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A new prediction model on debris flows caused by runoff mechanism

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Abstract

In areas with strong earthquakes, the triggering rainfall threshold for debris flow initiation decreased dramatically just after the quake, but will increase gradually during the subsequent raining seasons, until the level before the quake. The channel width and particle size in the source area of debris flows in catchments decreased dramatically during a strong earthquake due to the supply of finer material in channels by co-seismic landslides. Debris flows in these areas are initiated by run-off water in channels and the presence of loose materials and narrowed channels leads to a significant decrease of the critical rainfall threshold for debris flow initiation just after the earthquake. The gradually coarsening of the material and widening of the channels during the subsequent raining seasons by debris flows and flashfloods will rise again the triggering threshold. Based on these important principles, a revised prediction model on debris flows is proposed, which incorporates the effect of channel width and the particle size of channel materials. The new prediction model was successfully validated on a group of debris flow events in Dechang, Sichuan Province, China. The new prediction model was also able to successfully simulate the change of the triggering rainfall threshold before and after the Wenchuan Earthquake in the Wenjia Gully, Sichuan Province, China, where five debris flow events happened during three subsequent rainy seasons after the earthquake. It is suggested that the new prediction model on debris flows (can also be applied) is also valid in non-seismic areas where significant loose material is available supplied by large landslides.

Keywords Prediction · Debris flow · Runoff · Channel width · Particle size

Introduction

Debris flow is a rapid surging flow of saturated debris in a steep channel (Hungr et al. 2014; Alzo'ubi 2018). Many debris flows were triggered in the Wenchuan Earthquake area after the Ms8.0 Wenchuan earthquake in Wenchuan County, Sichuan, China on May 12, with the epicenter near Yingxiu town. The most well-known concentrations of debris flow events in this area affected by this strong earthquake, are the debris flows near Yingxiu town, Wenchuan County, Longchi town, Dujiangyan County, and Qingping town, Mianzu County, Sichuan, China which occurred on August 13, 2010 (Xu 2010; Tang et al. 2011; Horton et al.

2019). There were more than 60 debris flows triggered in these three areas. More than 50 persons died or were missing and the economic loss was more than 1 billion Chinese Yuan because of these debris flow events. Another group of debris flows occurred along the Minjiang River between Yingxiu town and Wenchuan County on July 13, 2013 (Yang et al. 2016). All these debris flows have the following common characteristics: (1) they are channelized debris flows, and initiated by the runoff mechanism; (2) there is a large number of earthquake-induced rock falls and landslides in these debris flow catchments, and (3) these catchments showed a low-frequency of debris flows before the earthquake and turned into high-frequency debris flow catchments after the earthquake; (4) and consequently, the triggering rainfall threshold of debris flow just after earthquake is significantly lower than before the earthquake, and (5) the triggering rainfall threshold for debris flows is gradually increasing during the subsequent rainy seasons, until the level before the quake. The early warning of debris flows caused by runoff, especially debris flows in areas with strong earthquake, is of

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great significance for post-disaster reconstruction, disaster prevention and mitigation in mountainous areas.

Up to now some empirical prediction models are proposed for debris flows (Gregoretti and Dalla Fontana 2007; Yu et al. 2011; Staley et al. 2013; Simoni et al. 2020). Shieh et al. (2009), and Wu et al. (1990) used the 1-h or 10-min rainfall intensity and effective cumulative precipitation to predict debris flows with runoff mechanism. However, these empirical models cannot forecast debris flows quite well in areas with strong earthquakes.

The triggering of these debris flows in areas with strong earthquakes provides a theoretical basis and reference cases for better comprehending the initiation mechanism, leading to a better prediction of debris flows. The evolution of the critical rainfall threshold for debris flows after the Chi-Chi Earthquake in Taiwan and the Wenchuan earthquakes is basically the same (Shieh et al. 2009; Yu et al. 2014a; Chang et al. 2011; Fan et al. 2018a). The fall and rise of triggering rainfall thresholds for debris flows varies from region to region after a strong earthquake, and also within in a region there are deviations from the average trend for single debris flow catchments, due to varieties in characteristics and quantities of available source material (Yu et al. 2014a).

The initiation mechanism of debris flow of loose debris transformation by water runoff is subject to progressive erosion by hydrodynamic forces from the top down (Kean et al. 2013; Takahashi 1991). Evidence was found in flume experiments (Tognacca et al. 2000; Hu et al. 2016) and in the field (McCoy et al. 2012). The runoff mechanism triggering a channelized debris flow can be described by a heavy rainfall forming a strong flash flood in the channel, eroding the sediments, that are deposited by (co-seismic) landslides and rock falls, and which may trigger a debris flow according to the "fire hose" principle (Yu et al. 2014b, 2016a; McGuire et al. 2017; van Asch et al. 2018). Rainfall is the major triggering factor for the initiation of channelized debris flows. But there are different triggering mechanisms for debris flows, which correspond to different rainfall types. For example, a short period of heavy rainfall often triggers a debris flow by runoff (Simoni et al. 2020). And a medium or long period of heavy rainfall often trigger debris flow by shallow soil slips (Yu et al. 2014b, 2016a, b). The initiation by runoff of debris flows in areas with strong earthquakes is caused by the presence of abundant sediments deposited in channels by co-seismic landslides and rock falls. The rainfall type triggering debris flows in the Wenchuan earthquake area proposed by Zhou et al. (2012), is similar to a generic rainfall type triggering debris flow by runoff proposed by Yu et al. (2014b, 2016a). It is characterized by a short period of heavy rainfall initiating strong flash floods. These short periods of heavy rainfall tend to refer to heavy rainfall periods of 10 min to 1 h (Yu et al. 2014b, 2016a). But some researchers found that the triggering of this kind of debris flows is more closely related to 5-min period of heavy rainfall (Kean et al. 2011). They suggest that the effect of the amount of cumulatively rainfall for the triggering of such kind of debris flows is less important than the short period with heavy rainfall.

