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Research on prediction of debris flows triggered in channels

Bin Yu

Abstract   The accurate prediction of debris flows occurrence that will allow the reduction or prevention of economic losses and human casualties is presently the most difficult aspect of debris flows studies but also the aspect that receives most attention. Most prediction methods are based on rainfall as the basic parameter, with the moment of occurrence as only result, and without a prediction of debris flow travel time and size. This paper takes Jiangjia Gully in Dongchuan of Yunnan Province as an example, and considers, on the basis of the fulfillment of the essential condition: the abundant availability of loose materials, the conditions for the formation of debris flows. Based on the mechanism of the initiation of debris flows in channels and the volume of rainfall in the basin, this paper also gives a systematic analysis on the travel time and size of the debris flow and suggests that the hydrological condition for forming debris flow is the unit discharge of the flood ≥ 0.35 m^3/s.m. It uses the 10-min rainfall intensity to calculate both the run-off of the rainfall and the unit discharge caused by the run-off, thus predicting the occurrence of debris flows. The velocity and the travel time of a debris flow can also be determined using the unit discharge of the run-off. The total volume of debris flows can be calculated using the 10-min intensity of rainfall and the total volume of the run-off, together with the volume concentration of the sediment in a debris flow.

Keywords   Debris flow · Rainfall · Unit discharge · Prediction · Channel

1 Introduction

Debris flows are common phenomena in mountainous regions capable of washing down houses, roads, railways, and power stations with sudden and fast moving mixtures of water, sediment, and large rock blocks, causing heavy economic losses and human casualties. Disasters could be avoided if a timely prediction can be made of the occurrence of debris

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flows. The study on the prediction of debris flow occurrence both by Chinese and international scholars already has a history of many years. In recent years, a large amount of work has been published on the short time and long time prediction of debris flow occurrence. Based on rainfall as the primary conditions, taking into account the geographical, geomorphologic, and geological characteristics, the volume and intensity of rainfall are then used as the basic parameters.

The volume of rainfall is expressed as total volume, daily volume, or 3-h volume; the intensity of rainfall is expressed as average intensity, 1-h intensity, 30-min intensity, and 10-min intensity. One-hour intensity and 10-min intensity were most widely used as the predictive parameters. Many rainfall thresholds have been identified and served for prediction and hazard warning. Thresholds of rainfall intensity and duration for the triggering of landslides have been developed for many regions worldwide using the principle of the importance of rainfall intensity–duration and based on ground-based rainfall measurements and documentation of landslides (Larson and Simon 1993; Crosta 1998; Wieczorek et al. 2000). In some areas, piezometric monitoring has confirmed the relationship between intense rainfall and piezomeric response and triggering of debris flows (Anderson and Sitar 1995; Wilson and Wieczorek 1995). Rainfall thresholds have been applied for regional real-time landslide warning (Keefer et al. 1987; Hansen et al. 1995; Deganutti and Marchi 2000; Caine 1980; Gostelow 1991; Fleismann 1986). Cheng et al. (1992), Xu and Feng (1992), LIGC CAS (1982), and Iwao and Hiroshi (1978) used a single rainfall index: conclusion of the foregoing is that the rainfall intensity is the critical parameter of the occurrence of channelized debris flows. Wu et al. (1990), Tan (1989), Tanbashi et al. (1989), Katsumi et al. (1978), Li (1997), Tan (1998), Zhong et al. (1990) applied a combination of rainfall factors to predict channelized debris flow. Aritsune et al. (1981) set up a debris flow prediction model by analyzing the depth of water in the channels and historical flood level data.

Though there is certain accuracy and easiness in using rainfall to predict the occurrence of debris flows, rainfall alone cannot be used to carry on research on the causes of debris flows, neither can it be used to explain its initiation mechanism. The application of the presented experience-based formulas is only limited to certain debris flow channels. The method cannot be used to carry out analysis and develop formulas for areas where the breakout frequency is relatively low or detailed rainfall records are lacking. When there is a change (such as an earthquake) in the triggering conditions for the debris flows, the existing experience-based formulas are no longer applicable. After analysis of the relationship between the formation of debris flows and the duration of rainfall, Hirano (1997) suggested that the cause of the debris flow is the formation of superficial soil flow initiated by rainfall. He also pointed out that besides the volume and duration of rainfall, the steepness of the slope (in his case over 22°) also plays a very important role in causing the occurrence of debris flow. The relationship of slope steepness for the initiation of landslides forming debris flows is well documented for many different localities by Campbell (1975), Ellen (1988), and Wieczorek et al. (2000) with slopes typically of about 30° being associated with the majority of debris flows. Currently, there are a few studies that involve the arrival time and the scale of debris flows. Wieczorek et al. (2000) estimated the velocity and volume of debris flows occurrence on June 27, 1995 in Virginia, US. The slope of erosive debris flow paths is more than 12°, and the slope of a depositional debris flow path is less than 10° in their research. Suwa and Yamakoshi (1997) analyzed the relationship between the total volume of debris flows, the 1-h and the 10-min rainfall intensity, divided the total volume of debris flows into three classes, and showed that the relationship between 10-min rainfall intensity and the total volume of debris flows is much

closer. Hirano (1997) used instantaneous unit hydrograph calculation to determine the run-offs with and without debris flow. This method, however, cannot describe the run-off of debris flows with important changes in its flow course.

