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Rainfall Threshold Calculation Method for Debris Flow Pre-Warning in Data-Poor Areas

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ABSTRACT: Debris flows are the one type of natural disaster that is most closely associated with human activities. Debris flows are characterized as being widely distributed and frequently activated. Rainfall is an important component of debris flows and is the most active factor when debris flows occur. Rainfall also determines the temporal and spatial distribution characteristics of the hazards. A reasonable rainfall threshold target is essential to ensuring the accuracy of debris flow pre-warning. Such a threshold is important for the study of the mechanisms of debris flow formation, predicting the characteristics of future activities and the design of prevention and engineering control measures. Most mountainous areas have little data regarding rainfall and hazards, especially in debris flow forming regions. Therefore, both the traditional demonstration method and frequency calculated method cannot satisfy the debris flow pre-warning requirements. This study presents the characteristics of pre-warning regions, included the rainfall, hydrologic and topographic conditions. An analogous area with abundant data and the same conditions as the pre-warning region was selected, and the rainfall threshold was calculated by proxy. This method resolved the problem of debris flow pre-warning in areas lacking data and provided a new approach for debris flow pre-warning in mountainous areas.
KEY WORDS: rainfall threshold, debris flow, pre-warning, calculation method, data lack area.

INTRODUCTION

Debris flows are one of the most common natural disasters and are most closely associated with human activities. Debris flows are widely distributed and frequently activated. The main conditions for the formation of rainstorm debris flow are a steep slope of the gully bed, abundant solid materials and a large number of high-intensity rainfall events. Among them, rainfall is the most active factor when debris flow outbreaks

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occur and determines the temporal and spatial distribution characteristics of the hazards. It has been demonstrated that the initiation of rainstorm-type debris flow is the result of both spot and antecedent precipitation. The existence and amount of antecedent precipitation has an important effect on debris flow formation and is one of the key parameters of debris flow forecast modeling. Precipitation factors with respect to spot rainfall process include the rainfall intensity, precipitation duration, precipitation amount and peak precipitation. Under the influence of the two rainfall factors, debris flow initiation mainly occurs at the time of peak precipitation. The amount of precipitation prior to a debris flow is a direct indicator. 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, a 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 actual debris flow pre-warning projects because long-term rainfall monitoring system do not exist in most debris flow basins where pre-warning systems are needed. In debris-flow forming regions, rainfall information is lacking, and we must obtain regional daily rainfall data by relying on local weather stations. However, it has not been possible to calculate a debris flow rainfall threshold and provide effective debris flow pre-warning for these basins.

For rainstorm debris flows, the precipitation and intensity of rainfall are the decisive factors of debris flow excitation. Where earthquakes and other extreme events are not important, bed conditions 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. A reasonable rainfall threshold target is essential to ensuring the accuracy of debris flow pre-warning systems. Such a threshold is important for the study of the mechanisms of debris flow formation, the prediction and characterization of future activities and the design of prevention and control engineering measures.

To date, studies of debris flow rainfall thresholds have used the following methods. (1) The traditional demonstration method uses a statistical analysis of actual rainfall and debris flow disaster data to obtain the relationship between the corresponding antecedent effective rainfall and characteristic rainfall (e.g., 10 min, 30 min, 1 h rainfall) and then constructs a rainfall threshold plot (Zhuang et al., 2009; Bai et al., 2008; Tian et al., 2008; Lin et al., 2001; Wang, 1996). This method is accurate but requires abundant and long-term rainfall sequence data and disaster materials. Thus, this approach is only applied to areas having a long-term observation history, such as Jiangjiagou, Yunnan, China, and Yakedake, Japan. (2) The frequency calculation method assumes that disasters and rainstorms occur at the same frequency, and thus, a debris flow rainfall threshold can be calculated based on the rainstorm frequency in the mountain towns that have abundant rainfall data but lack disaster data (Duan, 2009, 2008; Liang and Yao, 2008; Su et al., 2006; Yao, 1988). 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. Pan et al. (2012) calculated the threshold rainfall for debris flow pre-warning by calculating the critical depth of debris flow initiation combined with the amount and regulating factors of runoff generation.

The majority of debris flows occur distant from towns in China, especially western mountainous area where rainfall and disaster data are scarce. 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 pre-warning requirements in these areas. To solve this problem, we chose an area with abundant data and similar conditions to the study area as a reference and analyzed the characteristics of the rainfall in study area. To provide a scientific basis, we developed a method of calculating a rainfall threshold for debris flow pre-warning systems that can be applied to areas having a lack of data as well as a hydraulic debris flow-initiating mechanism.