The topographical factors of a catchment, which play a role in the initiation of debris flows have not changed too much after a strong earthquake. The changes in these catchments are related to the accumulation of a large number of loose solid materials supplied by co-seismic rock falls and landslides in the channels, narrowing its original width. Some channels were completely blocked by these rock falls and landslides. This paper only studies the debris flows caused by runoff (flash floods). The initiation of debris flows caused by breaching of landslide dams belongs not to the scope of this paper. The biggest effect of strong earthquakes on debris flow frequency in catchments is the change in geological factors in particular the change in the properties of loose solid materials. Apart from the presence of large amounts of solid materials after the earthquake, these materials are also characterized by smaller particle sizes compared to the loose material deposited before the earthquake. The channel width and particle size of the available loose material in channels in the source area of a debris flow catchment decreased dramatically after a strong earthquake. These will gradually increase with some debris flow and flood events during the subsequent rainy seasons (Chen et al. 2014; Zhang and Zhang 2017; Fan et al. 2018b; Domènech et al. 2019). These changes are important factors for the change of the triggering rainfall thresholds of debris flows. Therefore, for a better forecast of debris flows, the width and the particle size in the channel in source area must be involved in the prediction model.

This paper introduces the width and particle size in the channel in the source area of a catchment for a new prediction model of debris flows. Different debris flow models were proposed in the past, taking into account the topographical factors, geological factors, and normalized rainfall factors but did not take into account the important role of the channel width and the particle size of the material in the channel (Yu et al. 2014b, 2016a). This new prediction model for channelized debris flows triggered by runoff is more generic because it may be used also in areas not affected by strong earthquakes.

Reformulation of the prediction model on debris flows

During a strong earthquake, the seismic landslides and rock falls narrowed the channel width, and deposited plenty of fine sediment particles. These make the triggering rainfall threshold decreasing dramatically because the fine sediments in the narrowed channels are easier to erode and may form a debris flow. During the subsequent

raining seasons, the flash floods and debris flows will widen the channel again and will coarsen the particle size of the material in the channel (Zhang and Zhang 2017). The widening of the channel decreases the unit discharge and thus the water erosion and transport power, while the coarsening of materials decreases the erodibility. Both processes raise again the rainfall threshold for debris flow initiation. And therefore, we will include both factors in our new model.

A prediction model for debris flows triggered by a runoff-induced mechanism consist apart from rainfall also of factors related to topography, and geology. Because two short rainfall periods, 10-min and 1-h period can be defined, the rainfall factor of the prediction model consists of a 10-min model and 1 h-model, which deliver two groups of critical values (see below) (Yu et al. 2014b, 2016a). The prediction model can be described as follows:

$$P = RT^{0.2}/G^{0.5} \geq C_r \qquad (1)$$

in which P = the prediction factor; R = a dimensionless rainfall factor; T = a dimensionless topographic factor of the source area where the debris flows are initiated; G = a dimensionless geological factor related to the loose material of the debris flow; C_r = a critical value for the prediction of debris flows. The topographic factor can be described as follow:

$$T = JF(A/A_0)^{0.2} \qquad (2)$$

in which J = the average slope of the channel in the source area; F = a form factor of the source area; A = the area of the source area (km^2); A_0 = the unit area (= 1 km^2). The geological factor can be described as follow:

$$G = F_0 C_1 C_2 C_3 C_4 \qquad (3)$$

in which F_0 = the average firmness coefficient of the lithology in the source area; C_1 = a correction coefficient for seismic intensity in the source area; C_2 = a correction coefficient for tectonics (faults) in the source area; C_3 = the correction coefficient for physical weathering in the source area; C_4 = the correction coefficient for chemical weathering in the source area. The rainfall factor can be described as follow:

$$R = R^*/(R_0 C_v) = (B + kI)/(R_0 C_v) \qquad (4)$$

in which R^* = the critical rainfall index (mm), which can be used directly in the practical prediction of debris flows; R_0 = annual precipitation of the site (mm); C_v = the coefficient of variation of 10-min rainfall of the site; B = the cumulative precipitation, until the start of the debris flow (mm); k = 12.5 (1-h model) or 8 (10-min model); I = the amount of rainfall in the hour (1-h model) or in the 10 min (10-min model) before the start of the debris flow (mm).

The critical values C_{r1} and C_{r2} are 0.35 and 0.47 (1-h model) or $C_{r3} = 0.078$ and $C_{r4} = 0.103$ (10-min model), respectively, which form the boundaries for a subdivision into three classes of the probability of debris flow occurrence (Yu et al. 2014b, 2016a). Debris flows are hardly formed in the area with $P < 0.35$ (or $P < 0.078$). This area can be considered as a low probability or safe area (Green area). When $0.35 \leq P < 0.47$ (or $0.078 \leq P < 0.103$), a debris flow may be triggered; the area can be considered as a medium probability or an alarm area (Orange area). When $P \geq 0.47$ (or $P \geq 0.103$), a debris flow will be triggered; the area can be considered as a high-probability or an evacuation area (Red area).