Economic losses and human casualties can be reduced or prevented with accurate prediction of the occurrence of debris flows plus that of its arrival time and scale. To predict the occurrence of debris flows, the formation mechanism of occurrence of debris flow must be investigated. The channelized debris flows often have large discharge volumes and cause huge economic losses, and the prediction of their occurrence should be investigated and solved first.

This article takes the Jiangjia Gully in Dongchuan in Yunnan Province as an example for research on the mechanism of the initiation of debris flows for the geological, geographical, and the weather condition in the Jiagjia Gully. Based on many years of observations in the Jiangjia Gully, the research work focused on the rainfall intensity and the mobilization of the bedload. According to the volume of rainfall in the catchment, a systematic analysis of the occurrence, arrival time, and scale (volume) of debris flows is presented.

2 The initiation of rainfall-induced debris flows

There are two basic conditions for the initiation of debris flows in a basin: abundance of loose rock debris and a large amount and high intensity of rainfall. The loose rock debris in the channel may include debris contributed by earlier landslides and avalanches. There are several possibilities for the formation of debris flows in channels:

- debris in the channel carried off by fast flowing water;
- abundance of loose materials on the slope (leading to so-called slope debris flow) moving into the channels to form debris flows;
- landslides developing into debris flows;
- earth-fill dams formed by landslides and breached by impounded water to form dam-break debris flows.

  Both slope- and channelized debris flows are mainly triggered by rainfall.

- The slope debris flows are usually of a small size (sediment volume $< 1{,}000$ m^3) and occur on steep slopes (20–40°) and in small basins (<0.4 km^2).
- Channelized debris flows are usually of large size (sediment volume $> 1{,}000$ m^3), flowing down along a gentler slope (3–20°), and occur in a relatively large basin (0.4–100 km^2) (Wang 1999).

For channelized debris flows, a minimum flow speed has to be met to mobilize loose materials and to trigger and form debris flow. Generally also minimum discharge levels must be met before a landslide dam is breached and then develops into a debris flow. Slope debris flows are initiated by slope failure and rapid mobilization (Wieczorek et al. 2000). Debris flows on slopes and landslides to cause dam breaks, and then debris flows are not the issue we focused in this paper. We concern the triggering of debris flows in the channels: use run-off as the basic condition for triggering channelized debris flows. Larger volumes and higher velocities of run-off can carry debris material with larger diameters. Ordinary channel flow with small volumes and low velocities can only carry away fine particles on the channel bed, thus coarsening the material remaining in the channel bed. When the mobilized particles are large enough and the channels are strongly eroded by

high flow velocities, a debris flow may be triggered. To determine the hydraulic conditions needed to trigger a debris flow within a channel, the diameter of the coarse particles mobilized by a certain discharge should be determined first.

Since 1960, debris flows have occurred year after year in the Jiangjia Gully in Yunnan Province, China, with an occurrence average of 12 times/year (Fig. 1). These debris flows once blocked the Xiaojiang River. The catchment area of the Jiangjia Gully is 32.6 km^2 (upstream of the observation site), the slope of the observed channel section (where the photograph taken in Fig. 2) is 7%. In Jiangjia Gully, not only the common intermittent debris flows but also sequences of consecutive debris flows can be observed. Figure 2 shows a sequence of intermittent debris flows in Aug., 1995. The length of the debris flow sequence is hundreds of meters. There are sequences of tens to hundreds debris flows, and the discharge of each of the individual debris flows is hundreds to thousands of cubic meters per second in an intermittent debris flow process. The maximum discharge measured of one debris flow is 2,800 m^3/s (Wu et al. 1990).

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. Precambrian dolomites and shales, Permian basalts and volcanic breccia, and Quaternary fluvial, alluvial, and lacustrine deposits of clay, silt, and sand are exposed in the catchment slopes and channels. Due to tectonism and seismic activity, the rocks have been folded and faulted as well as strongly sheared.

The density of the debris flows in the Jiangjia Gully varies from 1.36 to 2.36 g/cm^3. The grain-size distribution of the particles differs widely with the different densities of the
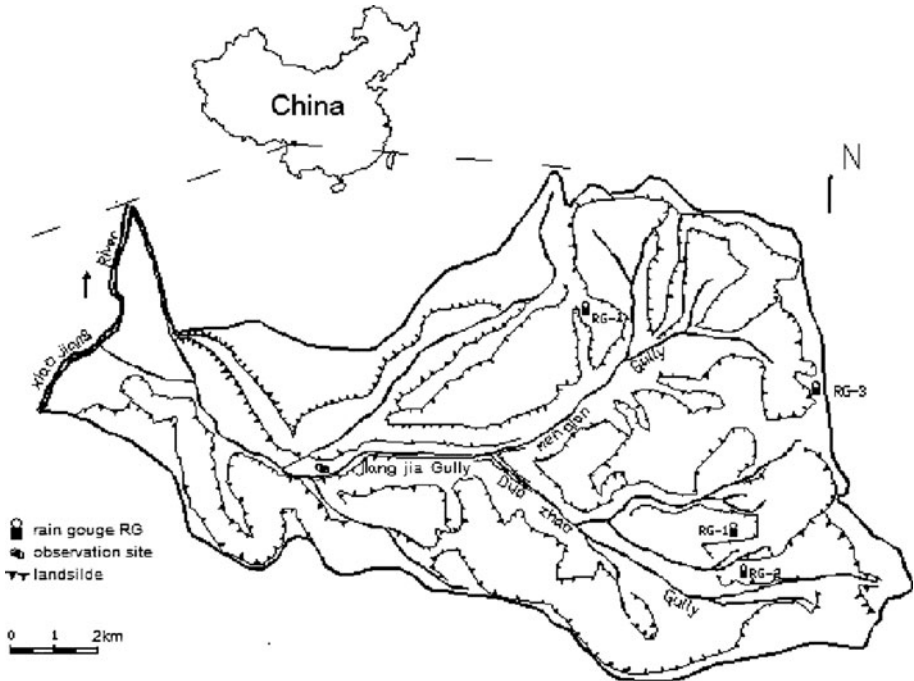
Fig. 1 General location map of the Jiangjia Gully in Yunnan Province, China. RG-1, RG-2, RG-3, and RG-4 are the installed rain gauges

