion

In this study, a typical runoff-triggered debris flow in a small watershed in Miyun County, Beijing, was analyzed, focusing mainly on the triggering rainfall conditions and the erosion process. Although two gauge stations were in close proximity to the debris flow site, the rainfall records at Bailongtan coincide more accurately with eyewitness accounts. In this event, the debris flow occurrence lagged the peak rainfall interval, indicating that the antecedent precipitation played an insignificant role in this event, but this precipitation should not be discounted for other runoff-triggered debris flows. Generally, the time to runoff, time to failure, and runoff rates are strongly affected by soil-water characteristic curves, initial soil moisture conditions, rainfall intensity, and slope angle (Cuomo and Sala 2013). In any given mountain basin, soil suction and rainfall intensity greatly influence the total peak discharge of water and sediments for conditions in which previous rainfall totals allow for surface runoff (Cuomo et al. 2015). Before this rainstorm, the antecedent precipitation was low and thus did not saturate the slope soils and stream sediments. Therefore, the debris flow in the Caozhuangzi Watershed occurred under conditions such that the triggering rainstorm decreased the degree of soil suction and promoted runoff having an intensity high enough to mobilize stream sediments.

Some previous studies have proposed rainfall intensity and duration thresholds as possible triggering conditions for such events. These circumstances are reliant on high-frequency hourly

rainfall intensity (Tognacca et al. 2000; Cannon et al. 2008; Coe et al. 2008). However, debris flows in the Caozhuangzi Watershed were caused by runoff erosion of stream sediments, rather than by slope failure or shallow landslides. The intensity of runoff is the key factor leading to stream sediment entrainment and debris flow events. Based on 10-min rainfall interval data from three rain stations where debris flow occurrence was documented, a mean 10-min rainfall intensity–duration expression with a duration of 1 h was developed. This expression is helpful for local hazard mitigation, but it requires further examination.

Three sites, including the stream section with gradient of  $13.6^\circ$ , the concave stream bank area, and the concave stream area connected to a  $28.8^\circ$  gradient channel section, have the similarities of abrupt change of channel profile and having undergone serious erosion. This indicates that these sites can be strongly denuded by debris flows and can lead to rapid increases in debris flow momentum. If the channel profile is relatively constant, stream sediments will be eroded by shearing stress, leading to a gradual increase in the momentum of the debris flow (Li et al. 2017a). The yield rate in this watershed does not seem proportional to the variations in stream gradient, but rather to the erosion depth, coinciding with the results of Breien et al. (2008) and in part with those of Theule et al. (2015). In detail, Breien et al. (2008) found that the yield rate in the watershed in their study did not seem proportional to either the variation of stream gradient or the width of the flow. Theule et al. (2015) found that debris flow volumes were supplied mainly by channel scouring and that debris flow scouring increased with slope. However, the 300-m channel length in this work contains an initial erosion stage of stream sediments and has its deepest erosion at the abrupt change of a concave channel. The yield rate in this study is close to the results of debris flow volumes from channel scouring, but it does not coincide with the results of scouring over distances with significant change in slope. This may be a result of the shorter length and smaller watershed area of this work.

As described above, the deepest erosion occurred in lower-elevation areas with gradients of  $9.1^\circ$  and  $9.8^\circ$ , where debris flows reach high momentum after accelerating from a steep channel. This documents the significance of volume as a factor for yield rate. In previous studies, positive and opposing effects, which are related to

sediment moisture content, have been found during debris flow entrainment (Iverson et al. 2011; Tian et al. 2014). This event might have been affected by higher moisture content because the debris flow occurrence lagged the peak rainfall interval. Nevertheless, the erosion depth and the sediment entrainment volume per 30 m in the initial 150 m of the channel and the area downstream of the forest area increase progressively, rather than decrease.

### Conclusions

In this paper, 10-min rainfall records supported by field investigations and an analysis of channel morphology changes were used to analyze the triggering conditions and erosion process of a runoff-triggered debris flow event that occurred on August 12, 2016, in the Caozhuangzi Watershed, Miyun County, Beijing. The following results were obtained:

1. Debris flow initiation in this event lagged the peak rainfall interval of the triggering rainstorm and the antecedent precipitation from rainfall; thus, initial-to-peak rainfall played an insignificant role in its formation. Based on 10-min rainfall interval data from three rain stations where debris flow occurrence was documented, a 10-min rainfall interval intensity analysis and consideration of durations of less than 1 h was suggested to aid local hazard forecasting and mitigation.
2. Debris flows in the Caozhuangzi Watershed were caused by runoff erosion of stream sediments, rather than by slope failure or shallow landslides. The intensity of runoff was the key factor leading to stream sediment entrainment and the debris flow events. The erosion depth along descending channel revealed that sites of abrupt change in channel profile experienced the most serious erosion, while the erosion depth at other sites increased progressively. This indicates that abrupt profile denudation can quickly strengthen the sediment entrainment ability of debris flows.
3. The maximum sediment erosion volume and erosion depth do not seem proportional to variations in stream gradient. The channel section with maximum sediment volume and erosion depth and the volume at the initial channel region and downstream region of the forest area show that entrained sediment volume was of prime importance for controlling the degree of erosion in this event.

