Dear Samuele Segoni,

Thank you for the chance that you kindly gave us about our manuscript entitled "**A method of rainfall threshold calculation for debris flow early warning in data-poor areas—a case study in Guojuanyan gully, Sichuan Province, China**" (No.nhess-2017-333). We truly appreciate all of the thoughtful comments from you and Referees as well as the interactive comment, and we have now revised our manuscript accordingly with a list of changes detailed below.

Response to Editor:

1) Please carefully check the reference list and rewrite it according to the style of NHESS journal, where needed.

We have checked the references.

2) Answering to referee comment #1 you state that "I-D model is one of the most popular approaches to account for antecedent prcipitations in geohazards". I disagree, as the ID approach is mostly used to account for peak intensity precipitation and it is not effective to account for antecedent precipitation. For this reason, ID thresholds are used for debris flows and shallow landslides, which are usually triggered by short and intense precipitation and in which antecedent precipitation does not necessarily play a decisive role.

We truly agree with you. I-D approach is mostly used to analyze the relationship between peak intensity precipitation and the hazards. We made a mistake by careless and we wanted to say that I-D model is one of the most popular approaches to calculate threshold of geological hazards.

3) Answers to referee comments are very generic. The Authors should put better efforts in revising the manuscript and in submitting a detailed list of point-to-point replies and amendments to the text.

Thanks very much for your kindly remind. We have made a careful revision and made a point-to point replies to the text.

4) There was a discussion among the Editorial board of NHESS and it was stressed that "technical notes" are not an accepted manuscript type. Therefore, I ask you to change your title in "Rainfall threshold calculation for debris flow early warning in areas with scarcity of data" and to better stress the general scientific outcomes of your work.

This has been changed as you suggested.

5) After performing all amendments to the text, please spend the due time to *check the text accurately for typos and for revising the English.*

We have thoroly checked the whole manuscript again.

Response to Short comment (SC1):

In the manuscript it is adopted the formula of the sediment concentration suggested by Takahashi (1977) (reported in eq. (1) of the paper) for describing the initiation mechanism of hydraulic-driven debris flows. The Takahashi relation was determined for stony debris ïn˘Cows propagating ´ over a rigid bed and, hence, with a minor effects of quasi-static actions near the bed. In order to obtain a correct estimate of the bulk concentration, the long lasting grain interactions at the boundary between the upper, grain inertial layer and the underlying C1 NHESSD Interactive comment Printer-friendly version Discussion paper static sediment bed should be accounted for. A recently published paper Lanzoni et al. [2017], slightly modified the mentioned Takahashi formulation, and validate the proposed formulation with a wide dateset of experimental data.

Thank your very much for your kindly discussion. We have the honor to read the paper you ciated carefully and find that you have done a very good job on the dynamics of coarse-grained debris flow dynamics. A remarkable collapse of the dimentionless profiles is obtained by scaling the debris flow velocity with the ruanoff velocity, and a power law characterization is proposed following a heuristic approach. The effects of flow rheology on the basis of velocity profiles are analyzed with attention to the role of different stress-generating mechanisms. Especially the work on the dynamic similarity is very important for it's one of the critical problems the debris flow subject grappling with. We have sited your study in the development and applications of Takahashi's model (Line 331-337). Our study aims to the initiation of loose solid materials in the gully under surface runoff; the interactions on the boundary are not involved. Therefore, Takahashi's model can be used in this study. And this is also an attempt to calculate the rainfall thershold in area with scarcity data; there are lots of further works to do to. We'll try to consider your method and results in our work in future. Thanks again for your thinking and comment.

Response to Anonymous Referee #1:

1) General comments:

…However, data characterizing mechanical, rheological and hydraulic behavior of the soil are not properly displayed. Moreover, the reliability of the physical approach for such cases is not properly substantiated.

The mothod used in this study is mainly focus on the Takahashi's model which considered the characteristic particle size and the volume concentration of sediment. And the hydraulic conductivity of solid material would represented by the maximum strorage capacity of watershed in the stored-full runoff model. We have made a further illustration in the manuscript in "Materals and methods" section (Line 262-276).

In particular, the choice of accounting for antecedent precipitations avoiding to adopt usual I-D approaches should be justified.

The I-D approaches would be demonstration method. This method is relatively accurate, but it needs very rich, long-term rainfall sequence data and disaster information; therefore, it can be applied only to areas with a history of long-term observations. This study is mainly focuse on the area with scarcity data; therfore; it can't calculate the rainfall threshold by I-D approaches.

2) Abstract

L28: please amend "scarcity" for "scaricty"

It has been amended yet.

3) Introduction:

L32-80: probably, reorganizing the first part of abstract could help readability; my proposal is first introducing debris flow and rainfall thresholds, after debris flow post earthquake and associated thresholds with the focus on debris flows post 2008 earthquake

The abtract has been rewritten according your advice.

L32-80: please amend "triggeringdebris" in "triggering debris"; please check the entire Manuscripts where several typos are recognized

We checked the whole paper thoroughly and amended the type mistakes.

L82: please stress the deep uncertainties affecting "frequency calculated meth*od"*

Because the frequency calculated method also needs series of rainfall data, in the areas with scarcity of data can't use it (Line 99-100).

4) Materials and methods:
L106-108: please check font size

This has been checked.

L109-110: what do you mean for "The characteristics of rainfall in the watershed were analyzed firstly by the field survey" (in this sense, also further details for figure 1 should be provided)

This sentence has been changed into "Firstly, to analyze the rainfall characteristics of the watershed by the field monitoring as well as record data if there is any; then to calculate the runoff yield and concentration based on field observation." (Line 249-251) and the figure (Figure 8 at present) has been changed accordingly.

L124-126: grain-size distribution regulates hydraulic properties and then duration and intensity of rainfalls triggering the event; please introduce such elements about it

The main influnce factors for the formation of debris flow event include the geomorphology of gully, characteristics of solid materials and high-intensity rainfall event. We have added some illustrations in the paper (Line 262-276).

L129: please cite as "Rianna et al., 2014"

This has been amended yet.

L130-138: the assumed link between debris flow initiation and rainfall pattern should be deepened; as reported in previous item, hydraulic properties of soils involved regulate what type of rainfalls can generate or not phenomena. As general rule, the higher the conductivity, the larger the influence of short heavy rainfall events able to totally entering the soil; on the other side, for soils characterized by low hydraulic conductivity, cumulative values on longer time spans are relevant for mass movements.

As metntioned in previous question, this paper put characteristics of materials and geomorphology of gully as backgroud data; hence these two were talked about little. We have rewritten this paragraph to clarify it. (Line 262-276)

L146: please move the Figure 3 below under the related text

This has been amended yet.

L148-156: please stress the constraints associated to such assumptions

The whole part had been rewitten already. Especially, the constraints of the assumption of Takahashi's model were explained in the last paragraph of this part (Line 326-337).

L161: avoid the term "density" for soil particles; "unit weight of soil" could be preferable

This has been amended as you suggested.

L162: please check font size

The whoe manuscript has been checked thoroughly and the spelling and format errors were corrected.

L172: avoid the term "density" for soil particles; "unit weight of soil" could be preferable

This has been amended as you suggested.

L172-174: please specify if such parameters can be assumed constant or featured for such soils; in this case, please move in "Case Study" section

In Takahashi's model, the volume concentration, the unit weight of loose deposits and the unit weight of water are usually unchanged while the channel bed slope and the internal friciton angle are characterized by different soils. In this part, the manuscript is mainly introducing the methdology used in this study. The perticular values of these parameters in this paper are showed carefully in "Case Study" section.

L176-177: please provide further details or brief definitions for d16, d50, d84

We added detail illustration under the Eq. (2) (Line 324-325).

L180: please specify what you intend for "stored-full runoff"

The stored-full runoff, one of the modes of runoff production, is also called as the super storage runoff. The reason of the runoff yeild is that the aeration zone and the saturation zone of the soil are saturated by rainfall. In the humid and semi humid areas where rainfall is plentful, because of the high groundwater level and soil moisture content, the loss of precipitation is no longer increased with the rains continue, after meet plant interception and infiltration, which produces a wide range of surface runoff (Line 342-347).

L190: please confirm that Im is roughly represented by porosity for soil depth

No, it can't represented by porosity for soil depth. I_m is the maximum water storage capacity for a specific watershed, it is a constant for a certain watershed that can be calculated by the infiltration curve or infiltration experiment data.

L196: why is 1h assumed as reference duration?

The precipitation intensity is a measure of the peak precipitation. At the same time, the duration of the peak precipitation is generally brief, lasting only up to tens of minutes. Therefore, 10-minute precipitation intensity (maximum precipitation over a 10-minute period during the rainfall event) is selected as the stimulating rainfall for debris flow, which is appropriate and most representative. However, it is difficult to obtain such short-duration rainfall data in areas with scarcity of data which is just our research range. Therefore, 1h is assumed as reference duration in this study (Line 365-370).

L202: what do you intend for "computational step"?

This has been changed into "Δt is the duration time, in this study it is 1 hour" (Line 377).

L204: how do you define such parameters?

Q is the average flow of the watershed, B is the width of the channel, V is the average velocity and h_0 is the critical depth (Line 377-381).

5) Case study

L218-219: please check the number of inhabitants

Yes, the Guojuanyan gully is very small and there is only 20 inhabitants living in this area.

L254: you could consider the table a simple list of events occurred; frequency is not calculated

We have merged table 1 and table 4 into one table as you suggested in the later.

L263: please define "abnormal"; in this perspective, the rainfall threshold could be used to define rainfalls of interest

This sentence has been changed into "When a rainstorm or a debris flow event occurs,…." (Line 172-173).

L265: please correct "monitroring"

This has been corrected.

L283: please correct as "Figure 9"

This has been corrected.

L282: you could report also reference percentiles of PDF (e.g. 25 and 75) in order to evaluate if 2011 and 2012 trends are included in range

Sorry we don't understand what the PDF means is. However, we analyzed the rainfall laws in latest years and it has the same regular pattern with the historical data. (Line 203-204, Figure 6). Actually, the laws of rainfall don't change as it still in the same rainstorm belt which would not be influenced by the earthquake.

L297-300: for debris flow, a graph similar to Figure 9 for monthly average maximum daily precipitation could be very useful; in this regard, to maintain consistency, you should use 1971-2000 time span

This has been amended as you suggested.

L301-310: information about hydraulic conductivity of involved soils is crucial to understand what could be the duration of interest; also for rainfall patterns reported in Figure 10, reporting hourly rainfall values could be interesting

Of course the hydraulic conductivity of involed soils is important. However, the mothod used in this study is mainly focus on the Takahashi's model which considered the characteristic particle size and the volume concentration of sediment. And the hydraulic conductivity of solid material would represented by the maximum strorage capacity of watershed in the stored-full runoff model. We have made a further illustration in the manuscript in "Materals and methods" section (Line 259-273). And as you suggested, the rainfall patterns is replaced by hourly rainfall values which were showed in Figure 13 (Line 214-216).