Fig. 2 Photograph of debris flows in the Jiangjia Gully at the observation site. The gradient of the channel bed at the observation site was 7%. The channel width was 50 m, the thickness of the front of the debris flow was estimated as 1 m, and the velocity was estimated as 8 m/s. Heavy rainfall occurred in the upper reaches of the Jiangjia Gully but at the observation site no rainfall was observed

debris flows. The particles in the debris flows in the Jiangjia Gully consist of slates, of which the density and internal friction angle are 2.75 g/cm^3 and 34.5° (for the particle size in the range of 1–10 mm only), respectively.

There are large quantities of clay, silt, and sand in the channel produced by landslides, avalanches, and previously deposited debris flows during the Pleistocene (Wieczorek et al. 1987). The gradient of the channel (where debris flows are initiated) is more than 10°, and rainstorms always produce large volumes of run-off and large flood discharges. These floods can erode the bed of the channel easily, and much more bedload and slurry are added to the flood, this causes more and more bedload to be eroded during the floods, which then develop into debris flows. The occurrence of debris flows is strongly correlated with the high values of intensity of 10-min rainfall (Wu et al. 1990). The rainfall in the upper reaches of the Jiangjia Gully strongly differs between the dry and wet seasons. Intensive rainstorms are concentrated in the wet season in the rainy summer months of June, July, and August when high intensity rainstorms occur (Wu et al. 1990). Though the annual rainfall in Jiangjia Gully basin is not very high, the rainy season and dry season are so clearly demarcated that debris flows often occur.

Figure 3 shows the grain-size distribution curve of solid particles in floods and debris flows. The samples are from 4 debris flows in the channel of Jiangjia Gully in 1999 and 4 floods in the channel in 2000. In the samples of the debris flows, there are particles with a diameter greater than 20 mm. Therefore, to form a debris flow, the diameter of the coarse particles mobilized by a flood should be greater than 20 mm.

Fig. 3 Grain-size distribution curve of the solid particles in floods and debris flows. *d* is the size of the particle, *P* is the cumulative percentage (%), and *r* is the density of the fluid (g/cm³)
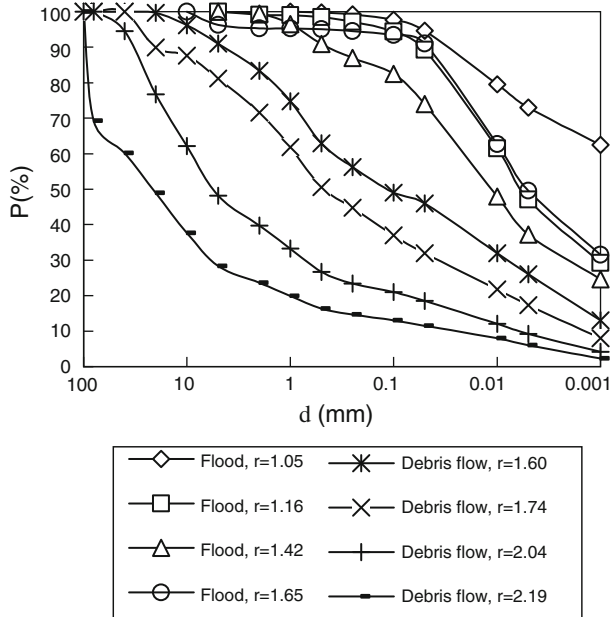
Table 1 The triggering discharge of debris flows

γ_C (g/cm³)	2.19	2.04	1.74	1.60
p (%)	13.2	20.9	37.1	49.2
γ (g/cm³)	1.39	1.42	1.38	1.36
C_V	0.23	0.25	0.22	0.21
K_C (g/cm.s)	400	500	350	285
q_1 (m³/s.m)	0.18	0.22	0.16	0.13

γ_C (g/cm³) is the density of the debris flows; p is the weight percentage of particles with diameter smaller than 0.1 mm in the debris flows

Wang and Zhang (1989) defined the conditions for the formation of debris flows by floods flowing through the channel bed:

$$\gamma q_1 J \geq K_c \qquad (1)$$

in which γ is the density of the liquid phase, q_1 is the unit discharge of fluid, J is the gradient of the channel bed, and K_C is the condition for the formation of debris flow, related to the solid volume concentration C_V in the liquid phase. Formula (1) is developed after experiments in which the maximum particle diameter in the liquid phase is 0.1 mm, but the coarse particles of debris flows have a diameter from 5 to 20 mm, and the average diameter is 10 mm. Table 1 shows the application of formula (1) to calculate the triggering discharge of the 4 debris flows in Fig. 3. J, the slope of the area where debris flows are formed, is 16%. The K_C value is derived from the curve and its extension line according to Wang and Zhang (1989).