The parameter J in the topographical factor T is the average slope of the channel in the source area. It represents the energy of flash flood and the initiation condition of sediment entrainment. The parameter F in the topographical factor T is the form factor of the source area. It is highly related to the form of the hydrograph: a larger form factor produces a larger (peak) discharge and velocity than a smaller form factor. Therefore, under the same conditions, a watershed area with a larger form factor has a higher likelihood to generate debris flows (Chang 2007; Yu et al. 2014b). The combination parameter A/A_0 in the topographical factor T is the dimensionless area of the source area of the debris flow catchment. It represents the discharge of a flood and the amount of loose materials. These parameters also influence the surface flow discharge and the flow velocity and thus the resulting down slope movement of sediments (Yu et al. 2014b).

In the Eqs. 2–4, the topographical factor T, geological factor G, and rainfall factor R are dimensionless and independent parameters as are the parameters of the new prediction model proposed in this paper. The average channel width in the source area becomes now one of the parameters of the topographical factor. The particle size of the coarsening layer of the source area represents the loose source material of a debris flow, and will be one of the geological parameters.

The channel width W in the source area of a debris flow catchment is negatively related to the unit discharge of the flood and thus has a negative influence on the initiation of debris flows. The parameter A, has a positive effect on the flood discharge (or unit discharge). We will use the unit discharge for the representation of the initiation condition of a debris flow. The extent (area) of the source area and channel width can both be used for expressing the unit discharge. Therefore in the Eq. 2, the unit area A_0 is replaced by W and because the new topographical factor T' is a dimensionless parameter, Eq. 5 is obtained as below:

$$T' = JF\left(\frac{A'}{W^2}\right)^{0.2} \tag{5}$$

in which T' = the new dimensionless topographic factor; A' = the area of the source area (m^2); W = the channel width in the source area (m).

The new topographical factor T' represents the surface flow unit discharge and thus the flow velocity influencing the initiation potential and down slope movement of sediments.

The particle size D of the coarsening layer in the channels in the source area characterizes the loose material for the debris flows and is therefore a geological parameter. To meet the dimensionless of the geological factor, a parameter D_0 is introduced in the new geological factor:

$$G' = \frac{D}{D_0} \tag{6}$$

in which G' = the new dimensionless geological factor, which completely replace the factor expressed by Eq. 3; D = median particle size (D50) of the coarsening layer in source area (mm); $D_0 = 2$ mm because the coarse sand is defined as sand with a particle size larger than 2 mm.

The relationship between the new topographical factor T' and the rainfall factor R can be described with Eq. 1 because the only distinction between the new topographical factor and old topographical factor is the discharge and unit discharge.

But the new geological factor G' is totally different from the old geological factor G. So the relationship between G' and R must be reformulated. The new prediction model can be expressed as:

$$P' = \frac{RT'^{0.2}}{G'^X} \ge Cr' \tag{7}$$

in which P' = the new prediction factor; C'_r = a critical value for the prediction of debris flows; X = an undetermined parameter.

The unknown parameters X and the critical value C'_r must now be recalibrated with field data of debris flow events. But first we want to explain a bit more the critical parameter C'_r, which was used in the former and current model to make a division in different probability classes for P'.

For a rain fall event which occurs in a number of individual catchments in a certain area one can make in a coordinate system a scatter plot of points with $T^{0.2}/G^X$ on X-axis and R on the Y-axis representing a probability P' a debris flow event in a certain catchment (see Fig. 1 and Eq. 7). The plotted points can be subdivided into three classes based on field observation: a catchment with debris flow, no debris flow or it was uncertain whether there was a debris flow [debris flows and shallow landslides are present, but it is not sure whether the debris flows are triggered by a runoff-induced
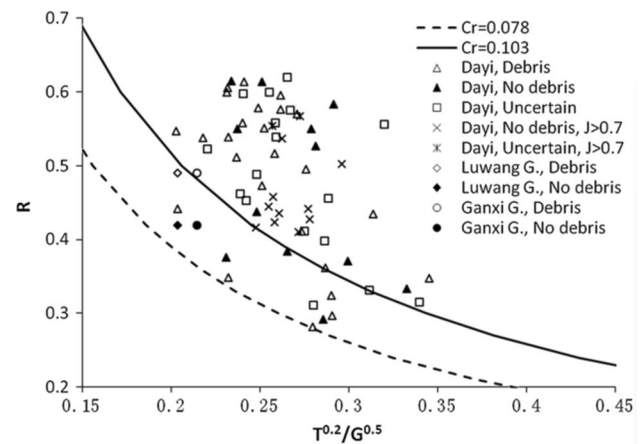

Fig. 1 Example of a Scatter plot of $T^{0.2}/G^{0.5}$ against R for debris flows in Yu et al. (2016a, Fig. 7)

mechanism (Yu et al. 2014b)]. This means that these catchments can be classified as catchments with a high, low and medium probability for debris flow initiation, respectively (see Fig. 1). The scatter plot of debris flow events can be subdivided into these three probability classes by selecting two critical values of C'_r. With Eq. 7, one can construct with this selected upper and lower critical value of C'_r two boundary curves, which subdivide in an optimal way the points assigned as events with "no debris flows" (low probability), "debris flows" (high probability) and "uncertain" (medium probability), respectively (Fig. 1).