TEMPORAL AND SPATIAL DISTRIBUTION OF RAINFALL

The Relationship between Rainfall and Elevation

To investigate the temporal variation of rainfall in the study area, we selected data from a nearby rainfall station and analyzed the temporal and spatial distribution characteristics of the rainfall. The analysis showed that within a certain range, the rainfall and elevation show a significant relationship. Therefore, by analyzing data from the rainfall station location and the rainfall characteristics (e.g., the average annual monsoon rainfall, daily rainfall and hours of rainfall) for the study area and its adjacent areas, we established the following relationship between the rainfall characteristics and altitude

$$H=AI^a \quad (1)$$

where H is the elevation (m a.s.l.), I is the rainfall characteristic (mm), A is a coefficient and a is an index.

Analysis of Rainstorm Types

The precipitation characteristics not only affect the formation of runoff, but 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. In summary, differences in precipitation not only affect the runoff, they also affect the supply of solid materials.

Rainfall patterns can be roughly divided into two types, flat-type and peak-type rainfall, according to the extent of the rainfall, as shown in Fig. 1. In a rainfall event, if the rainfall intensity shows little variation, there is no obvious peak in the rainfall process line; such rainfall patterns can be described as a flat-type. On the contrary, if the rainfall intensity increases suddenly during a certain period of time, the rainfall process line will have an obvious peak and is termed peak-type rainfall. Peak-type rainfall, may have one peak or more than one peak; based on its relative position, a peak may appear in the early, middle or late stage of a rainfall event; heavy rainfall events are generally brief, but may last an extended period of time. According to current disaster information, rainstorms that cause debris flows are mainly peak-type rainfall. Thus, in this analysis, a storm rainfall pattern is peak-type rainfall event, and the peak number considers only a single peak.

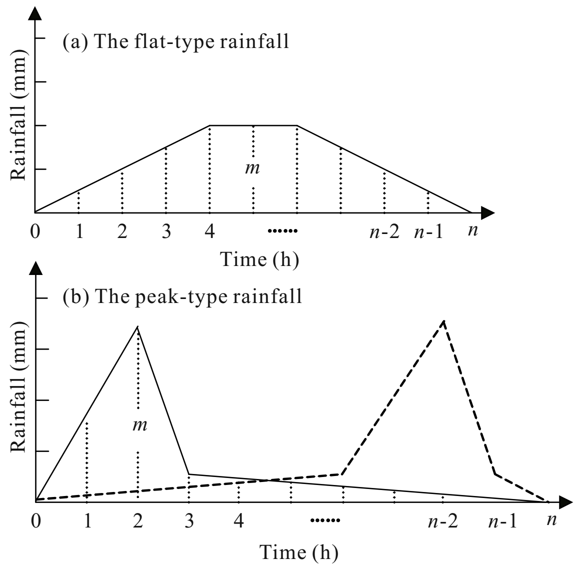

Figure 1. Typical rain styles analysis.

Calculation of the Antecedent Rainfall

The initiation of a debris flow is the result of both short-duration heavy rains and antecedent rainfall. Many previous observational data have shown that the instigation of a debris flow often appears at a certain time in the peak rainfall. The duration the peak rainfall is generally short, typically lasting only a few to tens of minutes; in debris flow research, this short duration peak rainfall is called the stimulating rainfall. Difference in short-duration rainstorms can explain the initiation of debris flows, we typically use a stimulating rainfall having a 10 min, 30 min or 1 h rainfall intensity depending on the specific circumstances. Here, we use the 1 h rainfall intensity as an example.

The antecedent rainfall refers to the total rainfall prior to the 1 h peak rainfall leading to debris flow initiation, which can be expressed as

$$P_a=P_{a0}+R_t \quad (2)$$

where P_a is the antecedent precipitation (mm), P_{a0} is the previous effective rainfall (mm) and R_t is the stimulating rainfall (mm).

The stimulating rainfall R_t refers to the total rainfall (days) prior to the 1 h rainfall peak, which directly affects the water content of the solid substances and supply conditions and is directly involved in the formation of debris flow. Thus, R_t can be expressed as follows

$$R_t = \sum_{t_0}^{t_n} r \tag{3}$$

where t_0 is the start time (days) for the rainfall on the given day, t_n is the time prior to the 1 h rainfall peak and r is the precipitation (mm).