The discharge q_1 triggering a debris flow as calculated in Table 1 ranges from 0.13 to 0.22 m³/s.m. But the maximum diameter of the initiated coarse particles experimented by Wang and Zhang (1989) is 20 mm, and the average diameter is 10 mm. As a result, the triggering flood discharge and the diameter of the mobilized coarse particles calculated with the method adopted by Wang and Zhang (1989) will tend to lead to smaller values for the discharge as their sediment size (coarse particle) was fine.

CIMDE CAS (2000) used the discharge in the channel to determine the diameter of the mobilized coarse particles with the following formula:

$$d_0 = 0.04 q_0^{2/3} \tag{2}$$

in which d_0 (m) is the diameter of the mobilized particles and q_0 (m³/s.m) is the discharge of the triggering flood. According to this formula (2), the discharge q_0 for particles 20 mm in diameter is

$$q_0 = 0.35 \text{m}^3/\text{s.m} \tag{3}$$

Apart from the discharge used as the condition for the mobilization of coarse particles, Han and He (1999) used the average velocity in the vertical profile to determine the condition for the asymmetrical mobilization of particles:

$$V_m = 0.0802 f(\lambda) \varphi(\Delta') \psi\left(\frac{H}{D}\right) \omega_0 \tag{4}$$

in which V_m is the average velocity, D is the diameter of the mobilized particles, λ is degree of flatness, Δ' is the relative exposure degree, and H is the depth of the water. According to water depth measurements conducted in the Jiangjia Gully, the water depth of ordinary floods is usually smaller than 0.2 m, so the depth H of water to initiate a debris flow = 0.2 m.In formula (4):

$$f(\lambda) = \lambda^{0.45} \tag{5}$$

in which λ = degree of flatness (Han and He 1999) of mobilized particles:

$$\lambda = \frac{\sqrt{ab}}{c} \tag{6}$$

in which a, b, and c are the longest, medium, and shortest diameters of the mobilized particles. b equals the value used for diameter D. For the 37 gravels sampled in Jiangjia Gully, the longest diameter varies from 25.0 to 68.4 mm, the medium diameter from 17.8 to 37.5 mm, and the shortest diameter from 4.6 to 23.4 mm. Calculated with formula (6), the average value of the degree of flatness is $\lambda = 3.13$.In formula (4),

$$\varphi(\Delta') = \sqrt{\frac{\sqrt{2\Delta' - \Delta^2}}{\left(\frac{4}{3} - \Delta'\right) + \frac{1}{4}\left(\frac{1}{3} + \sqrt{2\Delta' - \Delta^2}\right)}} \tag{7}$$

in which Δ' is the relative exposure degree is between 0 and 1. When a particle is on the top of other particles, $\Delta' = 0$; when a particle is between the other particles and has the same height, $\Delta' = 1$. For the particles in Jiangjia Gully, the value for Δ' is assumed to be 1. In formula (4),

$$\psi\left(\frac{H}{D}\right) = 6.5\left(\frac{H}{D}\right)^{\frac{1}{4+\lg(H/D)}} \tag{8}$$

$$\omega_0 = \sqrt{53.9D + \frac{2.98 \times 10^{-7}}{D}(1 + 0.85H)} \tag{9}$$

Using formulas (4, 5, 6, 7, 8, 9), we can calculate the average velocity for particles 20 mm in diameter:

$$V_m = 1.76\text{m/s} \tag{10}$$

Using formula (10) and the water depth H, the flood discharge for particles 20 mm in diameter can be calculated:

$$q_i = 0.35\text{m}^3/\text{s.m} \tag{11}$$

in which q_i is the triggering discharge.

So using particle diameter 20 mm and formulas (2) and (4), the corresponding calculated flood discharge needed for debris flow initiation is 0.35 m³/s.m. According to the survey conducted in June–August 2000 and 2001 in the Jiangjia Gully, the flood discharge after rainfall but without debris flow development is 0.10–0.25 m³/s.m. Using particles of 15 mm in diameter and formulas (2) and (4), the corresponding calculated flood discharge is 0.23 m³/s.m (with a water depth H in formula (4) of 0.15 m). This is consistent with the result of water depth measurements, and thus shows the relative accuracy of formula (2) and formula (4). It further shows that the discharge calculated with formula (1) tends to be smaller than when calculated with formula 4.

Based on the results calculated with formulas (1), (2), and (4), the critical unit discharge q_c to trigger a debris flow in a channel is

$$q_c = 0.35\text{m}^3/\text{s.m} \tag{12}$$

Formula (12) can be used as the criterion for the occurrence of debris flows in the Jiangjia Gully.