Calibration of the new prediction model

For a calibration of our new prediction model (X and C'_r), we selected a heavy rainfall storm which triggered many debris flows around Dayi town, Wangmo County, Guizhou Province, China. The storm lasted from 22:00, June 5 to 6:00, June 6, 2011. The maximum hourly rainfall was 105.9 mm at the Dayi station from 23:00 to 24:00, June 5. It was more than the hourly rainfall with a 100 years return period (104 mm). This storm was a typical example of a short period with heavy rainfall, which may initiate a debris flow by the mechanism of runoff. Some debris flows were triggered during this rainfall storm, but in some gullies, there was no debris flow activation. Yu et al. (2014b) classed 66 gullies around Dayi town into three types: no debris flow, debris flow, and uncertain. Figure 2 shows the location and the numbering of these gullies subdivided into three classes according to the above given definitions. The rainfall parameters and rainfall factors of these 66 gullies are listed in Table 1 of Yu et al. (2014b), and Table 2 of Yu et al. (2016a). All the topographical parameters except the channel width are listed in the Table 1 of Yu et al. (2014b). New field investigations were conducted for the parameterization of
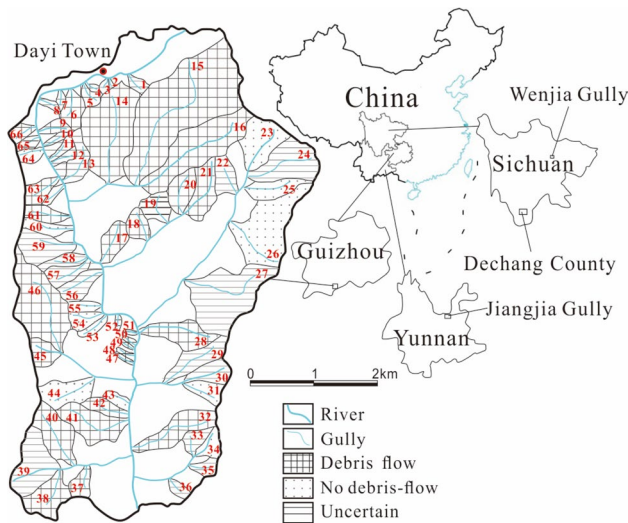
Fig. 2 Map with the distribution of debris flows near Dayi, Wangmo, Guizhou on June 6, 2011, and the location of the Jiangjia Gully, Yunnan, the Dechang, and the Wenjia Gully, Qingping, Sichuan

Table 1 Characteristics of several rainfall events in the Wenjia Gully

Time	Cumulatively rainfall (mm)	Max 1-h rainfall (mm)	Debris flow
Sep. 24, 2008	88.0	30.5	Yes
July 31, 2010	60.2	51.7	Yes
Aug. 13, 2010	185.9	70.6	Yes
Aug. 19, 2010	72.6	31.9	Yes
Sep. 18, 2010	52.0	29.0	Yes
Aug. 15, 1995	496.5	49.8	No

the channel width and particle size distribution of the material in the channel of the 66 gullies in 2018.

There are only three lithological units in the Dayi area: hard siltstones interbedded with 20–30% of thin shales or mudstones. Around the Dayi town, the lithological units of gullies number 1–6 are hard siltstones interbedded with thin mudstones. And the lithological units of gullies number 7–66 are hard siltstones interbedded with thin shales (Fig. 2). Field investigations were conducted in all these gullies except gully No. 65, because the source area of this gully could not be reached in the field. The parameter W in each channel is defined as the average channel width in the source area. The mean value of all these average channel widths in the gullies was: $W = 4.8$ m. About 30–40 particle sizes of individual pieces of stones and gravels > 5 mm in source area were measured in each gully. The particle size D is the average value of these particle sizes. The mean value of all these average sizes of individual particles in gullies was: $D = 280$ mm.

In Fig. 1 published by Yu et al. (2016a), there were two points with presence of debris flows just falling on the upper (No. 42 in Fig. 2) and lower critical lines (No. 38 in Fig. 2) of P in the 10-min model (see Fig. 1). Assuming that these two debris flow incidents lies also on the new critical line for P' you can construct this upper and lower critical lines of P' for various values of X, with the new topographical factors (including the channel widths in Eq. 5), geological factors (including the mean value of D calculated by Eq. 6), and rainfall factors (Yu et al. 2016a) of these two debris flows (see Fig. 3).

The new prediction model is not a local model but assumed a universal model. So, it can be used also for example in the Jiangjia Gully, Yunnan Province, China (see Fig. 2). Since 1960, debris flows have occurred year after year in the Jiangjia Gully with an average frequency of 12 times per year (Wu et al. 1990; Yu 2011). The Jiangjia Gully is located along the well-known Great Xiaojiang Fault. The area is part of an old intricate tectonic system, characterized by intense geotectonic and frequent seismic activity (Yu 2011). The former version of our model was developed in this area. The calibrated parameters of the 10-min model are given by Yu et al. (2016a). In addition to this we added in our new model the overall particle size parameter for the

Table 2 Comparison of the new model and the old model for the Dayi and Dechang area

Area	Model	Debris flow			No debris flow		
		Green[b]	Orange[c]	Red[d]	Green	Orange	Red
Dayi	Old model[a] of 10-min	0	5	20	10	3	9
	New model of 10-min	0	6	19	19	1	2
Dayi	Old model of 1-h	0	5	20	10	3	9
	New model of 1-h	0	6	19	19	1	2
Dechang	Old model of 1-h	1	3	6	3	4	0
	New model of 1-h	1	7	2	7	0	0

[a]The model of Yu et al. (2014b, 2016a)

[b]Low probability or safe area

[c]Medium probability or alarm area
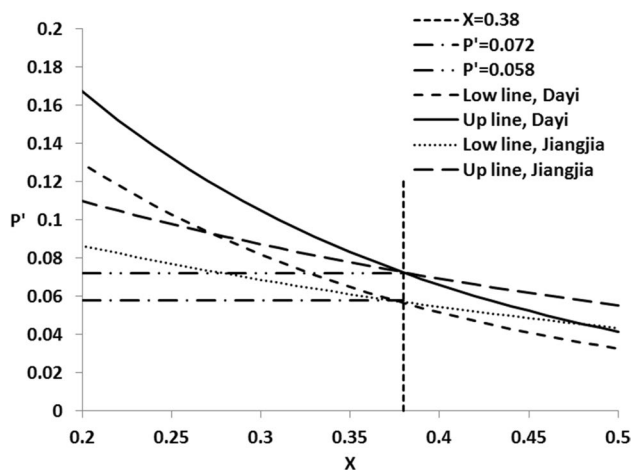
[d]High-probability or evacuation area

