Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-390
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 3 November 2017


# Multiply factors driving continual post-wildfire debris flows with varied rainfall thresholds in the Reneyong Valley, southwestern China

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**Abstract**: In early June of 2014, wildfire struck the Reneyong Valley in the central Hengduan Mountains of southwestern China. Three days after the wildfire, the first debris flow was triggered in branch No. 3, followed by 2 other debris flows that same year. In August 2015, another debris flow occurred in branches No. 1, No. 2 and No. 3, respectively. Rainfall data from three nearby rain gauges and rainfall totals speculated from debris flow volume suggest the three debris flows in 2014 were generated by isolated convective rainfall. Later, we found that varied rainfall thresholds existed among the branches and that these thresholds might be related to the geological and geomorphic characteristics. The results show that 1) the thresholds of post-fire debris flows tend to increase as time passes; 2) post-fire debris flows in the Reneyong Valley occur with high frequency not only because of the loss of the natural canopy, the occurrences of an ash layer and dry ravels and an increase in soil water repellency but also because of the geology, drainage area, channel gradient and regional arid climate, which may not be affected by wildfire; and 3) the varied rainfall thresholds among the different branches are dependent on the drainage area, as entrainment is controlled by the magnitude of discharge.

***Key words:*** wildfire; debris flows; multiple factors; rainfall threshold

## 1. Introduction

Wildfires can quickly destroy vegetation and change the features of mountainous areas, resulting in a high erosion rate (Conedera et al., 2003; Lane et al., 2006; Nyman et al., 2015; Orem and Pelletier,

2016) through debris flows, debris floods, debris slides, etc. The likelihood of post-fire debris flows increases in proportion with burn severity (Jordan, 2016). Post-fire debris flows are caused mainly by the runoff-triggered entrainment of hillslope material (Cannon et al., 2001; Santi et al., 2008; Kean et al., 2011, Parise and Cannon, 2012) and infiltration-triggered meter-scale shallow landslides (Wondzell and King, 2003; Cannon and Gartner, 2005; Parise and Cannon, 2012). Statistics show that the majority of post-fire debris flows are triggered by surface water runoff (Gartner, 2005; Parise and Cannon, 2012; DeGraff et al., 2015), especially in the first 1~2 summers after a wildfire, when large quantities of ash from burned vegetation and unaggregated fine-grained dry ravel are susceptible to overland runoff or debris flows. As time passes, the underground roots decay, and more infiltration-triggered meter-scale shallow landslides emerge and transform into debris flows(Jordan, 2016; DeGraff et al., 2015).

Surface water runoff can be generated when the rainfall intensity is greater than the infiltration rate. Wildfire can quickly destroy the vegetation in mountainous areas, making it possible for rainwater to directly reach the earth rather than being intercepted by the canopy (Robichaud, 2000; Wondzell and King, 2003; Larsen et al., 2009; Stoof et al., 2012). The sealing of surface soil pores by ash remnants and other unaggregated fine soil particles can reduce the infiltration capacity of the soil (Larsen et al., 2009; Woods and Balfour, 2010). In addition, soil water repellence increases after a fire so that the soil resists wetting for a time and its soil hydraulic ability declines (Doerr and Thomas, 2000; MacDonald and Huffman, 2004; Doerr et. al., 2006; Nyman et al., 2010). The hydraulic conductivity related to soil sealing, soil water repellency and other hydrological properties(MacDonald and Huffman, 2004; Moody et al., 2016). Moody et al.(2016)suggest that soil hydraulic conductivity is unchanged and remains equal to the values for soil unaffected by fire for low burn severity and exponentially decreases with burn severity when it is high. In short, a change of the surface soil properties caused by wildfire can significantly decrease the soil hydraulic conductivity and induce greater surface water runoff for a given amount of rainfall (Robichaud et al., 2000; Onda et al., 2008; Moody and Ebel, 2012; Moody and Ebel, 2014). In addition, the rainfall threshold for debris flows can greatly decline after a wildfire (Conedera et al., 2003; Cannon et al., 2008; Moody and Ebel, 2012; Staley et al., 2013).

The existing research on post-fire debris flows focuses more on western America (Robichaud et al., 2000;Cannon et al., 2008; Larsen et al., 2009; Kean et al., 2011; Moody et al., 2016), followed by southeastern Australia (Lane et al., 2006; Nyman et al, 2010; Smith et al., 2010); British Columbia, Canada (VanDine et al., 2005; Jordan, 2016);and Switzerland (Conedera et al., 2003). In western China, certain debris flows affected by wildfirehave been reported in Yangfan (Yunan Province) in the 1970s, Jiarongka (Sichuan Province) in 2015 and Reneyong (Sichuan Province)in 2014 and 2015;however, no detailed research has previously been conducted. This manuscript aims to:1) document the post-fire debris flows in western China; 2) explore the effects of the inherent climatic, geologic and geomorphic characteristics on post-fire debris flows; and 3) determine the reasons for the variations in rainfall threshold among debris flows.

## 2. Study area

### 2.1 Natural setting

The Reneyong Valley, located in Xiangcheng County in the central Hengduan Mountains of western China, covers an area of 24.28 km$^2$ with an outlet to the DingquRiver (which flows into the Jinsha River, upstream of the Yangtze River) at 29°08′N, 99°33′E (Fig. 1). This catchment has a nearly equilateral triangular shape and is surrounded by high mountains reaching 4222 m a.s.l. at the northernmost location and 2855 m a.s.l. at the westernmost location on a fork of the Dingqu River. There are 9 branches (No. 1~No.9) in this watershed (Fig. 1), and the width of the channels varies between 2 and 30 m. In general, the branches have V-shaped channels and the main channel is U-shaped. The geographic information for the three branches where debris flows occur is listed in Table 1.Branches No. 1, No. 2 and No. 3 are in the southern part of the catchment and have an elongated shape and a southeast-northwest orientation. Branches No. 1 and No. 2 have a similar channel gradient, but branch No. 3 is much gentler. The change in gradient along the stream is similar, with the steepest gradient in the central part and a relatively gentle gradient in the upper and lower portions.