3 Prediction of the occurrence of rainfall-induced debris flows

The Jiangjia Gully is very susceptible to debris flows because it meets almost all the essential physical conditions. But for a debris flow to be triggered another essential condition must be met: the condition of sufficient rainfall. The accurate prediction of the occurrence needs also the calculation of the flood discharge in the channel. A lot of research has already provided a rather deep analysis of the initiation, movement, prediction of occurrence, and the volume of debris flows (Wu et al. 1990; Yu et al. 2001):

$$W_w = \frac{C_w}{R_1}I^2\text{tA} \tan\theta r \tag{13}$$

in which W_W = the flow volume (l). C_W = the flow coefficient, related to the erosion factor of the soil, $C_W = 5$ (Yu et al. 2001). I = intensity of rainfall (in mm/min). t = the duration of rainfall (min). A (m²) = the area where run-off is produced by rainfall. θ = the slope of the terrain surface (in degrees). R_1 = the flow factor for the land use, (for arable land: $R_1 = 71$ mm/min; bare land: $R_1 = 71$ mm/min; forested and grass land: $R_1 = 710$ mm/min, Yu et al. 2001). r = the effect of antecedent rainfall (the surface water

content of soil, in %, determined by the antecedent rainfall, the value for r ranges from 8 to 15%, Yu et al. 2001). The Duozhao Gully and the Menqian Gully, two tributary gullies, of the Jiangjia Gully's are the two sources for debris flows. In the upper sections of each of these gullies, rain gauges were installed (4 rain gauges located in Fig. 1) to obtain rainfall data. The width of the channels in these two gullies often changes because of the strong erosion and sedimentation caused by debris flows. On-site surveys conducted in the two channels have shown that the width of Menqian channel is 28 m and that of Duozhao channel is 19 m. Without consideration of the time of concentration, the formula (13) can be used to calculate the average run-off discharge in the channels produced by 10 min of maximum rainfall intensity.

Figure 4 shows the relationship between the average run-off unit discharge in the channels produced by 10-min maximum rainfall intensity and the antecedent rainfall. The antecedent rainfall period is 7 days before the debris flow is triggered. The rainfall was measured by the rain gauges in August of 1998 and in June, July, and August of 1999, 2000, and 2001. There were 39 debris flow events occurrence in 69 rainfalls in the period. The calculation line of formula (12) is also plotted in the Fig. 4. According to formula (12), which determines whether debris flows will occur, 28 debris flows out of the 39 debris flows in the period could be predicted (an accuracy of 72%). Out of the total 69 predictions, 10 were predicted for debris flow occurrence but not correct (14.5%).

Figure 5 shows the cumulative rainfall and the observed time-lapse after the start of the rainfall at the different rain gauges until the occurrence of debris flows at the observation site.

Large rainfall volumes and high rainfall intensity are the main causes of debris flows, among which the rainfall intensity plays the most important role, because it can produce heavy concentrated flow in the channels. In the mountain areas in the upper reaches of Jiangjia Gully, the rainfalls are not evenly distributed, and torrential rain is often limited to small areas. Figure 6 shows the cumulative rainfall at different locations on July 4, 2000 and the time elapsed after the rainfall started until the start and the end of the occurrence of debris flows. If the sites where rain gauges are set up do not correspond with the sites where the debris flows usually develop, then it is possible that the data collected by the rain gauges do not reflect the real rainfall situation in the locations where the debris flows develop. For example, it may happen that at one rain gauge it rains intensively, while at the other there is not a single drop of rain. As debris flows often develop where landslides and avalanches break out, it is very difficult to set up rain gauges and conduct monitoring at the

Fig. 4 Relationship between unit discharge and amount of antecedent rainfall
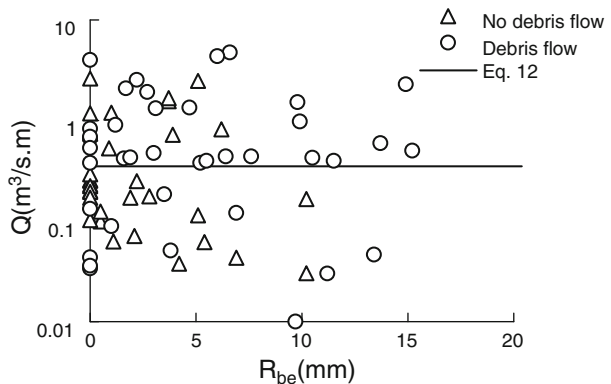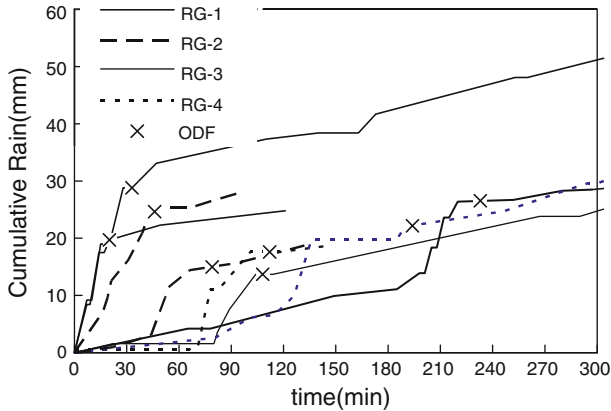
Fig. 5 Cumulative rainfall and observed times of debris flows at different time with different rain gauges. There is no antecedent rainfall a few days before the debris flows were triggered. ODF is the first observed arrival time of debris flows at the observation site. RG-1, RG-2, RG-3, and RG-4 are the rain gauge numbers at the locations shown in Fig. 1. The cumulative rainfall is the maximum intensity of the rainfall measured at the 4 gauges that were followed by a debris flow process. This Figure only gives part of typical rainfall observations followed by debris flows
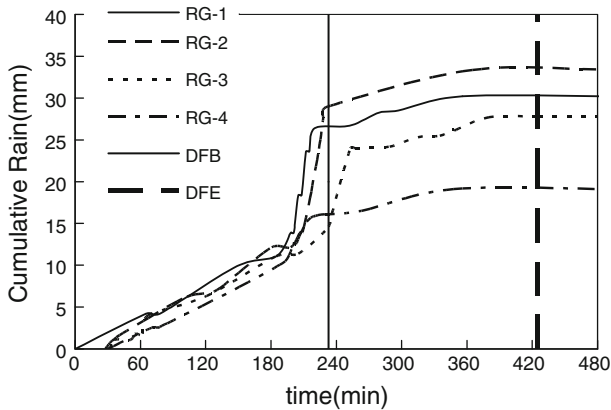
Fig. 6 Cumulative rainfall and times elapsed between the debris flows initiation and its end at different times, and with different rain gauge data. DFB is the start time of observations of debris flows at the observation site. DFE is the ending time of the debris flows observed at the observation site. The debris flow occurred on July 4, 2000. There was no antecedent rainfall 3 days before the debris flow was initiated. The rainfall began at 2:55 in the morning at number one rain gauge (RG-1), and rainfall ended at 10:00 in the morning at number three rain gauge (RG-3). The debris flows were observed for the first time at 6:48 in the morning and stopped at 10:00 in the morning at the observation site