Figure 11: please provide further details about annual average data; of course, you calculate only on wet fraction; what is the threshold for discriminating rainfall event? E.g. 1mm/d

This figure has been redrawn. It mainly calculated the critical rainfall events which had a large precipitation.

L320-321: please you confirm that the data reported in line in figure 11 are related to average values and not to average of maximum yearly data?

Yes, it's an average of maximum yearly data and we had corrceted this (Line 226, Line 229 and Line 235).

L333-338: an evaluation of hydraulic behavior is crucial; as you report short term durations are crucial. Are you sure that antecedent precipitations could play a relevant role for triggering events?

According to the previous studies, debris flow initiated is the result of the short duration rainfall (10-min rainfall, 1-h rainfall for example) and the effective antecedent precipitations (Cui et al., 2007; Zhao, 2011; Guo, 2013; Zhuang, 2015).

L343-351: the sentences could be moved in "Introduction" part

We have moved the sentences to "Introduction" part (Line 47-56).

6) Results
L358: please check the number of equation

This has been corrected.

L359: please report on y-axis that the graph reports "Percent passing by weight"

This has been corrected.

L365: please specify in which ways the value about velocity is retrieved

The average velocity of debris flows is calculated by the several debris flow events occurred in this gully (Line 399-400).

L367: please specify on what soil depth you evaluate Im

I_m is the maximum water storage capacity for a specific watershed, it is a constant for a certain watershed that can be calculated by the infiltration curve or infiltration experiment data.

L377-387: the formula is not clear; please provide further details; indeed, it is *not clear why you sum rainfalls (Rt) with effective rainfalls. Moreover, K parameter should be not related to atmospheric conditions but to geomorphological conditions regulating the "detection" time of water in the soil depth of interest (e.g. hydraulic conditions, bottom conditions, slope angle). Moreover, it could take into account the effect of evapotranspiration losses reducing the amount of soil water content . For very coarse soil, K could be very low. An interesting work about such parameter is carried out by Baum & Godt (2010) (DOI10.1007/s10346-009-0177-0) and cited works.*

We have rewritten the whole part of 4.2.1 and added a rainfall index classification figure to illustrate the equations and parameters (Line 411-433, Figure 12).

L396-397: the issue related to antecedent conditions is widely debated in literature; in this perspective several elements concur and then further details about involved soil are required

According to the previous studies, debris flow initiated is the result of the short duration rainfall (10-min rainfall, 1-h rainfall for example) and the effective antecedent precipitations (Cui et al., 2007; Zhao, 2011; Guo, 2013; Zhuang, 2015).

Table 4: it provides several information already available in Table 1; please merge the two ones

We have merged table 1 and table 4 into one.

Figure 14: please provide information about why the reliability of I-D rainfall thresholds accounting for only "triggering" event has not been assessed.

I-D approaches belong to demonstration method which is the most accurate method to calculate the debris flow thershold. Howere, it needs plenty of disaster data as well as correspongding rainfall data to statistic the laws between debris flow initiation and the characteristics of rainfall. In areas with scarcity of data, actually almost areas in mountainous are this situation, there is few hazard data and rainfall data. Therefore, the I-D approaches can't satisfy the early warning of debris flow. In fact, this is the consideration of our study, to propose a new thinking for the debris flow early warning in the areas with scarcity of data. We clarified this view in the "Introduction" section (Line 91-106).

Response to Anonymous Referee #2:

General comments:

However, given the debris flows initiation mechanism (surface runoff erosion) the use of the API index should be better argued. For instance, if I understood it *well the authors considered the cumulative precipitation of 20 days plus the 1-hour rainfall for the triggering of debris flows. Again, this must be deeply discussed given the debris flows initiation mechanism.*

According to the previous studies, debris flow initiated is the result of the short duration rainfall (10-min rainfall, 1-h rainfall for example) and the effective antecedent precipitations (Cui et al., 2007; Zhao, 2011; Guo, 2013; Zhuang, 2015). The precipitation intensity is a measure of the peak precipitation. At the same time, the duration of the peak precipitation is generally brief, lasting only up to tens of minutes. Therefore, 10-minute precipitation intensity (maximum precipitation over a 10-minute period during the rainfall event) is selected as the stimulating rainfall for debris flow, which is appropriate and most representative. However, it is difficult to obtain such short-duration rainfall data in areas with scarcity of data which is just our research range. Therefore, this study considered the effective antecedent precipitation of 20 days plus 1-h rainfall for the triggering of debris flow event.

Regarding the structure of the manuscript, I would suggest placing the section "3.1 Location and gully characteristics of the study area" after the "1. Introduction" and before the "2. Materials and methods".

We have changed order of section 2 and section 3, and now it is "2 Study site" and "3 Materials and methods".

Page 2, Line 48-49: Please, check the sentence because is not clear

This sentence has been checked (Line 59-61).

Page 3, Line 58-59: The references should be chronologically displayed

This has been corrected also along the whole manuscript.

Page 3, Line 67: Please, check how to cite the authors (and also along the manuscript)

This has been checked.

Page 4, Line 88-91: Please, check the sentence

This has been checked (Line 99-100).

Page 4, Line 109-110: Please, explain how this was done

Firstly, to analyze the rainfall characteristics of the watershed by the field monitoring as well as record data if there is any; then to calculate the runoff yield and concentration progress based on field observation. Additionally, the critical runoff depth to initiate debris flow was calculated by the initiation mechanism with the underlying surface condition (materials, longitudinal slope, etc.) of the gully (Line 249-255).

Page 4, Line 113-114: Please, explain why did the authors assumed a saturated *condition to explain the debris flows initiated by runoff?*

The method in this study mainly based on the stored-full runoff generation because the study site is in a humid area (Line 253-255, Line 342-353).

Page 5, Line 126-127: Please, provide some references that support this sentence

Some references have been added (Line 284).

Page 5-6, Line 132-134: When you mention "the great amount of antecedent precipitation" you should clarify the temporal resolution

This has been changed (Line 293-296).

Page 7, Line 164-167: Please, provide references

Some references have been added (Line330-337).

Page 9, Line 221: Please, indicate the average slope angle of the main channel in degrees

The average slope angle has been added (Line127).

Page 11, Line 247: Please, standardize the name of the gully along the manuscript. Sometimes is written as Guojuanyan gully, others as Guo Juanyan gully

The name of the gully has been unified as "Guojuanyan gully".

Page 13, Line 281: In which way is evaluated the spatial variability of rainfall?

Actually this study didn't analyze the spatial variability of rainfall. The sentence has been changed as "The characteristics of the rainfall are as following" (Line191-192).

Page 17, Line 348: Replace "was present" with "become available"

This has been corrected.

Page 17, Line 358: Please, check the equation number

This has been corrected.

Page 17, Line 361: Please, standardize the units used in Table 2 and Equation 3

This has been corrected.

Page 19, Line 391: Please, explain how equation 12 can be used to estimate the amount of solid material

I'm sorry, there was a mistake. It should be "Eq.9 can be used to estimate the mosisture content of solid material prior to the debris flow" (Line 434-435).

Page 23, Line 441-443: Please, check the sentence

The sentence has been corrected.

Page 23, Line 447: Please, refer which other factors should be addressed

The other factors means the factors mentioned before except the rainfall characteristics that accounting for in this study. We added some further illustrations in the manuscript (Line 478-479).

Finally, I suggest a rereading of the text in order to correct some minor mistakes.

As your nice suggestion, we have checked up the whole manuscript thoroughly and corrected some spelling and format mistakes.

Response to Anonymous Referee #3:

1) General comments:

Unlike this, the methodological proposal of the manuscript involves modeling with physical characteristics of the loose solid materials (landslide triggered by earthquake - loose deposits that have served as the source materials for debris flows) using the equations (3) and (4) – Takahashi's model. This issue is very important and should be highlighted (emphasized) in the manuscript, mainly because the rainfall thresholds obtained in this paper cannot be generalized and used to classical debris flow's early warning systems or, at best, used with reservation. In general, the manuscript needs to be more concise and written better.

We added some illustrations about the applicative conditions of the method proposed in this manuscript. Addtionally, made some discussions in the "Discussion" section.

3.4 Data collection and the characteristics of rainfall – in this point, the characteristics of the pattern rainfall need to be better explained scientifically, for example, as from others rainfall indexes (accumulated of 48h, 72h, 96h, etc.). In addition, some pattern rainfall indexes analyzed (lines 282 to 300) correspond to previous periods (1971 to 2000 and 1957 to 2008) to the occurrence of the debris flows events (2008 to 2014). In the case of a have information about the pattern rainfall from the debris flows events occurrence period, it is consider *fundamental to analyze in detail the rainfall indexes for this period, that is, from 2008 to 2014 (take as an example the information in Figure10 – page 15).*

We added some more illustrations about the rainfall indexes in the manuscript (Line 189- 192, Line 196-197, Line 203-204). However, as our on-site monitoring system usually affected by the bad weather or some other reasons, we only have the holonomic data of 2011 and 2012. Hence we only analyzed the yearly rainfall characteristics of these two years. As the laws of rainstorm are mainly based on the location in where the rainstorm area is, and the laws of the rainfall in 2011 and 2012 coincide to the historical data. Hence, we think this analysis can satisfy our research. In addition, as it is generally recognized that debris flow is usually triggered by short-duration rainstorms, we just analyzed the 10-min, 1-h and 24-h rainfall indexes. And the Figure 7 corroborates with this statement.

4.1.1 The critical depth of the Guojuanyan gully – the equation (1) used for calculate the critical depth (line 358, page 17) are wrong. The correct equations are (3) and (4).

This has been corrected.

4.1.2 The rainfall threshold curve of debris flow – in the lines 368 to 369, ". . ..rainfall threshold curve of debris flow in the Guojuanyan gully is shown in Table 3", was used which equation to calculate the threshold curve?

The equation has been illustrated above the table (Line 402-403).

4.2.2 The rainstorm and debris flow events in the Guojuanyan gully during 2010-2014 Analyzing the data of the Figures 13 (a, b, c, d and e), it is observed that the triggering rainfall of debris flow events are situated well above (136 to 165 mm) of the established rainfall threshold (107 mm). The data of the Figure 14 corroborates with this statement. Additionally, two points of debris flow no occurrence were verified above of the rainfall threshold curve. Therefore, the authors' assertion (lines 433 to 437) does not match the results presented and will have to be re-analyzed.