The continental monsoon plateau climate prevails in the study area, with rainfall concentrated from June to September and plentiful sunshine. According to the statistics of rainfall data from the Xiangcheng meteorological station (approximately 33 km to the southeast), the mean annual rainfall is 472.62 mm and the mean annual evaporation capacity of 2362 mm is 5.28 times the mean annual rainfall, indicating that the study area is quite arid. Tall trees, shrubs and herbs cover the entire watershed, and the majority of the trees are Pinus densata.

Faults tend to have a north-south orientation, and no single fault extends through the watershed(Fig. 2). As in the Three Parallel Rivers area, the Neotectonic movement is strong with the uplift of the Tibetan plateau; however, historically, earthquakes in Xiangcheng was reported to be lower than Ms. 6.0, and the strongest recorded earthquake (Ms. 5.3) occurred on 5June1974 in Dongjun village, 27 km northeast of this catchment. The bed lithology is soft rock and is divided into 4 units(Fig. 2) nearly parallel to the fault: black slate and sandstone of the Triassic system upstream, sandy slate and some limestone of the Triassic system in the middle stream, black slate and some limestone of the Triassic system on both sides downstream and alluvial deposits of the Quaternary system on the channel bed and in the accumulation fan downstream.

## 2.2 Debris flow cases

Ancient debris flow deposits exist in the accumulation fan, indicating historical debris flows. Interviews with local citizens indicated that no debris flows occurred in the 100 years before 2014, while at least 4 debris flows have occurred since the wildfire in June 2014 (Table 2).

The town of Zhengdou is on the accumulation fan of the Reneyong Valley. On 8 June2014, the local administrators were holding a seminar on reconstruction after the wildfire and were warned of debris flows by a patrolman (Jiuli) who was responsible for geological hazards after he had found no water flows in the channel. This first debris flow is identified as DF1 in this paper. After that debris flow, the Sichuan Institute of Geological Engineering Investigation was appointed to conduct a field survey. On 30 June, another debris flow occurred that is identified as DF2. On the night of 10July2014, when we were staying at the local elementary school, we heard the noise of a debris flow collision and then witnessed the debris flows in the downstream (this event is identified as DF3). On 24August2015, a storm was predicted by the weather report, and the local geologic hazards administrator issued a warning. Before the debris flows reached the downstream area, the patrolman (Jiuli) again found no water flows in the channel and warned the local people to escape. This event is identified as DF4. Fortunately, the 4 debris flows were reported before they reached the village, and although the debris flows destroyed houses (Fig. 3), roads (Fig. 4) and farmland, leading to an economic loss of 18 million Yuan, no people were killed.

In fact, as stated by a local citizen, in 2014, there were other debris flows rushing out from branch No. 1, carrying dozens or hundreds of cubic meters of sediment downstream and cutting off the Xiangcheng-Derong road. As the debris flows did not hit residential areas or destroy other facilities, the exact time of the debris flows remains unclear. In general, debris flows after the wildfire in Reneyong

Valley is of high frequency.

# 3. Methods

## 3.1 Meteorological data

In western China, most rain gauges are located in the valleys, where there are more residents and the basic facilities are better, while few exist in the upper areas where debris flows begin. The study site is in the central Hengduan Mountains, and the nearest three rain gauges, at Zhengdou, Adu and Reda near the study area, are applied(Fig. 2, Table 3). The firs train gauge, Zhengdou, is on the deposition fan of the Reneyong Valley; the second, Reda, is in another valley on the other side of the southeastern crest; and the third, Adu, is in the same valley as Reda on the other side of the northeastern crest. The three rain gauges form a triangle around the study area, monitoring rainfall sources from several sides. Other information about the three rain gauges is listed in Table 3.

As rainfall arriving at the initiation area can be transformed in different ways, rainfall data from the nearer rain gauge could be more important for determining the average rainfall process. Indeed, the reciprocal-distance-squared method can be used to deduce the average rainfall process in the initiation area as follows(Chow et al., 1988; Chen et al., 2012):

$$P = \sum_{i=1}^{3} \omega_i P_i \qquad (1)$$

where $P_i$ is the rainfall record from the rain gauges; $i$=1, 2, or 3 represents the Zhengdou, Reda and Adu rain gauges, respectively; and $\omega_i$ is the weighing factor corresponding to $P_i$. The weighting factor can be expressed by $\omega_i = d_i^{-2} / \sum_{i=1}^{3} d_i^{-2}$, where $d_i$ is the distance from rain gauge $i$ to the debris flow initiation area.

## 3.2 Field survey

After the debris flows, we conducted a field survey to evaluate the impact of the wildfire and investigated the initiation process and the magnitude of the debris flows to propose debris flow alleviation strategies. After DF1, we conducted the first field survey and personally witnessed DF2 moving downstream when we were living in the local elementary school. After DF4, we conducted a second field survey to investigate the debris flow imitation process and examine the impact of debris flows on the check dams to evaluate whether additional work was required to prevent future debris flows.