locations where debris flows are initiated. Because rain gauges are usually set up in residential areas without landslides, there is always some distance between them and the locations where debris flows occur. Consequently, it is unavoidable that there is some discrepancy between the rainfall data collected and the real rainfall situation at the debris fall initiation locations. For the above-mentioned reasons, in Fig. 4, some debris flows occur without high rainfall intensity and some of the great rainfall intensity values do not

lead to debris flows. Without taking into consideration the degree of correspondence between the location of the rain gauges and the location of debris flows development, the formulas (13) and (12) still can be used to accurately predict the unit discharge of rainfall and also the critical point of occurrence of a debris flow.

4 Prediction of the arrival time of debris flows

There is some time-lapse between the occurrence of a debris flow and the losses and damages caused by it in the downstream area. The duration of this time-lapse depends on the velocity of the debris flow and the distance between the source of the debris flow and the area where it causes destruction. In the past, based on the data of debris flows that had already taken place, the occurrence of a debris flow, could be predicted, but not the time-lapse between the initiation and the consequent losses. However, to prevent or reduce the calamities caused by debris flows, it is equally important to be able to predict the time that a debris flow needs to reach residential areas and other infrastructure. Through analysis of the factors of rainfall, the slope of the channel, the arrival time of a debris flow can be predicted.

As most debris flows in the Jiangjia Gully are viscous flows, the mean velocity equation of viscous debris flows can be used for the calculation of their velocity. Based on the unit discharge, the velocity of debris flows can be determined by the hydraulic radius the channel, the water depth, the slope of the channel, and the grain-size distribution of the transported particles (Yu 2008a):

$$U = 1.1(gR)^{1/2}J^{1/3}\left(\frac{D_{50}}{D_{10}}\right)^{1/4} \tag{14}$$

in which U is the average velocity of a debris flow, R is the hydraulic radius of the channel, g is the acceleration of gravity, J is the slope of the channel bed. D_{50} is the median grain size, and D_{10} is the 10% value of the grain size (see Fig. 3). The agreements of calculating velocities by Eq. 14 and observed velocities are very good in Jiangjia Gully. In Jiangjia Gully, the average D_{50}/D_{10} value is 946, which is much larger than in other basins and the velocity of debris flows in Jiangjia Gully is much larger than in other catchments (Yu 2008a). The channel length from the source of a debris flow to the observation point is 7 km, and the average slope of the channel bed over this distance is 11% ($J = 0.11$). Though the volume and velocity of a debris flow increase constantly during its movement, the formula (14) and the flood unit discharge that forms a debris flow still can be used to calculate its approximate velocity due to the fact that there is some slowdown due to blockages in the channel and due to the rough channel bottom. Most debris flows in Jiangjia Gully are of an intermittent type: there is a time interval between each individual burst which has an obvious head, body, and tail. Because of their bottom friction and the yield stress, debris flows will leave a certain layer in their channels, and they will gradually slow down due to the reduction in their thickness. When they have come to a total stop, the remaining part of their body will be deposited in the channel. This kind of deposit is known as 'the pavement of a debris flow'. After the first flow occurrence has paved the way, debris flows that are occurring later will no longer be affected by the remaining flow deposits (the pavement) and will move at a rather high speed to where the first occurring flow has stopped. They will then deposit their own layers in the channel, paving the way further downwards, then slow down, and stop their movement. After completion of the pavement