### Acknowledgements

The authors acknowledge the anonymous reviewers of this paper for their detailed remarks and helpful suggestions.

Funding information This study was supported by the Fundamental Research Funds for the Central Universities (grant No. 2016ZCQ06) and the National Natural Science Foundation of China (No. 41702369).

### References

Beijing Water authority (1999) Beijing hydrology handbook, (Unpublished in Chinese)

Berti M, Simoni A (2005) Experimental evidences and numerical modelling of debris flow initiated by channel runoff. *Landslides* 2(3):171–182

Breien H, Blasio FVD, Elverhøi A, Høeg K (2008) Erosion and morphology of a debris flow caused by a glacial lake outburst flood, western Norway. *Landslides* 5(3):271–280

Cannon SH, Gartner JE, Wilson RC, Bowers JC, Laber JL (2008) Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California. *Geomorphology* 96(3):250–269

Coe JA, Kinner DA, Godt JW (2008) Initiation conditions for debris flows generated by runoff at Chalk Cliffs, central Colorado. *Geomorphology* 96(3):270–297

Comiti F, Marchi L, Macconi P, Arattano M, Bertoldi G, Borga M, Brardinoni F, Cavalli M, D'Agostino VD, Penna D, Theule J (2014) A new monitoring station for debris flows in the European Alps: first observations in the Gadoria basin. *Nat Hazards* 73(3):1175–1198

Cui P, Guo XJ, Zhuang JQ (2014) Determination of the runoff threshold for triggering debris flows in the area affected by the Wenchuan earthquake. *Nat Hazards Earth Syst Sci Discuss* 2(7):4659–4684

Cuomo S, Sala MD (2013) Rainfall-induced infiltration, runoff and failure in steep unsaturated shallow soil deposits. *Eng Geol* 162(14):118–127

Cuomo S, Sala MD, Novità A (2015) Physically based modelling of soil erosion induced by rainfall in small mountain basins. *Geomorphology* 243:106–115

Egashira S, Honda N, Itoh T (2001) Experimental study on the entrainment of bed material into debris flow. *Phys Chem Earth Part C* 26(9):645–650

Fei X, Su A (2004) Movement mechanism and disaster control for debris flow. Press of Tsinghua University, Beijing, pp 49–61 (in Chinese)

Gabet EJ, Mudd SM (2006) The mobilization of debris flows from shallow landslides. *Geomorphology* 74(1–4):207–218

Godt JW, Coe JA (2007) Alpine debris flows triggered by a 28 July 1999 thunderstorm in the central front range, Colorado. *Geomorphology* 84(1):80–97

Gregoretti C, Fontana GD (2008) The triggering of debris flow due to channel-bed failure in some alpine headwater basins of the dolomites: analyses of critical runoff. *Hydrological Process* 22(13):2248–2263

Guo XJ, Cui P, Li Y (2013) Debris flow warning threshold based on antecedent rainfall: a case study in Jiangjia Ravine, Yunnan, China. *J Mt Sci* 10(2):305–314

Guo X, Cui P, Li Y, Ma L, Ge Y, Mahoney WB (2016) Intensity–duration threshold of rainfall-triggered debris flows in the Wenchuan earthquake affected area, China. *Geomorphology* 253:208–216

Hu KH, Wei FQ, Li Y (2011) Real-time measurement and preliminary analysis of debris-flow impact force at Jiangjia Ravine, China. *Earth Surf Process Landf* 36(9):1268–1278

Hungr O, Morgan GC, Kellershals R (1984) Quantitative analysis of debris torrent hazards for design of remedial. *Can Geotech J* 21(4):663–677

Hungr O, McDougall S, Bovis M (2005) Entrainment of material by debris flows. Springer Praxis Books, pp 135–158

Iverson RM (1997) The physics of debris flow. *Rev Geophys* 35(3):245–296

Iverson RM, Ouyang C (2015) Entrainment of bed material by earth-surface mass flows: review and reformulation of depth-integrated theory. *Rev Geophys* 53(1):27–58

Iverson RM, Reid ME, Logan M, Lahusen RG, Godt JW, Griswold JP (2011) Positive feedback and momentum growth during debris-flow entrainment of wet bed sediment. *Nat Geosci* 4(2):116–121

Kang ZC, Cui P, Wei FQ, He SF (2006) Observed dataset of Dongchuan debris flow observation and research station, Chinese Academy of Science (1961–1984). Science press, Beijing (in Chinese)

Kean JW, McCoy SW, Tucker GE, Staley DM, Coe JA (2013) Runoff-generated debris flows: observations and modeling of surge initiation, magnitude, and frequency. *J Geophys Res Earth Surf* 118(4):2190–2207

Kean JW, Coe JA, Coviello V, Smith JB, McCoy SW, Arattano M (2015) Estimating rates of debris flow entrainment from ground vibrations. *Geophys Res Lett* 42(15):6365–6372

Li JH, Yu XX, Xie BY, Gao JR (2007) Debris flows and floods in mountain regions near Beijing. China Forestry Publishing House, Beijing (in Chinese)