(1) Detecting the scope of the wildfire

We interviewed the local citizens and were informed that the fire was accidentally set by workers who were building an iron tower for an electrical transmission line at 18:00 on 1 June 2014. After the fire, fire fighters, armed police and local citizens gathered to fight the fire and it was extinguished at 10:00 on 5 June.

After the wildfire, the forest administrators measured the scope of the wildfire. They walked along its boundary and marked the scope on a contour map (with a scale of 1:100000). According to this map, an area of 5.4 $km^2$ in the catchment was affected by the wildfire (Fig. 1), accounting for 22.2% of the entire watershed. In detail, branches No. 1, No. 2 and No. 3 were within the scope. The majority of the trees are Pinus densata, under which are shrubs and herbs, a good place for yaks and sheep to graze (Fig. 5).

(2) Sediment investigation

Our field survey was conducted along the channel, and a laser range finder was applied to gather measurements. We measured the bank failure and the high erosive deposits along the two sides of the channel, the bank-failure induced soil slide, and the scope and amount of spoil along the Xiangcheng-Derong road. We marked these on a contour map and recorded them in a notebook, respectively. We dug six troughs, 1.5m in length, 0.5 m in width and 0.3~0.6 m in depth (Fig. 6), on the slope where the wildfire burned to detect the depth of the ashes and the variety and extent of roots destroyed by the wildfire. We also collected soils from the troughs to measure the particle size distribution and the natural water content. In addition, a borehole was used to measure the depth of the debris flow deposits and the loose gravel deposits underneath.

(3) Measurement of debris flow deposits

The volume of debris flows can be used to evaluate the magnitude, which can be found by measuring the sporadic deposit division. For each deposit division, we used a laser range finder to measure the scope and average depth to calculate its volume. The precision of the volume was more dependent on the measurement of the average depth, which can reach 100 $m^3$, thus the volume of each division larger than 50$m^3$ would be recorded as 100 $m^3$, otherwise, it would be not included.

The majority of DF4 is deposited behind two newly built check dams and only a few portions

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-390
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
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reached downstream by passing through cracks on the check dams. We measured and marked the boundaries of the deposits on the contour map that was completed during the first field survey before the check dams were built. We measured the height of the check dams above the deposits and obtained the depth buried by the deposits, which is the greatest depth of the deposit. We divided the largest deposit depth into several parts and calculated the volume as follows:

$$V = \sum_{i=1}^{n} h_i A_i \tag{2}$$

where $V$ is the volume of the deposits; $h_i$ is the height of each part of the deposits; $A_i$ is the area of the horizontal area; $i$ =1, 2, …… , and n represents the parts that were divided. Normally, we set $h_i$ =1m, which means that the deposits from the toe of the dam to the end of the deposit after the dam were divided into n parts and that each part had a height of 1m. $A_i$ is the area circled by the axis of the dam and the corresponding contour line and can be obtained using a 1:500 contour map.

In the deposit zone, we measured particle size and lithology. We placed a ruler of 50 m on the surface of the deposits randomly. We measured particle size and recorded the lithology of the stones at a 1-m interval along the ruler (Fig. 7). For particles larger than 60 mm, the diameter and lithology were recorded, otherwise, only the lithology was recorded. Deposits smaller than 60 mm were collected to complete particle size distribution tests in the laboratory.

# 4. Analysis and results

## 4.1 Recorded rainfall process

Before the debris flows daily rainfall data were collected from Zhengdou, Reda and Adu, and the reciprocal-distance-squared method was applied to obtain the average rainfall(Table 3). Table 2 shows that in 2014, there was only occasional drizzle in the preceding days and the 3-day accumulated rainfall was only a few millimeters except in the case of DF3, when it was 14.84 mm. In 2015, it sprinkled for several days, and the 3-day accumulated rainfall before DF4reached nearly 40 mm (daily rainfall data for the day before DF4 is missing because of instrument error, and rainfall data from the Xiangcheng meteorological station, 33 km to the southeast, were used). In the year that the wildfire occurred, the 3-day accumulated rainfall for the 3 debris flows varied greatly, which suggests that post-fire debris flows were not correlated with the antecedent rainfall; however, the antecedent rainfall significantly

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increased in the second summer.

Hourly rainfall data before and after the debris flows were collected from Zhengdou, Reda and Adu, which were applied to determine the average rainfall process by the reciprocal-distance-squared method. The rainfall processes before and after the four debris flows are depicted in Fig. 8, which shows there was short-term low-intensity rainfall before the three debris flows in 2014. The rain gauge worked well, as local administrators discussing reconstruction after the wildfire recalled that only occasional drizzle had occurred prior toDF1. When we were living in the local elementary school we witnessed only sprinkles when DF3 occurred. However, it seems impossible for a rainfall intensity of 1mm/h or less to generate sufficient surface runoff and the subsequent debris flows. Instead, local convective rainfall in the mountains could be the trigger which cannot be recorded by the nearby rain gauges.

On 24 August2015, the storm began at approximately 19:00, and the average rainfall intensity reached 26.39 mm/h. In the outlet of the main channel, the rainfall intensity reached 38.5 mm/h and then declined to less than 5 mm/h. DF4 arrived in the downstream area at approximately 19:43, and if we deduct the time needed for it to move from the initiation area to the outlet, we find that the debris flows were likely initiated shortly after the rainfall began.