over the length of the whole channel, new debris flows can flow from the upper reaches of the catchment to the lower reaches. Because of this phenomenon of pavement formation, debris flows in the Jiangjia Gully are delayed in their development. Figure 7 shows the comparison of arrival time between the measured time and the calculated time, in which T_M is the measured time elapsed between the moment when the maximum 10-min rainfall intensity is recorded and the moment when a debris flow reaches the observation site (in minutes). The maximum 10-min rainfall intensity means the critical rainfall intensity that triggers the occurrence of a debris flow. T_C is the calculated time difference between the recording of the maximum 10-min rainfall intensity and the time when a debris flow reaches the observation site (in minutes). Figure 7 shows this comparison between the calculated and observed delay time of 28 debris flows out of the 39 debris flows that occurred in Jiangjia Gully in the years of 1998, 1999, 2000, and 2001. The other 11 debris flows could not be predicted, as is indicated in Fig. 4. The calculated arrival time of the debris flows has a relatively small range: between 18.3 (min) and 73.1(min), while the observed arrival time of a debris flow has a pretty large range: between 5 (min) and 357 (min). The reason is that landslides and avalanches often develop blockages in the pathway of debris flows due to the erosion caused by the surface run-off. The velocity and arrival time of the debris flows will be affected by such blockages and by the delay due to the formation of pavement as described above. Because of the phenomenon of the pavement formation, the arrival time of a debris flow is very difficult, if not impossible, to be accurately predicted. In Fig. 7, nearly half of the calculated times are very close to the real measured times, indicating that rainfall and flood unit discharge initiating a debris flow can be used to predict the arrival time. But another half of the predicted times are poor. More work should be done on this issue to obtain more accurate data in the future.

5 Prediction of the size of rainfall-induced debris flows

It is not enough to predict the actual occurrence and the arrival time of a debris flow. To reduce its destructive impact on property and human life, the prediction of its size is also of great importance. Current studies that combine the prediction of the occurrence of a debris flow and its size are only limited to the relationship between the rainfall volume and the total volume of debris flows (Suwa and Yamakoshi 1997), whereby the volume of debris flows is only roughly divided into three classes: large, medium, and small. The occurrence of a debris flow is closely related to the rainfall intensity, and the total volume of debris

Fig. 7 Comparison of the arrival time between the measured time T_m and the calculation time T_c
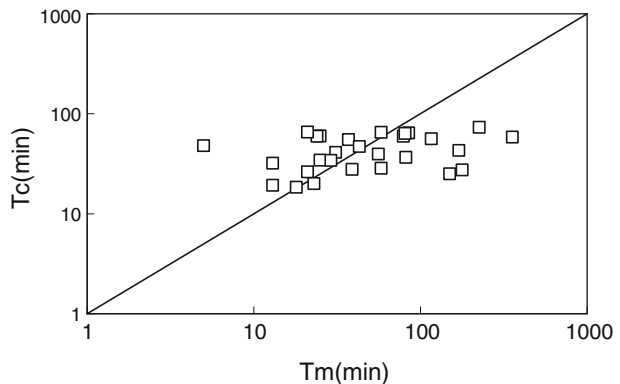
flows is closely related to the volume of rainfall, more specifically the volume of the run-off caused by the rainfall. The size of a debris flow can be predicted from the rainfall volume in the basin, by calculation of the total flow at the location of occurrence of a debris flow (Yu et al. 2001), and by considering the formation process of a debris flow.

The run-off produced by torrential rains after the maximum ten-minute rainfall intensity is the hydraulic condition for triggering of a debris flow. Formula (13) can be used to determine the total volume of water of the surface run-off. As pointed out by Yu et al. (2001) in a debris flow of high density, the water content is lower than the sediment content. So, when calculating the total run-off, the water content is also less than the sediment content. This means that the influence of the volume concentration of the sediment must be taken into consideration. The relationship between the volume concentration of the sediment and the particle size in the debris flow used here is (Yu 2008b)

$$C = \frac{r - r_w}{r_s - r_w} \tag{15}$$

$$r = P_{05}^{0.35} P_2 r_V + r_0 \tag{16}$$

in which C = the volume concentration of the sediment, r = the density of debris flows (g/cm^3), r_w = the density of water (g/cm^3), r_s = the density of sand in the debris flow (g/cm^3), P_{05} = the percentage of fine particles (<0.05 mm) in the debris flow, P_2 = the percentage of coarse particles (>2 mm) in the debris flow, r_v and r_0 are constant, r_v = 2.0 g/cm^3, r_0 = 1.5 g/cm^3. For Jiangjia Gully, the volume concentration could be determined in the field: the average value is 2.1 g/cm^3. The Eq. 16 is not for muddy flow, stony debris flow, and homogeneous size debris flow. It is used for the debris flow with wide particle size distribution.

In addition, because of the loose solid materials and landslide deposits in the channels, a block-up coefficient in debris flow basins should also be taken into account while calculating the total discharge of a debris flow (Wu et al. 1990). For different basins, there are different block-up coefficients for calculation of the volume of debris flows. For the Jiangjia Gully, the typical block-up coefficient is 3 (Wu et al. 1990). The total discharge volume of a debris flow can now be calculated from the total water volume (Yu et al. 2001) as follows:

$$W = \frac{\varphi W_{10}}{1 - C} \tag{17}$$

in which W = the total volume of a debris flow (m^3), W_{10} = the total water volume produced by the 10-min maximum rainfall intensity that triggers a debris flow (m^3), Φ = the block-up coefficient. Figure 8 shows the comparison between field observation values and the calculated values of volumes of debris flows which occurred in 1998, 1999, 2000, and 2001 in Jiangjia Gully. W_M = the field measurement value (m^3). Like Figs. 7 and 8 also compares the field measured values with the calculation values for 28 debris flows.