The antecedent precipitation index (*API*) in the manuscript includes two parts: the effective antecedent precipitation and the direcet antecedent precipitation, which is the precipitation from the beginning of the rainfall that trigger debris flow to the 1 hour before the debris flow. And the I_{60} in the threshold curve is the precipitation 1 hour before the time debris flow occurred. The relationship of the rainfall indexes is shown in Figure 12. The rainfall indexes of debris flow events happened in Guojuanyan gully mentioned in figure 13 were shown in Table 4. Although the total precipitations are between 136 to 165mm, the I_{60} varies from 18.9 to 42.3 mm. It is much smaller than the threshold (107 mm). It should plus the *API* value to situate above the threshold curve to trigger a debris flow. To validate the result, we added some typical raifalls whose daily rainfall were greater than 50 mm but didn’t trigger a debris flow to Figure 14. All of the debris flow event’s point are lay above the curve and most of the rainstorms tha didn’t trigger debris flow are lay below the curve. It indicates that the proposed method is reasonalbe. However, the triggering factors for a debris flow are very complex and uncertain. Not only the factors mentioned in this study, the *API* and I_{60}, but also the amount of loose deposits, channel and slope characteristics, and et al. would affect the initiation of debris flow. Hence, we should further study the characteristics of the movable solid materials, the shape of gully, and so on. Maybe this is the main reason of the two points lay above the curve but didn’t trigger a debris flow. We discussed this in the “Discussion” section (Line 471-479).

6 Conclusions - The statements contained in the paragraph between the lines 481 to 483 need to represent better the results presented in Figures 13 and 14, this is, the rainfall threshold curve proposed should be used with caution, because it contains relevant uncertainties due to the scarcity of data.

The sentences have been reorganized and modified (Line 515-519).

Line 101 - “. . ..method nor frequency. . ...” change to “. . .. . .method for frequency . . ..”

The sentence is right. It means both the traditional demonstraion method and frequcency calculated method can’t satisfy the debris flow early warning requirements in the areas with scarcity data.

Line 125 - “. . .., corrosion resistance,. . ..” the correct meaning is not “. . .., shear resistance,. . ..”?

This has been corrected.

Lines 246 to 248 - “The Guojuanyan gully had no debris flows before the earthquake; however, it became a debris flow gully after the earthquake, and debris flows occurred in the following years (Table 1)”. This does not seem obvious, because before there was no material deposited!

Yes, you are right. Because there was little loose solid materials in the gully before the earthquake, there was no debris flow at all. We added a detail illustraion in the manuscript to make is much more clear (Line 152-154).

Lines 249/250 - “. . ..density of the debris flow was between 1.8 and 2.1 g/cm3. . .” the correct meaning is not “. . ..density of the soil was between 1.8 and 2.1 g/cm3,. . ..”?

It’s the debris flows’ density.

Line 265 - ". . .., monitroring center,. . .." change to ". . .. . .monitoring center . . .."

This has been corrected.

Line 321 - ". . ..obsevation. . ..." change to ". . .. . .observation. . .."

This has been corrected.

Line 327 - ". . ..maxmum. . ..." change to ". . .. . .maximum. . .."

This has been corrected.

Figure 13 (e) – reform the label "debirs flow" Figure 13 – standardize the figure's legend

This has been checked.

We wish that with the above revisions made, our manuscript can now be accepted for publication on *Nature Hazards and Earth System Sciences* soon. Please do not hesitate to contact me if you have any additional questions or comments.

Looking forward to hearing from you.

Regards

JIANG Yuanjun

Rainfall threshold calculation for debris flow early warning in areas with scarcity of data

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Abstract: Debris flows are one of the natural disasters that frequently occur in mountain areas, usually accompanied by serious loss of lives and properties. One of the most used approaches to mitigate the risk associated to debris flows is the implementation of early warning systems based on well calibrated rainfall thresholds. However, many mountainous areas have little data regarding rainfall and hazards, especially in debris flow forming regions. Therefore, the traditional statistical analysis method that determines the empirical relationship between rainstorm and debris flow events cannot be effectively used to calculate reliable rainfall threshold in these areas. After the severe Wenchuan earthuake, there were plenty of diposits deposited in the gullies which resulted in lots of debris flow events subsequently. The triggering rainfall threshold has decreased obviously. To get a reliable and accurate rainfall threshold and improve the accuracy of debris flow early warning, this paper developed a quantitative method, which is suit for debris flow triggering mechanism in meizoseismal areas, to identify rainfall threshold for debris flow early warning in areas with scarcity of data based on the initiation mechanism of hydraulic-driven debris flow. First, we studied the characteristics of the study area, including meteorology, hydrology, topography and physical characteristics of the loose solid materials. Then, the rainfall threshold was calculated by the initiation mechanism of the hydraulic debris flow. The results show that the proposed rainfall threshold curve is a function of the antecedent precipitation index and 1-h rainfall. The function is a line with a negative slope. To test the proposed method, we selected the Guojuanyan gully, a typical debris flow valley that during the 2008-2013 period experienced several debris flow events and that is located in the meizoseismal areas of Wenchuan earthquake, as a case study. We compared the calculated threshold with observation data, showing that the accuracy of the method is satisfying and thus can be used for debris flow early warning in areas with scarcity of data.

Keywords: Debris flow; rainfall threshold curve; rainfall threshold; areas with scarcity of data

1 Introduction

Debris flow is rapid, gravity-induced mass movement consisting of a mixture of water, sediment, wood and anthropogenic debris that propagate along channels incised on mountain slopes and onto debris fans (Gregoretti et al., 2016). It has been reported in over 70 countries in the world and often causes severe economic losses and human casualties, seriously retarding social and economic development (Imaizumi et al., 2006;Tecca and Genevois, 2009; Dahal et al., 2009; Liu et al., 2010; Cui et al., 2011; McCoy et al., 2012; Degetto et al., 2015; Tiranti and Deangeli, 2015; Hu et al., 2016;). On 12 May 2008, the Wenchuan earthquake occurred in the Longmenshan tectonic belt on the eastern edge of the Tibetan plateau, China (Xu et al., 2008; Wang and Meng, 2009). A huge amount of loose deposits remained in the channels and on the slopes of the plateau after the Wenchuan earthquake. These loose deposits have served as source materials for debris flow and shallow landslide in the years since the earthquake (Tang et al. 2009, 2012; Xu et al. 2012; Hu et al. 2014). For example, the Guojuanyang gully, a small gully located in the meizoseismal areas of the big earthquake, has no debris flows under the annual average rainfall before 2008, but it became a debris flow gully after the earthquake under the same conditions, even the rainfall was smaller than the annual average rainfall. This indicates that earthquakes have a big influence on debris flow occurrence. The Wenchuan earthquake triggered a landslide in the Guojuanyang gully and a huge volume of loose deposits become available on the channels and slopes. These loose deposits provide abundant loose source materials for debris flow activity. Therefore, the rainfall threshold of debris flow post-earthquake is an important and urgent issue to study for debris flow early warning and mitigation.

As an important and effective means of disaster mitigation, debris flow early warning have received much attention from researchers. The rainfall threshold is the core of the debris flow early warning , on which have a great deal of researches yet (Cannon et al., 2008; Chen and Huang 2010; Baum and Godt, 2010;Staley et al., 2013; Winter et al., 2013; Zhou and Tang, 2014; Segoni et al., 2015; Rosi et al 2015). Although the formation mechanism of debris flow has been extensively studied, it is difficult to perform distributed physically based modeling over large areas, mainly because the spatial variability of geotechnical parameters is very difficult to assess (Tofani et al., 2017). Therefore, many researchers (Wilson and Joyko, 1997; Campbell, 1975; Cheng et al., 1998) have had to determine the empirical relationship between rainfall and debris flow events and to determine the rainfall threshold depending on the combinations of rainfall parameters, such as antecedent rainfall, rainfall intensity, cumulative rainfall, et al.. Takahashi (1978), Iverson (1989)and Cui (1991) predicted the formation of debris flow based on studies ofslope stability, hydrodynamic action and the influence of pore water pressure on the formation process of debris flow. Caine (1980) first statistically analyzed the empirical relationship between rainfall intensity and the duration of debris flows and shallow landslides and proposed an exponential expression($I = 14.82D^{-0.39}$). Afterwards, other researchers, such as Wieczorek (1987), Jison (1989), Hong et al. (2005), Dahal and Hasegawa (2008), Guzzetti et al. (2008) and Saito et al. (2010), carried out further research on the empirical relationship between rainfall intensity and the duration of debris flows, established the empirical expression of rainfall intensity - duration ($I = D$) and proposed debris flow prediction models. Shied and Chen (1995) established the critical condition of debris flow based on the relationship between cumulative rainfall and rainfall intensity. Zhang (2014) developed a model for debris flow forecasting based on the water-soil coupling mechanism at the watershed scale. Tang et al. (2012) analyzed the critical rainfall of Beichuan city and found that the cumulative rainfall triggering debris flow decreased by 14.8%-22.1% when compared with the pre-earthquake period, and the critical hour rainfall decreased by 25.4%-31.6%. Chen et al. (2013)analyzed the pre- and post-earthquake critical rainfall for debris flow of Xiaogangjian gully and found that the critical rainfall fordebris flow in 2011 was approximately 23% lower than the value during the pre-earthquake period. Other researches, such as Chen et al. (2008) and Shied et al. (2009) has reached similar conclusions that the post-earthquake critical rainfall for debris flow is markedly lower than that of the pre-earthquake period. Zhenlei Wei et al. (2017) investigated a rainfall threshold method for predicting the initiation of channelized debris flows in a small catchment, using field measurements of rainfall and runoff data.

Overall, the studies on the rainfall threshold of debris flow can be summarized as two methods: the demonstration method and the frequency calculated method. The demonstration method employs statistical analysis of rainfall and debris flow data to study the relationship between rainfall and debris flow events and to obtain the rainfall threshold curve (Bai et al., 2008; Tian et al., 2008; Zhuang, et al., 2009). The I-D approaches would be this kind of method. This method is relatively accurate, but it needs very rich, long-term rainfall sequence data and disaster information; therefore, it can be applied only to areas with a history of long-term observations, such as Jiangjiagou, Yunnan, China, and Yakedake, Japan. The frequency calculated method, assumptting that debris flow and torrential rain have the same frequency, and thus, debris flow rainfall threshold can be calculated based on the rainstorm frequency in the mountain towns where have abundant rainfall data but lack of disaster data (Yao, 1988; Liang and Yao, 2008). Researchers have also analyzed the relationship between debris flow occurrences and precipitation and soil moisture content based on initial debris flow conditions (Hu and Wang, 2003). However, this approach is rarely applied to the determination of debris flow rainfall thresholds because it needs series of rainfall data. Pan et al. (2013) calculated the threshold rainfall for debris flow pre-warning by calculating the critical depth of debrisflow initiation combined with the amount and regulating factors of runoff generation.

Most mountainous areas have little data regarding rainfall and hazards, especially in Western China. When a debris flow outbreak occurs, it often causes serious harm to villages, farmland, transport centers and water conservation facilities in the downstream area. Neither the traditional demonstration method nor frequency calculated method can satisfy the debris flow early warning requirements in these areas. Therefore, how to calculate the rainfall threshold in these data-poor areas has become one of the most important challenges for the debris flow early warning systems. To solve this problem, this paper developed a quantitative method of calculating rainfall threshold for debris flow early warning in areas with scarcity of data based on the initiation mechanism of hydraulic-driven debris flows.