## 4.2 Debris flow initiation process

According to the location of the debris flow deposits and the residual scar left by debris flow erosion, all the debris flows originated in the fire-affected area, with DF1, DF2 and DF3 deriving from branch No. 3 and DF4from branches No. 1, No. 2 and No. 3 and some smaller neighboring catchments on 24August2015. However, as some catchments' drainage is too small to depict accurately in Fig. 1, this paper considers only branches No. 1, No. 2 and No. 3.

(1) Debris flows in 2014

In 2014, the debris flows were triggered in the upstream area of branch No. 3. Upstream, trunks were surrounded by charcoal and ashes, and only a few trunks toppled over. Shrubs, herbs and litter were consumed by the wildfire, and the slope surface was covered by ashes, but the underground root system survived and the affected soil was concentrated in only a few centimeters. Unaggregated dry ravel is widely distributed, and dry ravel remnants mixed with ashes were found to have flowed along the slope, indicating that the entrainment of the surface runoff should be the origin of the debris flows.

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The channel is only 0.5~0.8 m wideand0.4~0.6 m deep on a steep slope with exposed stones and no debris flow deposits (Fig. 9). Items above the channel fell parallel to the channel, suggesting that the debris flows submerged the entire channel and that the discharge was still smaller than 1 $m^3/s$. Erosion caused by the debris flows is limited by the small discharge, and the transported soil particles were limited in the smaller debris flows. In the middle stream and downstream areas of branch No. 3, the channel gradient decreases, while the slope of both sides increases to 35~45°, forming a narrow V-shaped gully. The moving debris flows entrained the bed sediment and scored the base of the banks, leading to bank failure on both sides. The intensive scars of landslides with no vegetation can be found on both sides along the channel. These shallow landslides were meter-scale, with a volume ranging from tens of cubic meters to thousands of cubic meters. At the beginning, where the channel is quite narrow, it can be blocked by landslide deposits of a small magnitude; as more sediment is deposited in the channel, the broadened channel can be partly blocked by a small landslide and entirely blocked by a large one (Fig. 10). In addition, the burned trunks can favor channel blocking. Channel blocking alleviates the debris flow process, and the outburst debris flows have a significantly larger discharge (Cui et al., 2013; Zhu, 2013).

(2) Debris flows in 2015

The debris flow initiated in branch No. 2 (Fig. 11) is similar to that initiated in branch No. 3, while that initiated in branch No. 1 (Fig. 12) is slightly different. Shrubs, herbs and the lower parts of the trees were partly consumed by the wildfire. In the second summer after the wildfire, the trees were again covered by green crowns. Branch No. 1 can be divided into three parts according to the channel gradient, with the steepest gradient (32°) in the middle part, where the debris flow was initiated, and a gentle gradient in the source area. Two smaller gullies converge at the debris flow initiation zone, forming a platform between them. During the storm, the surface water runoff in the source area entrained sediment and formed a debris flood. Following the debris flow initiation zone, which is quite steep, the debris flood from the two gullies had a higher erosion ability; it scored both sides of the platform and triggered bank failure, followed by the retrogressive meter-scale landslide failure of the platform. The debris flood mixed with the detached bank slope and formed debris flows; meanwhile, the 9.2 mm of accumulative rainfall over the previous three days endowed the surface layer with relatively higher water content, and the retrogressive landslide failure caused it to slide and liquefy into debris flows. In the lower stream, a debris flow moving over wet sediment can greatly increase sediment entrainment and significantly amplify the magnitude of the flow (Iverson et al., 2011; McCoy et al., 2012).

### 4.3 Debris flow deposits

The majority of DF1 deposited in the wide section of the channel downstream of the fork with branch No. 3. Some of it jumped the channel banks and destroyed houses, and the remaining rushed into the Dingqu River though it did not block the river (Fig. 13a). DF2 traced the previous path, leaving a slight depth of debris covering the DF1 deposits and striking our borehole instrument (Fig. 13b). The volume of DF2 is much smaller than that of DF1. DF3 continually traced these deposits and left considerable deposits in the wide section. DF3 also jumped the river banks and buried some parts of the road in the residential area and the remaining partially blocked the Dingqu River (Fig. 13c). As two check dams were completed, the deposits of DF4are much different. The majority of DF4 was intercepted by the two check dams except a portion in the mainstream. Debris reached the top of check dam No. 1 (with a height of 4 m) and only the upper 6 m of check dam No. 2 was above the deposits (Fig. 13d), leaving the lower 12 m buried by the deposits.

Based on field measurements and indoor calculations, we determined the volume of the four debris flows (Table 2). There are large differences among the volumes of the debris flows, of which, the volume of DF4 is the largest, reaching 154,500m$^3$, followed by DF1at 86,200m$^3$, DF3at 3,2300 m$^3$ and DF2at 5,100m$^3$. Although the volumes of DF2 and DF3are smaller than that of DF1, they still arrived downstream and were dangerous, as DF1 had paved a path, and the friction of the stream had decreased significantly. Statistics show the deposits are angular, and the majority of them are sandy slate (90.48%), followed by slate (7.14%) and limestone (2.38%), which suggests that the debris flows originated from branches Nos. 1~3, where sandy slate dominates, and this suggestion is consistent with our field survey.

## 5. Discussion

Debris flows do not occur in all fire-affected watersheds; instead, the response to rainfall could be debris flows (in a proportion of 40%) (Cannon, 2001; Nyman et al., 2010; Kean et al, 2011), flash floods (Cannon, 2001; Kean et al. 2011)or no response (Cannon, 2001; Smith et al. 2010). The debris flows in the Reneyong Valley are unusual because the debris flows are of high frequency; in addition, although three debris flows occurred in branch No. 3 in 2014, branches No. 1 and No. 2 had no response to rainfall even though they had steeper gradients and debris flows are more likely to occur in the first year following wildfire.