The locations where the debris flows occurred and the rainfall observation points do not coincide, thus the rainfall data do not totally reflect the rainfall situation at the locations where the debris flows developed. Besides, the rainfall volume produced during the period of the maximum 10-min rainfall intensity is less than the total run-off caused by the rainfall. At the same time, the field observation of the total volume of a debris flow also depends on the available observation equipment, the weather, and the visibility and will never yield exact values for the flow characteristics and the total discharge of a debris flow. Nevertheless, in Fig. 8, two-third calculated and measured volume values are relatively

Fig. 8 Comparison of the total volume of debris flows between field measurement values and calculated values of the run-offs which triggered debris flows
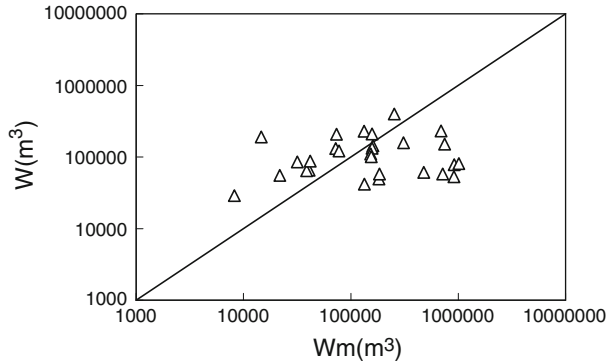
close together. Even considering such factors as the errors in observation, variation of rainfall in the basin, approximative calculation of the run-off caused by the rainfall, the figures show that the volume of a debris flow can be predicted reasonably well using the formula 17. But one-third predicted data are poor. More work should be done on this issue to obtain more accurate data in the future.

6 Conclusions

The accurate prediction of the occurrence, travel time, and volume of debris flows allowing a reduction or even prevention of economic losses and human casualties is currently a major, but difficult point of study on debris flows. Most predictive methods have relied on rainfall as the basic parameter, with the result that only the actual occurrence is predicted. For the prediction of the related arrival times and debris flow volumes, basic information is essential about the causes of and conditions for the initiation of debris flows, and about the rainfall data in the source catchment. There are two primary conditions to be fulfilled for the initiation of debris flows in the Jiangjia basin: abundance of loose solid materials in the channel, including solid materials produced by landslides and avalanches, and large amounts and high intensities of rainfall leading to strong floods in the channel capable to carry away solid matters.

Based on an assumed mechanism for the initiation of debris flows and on the observed rainfall characteristics in the basin, this paper also gives a systematic analysis of the arrival time and size of debris flows, leading to the following conclusions:

(1) Ordinary channel flows can carry away fine particles, but to form a debris flow, the diameter of the coarse particles mobilized by a flood should be greater than 20 mm in Jiangjia Gully. To carry away such coarse particles, the unit discharge of a flood has to be greater than 0.35 m^3/s.m.

(2) The run-off caused by rainfall is influenced greatly by the rainfall intensity. The occurrence of a rainfall-related debris flow is triggered off by short-duration torrential rains of high intensity. In the Jiangjia Gully, a debris flow occurs due to the run-off caused by the maximum intensity 10-min rainfall.

(3) The velocity and the travel time of debris flows in the Jiangjia Gully can be calculated using the values for the run-off caused by the maximum intensity 10-min rainfall and the channel discharge caused by this run-off.

(4) The size (volume) of a debris flow can be calculated using the run-off caused by the 10-min rainfall intensity, the volume concentration of sediment, and the block-up coefficient.

This article takes the Jiangjia Gully in Dongchuan in Yunnan Province as an example for research on the mechanism of the initiation of channelized debris flows. The research work focused on the rainfall intensity and the mobilization of the bedload. According to the volume of rainfall in the catchment, a systematic analysis of the occurrence, arrival time, and scale (volume) of debris flows is presented. The research work can help understanding the mechanism of the trigger of channelized debris flows in the world and may help reducing the economic losses and human casualties cause by debris flows.

The study in this paper focused on the mechanism of the initiation of debris flows by the prevailing geological and geographical conditions and the weather condition. The results of the study have shown that for the initiation of debris flows, the bedload was mobilized by the channel flood caused by the run-off due to heavy rainfall. The arrival time and scale of debris flow can be predicted from the rainfall data. These predictions could be made for the Jiangjia Gully in Dongchuan of Yunnan Province because there are plenty of observation data. Some of the predicted values do not fit in the range of field measured debris flows as the rainfall records that are used may not be accurate. The peak discharge of debris flow is the most important parameter for the hazard mitigation. The peak discharge of debris flow cannot be predicted by the model developed in this paper and leave mystery to discover in the future work. For other debris flow gullies, rainfall records may be a great problem for prediction of the occurrence of debris flows. Until now, the rainfall predictions are all providing values for large areas, but almost all debris flow gullies are small catchments, of sizes less than 100 km^2. On the other hand, many debris flows are initiated by landslides, or by dam breaks, or by destabilized slopes which are different from the catchments studied in this paper. The initiation mechanism and prediction method for such catchments of a different character need to be researched in future work.

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