Fig. 3 Relationship of X and the critical probability values

channel material in the source area that was $D = 20$ mm, and the average channel widths W in two tributaries in the source area of Jiangjia Gully that were 28 m and 19 m, respectively (Yu 2011). There are two values of the topographical factors T' because there are two values of channel widths of these tributaries called the Menqian Gully and Duozhao Gully. There are also two rainfall factor R (Yu et al. 2016a). From the T' and the R, one can obtain the maximum and the minimum values for these four data of $RT'^{0.2}$. These maximum and minimum values correspond to the upper and lower critical value for P' with the geological factor G' in Eq. 7. Then the relationship between undetermined parameter X and the up and low critical lines of P' can be obtained for the Jiangjia Gully (see Fig. 3).

Figure 3 shows the relationship of undetermined parameter X and the upper and lower critical values of the debris flows of the Dayi area and the Jiangjia Gully. Because our new prediction model is assumed a universal model, Eq. 7 should contain only one value for X for the upper and lower P' line for both areas in Eq. 7. The two points of intersection of the upper and lower critical line of Dayi and Jianjia deliver an $X = 0.38$ (Fig. 3), which can be used to solve with Eq. 7 the new upper and lower critical value of Cr'. With value $X = 0.38$ of the undetermined general parameter the upper and lower critical values P' (10-min model) become 0.072 (C'_{r2}) and 0.058 (C'_{r1}), respectively. The assumption of universal model will be validated below.

The new prediction model on debris flows caused by the runoff mechanism is now given by Eq. 4, 5, 6, and 8:

$$P' = \frac{RT'^{0.2}}{G'^{0.38}} \geq Cr' \tag{8}$$

In which: for the 10-min model, $C'_{r1} = 0.058$, $C'_{r2} = 0.072$ which form the boundaries for a subdivision

into three classes of the probability of debris flow occurrence. The probability of debris flow occurrence is low in the area with $P' < 0.058$. Between $0.058 \leq P' < 0.072$, medium and when $P' \geq 0.072$, the probability is high.

Yu et al. (2014b, 2016a) presented the prediction model of 1-h and 10-min for in the Dayi area. There exists a proportional relationship between the upper and lower critical values between these two models in the Dayi area: $P_{U1}/P_{U10} = 4.6$, $P_{L1}/P_{L10} = 4.5$ (P_{U1} and P_{L1} are the upper and lower critical values of 1-h model; P_{U10} and P_{L10} are the upper and lower critical values of 10-min model). Therefore one can obtain the lower and upper critical values for the 1-h model from the lower and upper critical values of the 10-min model: $C'_{r3} = 0.26$, $C'_{r4} = 0.33$.

The validation of the new prediction model

The new field campaign in the Dayi area provided the data for the revision and validation of the new prediction model. There were 9 "No debris" points above the upper critical lines (high-probability of debris flow) in both 1-h model and 10 min in the old model proposed by Yu et al. (2014b, 2016a). The new investigations revealed that some of these points represented catchments without loose materials. It is evident that no debris flows can be initiated in these catchments. Figure 4a, b show the validations of the new 10-min and 1-h prediction models in Dayi area. There are 2 "Debris flow" points below the lowest critical line (low probability of debris flow) but very close to it both in 10-min model and 1-h model. So a revision can be made for the new prediction model by lowering the lower critical line so that all the "Debris flow" points observed in the field, are now above the new lower critical line: (1) for the 10-min model, the revised critical values are $C'_{r5} = 0.055$, $C'_{r6} = 0.072$; 2) for the 1-h model, the revised critical values are $C'_{r7} = 0.24$, $C'_{r8} = 0.33$. With the new revised prediction model, there is no "Debris flow" point below the lower critical line. And there are only 2 "No debris flow" points (not observed in the field) above the upper critical line. This means there will be less false prediction with the new prediction model.

For a second validation, we selected the event which occurred around Kuanyu town, Dechang County, Sichuan Province (see Fig. 2) from August 22 to 24, 2004. The heavy event, had a maximum 1-h rainfall of 56 mm, and a cumulative rainfall of 161 mm within 31 h (Zhu et al. 2014). This rainfall triggered ten gully-type debris flows by runoff on August 24, 2004. This rainfall suggests that apart from the short period of heavy rainfall, the effect of the large cumulative rainfall period may also be important for the triggering of these debris flows. There are 17 potential debris flow gullies in the catchment area of Kuanyu town, 10 of them with presence of the August 2004 debris flows, and seven of them without debris flows during this event (Yu et al. 2014b; Zhu