These facts lead us to believe that the likelihood of debris flows is correlated with the impact of wildfire but also with the geology, drainage area, channel gradient, and regional climate, which are not affected by wildfire. In the later discussion, we attempt to discuss these factors to resolve the doubt we have encountered regarding the post-fire debris flows in the Reneyong Valley.

## 5.1 Rainfall threshold

The 4 post-wildfire debris flows in the Reneyong Valley were generated by surface water runoff. The rainfall intensity recorded by the downstream rain gauge was 1 mm/h or less and the duration was quite short, which is in line with the memory of the local citizen in the downstream area who witnessed the flow, suggesting the rain gauge was working well; however, it seems impossible for a low-intensity short-duration rainfall to generate surface water runoff, let alone entrain sediment and trigger debris flows. In the Hengduan Mountains, isolated convective rainfall is common and has been found to be an important trigger of debris flows in this area (Tang et al., 2011; Ni et al., 2014); in addition, rainfall intensity has also been found to increase with elevation in the Jinsha Basin(Tan et al., 1994). Here, we speculate that the three post-wildfire debris flows in 2014 were triggered by isolated convective rainfall and that the rain gauges down slope can definitely record the triggering rainfall.

Observations of debris flows in the Jiangjia Valley show that higher intensity rain can generate debris flows of larger magnitude, and an exponential increasing model was built (Zhuang et al., 2009) that might model the process of rainfall amplifying the activity of debris, resulting in more soil slides and of greater magnitude (Dai and Lee., 2001; Guo et al., 2013). In addition, sediment wetted or saturated by rainfall is more susceptible to entrainment by debris flows (Iverson，2011；McCoy et al., 2012). Similar research can be found in post-wildfire research, just as rainfall totals have been applied in the magnitude prediction model, other factors, including drainage area and burned areas of high and moderate severity, have been incorporated (Gartner et al., 2008; Cannot et al., 2010).

In a given catchment, we attempted to use the volume of the debris flows to deduce the possible triggering rainfall as follows: the volume of DF4 is much larger, suggesting the highest triggering rainfall, followed by DF1, DF3 and DF2, respectively. In a word, low rainfall in 2014 did trigger three debris flows in branch No. 3, while none occurred in branches No. 1 and No. 2. Greater rainfall in 2015

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generated debris flows in the three branches, which indicates that the rainfall threshold for post-wildfire debris flows in the Reneyong Valley was quite low during the first summer after wildfire and that it increased as time passed. In addition, debris flows in branches No. 1 and No. 2 had a higher rainfall threshold compared to that of branch No. 3.

## 5.2 Regional climate

Soil water repellency could be of high significance in reducing soil hydraulic conductivity and amplifying surface water runoff immediately after a wildfire(MacDonald and Huffman, 2004; Doerr et. al., 2006; Moody et al., 2013). It may also inhibit the soil rewetting process (Doerr et al.,2000), which may require days to weeks and will be quite small or nonexistent in the second summer after a fire (MacDonald and Huffman, 2004; Larsen et al., 2009).According to our trough test, soil in the burned area was covered by a centimeter of ashes and the surface layer affected by wildfire was concentrated in only a few millimeters(Fig.6), and the soil water repellency of the surface layer should have been limited, which might have played a key role in triggering DF1 and might have had no effect on DF4.

The surface soil could have low water content as a result of the long-duration arid climate, so that the surface layer could also have low hydraulic conductivity (Moody and Ebel, 2012; Sheridan et al, 2016). This low conductivity may be responsible for the quite low rainfall threshold for the later debris flows, as rainfall infiltration into the soil is limited and surface runoff can easily occur. Indeed, if a hyper-dry condition is reached, no rain can infiltrate into the soil (Moody and Ebel, 2012). The effect of a long-duration arid climate on soil water content could be meter-scale, while the depth of rainfall infiltration is limited to the surface and the time for the soil to recover aridity could be only days. Aridity should be a key theme because the drought ravel in steep arid catchments has been identified as an important source of runoff-triggered debris flows (Kean et al., 2011, 2013; Staley et al., 2014; Noske et al., 2016).

It is highly difficult for vegetation to recover in newly generated landslide scars in an arid climate, and the uncovered loose sediment can be much more easily entrained by debris flows without the binding effect of roots (Ziemer,1981; Gyssels et al., 2005). In general, the increase in soil water repellency and decline in hydraulic conductivity induced by wildfire should be transient and the effect of an arid climate on erosion could be perennial, which has been verified in the non-fire-affected area (Carretier et al.,2013).

### 5.3 Geology and soil properties

Sandy slate from the Triassic system dominated the three branches, accompanied by small amounts of limestone. Sandy slate is soft and susceptible to the weathering process, resulting in a deep mantle of soil covering the bedrock with a high fine-particle content and more boulders of limestone. Based on the field survey of the successive landslide scars along the branches, the sediment is fine grained, arid and loose, characteristics that make it vulnerable to debris flow entrainment. As the weathered eluvium is abundant, the channel is charged with sediment, resulting in a high frequency of debris flows (Bovis and Jakob, 1999; Jakob et al., 2005). In the branches, the underlying bedrock can hardly be found, and bedrock in some sections of the main channel is uncovered, suggesting that the downward erosion of debris flows is an important process in the steep branches and that the successive bank failures are generated by debris flow bulking(Hungr et al., 2005; Gabet and Bookter, 2008; Zhu, 2013). These landslides can partly or wholly block the channel, and debris flows can be greatly amplified after an outburst(Cui et al., 2013; Zhu, 2013).