The previous effective rainfall P_{a0} is the rainfall that continues to have an effect on the water content and supply of solid substances prior the occurrence of the debris flow, which is often influenced by spatial and temporal changes in the radiation, evaporation, soil infiltration capacity and other factors. The following formula can be used to properly assess the actual supply of solid material and the moisture content

$$P_{a0}=KP_1+K^2P_2+K^3P_3+\ldots+K^nP_n \tag{4}$$

where P_n (n=1,2,3,…n) is the daily rainfall prior to the debris flow event and K is a decline factor.

Equation (4) can reasonably estimate the amount of solid material and the moisture content prior to the debris flow; however, a problem arises in the calculation of the evaporation loss coefficient (K). In hydrological calculations, K is typically 0.8 to 0.9 and varies according to the weather condition, such as sunny or cloudy conditions.

The effect of a rainfall event usually diminishes within 20 days and decreased with lower daily K values. Different types 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 previous rainfall of a debris flow. A typical rainstorm debris flow gullies requires 20 days of antecedent rainfall, and heavy rain debris flow gullies require 10 days of antecedent rainfall. However, the antecedent rainfall can often be negligible in torrential rain debris flow gullies, which are mainly determined by the typical rainfall process.

ANALOGY METHODS FOR CALCULATING RAINFALL THRESHOLDS FOR DEBRIIS FLOW PRE-WARNING

Basis of the Analogy Method

Because many weather sites have been established, long-term rainfall data (e.g., annual, seasonal, monthly and daily rainfall) are available for most areas that require debris flow pre-warning systems. In most mountainous areas, rainfall stations are built in the larger towns. Thus, there are few rainfall data available for debris flow gullies, especially for debris flow formation areas. However, short-term rainfall data (e.g., 1 h, 30 min or 10 min rainfall data) are needed for the threshold calculations. There is a certain relationship between the characteristic rainfalls for different units of time. For example, daily rainfall amounts vary based on elevation, as indicated by 1 h rainfall values. Thus, we can apply it to the 1 h rainfall after correcting the equation for the relationship between daily rainfall and altitude in areas lacking short-term rainfall data (namely pre-warning areas).

The occurrence of rainstorm debris flow requires appropriate topography and geomorphology, elastic solid materials and water conditions, i.e., the topography and geomorphology are appropriate to store, move and stop sediment, contain abundant loose soil and rock sources, can provide abundant water within a short period of time and have a proper stimulating factor. When the first two conditions can be identified, the water conditions for debris flow are met. Therefore, the debris flow watershed would also have the same hydraulic conditions when it has the same geomorphology and elastic solid materials as in the pre-warning area. We can select a mature debris flow study area as an analogous area. By analogy, we are able to obtain the necessary data that are lacking in the pre-warning area.

The analogous area is one that has a similar topography as the study area, abundant rainfall and is disaster data.

Analysis of the Rainfall Characteristics of the Analogous and Study Area

Based on Equation (1), we analyzed the relationship between the characteristic rainfall and altitude in the study and analogy area and derived an equation for the study area

$$H_1=A_1\times I_1^{\,a} \tag{5}$$

where H_1 (m) is the altitude of the rainfall monitoring site in the study area, I_1 (mm) is the daily rainfall of the study area, A_1 is a coefficient and a is an index.

The relationship between daily rainfall and altitude in analogy area is

$$H_2=A_2\times I_2^{\beta} \quad (6)$$

where H_2 (m) is the altitude of the rainfall monitoring site in the analogous area, I_2 (mm) is the daily rainfall of the analogous area, A_2 is a coefficient and β is an index.

The study area is lacking short-term rainfall data. Using the equation for the daily rainfall and altitude in two areas and hourly rainfall data of a typical rainstorm in the analogous area, the daily rainfall in the study area is derived as the hourly rainfall using the following relationship

$$I_3=\left(\frac{A_2\times I_4^{\beta}\times H_3}{A_1\times H_4}\right)^{\frac{1}{\alpha}} \quad (7)$$

where I_3 (mm) in the hourly characteristic rainfall during a typical rainstorm at the rainfall monitoring site in the study area, I_4 (mm) is the hourly characteristic rainfall during a typical rainstorm in the analogous area; H_3 (m) is the measured altitude of the rainfall monitoring site in the study area and H_4 (m) is the measured altitude of the rainfall monitoring site in the analogous area.