Fig. 4 Validation in the Dayi area with the 10-min model (**a**) and the 1-h model (**b**)

a

b
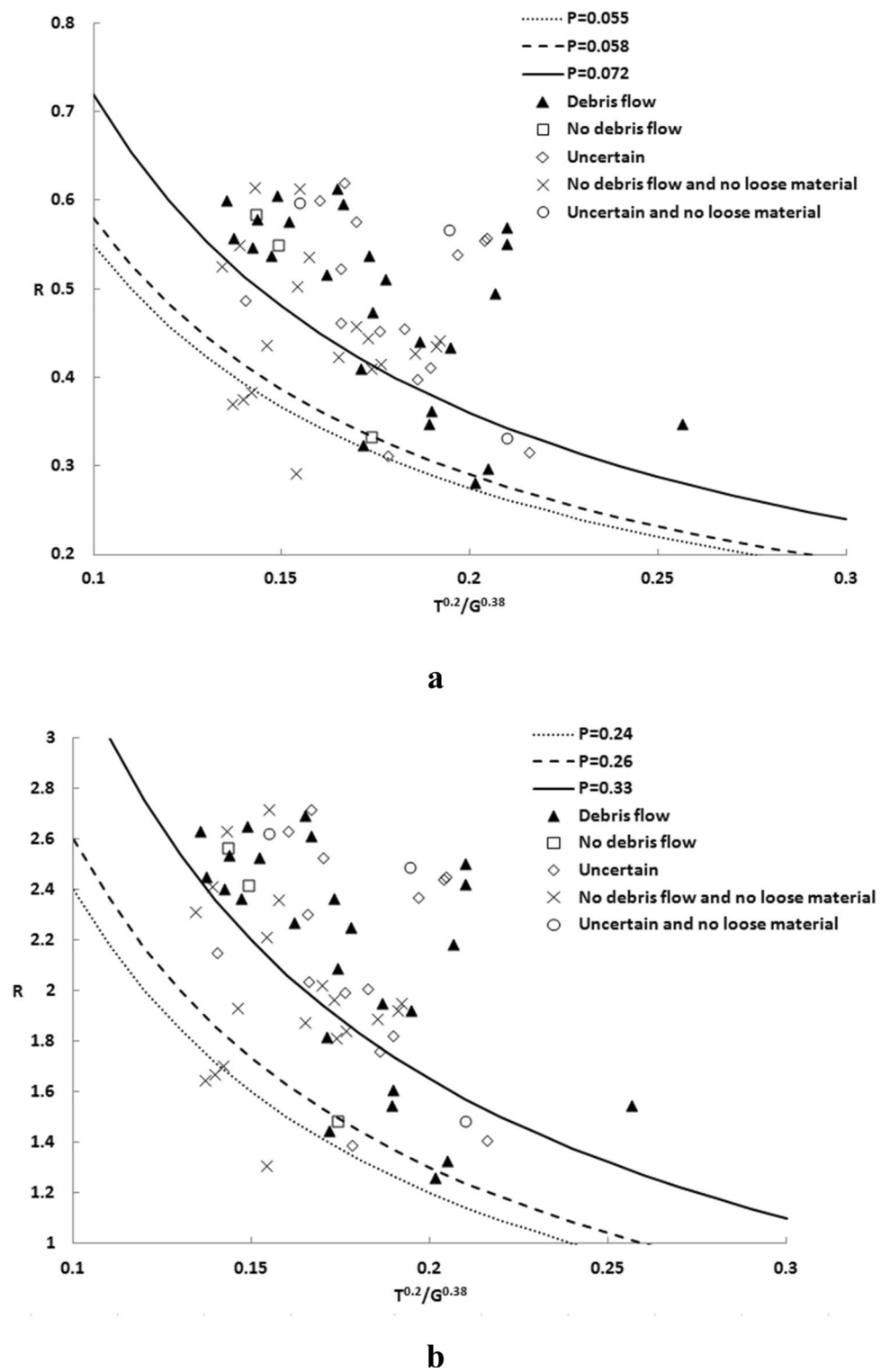
et al. 2014). The lithological units in this area are granite, dolomite, phyllite, and sandstone.

The new field campaign in these 17 gullies around Kuanyu Town, Dechang County (see Fig. 1) were conducted in 2018 to collect the data about channel widths and particle sizes in the source areas of these debris flow catchments.

There was no loose material found in one of these gullies, and therefore no debris flow could be triggered in this gully during the August 2004 event. Figure 5 shows the validation of the new prediction model for the debris flows in Dechang County. All the "No debris flow" points are below the lower critical line (low probability of debris flows). So no false
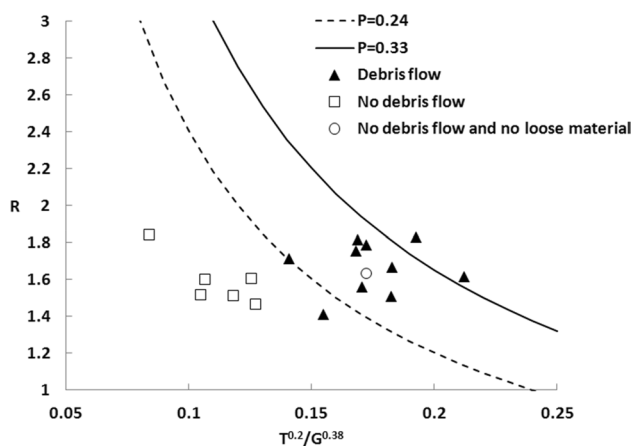
Fig. 5 Validation for the Dechang area with the 1-h model

Fig. 6 Validation for the Wenjia Gully for the 1-h model

prediction. Except for one point, the other 9 "Debris flow" point are above the lower critical line (medium or high probability of debris flow). The "Debris flow" point, which scored below the lower critical line lies however very close to this line. In this catchment, there was a cement quarry and a constructed road to the quarry in the source area of this gully. The waste materials of the quarry and the road construction provided plenty of sediment material in the channel. The lithological unit exposed in this gully is dolomite and the sediment size produced by nature is larger than the size of the man-made sediment. However, the 2004 debris washed away these fine sediments. This means that we measured for our model the particle size of the natural (coarser) sediments during the field campaign of 2018, which explains the relative low failure probability score of the 2004 debris flow. Except this point, the new model shows a high accuracy in the forecast of the debris flows.