### 5.4 Channel gradient and drainage area

The three catchments share a similar channel gradient, with the largest gradient in the central part and smaller gradients in the upper and lower parts (Table 1). This configuration tends to produce a greater surface runoff for a given rainfall process and to exert higher erosion ability in the middle area with the largest gradient to produce debris flows of greater magnitude(Coe et al., 2008; McCoy et al., 2012), as entrainment in steep terrain can increase rapidly with slope owing to both shearing stress and transport capacity (Foster and Meyer, 1972; Stock and Dietrich, 2003; Hungr et al, 2005; Moody et al, 2013; Kean et al, 2013).

Drainage area, the scope of the area that rainfall can flow into, is a more dominant factor for the magnitude of surface runoff. Of the three sub-catchments, branch No. 3 has the largest drainage area, followed by branches No. 2 and No. 1, each of which has a drainage area smaller than 1 $km^2$. In 2014, the debris flows originated solely in branch No. 3; however, in 2015, debris flows occurred in branches No. 1~3 and some smaller sub-catchments where the rainfall intensity reached 38.5 mm/h. Here, we hypothesize that the terrain is similar: a larger area tends to have greater surface water runoff, and the likelihood of debris flow occurrence could be higher; thus, greater rainfall is required to trigger post-fire debris flows in a relatively smaller area.

This principle should not be applied in all fire-affected areas, as the statistics developed in earlier studies (Gartner, 2005; Cannon et al., 2010)suggest that post-fire debris flows can occur where the drainage area is smaller than 25 km$^2$ and even where it is smaller than 5 km$^2$. The reasons may be that the terrain of a smaller catchment is apt to be steep and the surface water runoff can have higher erosion ability (Hungr et al, 2005; Moody et al, 2013), increasing the susceptibility to debris flow occurrence; as the drainage area increases, the catchments tend to have wider channels and gentler gradients(Stock and Dietrich, 2003), resulting in smaller-unit runoff discharge and lower erosion ability. When the drainage area is larger than 25 km$^2$, the unfavorable effects of a wider channel and gentler gradient on post-fire debris flows might surpass the favorable effect of wildfire, resulting in no response to the wildfire.

### 5.5 Human activity

In addition to the wildfire set accidentally by people, the construction of the Xiangcheng-Derong road is another important factor for the amplification of debris flows. The Xiangcheng-Derong road crosses the port on the eastern border and stretches along the main channel from the outlet of channel No. 5. Approximately 13.64 km is distributed in the Reneyong watershed, and abundant spoils were produced when it was constructed. These spoils were deposited on the southern slope of the main channel with a gradient slightly larger than the friction angle and only a few retaining walls; thus, some of them have reached the main channel, resulting in a narrowing of the channel. Spoils can also be found in some other branches. The spoils are composed of fine-grained particles and are only slightly covered by vegetation because of the arid climate. Although spoils outside the main channel were not affected by the wildfire, these spoils are still arid, with low hydraulic conductivity owing to long-term drought(Moody and Ebel, 2012; Sheridan et al, 2016). Low rainfall intensity is required to trigger surface water runoff and the consequent debris flows(Coe et al., 2008; Kean et al., 2011), which can partly or wholly block the channel (Fig. 14). This narrowed channel can also be blocked by the large trunks carried by debris flows.

At the narrowed channel section, the debris flows would have a greater depth, resulting in an increase in the debris flow velocity and greatly enhancing the subsequent erosion ability. A large amount of the erodible spoils was enrolled by the debris flows, significantly amplifying the magnitude (Cui et al., 2013; Iverson and Ouyang, 2015). After DF1, abundant spoils were entrained by the debris flows, and remnants of the deposited spoils can be found in a steep section 2~4 m high(Fig. 15). From the outlet of branch No. 3, there were more than 10 narrowed channel sections; one would induce a significant entrainment process that could amplify debris flows.

## 6. Conclusion

The existing research on post-wildfire debris flows focuses mainly on the decline in hydraulic conductivity resulting from the increase in soil water repellency (Doerr and Thomas, 2000; MacDonald and Huffman, 2004; Doerr et. al., 2006; Nyman et al., 2010), the process of soil sealing(Larsen et al., 2009; Woods and Balfour, 2010), and the low rainfall intensity needed to produce surface water runoff and trigger debris flows. In addition, the geologic and geomorphic characteristic of the catchment that may not be affected by wildfire can still produce favorable effects for the magnitude and frequency of debris flows as follows: 1) The arid climate can reduce the soil water content and hydraulic conductivity, which can have a positive effect on debris flows, as soil water repellency will quickly decrease after rainfall; in addition, the arid climate leads to slow vegetation recovery. 2) The deep weathered remnant of sandy slate has high fine-particle content and high susceptibility to debris flow entrainment; therefore, the watershed is charged with abundant sediment. 3) The "gentle-steep-gentle" gradient can contribute to greater surface water runoff and the subsequent severe erosion process in the steep area. 4) The downward erosion of debris flows in the steep branches generates successive bank failure, which amplifies debris flows. 5) Statistics show that post-fire debris flows tend to occur in catchments smaller than 5 $km^2$ (Cannon et al., 2010) and debris flows in smaller watersheds are apt to be triggered by a higher rainfall threshold, such as for branches No. 1 and No. 2.

## Acknowledgements

This research was supported by the National Natural Science Foundation of China (grant Nos. 41661134012 and 41402283). We wish to acknowledge the editors of the Natural Hazards and Earth System Science Editorial Office and the anonymous reviewers for their constructive comments, which helped us improve the content and presentation of the manuscript.