Debris Flow Rainfall Threshold

For the aforementioned analysis, we selected a typical rainstorm to calculate the hourly rainfall I_{60} and corresponding effective rainfall P_a using equations (2)–(4). The hourly rainfall was the abscissa, and the previous effective rainfall was the ordinate. The characteristic rainfalls of every rainstorm were plotted in the same form. If there were disaster data in the watershed, the corresponding rainfall data were also plotted. We were then able to initially identify the rainfall threshold of the debris flow gully.

CASE STUDY

Study Area

Qiaojia County lies in the north-eastern region of Yunnan Province, which is located between 102°52'E–103°26'E and 26°32'N–27°25'N. The county is situated upstream of a debris flow deposition and is on the right hand side of Jinsha River. The distance from the Shuinian River to the county is ca. 7 km. This site is one of the most dangerous debris flow gullies of Qiaojia County. Abundant loosen materials cover the land surface and threatens the local people and surrounding farmland during heavy rainfall. The watershed area of the Shuinian River is 57.6 km^2. The formation area comprises 21.43 km^2 with a length of 31 km and a mainly gully length of 13 km. The relative elevation of Shuinian River exceeds 1 500 m a.s.l., and the watershed consist of a long corridor having a length of 11.5 km and a width of 9.2 km. The peak point elevation of Jiaoding Mountain is 3 555 m a.s.l., and the lowest point of the deposition area at the outlet near the Jinsha River is 645 m a.s.l.. The relative elevation is 2 910 m a.s.l., the slope is 138‰, and the area displays an obviously steepness in the upstream area and becomes gentle in the downstream regions (Fig. 2 and Table 1).

According to field surveys and analyses of local debris flow hazard information, this gully belongs to a high-frequency viscous debris flow valley, and the density of debris flow is 2.0–2.34 t/m^3. The presence of loose materials on the banks of the gully further support the condition of the materials (Fig. 3).

Based on the observation principle, three rainfall stations were situated within the Shijia gully watershed, Songlinlaobao, Yeyacun and the pre-warning station, at elevations of 1 790, 1 300 and 733 m a.s.l., respectively.

We used a long-term historical sequence of precipitation dating from 1964 to 2005 from 24 rainfall stations near the research area to analyze the regional rainfall characteristics. We developed a following relation between the daily precipitation and elevation

$$H=1.842I^{1.55} \quad (8)$$

Comparability Analysis of the Analogous Area

Jiangjia gully, which is located in the Dongchuan District, Yunnan Province, is a typical rainstorm debris flow gully. It lies on the right hand side of the Jinsha River. The watershed area is 48.6 km^2, and the gully length is 13.9 km. Debris flows typically occur every year. Statistically, there are ca. 12–20 debris flow events during the rainy season (May to Oct.); the discharge reaches hundreds, or even thousands, of m^3/s, and the density is as high as 2.37 t/m^3. Accordingly this area has been called “a natural museum” of debris flow.