The new model was also validated for the forecast of debris flows in the Wenjia Gully located near Qingping Town, Sichuan Province, China (see Fig. 2). The Wenjia Gully lies north of Qingping Town, with a catchment area of 7.81 km^2 and a 5.2-km-long main channel (Yu et al. 2014b). The lithological unit exposed in this gully is limestone. Before the Wenchuan Earthquake, the loose source material for debris flow was supplied by the rock falls in the catchment. The particle size was large, and the channel width must have been wide. So one can speculate that the channel width was around $W = 10$ m, and particle size $D = 300$ mm before the Wenchuan Earthquake.

There were no records of debris flow events in the period 1930–2007 despite a very heavy rainfall event from August 14 to 15, 1995. During this heavy rainfall, which occurred around Qingping town, a maximum 1-h rainfall of 49.8 mm, and cumulative rainfall of 496.5 mm in 24-h was measured (Yu et al. 2013). The 2008 Wenchuan Earthquake produced the second largest landslide in the Wenjia Gully. The largest
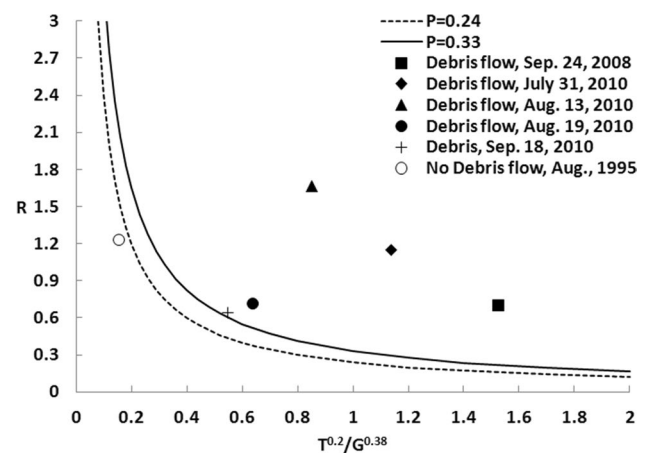
part of the landslide material with a volume of 30×10^6 m^3 was deposited in the channel of the Wenjia Gully. Because of the high speed of the landslide and consequent fragmentation and its collision against an opposite valley wall, a part of the deposited material consists of fine sand and gravel (Xu 2010).

The large quantity of loose materials with relative fine particles and the extreme narrow channel, which developed afterwards in these deposits, greatly changed the formation conditions for debris flows in the Wenjia Gully. As a consequence, the triggering rainfall threshold for debris flows decreased dramatically just after the Wenchuan Earthquake. On September 24, 2008, 4 months after the Wenchuan earthquake, a rainfall of 88 mm in 24 h with a maximum 1-h rainfall of 30.5 mm triggered a debris flow in the Wenjia Gully (Xu 2010). And four other debris flows were triggered in the Wenjia Gully on July 31, August 13, August 19, and September 18 in 2010 (Xu 2010; Yu et al. 2013). Table 1 shows the rainfall characteristics of these five debris flow events, together with the heavy rainfall event before the quake in August, 1995. The values of the cumulatively rainfall of the rainfall event of 1995 with no debris flow are much larger than those of the post-earthquake events with debris flows. And the values of the maximum 1-h rainfall of the rainfall event of 1995 are also much larger than those of three post-earthquake events with debris flows. The prediction model proposed by Yu et al. (2014b) could not predict the change in the debris flow occurrence probability after the strong Wenchuan earthquake caused by this dramatic change in triggering conditions and the consequent decrease of the rainfall threshold.

The field investigation conducted at the end of September, 2010 provided an average channel width of $W = 16.5$ m, and a particle size $D = 22$ mm (see Fig. 6 of Yu et al. 2013). We assume that the channel width W increased each time after a debris flow event with 0.5 m and the particle size

D with 1 mm before Sep. 24, 2008. This is consistent with the estimation of the grain size by a picture of the deposits of the landslide just after Wenchuan Earthquake. With this assumption one can obtain the current channel widths and the particle sizes before each debris flow event. The other topographical and rainfall parameters are provided by Yu et al. (2014b).

Figure 6 shows the validation of the new prediction model for the debris flows in the Wenjia Gully. The new model predicts very well the occurrence of the debris flow events from September, 2008 to September, 2010, and the absence of a debris flow during the rainfall event of August, 1995. This suggests that the new prediction model may successful for the prediction of debris flows in strong earthquake areas.

Discussion

Frank et al. (2019) observed an increase in debris-flow activity and sediment yield, following one or more large rock-avalanche or rockslide events in the Swiss Alps. The increase of debris flow activity was apparent for one to eight years following the landslide event. This phenomenon is similar to the increase in debris-flow activity following co-seismic landslides and rock falls events. The dramatic change of the triggering rainfall threshold for debris flows after a strong earthquake is not caused by the earthquake itself, but by the co-seismic landslides and rock falls delivering an abundant source material for debris flow initiation after the quake. Therefore, rainfall threshold for debris flows can also decline in catchments after the occurrence of large landslides not triggered by strong earthquakes, producing relatively finer materials (Yin et al. 2010). Consequently the new prediction model may also be used in non-seismic areas in the catchments with recent major landslides.

Depletion of the hillslope material is a primary cause of decreasing debris flow volumes under a given hydrological forcing (Saito et al. 2014; Zhang and Zhang 2017; van Asch et al. 2014; Dominech et al. 2019). However, the initiation of debris flows by the runoff mechanism is located in the channel through the entrainment of channel sediments by floods with a high erosive power. Shieh et al. (2009) indicated that a decreasing amount of available sediment material in the streambed has also a positive effect on the rainfall threshold. But the depletion of the sediment was not considered in this study.