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Table 1. Geographic information for branches No.1~No.3

| No. | Drainage area ($km^2$) | Maximum basin relief (m) | Gradient (degrees) | Gradient (central part) (degrees) | Gradient (upper part) (degrees) |
|---|---|---|---|---|---|
| Branch No.1 | 0.37 | 544 | 27 | 32 | 18 |
| Branch No.2 | 0.73 | 755 | 26 | 35 | 18 |
| Branch No.3 | 2.30 | 836 | 15 | 20 | 14 |

577 Table 2. Basic information regarding the debris flows

| No. | Time | Location | Recorded 3-day antecedent precipitation(mm) | Debris flow volume (1000 $m^3$) |
|---|---|---|---|---|
| DF1 | 16:08, June 8, 2014 | No. 3 | 1.11 | 86.2 |
| DF2 | 16:00, June 30, 2014 | No. 3 | 14.84 | 5.1 |
| DF3 | 23:20, July 10, 2014 | No. 3 | 0.81 | 32.3 |
| DF4 | 19:43, August 24, 2015 | No.1, No.2 and No.3 | 39.97 | 154.5 |

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Table 3. Basic information regardingthe three rain gauges

| No. | Name | Location | Elevation (m) | Distance (km) | Precision (mm) | $\omega_i$ |
|---|---|---|---|---|---|---|
| 1 | Zhengdou | 29°08′N, 99°33′E | 2858 | 3.90 | 0.1 | 0.60 |
| 2 | Reda | 29°06′N, 99°38′E | 3363 | 5.56 | 0.1 | 0.30 |
| 3 | Adu | 29°11′N, 99°39′E | 2783 | 9.40 | 0.1 | 0.10 |

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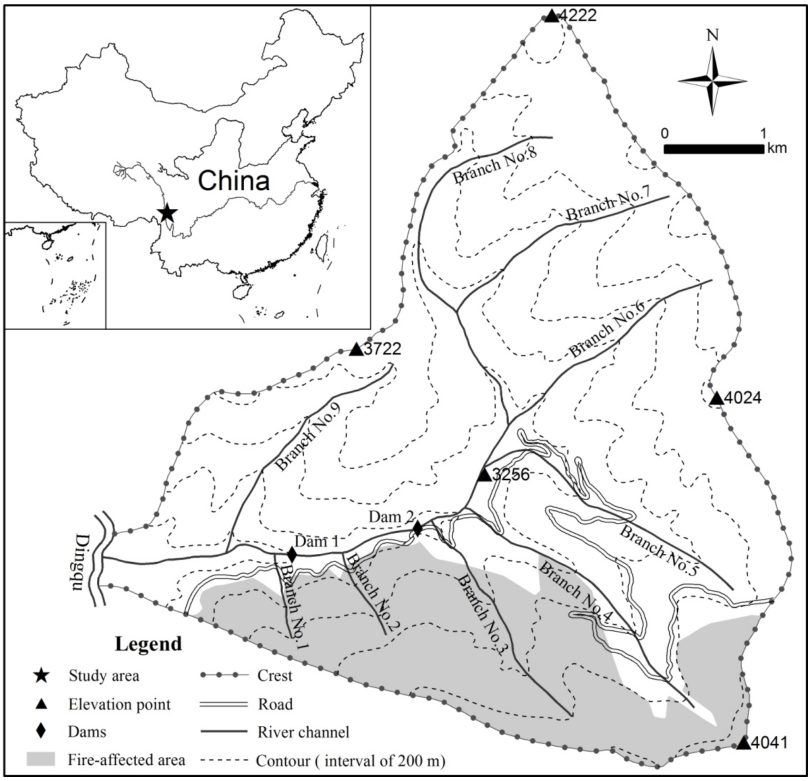


582
583 Figure. 1. Location of Reneyong Valley and related geographic features

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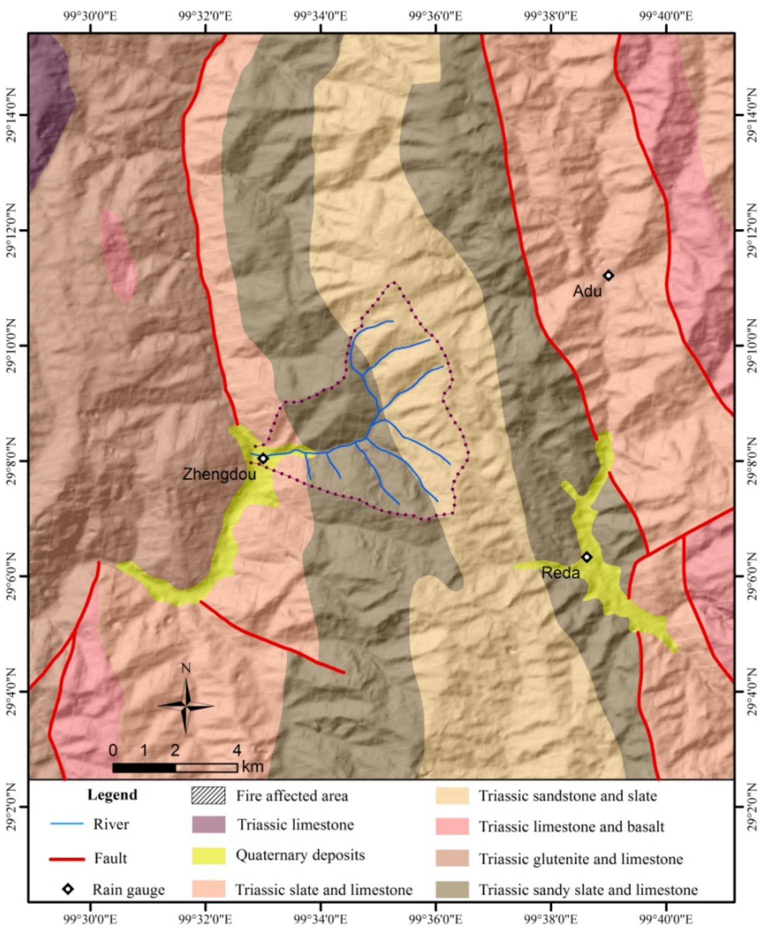