Li P, Hu K, Wang X (2017a) Debris flow entrainment rates in non-uniform channels with convex and concave slopes. *J Hydraul Res* 8:1–12

Li Y, Ma C, Wang Y (2017b) Landslides and debris flows caused by an extreme rainstorm on 21 July 2012 in mountains near Beijing, China. *Bull Eng Geol Environ* 3:1–16

Ma C, Wang YJ, Du C, Wang YQ, Li YP (2016) Variation in initiation condition of debris flows in the mountain regions surrounding Beijing. *Geomorphology* 273:323–334

Ma C, Wang Y, Hu K, Du C, Yang W (2017) Rainfall intensity–duration threshold and erosion competence of debris flows in four areas affected by the 2008 Wenchuan earthquake. *Geomorphology* 282:85–95

Marchi L, Arattano M, Deganutti AM (2002) Ten years of debris-flow monitoring in the Moscardo Torrent (Italian Alps). *Geomorphology* 46(1–2):1–17

McCoy SW, Kean JW, Coe JA, Tucker GE, Staley DM, Wasklewicz TA (2012) Sediment entrainment by debris flows: in situ measurements from the headwaters of a steep catchment. *J Geophys Res Earth Surf* 117(F3):F03016

Navratil O, Liébault F, Bellot H, Travaglini E, Theule J, Chambon G (2013) High-frequency monitoring of debris-flow propagation along the Réal Torrent, southern French Prealps. *Geomorphology* 201:157–171

O'Connor J E, Hardison J H, Costa J E (2001) Debris flows from failures of Neoglacial-age moraine dams in the three sisters and Mount Jefferson Wilderness areas, Oregon. Geological Survey professional paper, 1606: 1044–9612



- Papa M, Egashira S, Itoh T (2004) Critical conditions of bed sediment entrainment due to debris flow. *Nat Hazards Earth Syst Sci* 4(3):469–474
- Santi PM, Dewolfe VG, Higgins JD, Cannon SH, Gartner JE (2008) Sources of debris flow material in burned areas. *Geomorphology* 96(3):310–321
- Takahashi T (2014) *Debris flow: mechanics, prediction and countermeasures*. Taylor & Francis
- Tang C, Zhu J, Li WL, Liang JT (2009) Rainfall-triggered debris flows following the Wenchuan earthquake. *Bull Eng Geol Environ* 68(2):187–194
- Tang C, Zhu J, Ding J, Cui XF, Chen L, Zhang JS (2011) Catastrophic debris flows triggered by a 14 August 2010 rainfall at the epicenter of the Wenchuan earthquake. *Landslides* 8(4):485–497
- Tang C, Asch TWJV, 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(2):559–576
- Theule JI, Liébault F, Loye A, Laigle D, Jaboyedoff M (2015) Channel scour and fill by debris flows and bedload transport. *Geomorphology* 243:92–105
- Tian M, Hu KH, Ma C, Lei FH (2014) Effect of bed sediment entrainment on debris-flow resistance. *J Hydraul Eng* 140(1):115–120
- Tognacca C, Bezzola GR, Minor HE (2000) Threshold criterion for debris-flow initiation due to channel-bed failure. In: *Proceedings of the 2nd International Conference on Debris Flow Hazard Mitigation: Mechanics, Prediction and Assessment*, Taipei, Taiwan, 16–18 Aug 2000. Balkema, Rotterdam, pp 89–97
- Tu J, Ma C, Yang HL (2017) Rainfall condition of triggering debris flows in Beijing mountain regions. *Sci Soil Water Conserv* 15(5):103–110 (in Chinese)
- Wang G, Sassa K (2003) Pore-pressure generation and movement of rainfall-induced landslides: effects of grain size and fine-particle content. *Eng Geol* 69(1–2):109–125
- Wang G, Sassa K, Fukuoka H (2003) Downslope volume enlargement of a debris slide–debris flow in the 1999 Hiroshima, Japan, rainstorm. *Eng Geol* 69(3–4):309–330
- Wieczorek GF, Glade T (2005) Climatic factors influencing occurrence of debris flows. In: *Debris-flow hazards and related phenomena*. Springer Berlin Heidelberg
- Zhong DL, Xie H, Wang SG, Wei FQ, Ji HC, Liu SJ, Tang JF, Yang JH (2004) *Debris flows in mountain regions near Beijing*. The Commercial Press, Beijing (in Chinese)
- Zhou W, Tang C (2014) Rainfall thresholds for debris flow initiation in the Wenchuan earthquake-stricken area, southwestern China. *Landslides* 11(5):877–887

---

**C. Ma** (✉) · **J. Deng** · **R. Wang**

Jinyun Forest Ecosystem Research Station, School of Soil and Water Conservation, Beijing Forestry University, Beijing, 100083, People's Republic of China  
Email: sanguoxumei@163.com

**C. Ma** · **J. Deng** · **R. Wang**

Beijing Engineering Research Center of Soil and Water Conservation, Beijing Forestry University, Beijing, 100083, People's Republic of China