2 Study site

2.1 Location and gully characteristics of the study area

The Guojuanyan gully in Du Jiangyan city, located in the meizoseismal areas of the Wenchuan earthquake, China, was selected as the study area (Fig. 1). It is located at the Baisha River, which is the first tributary of the Minjiang River. The seismic intensity of the study area was XI, which was the maximum seismic intensity of the Wenchuan earthquake. The Shenxi Gully Earthquake Site Park is at the right side of this gully. The area extends from 31°05′27″ N to 31°05′46″ N latitude and 103°36′58″ E to 103°37′09″ E longitude, covering an area of 0.15 km^2 with a population of 20 inhabitants. The elevation range is from 943 m to 1222 m, the average gradient of the main channel is 270‰ (the average slope angle is 15.1°), and the length of the main channel is approximately 580m.

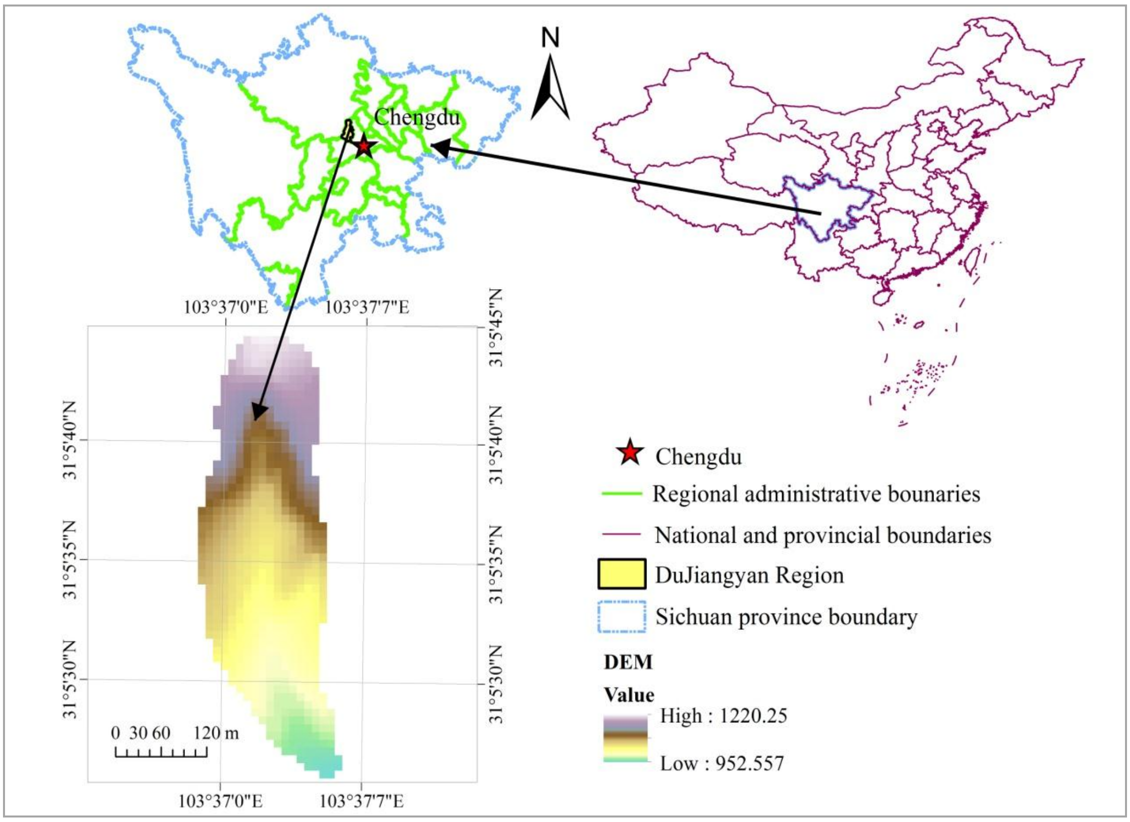


Figure 1. The location of the Guojuanyan gully

Geologically, the Guojuanyan gully is composed of bedrock and Quaternary strata. The bedrock is upper Triassic Xujiahe petrofabric (T_3x) whose lithology is mainly sandstone;

mudstone; carbonaceous shale belonging to layered, massive structures; and semi solid-solid petrofabric. The Quaternary strata are alluvium (Q_4^{el+pl}), alluvial materials (Q_4^{pl+dl}), landslide accumulations and debris flow deposits ($Q_4^{sef+del}$). The thickness of the Quaternary strata ranges from 1 m to 20 m and varies greatly. The strata profile of the Guojuanyan gully is shown in Fig. 2.

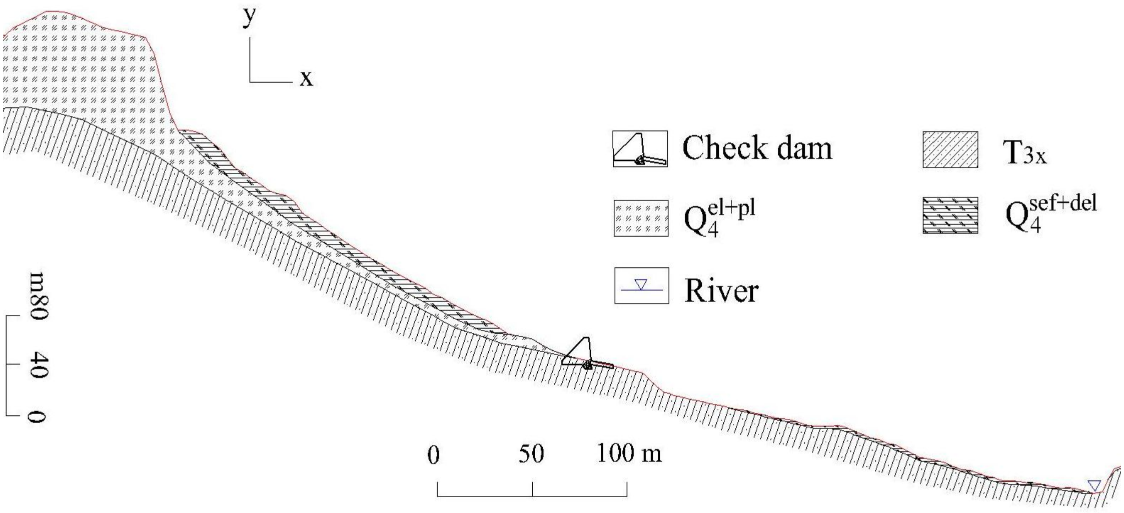


Figure 2. The strata profile of the Guojuanyan gully (Jun Wang et al, 2017)

Geomorphologically, the study area belongs to the Longmenshan Mountains. The famous Longmenshan tectonic belt has a significant effect on this region, especially the Hongkou-Yinxiu fault. The study area has strong tectonic movement and strong erosion, and the main channel is “V”-shaped. The area is characterized by a rugged topography, and the main slope gradient interval of the gully is 20° to 40°, accounting for 52.38% of the entire study area.

Climatically, this area has a subtropical and humid climate, with an average annual temperature of 15.2°C and an average annual rainfall of 1200 mm (Wang et al., 2014).

2.2 Materials and debris flow characteristics of the study area

The Wenchuan earthquake generated a landslide in the Guojuanyan gully, leading to an abundance of loose deposits that have served as the source materials for debris flows. A comparison of the Guojuanyan gully before and after the Wenchuan earthquake is shown in Fig. 3. The field investigations show that the volume of materials is more than 20×10^4 m^3. Therefore, the trigger rainfall for debris flow has decreased greatly. The Guojuanyan gully had no debris flows before the earthquake because of the lack of loose solid materials before the earthquake; however, it became a debris flow gully after the earthquake, and debris flows occurred in the following years (Table 1). The specific conditions of these debris flow events were collected through field investigations and interviews. The field investigations and experiments determined that the density of the debris flow was between 1.8 and 2.1 g/cm^3. Unfortunately, there were no rainfall data before 2011, when we started field surveys in the Guojuanyan gully.

(a) 14 September, 2006 (b) 28 June, 2008

Figure 3. The Guojuanyan gully before (a) and after the Wenchuan earthquake (b) (from Google Earth)

Table 1. The specific conditions of debris flow events in the Guojuanyan gully after the earthquake

Time	Volume (10^4 m^3)	Surges	Rainfall data record
24 September, 2008	0.6	1	No
17 July, 2009	0.8	1	No
13 August, 2010	4.0	3	No
17 August, 2010	0.4	1	No
1 July, 2011	0.8	1	Yes
17 August, 2012	0.7	1	Yes
9 July, 2013	0.4	1	Yes
26 July, 2013	2.0	2	Yes
18 July, 2014	1.5	1	Yes

2.3 Debris flow monitoring and streambed survey of the study area

After the Wenchuan earthquake, continuous field surveillance was undertaken in the study area. A debris flow monitoring system was also established in the study area. To identify the debris flow events, this monitoring system recorded stream water depth, precipitation and real-time video of the gully (Fig. 4). The water depth was measured using an ultrasonic level meter, and precipitation was recorded by a self-registering rain gauge. The real-time video was recorded onto a data logger and transmitted to the monitoring center, located in the Institute of Mountain Hazards and Environment, Chinese Academy of Sciences. When a rainstorm or a debris flow event occurs, the realtime data, including rainfall data, video record, and water depth data, can be observed and queried directly in the remote client computer in the monitoring center. Fig. 5 shows images taken from the recorded video. These data can be used to analyze the rainfall or other characteristics, such as the 10-min, 1- and 24-h critical rainfall. The recorded video is usually used to analyse the whole inundated process of debris flow events and to identify debris flow events as well as the data from rainfall, flow depth, and field investigation.

(a)Real-time camera and rain gauge (b) Ultrasonic level meters

Figure 4. Debris flow monitoring system in the study area

Figure 5. Real-time images from video taken during the debris flow movement

2.4 Data collection and the characteristics of rainfall

The Wenchuan earthquake occurred in the Longmenshan tectonic belt, located on the eastern edge of the Tibetan plateau, China, which is one of three rainstorm areas of Sichuan Province (Longmen mountain rainstorm area, Qingyi river rainstorm area and Daba mountain rainstorm area). Heavy rainstorms and extreme rainfall events occur frequently. Because there were few data in the mountain areas, we collected the rainfall data from 1971- 2000 and 2011-2012 (from our own on-site monitoring); the characteristics of the rainfalls are as following:

(1) Abundant precipitation: The average annual precipitation was 1177.3 mm from 1971 to 2000, and the average monthly precipitation is shown in Fig. 6. From 1971 to 2000, the minimum annual precipitation of 713.5 mm occurred in 1974, and the maximum annual precipitation of 1605.4 mm occurred in 1978. The total precipitation in 2012 is 1148mm, in the trend range of the historical data.