584

585 Figure 2. Simplified geologic map and distribution of applied rainfall gauges

586 

587 Figure 3. Houses destroyed by debris flows in the downstream

588 

589 Figure 4. Road buried by debris flows from branch No. 3

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Figure 5. Overlooking the fire-affected area

Figure 6. Trough test in the fire-affected area

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596 Figure 7. Particle size measurement of debris flow deposits(DF1)

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Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
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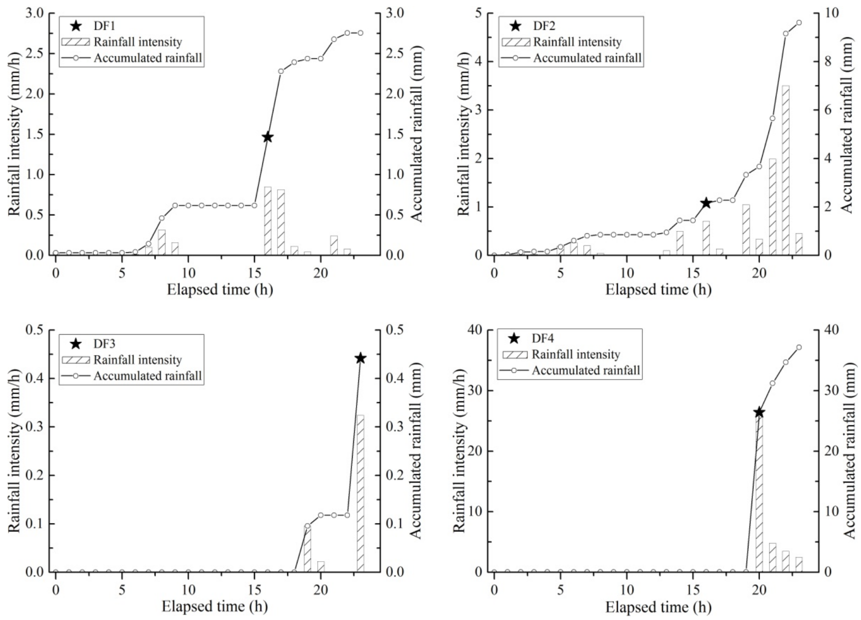


Figure 8. Recorded rainfall prior to the debris flows(rainfall data from theZhengdou, Reda and Adu rain gauges were applied)

Figure 9. Upstream of branch No. 3 after DF1 (no debris flow remnants)

Figure 10. Middle stream of branch No. 3 after DF1

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606 Figure 11. Branch No. 2 after DF4

Figure 12. Branch No. 1 after DF4

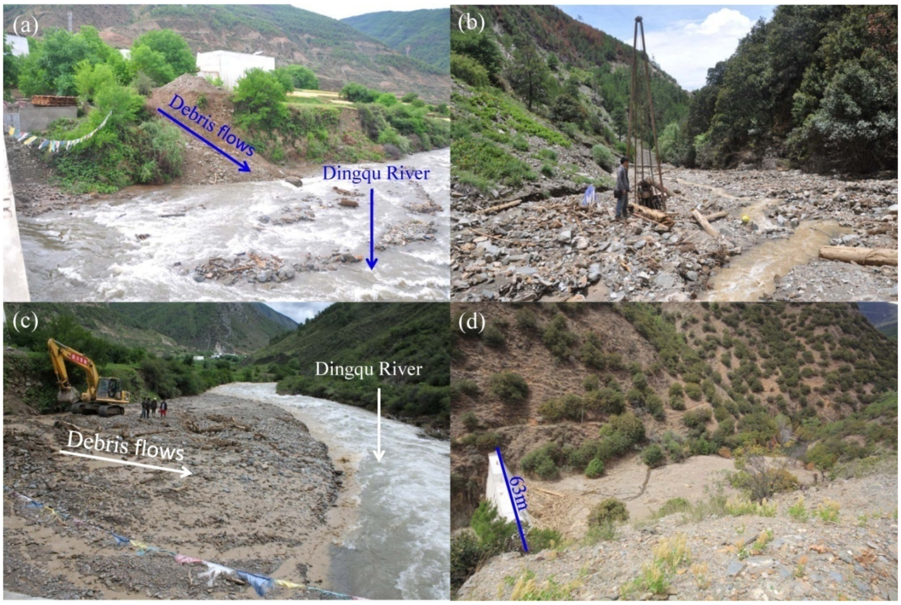


Figure 13. Debris flow deposits of (a) DF1 in the Dingqu River, (b) DF2 slightly striking the borehole instrument, (c) DF3partly blocking the Dingqu River, and d) DF4 intercepted by check dam 2


613

614 Figure 14. The main channel narrowed by spoil and spoil-induced debris flows


Figure 15. Remnants of a spoil dam after debris flows