Because large increases in soil strength is only achievable by extensive root systems that take several years to develop, revegetation of the co-seismic deposits seems to have a little influence on debris flow occurrence over a shorter term (Dominech et al. 2019). However, the vegetation also influences the hydraulic properties of the soil and the hydrodynamics of flash floods, and may give different results for the critical value C'_r. To get a more precise prediction model for debris flows, the role of revegetation must be considered in the future work.

The prediction model of Yu et al. (2014b, 2016a) is easy to apply because the parameters can be obtained from topographical (also Google Earth if available) and geological maps, and local hydrology manuals. The GIS tool can be used in gaining the parameters of topographical factors and geological factors. No field investigation is needed. In the new prediction model, however, the parameters for the particle size and channel width in source area, must be obtained by field measurements, which costs more time and money. The new model cannot be used in catchments where the source area is inaccessible. Nevertheless, in catchments where the loose material is abundant and plays a dominant role in the initiation process, through the presence of large (co-seismic) landslides or plenty of waste material from mining and road constructions the previous prediction model of Yu et al. (2014b, 2016a) is less successful.

In this older version of the model, the correction coefficient for physical weathering C_3 is in the range of 0.9–1. However this correction coefficient cannot distinguish between non weathered and strongly weathered granite, that produce quite different particle sizes for source materials in channels (Ma et al. 2014). Therefore, in areas with strongly weathered granite the new model is also more suitable.

The parameters of the geological factor in the old prediction model of Yu et al. (2014b, 2016a) have in an indirect way influence on the material characteristics determining the probability of debris flows. The new parameter *D* describes an important physical property of the loose material in the channel, which has a direct effect on the entrainment process initiating debris flows. And thus it is recommendable to use this physical parameter in non earthquake areas.

When the average slope *J* of the channel in the source area is larger than 0.7 (or 35 degree), a debris flow cannot develop whatever the values of the geological and rainfall factor, because based on the dynamic friction angle of the bed sediments no source material can be deposited on these steep channel slopes (Yu et al. 2014b). Field observations showed that in some catchments in Dayi area there was no source material present even on the average slopes less than $J = 0.7$ (35 degrees). This caused some false predictions by Yu et al. (2014b, 2016a). Less false predictions will be made with the new prediction model because the field investigations will detect all the catchments without source material.

Table 2 shows the comparison of the new model with the old model (Yu et al. 2014b, 2016a) applied in the Dayi and Dechang area. For the observed presence of debris flows in Dayi area, (first three columns with numbers) there is one more point in "Red" (high-probability or evacuation area) scored by the old model, and one more point in "Orange" (medium probability or alarm

area) scored by the new model for both the 10-min and 1-h model. The new model is slightly worse than the old model. For the absence of debris flows (last three columns with numbers) in Dayi area, there are seven more points in "Red" (false positive) and 2 more points in "Orange" predicted by the old model, and nine more points in "Green" (low probability or safe area) calculated by the new model both for the 10-min and 1-h model. The new model scores here significantly better than the old model. We can say that generally the new model is better than the old model.

For the presence of debris flows in the Dechang area for the 1-h model, there are four more points in "Red" scored with the old model, and four more points in "Orange" predicted with the new model. The new model is slightly worse than the old model. Regarding the absence of debris flows in the Dechang area, there are 4 more points in "Orange" using the old model, and four more points in "Green" with the new model. The new model is slightly better than the old model. So the two prediction models perform almost the same in this area. If these two models are applied in the catchment with the quarry and the related road construction before the triggering of the debris flow (presence of fine waste material), the result will be the same by the old model, but the prediction may be in "Orange" or "Red" by the new model. It means that the new model performs better in the Dechang area. Generally the new model is better than the old model in prediction of debris flows in Dayi area and Dechang area.

Equations 1 and 7 shows that the rainfall factor R has the largest influence in the old and new model compared to the other two factors. The exponential values of G' and T' are 0.38 and 0.2, and of D and W are 0.38 and 0.08, respectively. Therefore, the geological factor G' and the particle size D are more important than the topographic factor T' and the channel width W.

The smaller the difference between the upper and lower critical values C'_r, separating the three probability classes, the better the performance of the prediction model. If there is only one critical value, there is one line separating two classes with no debris and debris flows without a class with medium probability. It means that the performance of the prediction model is the best because the definiteness of probability is high. The critical value C'_{r6} (0.072) is 30.9% higher than the critical value C'_{r5} (0.055), and the critical value C'_{r8} (0.33) is 37.5% higher than the critical value C'_{r7} (0.24) in Eq. 7, which shows a moderate performance of the prediction model. In this study, the validations are only limited to three subsequent raining seasons for the prediction of debris flows in strong earthquake areas. For the long-term prediction of debris flows, more validations are needed to test the performance of the new model.

Conclusions

Using new data of field measurements on channel widths and particle sizes of source materials in source areas of debris flow catchments, a new prediction model for debris flows initiated by runoff was obtained by revising an existing prediction model of debris flows. The following conclusions can be made:

1. The dramatic change of the triggering rainfall threshold for debris flows in catchments located in strong earthquake areas is caused by the change of the channel width and particle size of source material in the source areas after the quake.
2. The new prediction model was successful validated for the group of debris flow events in Dechang, and the series of debris flow events in the Wenjia Gully before and after the Wenchuan Earthquake.
3. The new prediction model on debris flows can be used in catchments in non-seismic areas with large landslides producing a lot of relative fine loose source materials for debris flows.

Compliance with ethical standards

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