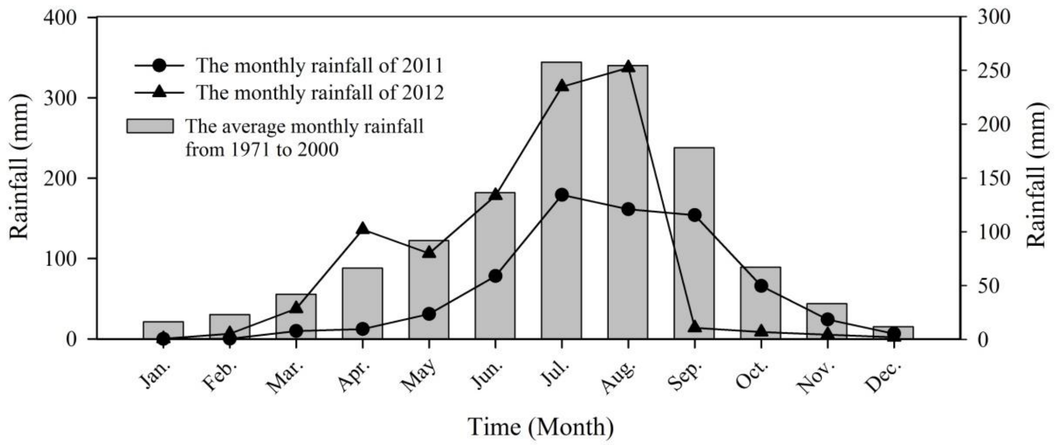


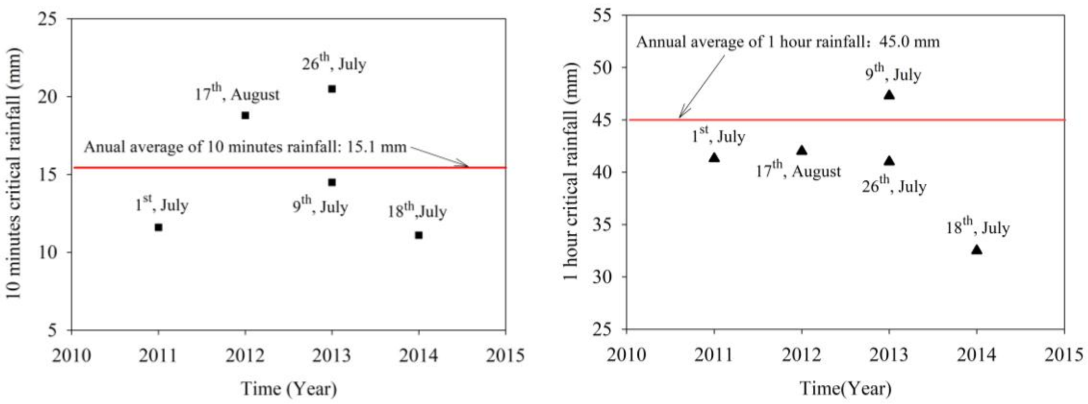
Figure 6. The average monthly precipitation of the Guojuanyan gully from 1971 to 2000 and the monthly rainfall of 2011 and 2012

(2) Severely inhomogeneous distribution of precipitation in time: from Fig. 6 we can observe that rainfall is seasonal, with approximately 80% of the total rainfall occurring during the monsoon season (from June to September) and the other 20% in other seasons. And the laws of monthly rainfall in 2011 and 2012 coincide to the historical data. For instance, in 2012, the total annual rainfall in this area was approximately 1148 mm, and rainfall in the monsoon season from June to September was 961 mm, accounting for 83.7% of the annual total.

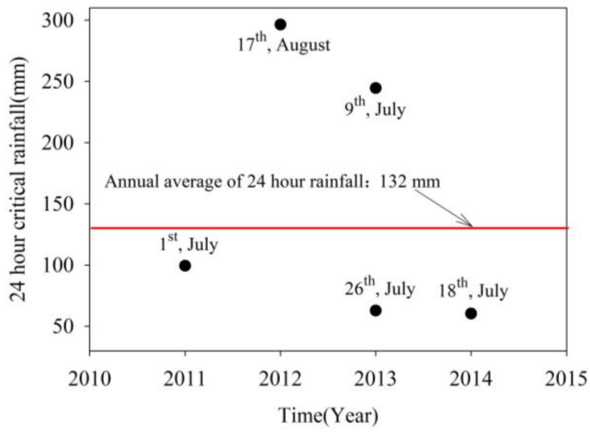
(3) Due to the impact of the atmospheric environment, the regional and annual distribution of rainfall is seriously inhomogeneous; moreover, the rainfall intensity has great differ-

ences. From 1971 to 2000, the maximum monthly rainfall was 592.9 mm, the daily maximum rainfall was 233.8 mm, the hourly maximum rainfall was 83.9 mm, the 10 minute maximum rainfall was 28.3 mm, and the longest continuous rainfall time was 28 days.

Debris flow field monitoring data and on-site investigation data were used to identify the debris flow events and to analyze the characteristics of the rainfall pattern and the critical rainfall characteristics. Analysing the typical rainfall process curves (Fig. 13), we can find that the hourly rainfall pattern of the Guojuanyang gully is the peak pattern, displaying the single peak and multipeak, a characteristic of short-duration rainstorms. Through the statistical analysis of the 10-min, 1-, and 24-h critical rainfall of debris flow events after the earthquake, their characteristics can be obtained, as shown in Fig. 7.



(a) The 10-min critical rainfall (b) The 1-h critical rainfall



(c) The 24-h critical rainfall

Figure 7. The critical rainfall of debris flows in the Guojuanyan gully

Fig. 7a shows that the observed 10-min critical rainfall is between 11.1 mm and 21.5 mm. According to the Sichuan Hydrology Record Handbook (Sichuan Water and Power Department 1984), the annual average of maximum 10-min rainfall of the study area is approximately 15.1 mm. According to the observation, 60% of debris flow events occurred below the annual average 10-min rainfall. In addtion, the 1-h critical rainfall varied between 34.5 mm and 47.3 mm in the study area (Fig. 7b). And the annual average of maximum 1-h rainfall is 45.0 mm based on the Sichuan Hydrology Record Handbook (Sichuan Water and Power Department 1984). Figure 10b shows that 80% debris flow events occurred below the annual average 1-h rainfall, except for the debris flow event occurred on July 9, 2013. At last, the minimum value of 24-h critical rainfall is 60.4 mm and the maximum value is 296.4 mm in the study area. According to the Sichuan Hydrology Record Handbook (Sichuan Water and Power Department 1984), the annual average of maximum 24-h rainfall is 132 mm. From Fig. 7c, we can see that 24-h critical rainfall for different debris flow events vary widely and 60% debris flow events occurred below the annual average 24-h rainfall.

From the above study, we can find that the 10-min and the 1-h critical rainfalls of different debris flow events have minor differences; however, the 24-h critical rainfalls vary widely. The reason is that debris flow is usually triggered by short-duration rainstorms. Therefore, the short-durations of 10-min and 1-h rainfall have higher correlation with debris flow occurrence and have the minor differences. Further analyzing the 10-min and 1-h critical rainfalls, we can find that they vary with the antecedent precipitation index (API). They are variable rather than constant. In this paper, the antecedent precipitation index (API) and the 1-h rainfall (I_{60}) were used to calculate the rainfall threshold curve of debris flows in the Guojuanyan gully.

3 Materials and methods

This study makes an attempt to analyze the trigger rainfall threshold for debris flow by using the initiation mechanism of debris flow. Firstly, to analyze the rainfall characteristics of the watershed by the field monitoring as well as record data if there is any; then to calculate the runoff yield and concentration progress based on field observation. Additionally, the critical runoff depth to initiate debris flow was calculated by the initiation mechanism with the underlying surface condition (materials, longitudinal slope, etc.) of the gully. Then, the corresponding rainfall for the initiation of debris was back-calculated based on the stored- full runoff generation. At last, these factors were combined to build the rainfall threshold model. This method can be applied to the early warning system in the areas with scarcity of rainfall data.

The flow chart of the research is shown in Fig. 8.

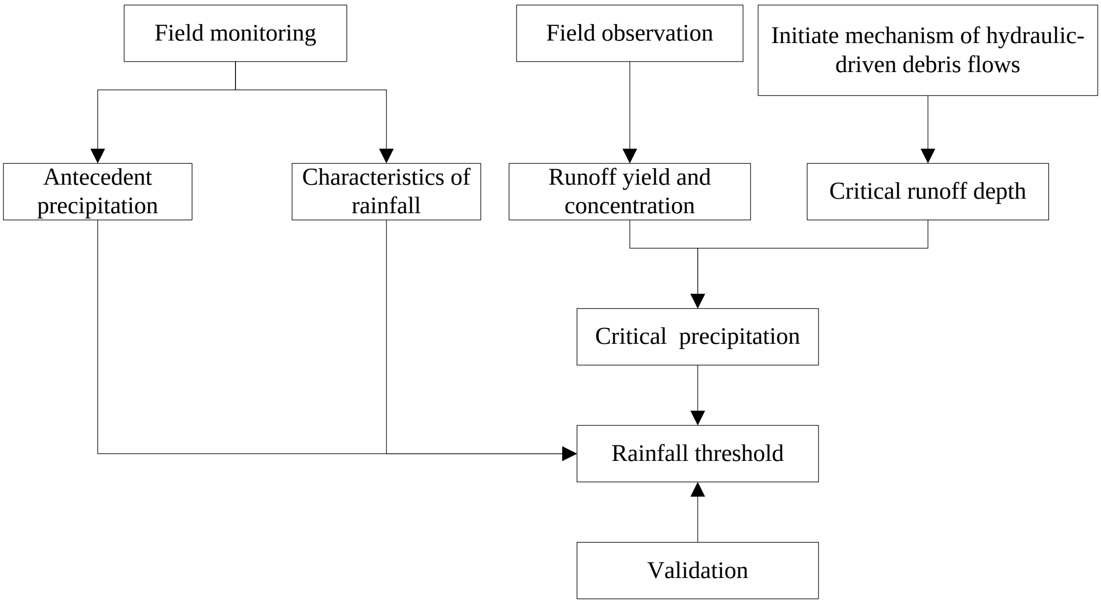


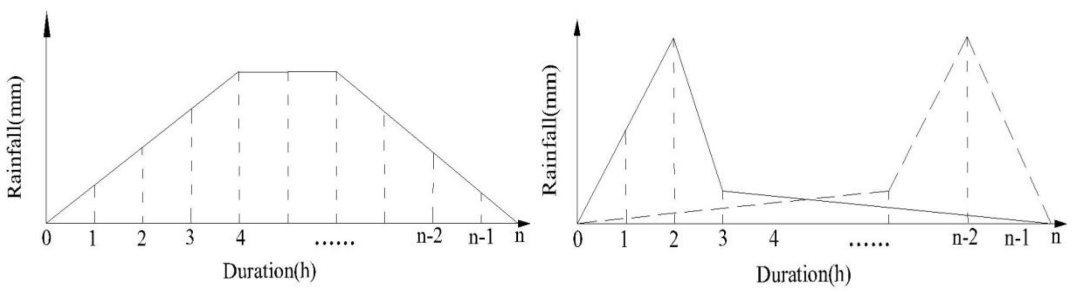
Figure 8. The flow chart of the research

The main influnce factors for the formation of debris flow event include three parts: a steep slope of the gully, abundant solid materials and high-intensity rainfall event. For rainstorm debris flows, the precipitation and intensity of rainfall are the decisive factors of debris flow initiation. Where if there is no earthquakes or other extreme events, the topography of the gully can be considered relatively stable. In contrast, rainfall conditions and the distribution of solid materials that determine the occurrence of debris flows can display temporal and spatial variation within the same watershed. Therefore, it is common to provide warning of debris flows based rainfall data after assessing the supply and distribution of loose solid materials. In Takahashi's model, the characteristics of soil, such as the pososity and the hydraulic conductivity of soils, are not considered, and considered the characteristic particle size and the volume concentration of sediment; while the characteristics of topgraphy is mainly represented by the longitudinal slope of the gully. Furthermore, in the stored-full runoff model, and the maximum storage capacity of watershed can represent the characteristic of the hydraulic conductivity of solid material. Therefore, this study wouldn't consider the hydraulic conducrivity any more.