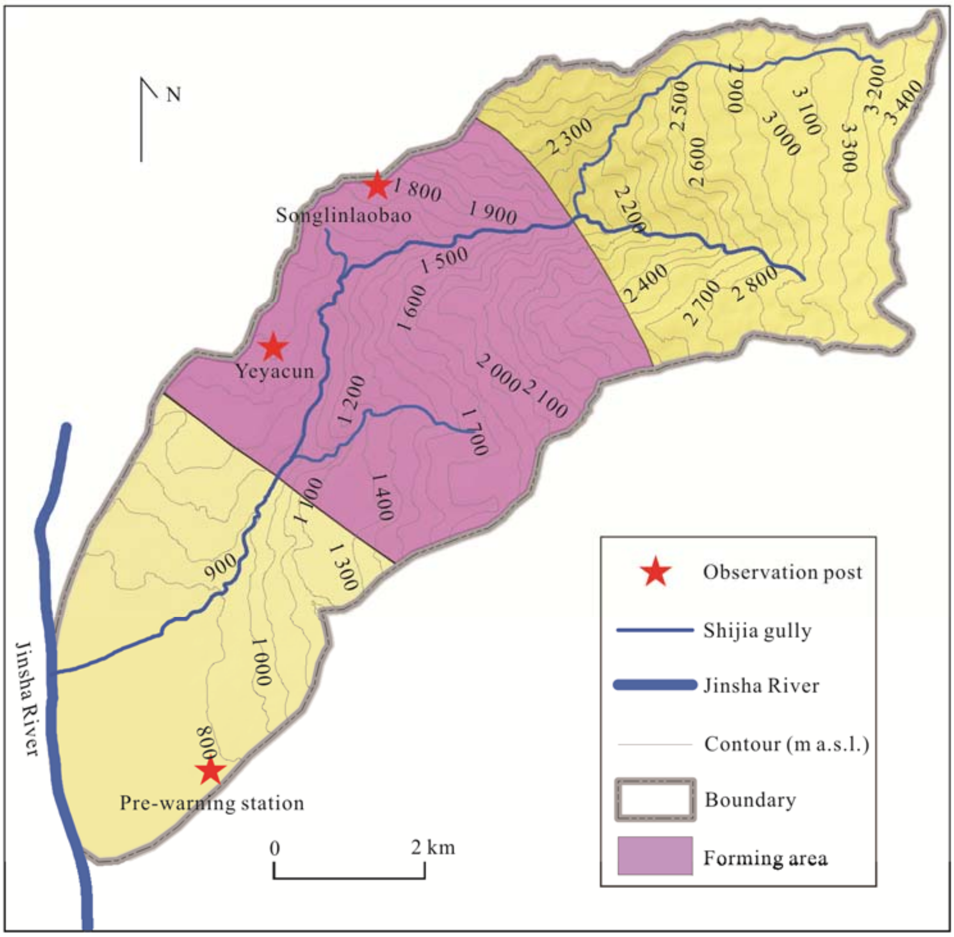

Figure 2. Map of the Shuinian River watershed.

Table 1 Characteristic parameters of the Shuinian River

Name	Watershed area, F (km^2)	Gully length, L (km)	Mean slope angle, I (‰)
Shuinian River	57.6	15	0.138

Debris flows in Qiaojia County occur as typical rainstorm debris flows. A detailed investigation showed that the flows are high-density viscous debris flows. The Shuinian River and Jiangjia gully are both on the Xiaojiang fault, and crushed rock constitutes abundant material for debris flows. In addition, the Shuinian River and Jiangjia gully are facing the Jinsha River water vapor channel, and the climate is affected by the same air stream that results the similar hydrological and meteorological conditions. Thus, we could assume that the two regions have a certain correlation with respect to the mean rainfall, rainy season rainfall and daily rainfall.

Regarding the Jiangjia gully, many scholars have performed long-term sequence observations and research. A national station, Dongchuan, and a debris flow observation and research station, Chinese Academy of Sciences, have been used to perform observational work for more than 40 years, which has provided important observational, hazard and rainfall data. Through an analysis of the correlation between the rainfall of the research valley and Jiangjia gully, as well as the main differences in the short-term rainfall characteristics and conceptualized rain type, we were able to determine the rainfall process curve of the study area.

Calculation of the Shuinian River Debris Flow Rainfall Threshold Using the Analogy Method

Data for heavy rain events greater than 50 mm in Shuinian River basin were classified as having a peak-type pattern. Based on the calculation method for the antecedent precipitation and the relationship between the short-duration rainfall and altitude, we can calculate the antecedent precipitation and intensity of each rainfall site in hours to obtain the distribution of data points within a certain range (Fig. 4).

Rainfall Threshold Curves for the Monitoring Sites

A typical rainstorm for Shuinian River did not lead to a watershed debris flow; i.e., these points are below the rainfall threshold curve. Thus, according to the rainstorm plot, we can preliminary identify the rainfall threshold curves for the three monitoring sites.

Debris flows have occurred many times in Shuinian River (e.g., in 1916, 1946, 1955, 1970, 1980, 1981 and 1989), and one super-large debris flow has occurred. The volume of each debris flow was greater than 1.0×10^6 m^3. On the morning of August 24, 1980, a debris flow occurred in the Shuinian River gully, with a volume of 1.34×10^6 m^3, destroying 2 040 acres of land, killing eight people and injuring 13 people. On May 6, 1989, another debris flow occurred in the Shuinian River gully, with a volume of 1.15 million cubic meters, destroying approximately 2 000 acres and resulting in road traffic disruption and direct economic losses of more than1.6×10^9 yuan.