3.1 Rainfall pattern and the spatial-temporal distribution characteristics

Mountain hazards such as debris flows are closely related to rainfall duration, rainfall amount and rainfall pattern (Liu et al., 2009). Rainfall pattern not only affects the formation of surface runoff but also affects the formation and development of debris flows. Different rainfall patterns result in different soil water contents; thus, the internal structure of the soil, stress conditions, shear resistance, slip resistance and removable thickness can vary. The initiation of a debris flow is the result of both short-duration heavy rains and the antecedent rainfall (Cui et al., 2007; Guo et al., 2013). Many previous observational data have shown that the initiation of a debris flow often appears at a certain time that has a high correlation with the rainfall pattern (Rianna et al., 2014; Mohamad Ayob Mohamadi, 2015).

The precipitation characteristics not only affect the formation of runoff, also affect the formation and development of the debris flow. Different rainfalls result in different soil water contents, and thus the internal structure of the soil, stress conditions, corrosion resistance and slip resistance can vary (Pan et al., 2013). Based on the rainfall characteristics, rainfall patterns can be roughly divided into two kinds, the flat pattern and the peak pattern, as shown in Fig. 9. If the rainfall intensity has little variation, there is no obvious peak in the whole rainfall process; such rainfall can be described as flat pattern rainfall. If the soils characterized by low hydraulic conductivity, this kind of rainfall no longer time spans are relevant for mass movements. And the debris flows, if occur, are mainly caused by the great amount of effective antecedent precipitation. While if the rainfall intensity increases suddenly during a certain period of time, the rainfall process will have an obvious peak and is termed peak pattern rainfall. If the hydraulic conductivity is high enough, the rainfall can totally entering the soil and mass can move easily. These debris flows are mainly controlled by the short-duration heavy rains. Peak pattern rainfall may have one peak or multi-peak (Pan, et al., 2013).



(a) Flat pattern rainfall (b) Peak pattern rainfall

Figure 9. The diagram of rainfall patterns

Through analyzing the rainfall data of the Guojuanyan gully, the rainfall pattern and the spatial-temporal distribution characteristics can be obtained.

3.2 The rainfall threshold curve of debris flows

3.2.1 The initiation mechanism of hydraulic-driven debris flows

When the watershed hydrodynamics, which include the runoff, soil moisture content and the discharge, reach to a certain level, the loose deposits in the channel bed will initiate movement and the sediment concentration of the flow will increase, leading the sediment laden flow to transform into a debris flow. The formation of this kind of debris flow is a completely hydrodynamic process. Therefore, it can be regarded as the initiation problem of debris flow under hydrodynamic force. The forming process of hydraulic-driven debris flows is shown in Fig. 10.

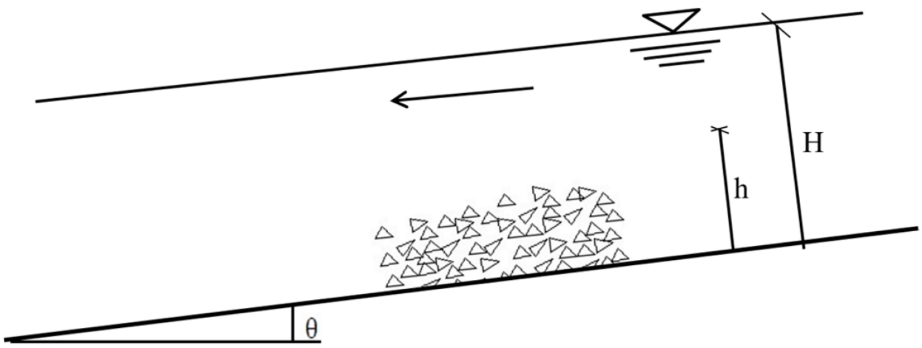


Figure 10. The typical debris flow initiate model

According to Takahashi's model, the critical depth for hydraulic-driven debris flows is:

$$h_0 = \left[\frac{C_*(\sigma - \rho)\tan\phi}{\rho \tan\theta} - \frac{C_*(\sigma - \rho)}{\rho} - 1 \right] d_m \quad (1)$$

where C_* is the volume concentration obtained by experiments(0.812); σ is the unit weight of loose deposits (usually is 2.65 g/cm3); ρ is the unit weight of water,1.0 g/cm3; θ is the channel bed slope (°); ϕ is the internal friction angle (°) and can be measured by shear tests ; And d_m is the average grain diameter (mm), which can be expressed as:

$$d_m = \frac{d_{16} + d_{50} + d_{84}}{3} \quad (2)$$

where d_{16}, d_{50} and d_{84} are characteristic particle sizes of the loose deposits (mm), whose weight percentage are 16%, 50% and 84% separately.

Takahashi's model became one of the most common for the initiation of debris flow after it was presented. A great deal of related studies was published based on Takahashi's model later. Some discussed the laws of debris flow according to the geomorphology and the water content while others examined the critical conditions of debris flow with mechanical stability analysis. However, Takahashi's relation was determed for debris flow propagating ouver a rigid bed, hence, with a minor effect of quasi-static actions near the bed. Lanzoni et al. (2017) slightly modified the Takahashi's formulation of the bulk concentration, which considered the long lasting grain interactions at the boundary between the upper, grain inertial layer and the underlying static sediment bed, and validated the proposed formulation with a wide dateset of experimental data (Takahashi, 1978, Tsubaki et al., 1983, Lanzoni, 1993, Armanini et al., 2005). The effects of flow rheology on the basis of velocity profiles are analyzed with attention to the role of different stress-generating mechanisms.

This study aims to the initiation of loose solid materials in the gully under surface runoff; the interactions on the boundary are not involved. Therefore, Takahashi's model can be used in this study.

3.2.2 Calculation of watershed runoff yield and concentration

The stored-full runoff, one of the modes of runoff production, is also called as the super storage runoff. The reason of the runoff yeild is that the aeration zone and the satruration zone of the soil are saturated by rainfall. In the humid and semi humid areas where rainfall is plentful, because of the high groundwater level and soil moisture content, the loss of precipitation is no longer increased with the rains continue, after meet plant interception and infiltration, which produces a wide range of surface runoff. The Guojuanyan gully is located in Du Jiangyan city, which is in a humid area. Therefore, stored-full runoff is the main pattern runoff producing in this gully, and this runoff yield pattern is used to calculate the watershed runoff. That is, it is supposed that the water storage can reach the maximum storage capacity of the watershed after each heavy rain. Therefore, the rainfall loss in each time I is the difference between the maximum water storage capacity I_m and the soil moisture content before the rain P_a. Hence, the water balance equation of stored-full runoff is expressed as follows (Ye, et al., 1992):

$$R = P - I = P - (I_m - P_a) \tag{3}$$

where R is the runoff depth (mm); P is the precipitation of one rainfall (mm); I is the rainfall loss (mm); I_m is the watershed maximum storage capacity (mm) for a certain watershed, it is a constant for a certain watershed that can be calculated by the infiltration curve or infiltration experiment data. In this study, I_m has been picked up from Handbook of rainstorm and flood in Sichuan (Sichuan Water and Power Department 1984); and P_a is the antecedent precipitation index, referring to the total rainfall prior to the 1 hour peak rainfall leading to debris flow initiation.

Eq. 5 can be expressed as follows:

$$P + P_a = R + I_m \tag{4}$$

The precipitation intensity is a measure of the peak precipitation. At the same time, the duration of the peak precipitation is generally brief, lasting only up to tens of minutes. Therefore, 10-minute precipitation intensity (maximum precipitation over a 10-minute period during the rainfall event) is selected as the stimulating rainfall for debris flow, which is appropriate and most representative. However, it is difficult to obtain such short-duration rainfall data in areas with scarcity of data. Therefore, in this study, P and P_a are replaced by I_{60} (1 hour rainfall) and API (the antecedent precipitation index), respectively; thus, Eq. 6 is expressed as:

$$I_{60} + API = R + I_m \tag{5}$$

In the hydrological study, the runoff depth R is:

$$R = \frac{W}{1000F} = \frac{3.6\sum Q \cdot \Delta t}{F} = \frac{3.6Q}{F} \tag{6}$$

where R is the runoff depth (m); W is the total volume of runoff (m^3); F is the watershed area (km^2); Δt is the duration time, in this study it is 1 hour; and Q is the average flow of the watershed (m^3/s), which can be expressed as follows:

$$Q = BVh_0 \qquad (7)$$

where B is the width of the channel (m), V is the average velocity (m/s) and h_0 is the critical depth (m).

Eq. 5 is the expression of the rainfall threshold curve for a watershed, which can be used for debris flow early warning. This proposed rainfall threshold curve is a function of the antecedent precipitation index (API) and 1 hour rainfall (I_{60}), which is a line and a negative slope.

4 Results

4.1 The rainfall threshold curve of debris flow

4.1.1 The critical depth of the Guojuanyan gully

The grain grading graph (Fig. 11) is obtained by laboratory grain size analysis experiments for the loose deposits of the Guojuanyan gully. Figure 11 shows that the characteristic particle sizes d_{16} , d_{50} , d_{84} and d_m are 0.18 mm, 1.9 mm, and 10.2 mm, 4.1 mm, respectively. According to Eq. (1), the critical depth (h_0) of the Guojuanyan gully is 7.04 mm.