The Shuinian River was included in the landslide and debris flow early warning system for the upper reaches of the Yangtze River by the Soil and Water Conservation Bureau of Yangtze River Water Resources Commission in 1991. Rainfall stations, telemetry rainfall stations and an NBJ type III debris flow warning device were installed in Sanjia Village at an altitude of 2 460 m a.s.l. and in Laoshanjian at an altitude of 2 410.8 m a.s.l.. These stations have had a monitoring life of 17 years. Based on rainfall data, we calculated an antecedent precipitation for the Liming Station (early warning stations) of 20 mm and 1 h rainfall intensity of 40 mm on August 24, 1980; for the second event on May 6, 1989, the antecedent precipitation was 63 mm, and the 1 h rainfall intensity was 7.3 mm. The rainfall data of the two debris flows are plotted on the rainfall analysis diagram (Table 2).

When analyzing the relationship between points and the position of threshold curve, if the points are above the rainfall threshold curve, then the rainfall

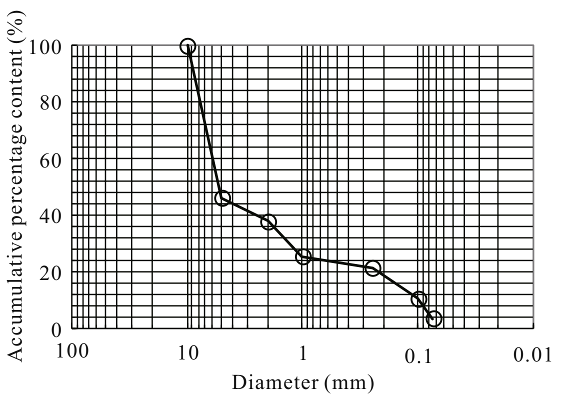

Figure 3. Grading curve of soils in the Shuinian River watershed.

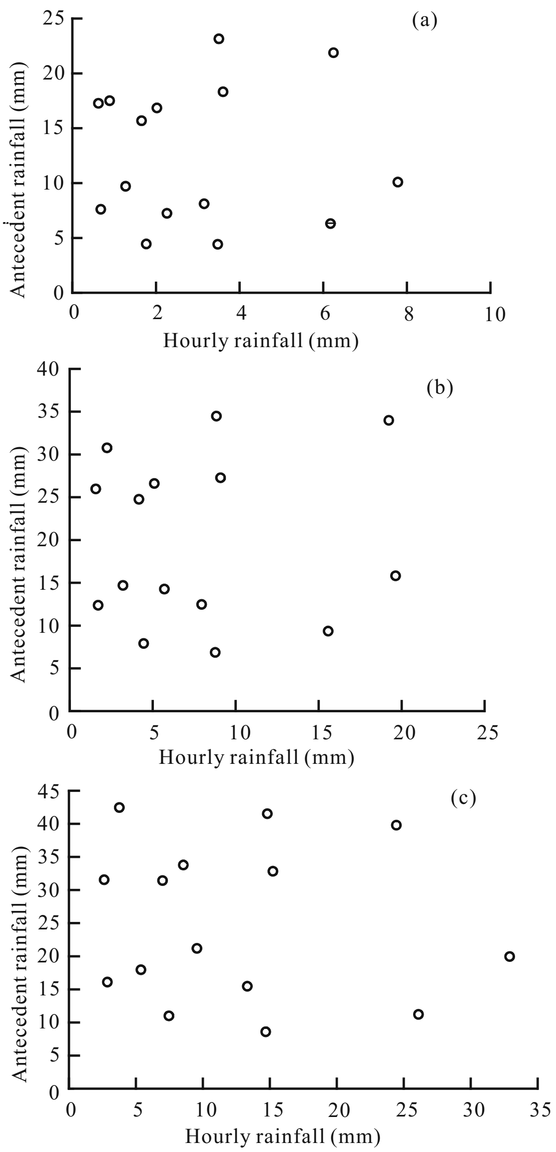

Figure 4. Rainstorm analysis map of Shuinian River watershed (analogy method). (a) Pre-warning station; (b) Yeyacun; (c) Songlinlaobao.