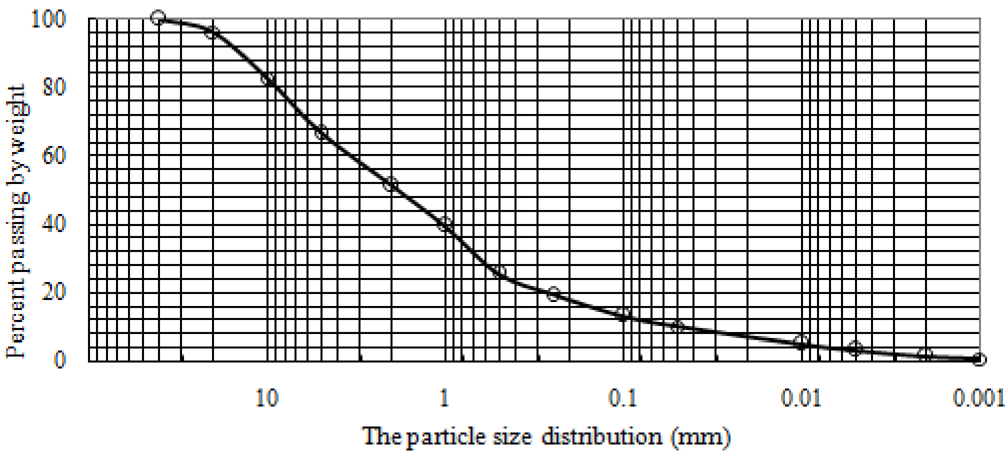


Figure 11. The grain grading graph of the Guojuanyan gully

Table 2. Critical water depth of debris flow triggering in Guojuanyan gully

C_*	σ (g/cm³)	ρ (g/cm³)	$\tan\theta$	d_{16} (mm)	d_{50} (mm)	d_{84} (mm)	d_m (mm)	ϕ (°)	$\tan\phi$	h_0 (mm)
0.812	2.67	1.0	0.333	0.18	1.9	10.2	4.1	21.21	0.388	7.04

4.1.2 The rainfall threshold curve of debris flow

Taking the cross-section at the outlet of the debris flow formation region as the computation object, based on the field investigations and measurements, the width of the cross-section is 20 m, and the average velocity of debris flows which is calculated by the several debris flow events, is 1.5m/s. Based on the Handbook of rainstorm and flood in Sichuan (Sichuan Water and Power Department 1984), the watershed maximum storage capacity (I_m) of the Guojuanyan gully is 100mm. According to Eq. (5) - Eq. (7), the calculated rainfall threshold curve of debris flow in the Guojuanyan gully is shown in Table 3.

Table 3. The calculated process of the rainfall threshold

Watershed	h_0 (mm)	B (m)	V (m/s)	Q (m^3/s)	Δt (h)	F (km^2)	R (mm)	I_m (mm)	$R+I_m$ (mm)
Guojuanyan	7.04	20.0	1.5	0.197	1	0.11	6.9	100	106.9

From the calculated results, we can conclude the rainfall threshold of the debris flow is $I_{60} + API = R + I_m = 106.9 \approx 107$ mm; that is, when the sum of the antecedent precipitation index (API) and the 1 hour rainfall (I_{60}) reaches 107 mm (early warning area), the gully may trigger debris flow.

4.2 Validation of the results

4.2.1 The calculation of the antecedent precipitation index (API)

The rainfall factor influencing debris flows consists of three parts: indirect antecedent precipitation (IAP), direct antecedent precipitation (DAP), and triggering precipitation (TP). Obviously, IAP increases soil moisture and decreases the soil stability, and DAP saturates soils and thus decrease the critical condition of debris flow occurrence. Although TP is believed to initiate debris flows directly, its contribution amounts to only 37% of total water (Cui et al. 2007).

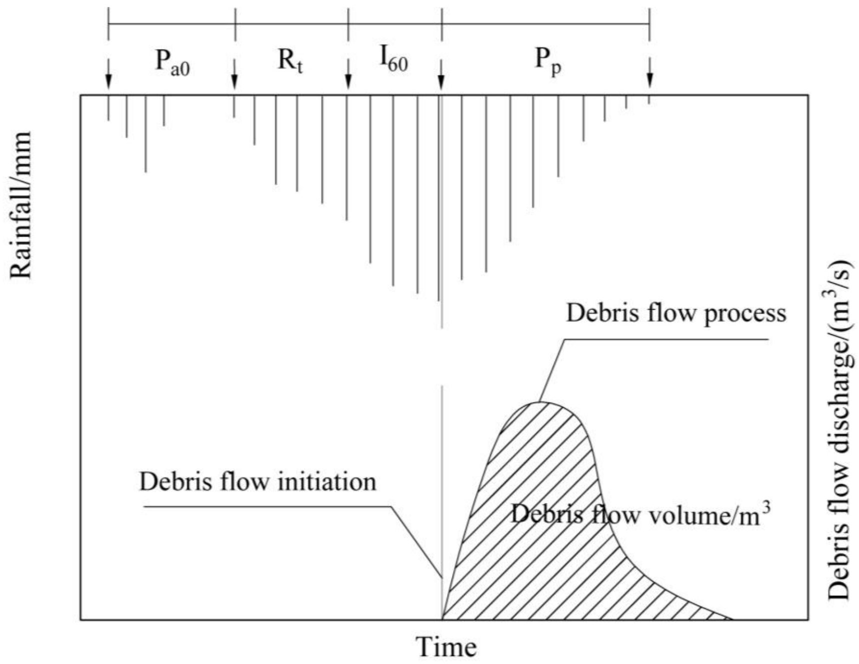


Figure 12. Rainfall index classifications

As Fig. 12 shows, take 1-h rainfall (I_{60}) that obtained from the observed data of the Guojuanyan gully for the TP. The antecedent precipitation index (API) includes IAP and DAP, calculated as the following expression (Zhao, 2011; Guo, 2013; Zhuang, 2015):

$$API = P_{a0} + R_t \tag{8}$$

where P_{a0} is the effective antecedent precipitation (mm) and R_t is the direct antecedent precipitation (mm), which is the precipitation from the beginning of the rainfall that trigger debris flow to the 1 hour before the debris flow.

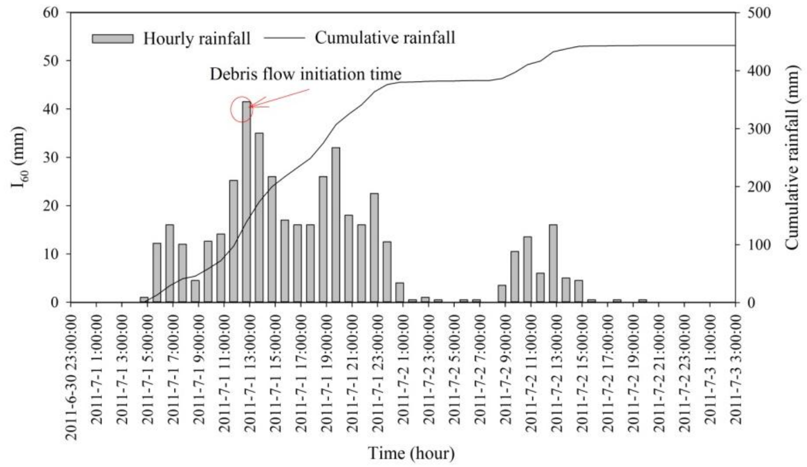
It's difficult to study the influence of antecedent rainfall to debris flow as it mainly relies on the heterogeneity of soils (strength and permeability properties), which makes it hard to measure the moisture. Usually, the frequently used method for calculating antecedent daily rainfall is the weighted sum equation as below (Crozier and Eyles 1980; Glade et al. 2000):

$$P_{a0} = \sum_{1}^{n} P_i \cdot K_i \tag{9}$$

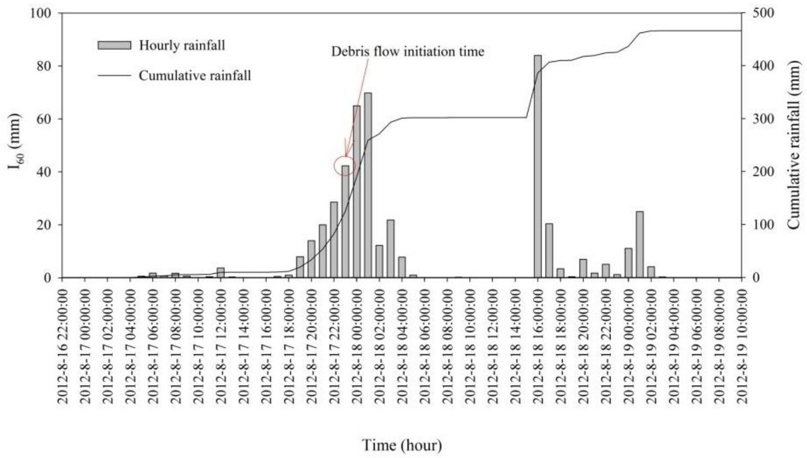
Where P_i is the daily precipitation in the i-th day proceeding to the debris flow event ($1 \le i \le n$) and K_i is a decay coefficient due to evaporation and gomomorphological conditions of the soil.

Eq.9 can be used to estimate the moisture content of solid material prior to the debris flow. The effect of a rainfall event usually diminishes within 20days and decreases with lower daily *K* values. Different patterns of storm debris flow gullies require different numbers of previous indirect rainfall days, which can be determined by the relationship between the stimulating rainfall and the antecedent rainfall of a debris flow (Pan, et al., 2013). Generally, a typical rainstorm debris flow gully requires 20 days of antecedent rainfall.

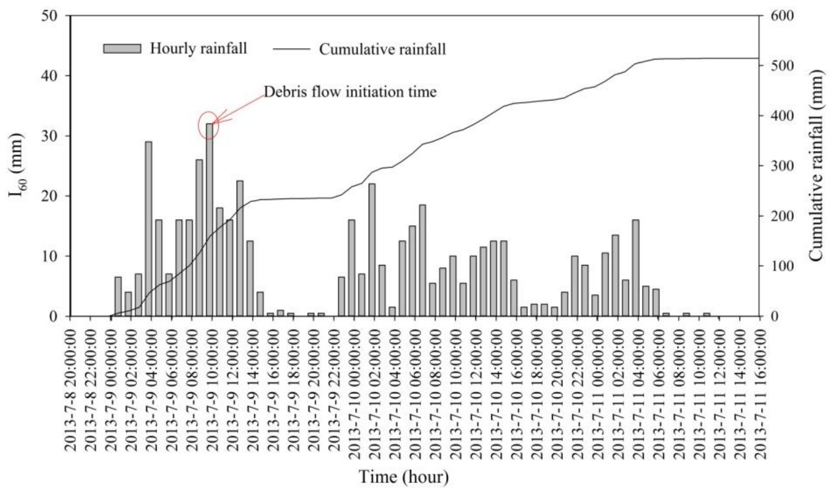
4.2.2 The rainstorm and debris flow events in the Guojuanyan gully during 2010-2014