Table 2 Respective rainfall threshold of the observation stations

Observation station	Elevation (m a.s.l.)	I_{60}+P_a (mm)
Songlinlaobao	1 790	55
Yeyacun	1 300	80
Pre-warning station	733	95

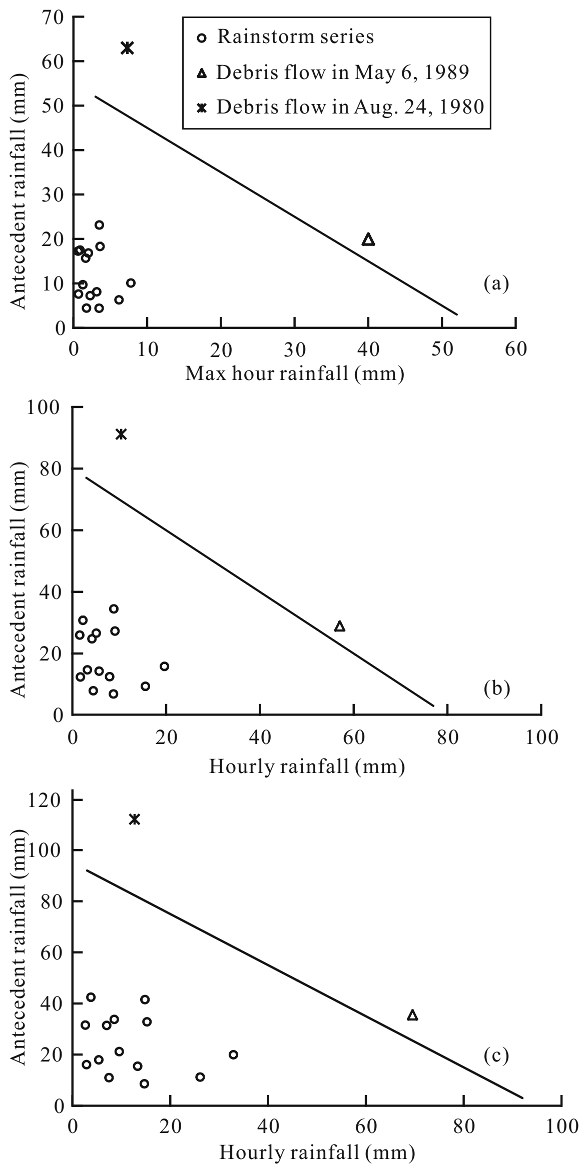

Figure 5. Rainfall threshold curve for debris flow pre-warning of Shuinian River. (a) Pre-warning station; (b) Yeyacun; (c) Songlinlaobao.

threshold curve is consider reasonable; however, if the points are below the rainfall threshold curve, then the calculated rainfall threshold curve is too high and should he adjusted such that the points are above the curve. Considering the limitation of the data and safety factors, we can adjust $I_{60}+P_a$ to correspond to a rainfall threshold curve of approximately 1 mm. After validation or correction, a debris flow rainfall threshold forecast map can be presented as in Fig. 5.

CONCLUSIONS

Based on the actual location, meteorological and hydrological characteristics and surface conditions, the selection of an analogous area that has sufficient rainfall data and hazard information could solve the problem of a lack of rainfall data, especially with respect to short-term rainfall data, in a given watershed. The development of a pre-warning rainfall threshold index for debris flows presents and additional new method to address debris flow warning and forecasting in remote mountainous areas. The follow conclusions were drawn using a case study.

(1) In certain areas, there is a relationship between precipitation and elevation. With increasing elevation, precipitation (including the annual rainfall and short-term rainfall characteristics) increases exponentially.

(2) The occurrence of a debris flow is closely related to precipitation, which is mainly affected by antecedent precipitation and short-term rainfall characteristics. For example, an hourly precipitation debris flow pre-warning index is based on an analysis of the relationship between the daily rainfall of research area, hourly rainfall characteristics of the analogous area and the change of elevation. When the antecedent precipitation plus the hourly rainfall reaches a certain value that could initiate a debris flow, this value is considered as the debris flow pre-warning rainfall threshold.

(3) If hazard records and relevant precipitation data are available, then the corresponding hourly rainfall and antecedent precipitation are plotted on the rainfall curve for each monitoring site. This plot can be used to validate the rainfall threshold curve.

(4) Because investigated areas often lack relevant data, and thus available data cannot be used to verify rainfall threshold curves, threshold curves calculated by this method should be considered preliminary values. However, threshold curves can be validated in the future based on conditions measured at proposed precipitation monitoring sites.

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