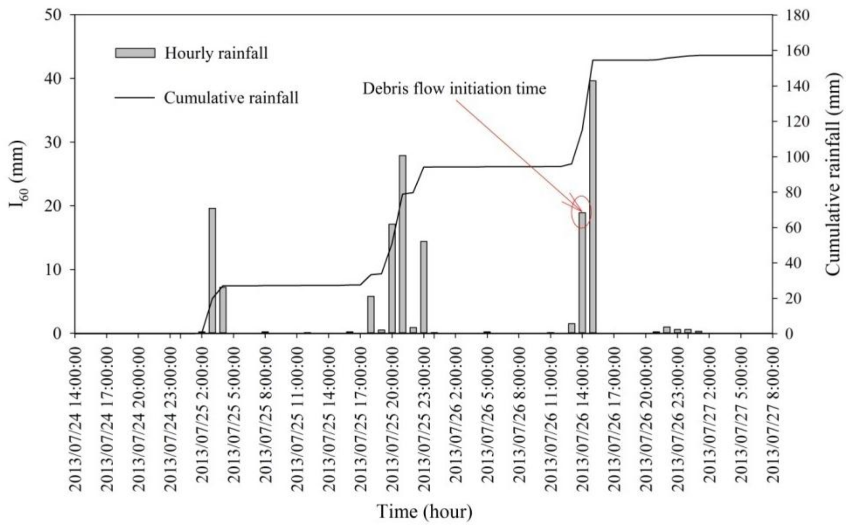
(a)



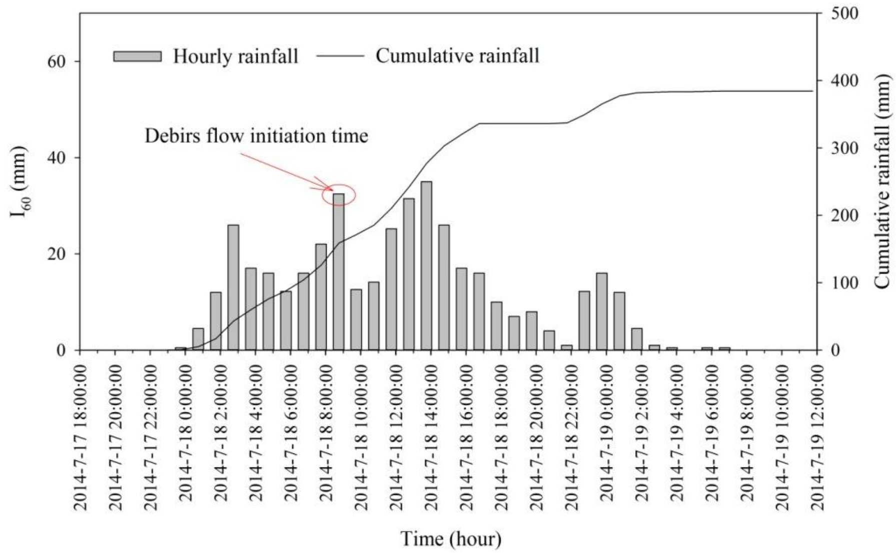
(b)


Hourly rainfall
Cumulative rainfall
Debris flow initiation time
I60 (mm)
Cumulative rainfall (mm)
Time (hour)

(c)


Hourly rainfall
Cumulative rainfall
Debris flow initiation time
I60 (mm)
Cumulative rainfall (mm)
Time (hour)

(d)


Hourly rainfall
Cumulative rainfall
Debirs flow initiation time
I60 (mm)
Cumulative rainfall (mm)
Time (hour)

(e)

Figure 13. The rainfall process of debris flowe vents in the Guojuanyan gully from 2011 to 2014 (a, July 1, 2011; b, August 17, 2012; c, July 9, 2013; d, July 26, 2013; e, July 18, 2014)

Table 1 shows that debris flows occurred almost every year after the earthquake. The *K* and *n* in Equation (9) are identified as 0.8 and 20 days (Cui et al. 2007). Thus, the duration and intensity of the 1-h triggering rainfall and cumulative rainfall for the typical rainfalls are shown in Table 4.

In addition to the rainfall process of the 5 debris flow events (Fig. 13), some typical rainfalls whose daily rainfall were greater than 50 mm but did not trigger a debris flow were also calculated; the greatest 1-h rainfall is considered as I_{60} (Table 4).

Table 4. The data of typical rainfall in the Guojuanyan gully after the earthquake

Time	Daily rainfall (mm)	Pa_0 (mm)	R_t (mm)	*API* (mm)	I_{60} (mm)	API+I_{60} (mm)	Location to the threshold line	Triggered debris flow
1 July, 2011		9.7	97.6	107.3	41.5	148.8	Above	Yes
17 August , 2012		12.1	81.9	94.0	42.3	136.3	Above	Yes
9 July , 2013		5.7	127.5	133.2	32	165.2	Above	Yes
26 July , 2013		22.4	96.0	118.4	18.9	137.3	Above	Yes
18 July, 2014		10.7	116.2	126.9	32.5	159.4	Above	Yes
20 August , 2011	82.8	8.5	19.0	27.5	26.8	54.3	Below	No
5 September , 2011	52.1	48.7	1.2	49.9	16.2	66.1	Below	No
16 June , 2012	55.8	5.6	6.6	12.2	27.0	39.2	Below	No
3 August , 2012	148.3	7.5	84.3	91.8	26.7	118.5	Above	No
18 August , 2012	125.7	54.3	0	54.3	65.0	119.3	Above	No
18 June , 2013	50.6	6.2	3.8	10.0	40.0	50.0	Below	No
28 July , 2013	59.4	13.4	30.0	43.4	29.4	72.8	Below	No
6 August , 2013	56.1	12.4	34.0	46.4	17.1	63.5	Below	No

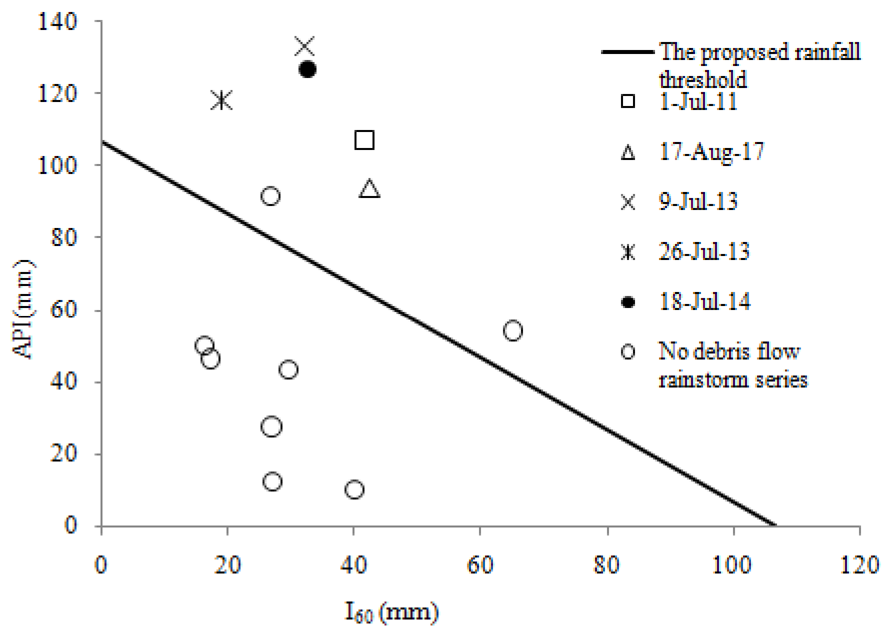


Figure 14. The proposed rainfall threshold curve of debris flow in the Guojuanyan gully

The proposed rainfall threshold curve is a function of the antecedent precipitation index (API) and 1-h rainfall (I_{60}), which is a line and a negative slope. Fig. 14 shows that the calculated values $I_{60}+API$ of debris flow events in the Guojuanyan gully are all above the rainfall threshold curve, while most of the rainstorms that did not trigger debris flow are lay below the curve. That is, the proposed rainfall threshold curve is reasonable through the validation by rainfall and hazards data of the Guojuanyan gully.

5 Discussions

The proposed rainfall threshold curve is a function of the antecedent precipitation index (API) and the 1-h rainfall (I_{60}), which has been validated by rainfall and hazards data and can be applied to debris flow early warning and mitigation. However, the special and complex formative environment of debris flow after earthquake caused the rainfall threshold is much more complex and uncertain. The rainfall threshold of debris flow varies with the antecedent precipitation index (API), rainfall characteristics, amount of loose deposits, channel and slope characteristics, and so on. In Figure 14, there are two points above the curve that did not trigger debris flow at all; therefore, we should further study the characteristics of the movable solid materials, the shape of gully, and so on to modify the rainfall threshold curve.

In addition, restricted by the limited rainfall data, this study was validated by only 5 debris flow events. The value of the curve should be further validated and continuously corrected with more rainfall and disaster data in later years.

It should be noted that the mothodological proposal of this study is based on the physical process of debris flow initiation and involves modeling with physical characteristics of the loose solid materials which served by the landslides triggered by earthquake; therefore, it's suit for the areas with scarcity of data especially the earthquake affected areas. For the classical debris flow's early warning systems, the initiation mechanism would be suit for the characterisitcs of the gully and materials. Furthermore, as the initiation depth in distrinct watershed is different from each other because of the different topography and loose solid materials, hence the rainfall threshold is independent for each watershed. While most of debris flow gullies in Wenchuan earthquake affected areas with scarcity of rainfall data and disaster data, therefore, the approach proposed in this study hasn't been validated by other gullies except the Guojuanyan gully so far.

6 Conclusions

(1) In the Wenchuan earthquake-stricken areas, loose deposits are widely distributed, causing dramatic changes on the environmental development for the occurrence of debris flow; thus, the debris flow occurrence increased dramatically in the subsequent years. The characteristics of the 10-min, 1-h and 24-h critical rainfalls were represented based on a comprehensive analysis of limited rainfall and hazards data. The statistical results show that the 10-min and 1-h critical rainfalls of different debris flow events have minor differences; however, the 24 hour critical rainfalls vary widely. The 10-min and 1-h critical rainfalls have a notably higher correlation with debris flow occurrences than to the 24-h critical rainfalls.

(2) The rainfall pattern of the Guojuanyan gully is the peak pattern, both single peak and multi-peak. The antecedent precipitation index (*API*) was fully explored by the antecedent effective rainfall and stimulating rainfall.

(3) As an important and effective means of debris flow early warning and mitigation, the rainfall threshold of debris flow was determined in this paper, and a new method to calculate the rainfall threshold is put forward. Firstly, the rainfall characteristics, hydrological characteristics, and some other topography conditions were analysed. Then, the critical water depth

for the initiation of debris flows is calculated according to the topography conditions and physical characteristics of the loose solid materials. Finally, according to the initiation mechanism of hydraulic-driven debris flow, combined with the runoff yield and concentration laws of the watershed, this study promoted a new method to calculate the debris flow rainfall threshold. At last, the hydrological condition for the initiation of a debris flow is the result of both short-duration heavy rains (I_{60}) and the antecedent precipitation index (API). The proposed approach resolves the problem of debris flow early warning in areas with scarcity data, can be used to establish warning systems of debris flows for similar catchments in areas with scaricty data although it still need further modification. This study provides a new thinking for the debris flow early warning in the mountain areas.

Acknowledgments

This paper is supported by the CRSRI Open Research Program (Program No: CKWV2015229/KY), CAS Pioneer Hundred Talents Program, and National Nature Science Foundation of China (No. 41372331 & No. 41672318).

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