Determination of rainfall thresholds for shallow landslides by a probabilistic and empirical method

J. Huang, N. P. Ju, Y. J. Liao, and D. D. Liu

State Key Laboratory of Geohazard Prevention and Geoenvironment Protection
Chengdu University of Technology
Chengdu, Sichuan 610059, China
Correspondence to: J. Huang (huangjian2010@gmail.com)

Abstract:

Rainfall-induced landslides not only cause property loss, but also kill and injure large numbers of people every year in mountainous areas in China. These losses and casualties may be avoided to some extent with rainfall threshold values used in an early warning system at a regional scale for the occurrence of landslides. However, the limited availability of data always causes difficulties. In this paper we present a method to calculate rainfall threshold values with limited data sets for the two rainfall parameters: hourly rainfall intensity and accumulated precipitation. The method has been applied to the Huangshan region, in Anhui Province, China. Four early warning levels (Zero, Outlook, Attention, and Warning) have been adopted and the corresponding rainfall threshold values have been defined by probability lines. A validation procedure showed that this method can significantly enhance the effectiveness of a warning system, and finally reduce and mitigate the risk from shallow landslides in mountainous regions.

1 Introduction

Landslide risks have increased all over the world during recent decades, because of the uncontrolled urban sprawl by fast population growth and accelerated economic development. Particularly in many mountainous regions of developing countries, such as China, natural hazards have already become one of the most significant threats to people and property. On August 7, 2010, two debris-flows occurred in Sanyanyu gully and Loujiayu gully, nearly Zhouqu County, Gansu Province, Northwestern China, which took about 1765 people's lives of people living on the densely urbanized fan (Tang et al. 2011). On January 11, 2013, a large landslide induced by rainfall in Zhenxiong County, Yunnan Province, killed 46 people (Yin et al., 2013). Not only in China, but also in a number of developed countries, such as the Daunia region in Southern Italy, also abundant mass movements cause a high level of potential risk to the urban centers and transportation systems (Pellicani et al. 2013). In September 2004, a hurricane-induced debris-flow killed 5 persons in North Carolina (Wooten et al. 2007), and a landslide killed 10 persons at La Conchita in January 2005 (Jibson 2005). Additionally in Southwest of China, this area is one of the most affected regions by more catastrophic events, where the complicated geological condition exists and gestates earthquakes (e.g., Wenchuan earthquake on May 12, 2008 and Lushan earthquake on April 20, 2013). These phenomena have illustrated the vulnerability to natural hazards, the underestimation of the potential risks and revealed the lack of policies for disaster reduction and mitigation in these regions. The public and government have been sensitized that there is an urgent demand for effective warning systems in landslide prone areas.

Generally, rainfall-induced shallow landslides are less than 3-5 m thick and move with quite a high velocity. Usually they are widespread in mountainous areas. In order to reduce this impact, more and more scientists are working on forecasting the occurrence of shallow landslides. According to the different scale of study area, it can be concluded into two categories: local study and regional study. For local research, first physical slope stability models must be developed to understand the instability mechanism of an individual landslide, then a monitoring system for rainfall and slope movements has to be installed, which is then followed by a comprehensive analysis of the monitoring data. For more information about single landslide early warning systems in various parts of the world, see Thiebes (2012) , Carey and Petley (2014) and others. When working over larger areas, the method used in early warning system to forecast shallow landslide occurrence is frequently based on statistical and empirical models relying on one or two parameters from the rainfall events, e.g. rainfall intensity and duration, or antecedent precipitation. Generally, there are five types of methods to obtain the threshold line for rainfall-induced shallow landslide: (i) precipitation intensity-duration (I-D) thresholds, e.g. Keefer et al. (1987), Guzzetti et al. (2007a), Cannon et al. (2008) and Segoni et al. (2014b), which is perhaps the most popular one among rainfall thresholds methods. (ii) daily precipitation and antecedent effective rainfall, e.g. Glade et al. (2000), Guo et al. (2013). (iii) cumulative precipitation-duration thresholds, e.g. Aleotti (2004). (iv) cumulative precipitation-average rainfall intensity thresholds, e.g. Hong et al. (2005). (v) combination of cumulative rainfall threshold, rainfall intensity-duration threshold and antecedent water index or soil wetness, e.g. Baum and Godt (2009). In particular, empirical rainfall thresholds have already proven their value to forecast the occurrence of landslides, and frequently used in operational warning systems (Baum and Godt 2009; Glade et al. 2000; Greco et al. 2013; Guzzetti et al. 2007a; Guzzetti et al. 2007b; Keefer et al. 1987; Osanai et al. 2010; Segoni et al. 2014a; Segoni et al. 2014b; Wei et al. 2015; Zêzere et al. 2014). However, as shown by Intrieri et al. (2012), an early warning system (EWS) is a very complicated system. According to United Nations International Strategy for Disaster Reduction (UNISDR, 2009) it was defined as "the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss."

Several excellent examples of EWS have already been proposed for different regions, such as Seattle, on the West Coast of the USA (Baum and Godt 2009), Adriatic Danubian area in central and southern Europe (Guzzetti et al. 2007b), and Xi' an, Shanxi Province, China (Zhuang et al. 2014). For Tuscany, Italy, Segoni et al. (2014b) presented a mosaic of several local rainfall thresholds instead of a single regional one. They established a relation between the threshold parameters and the prevailing lithology, which significantly enhances the effectiveness of an early warning system. However, all these critical thresholds and equations strongly depend on the local physiographic, hydrological and meteorological conditions (Guzzetti et al. 2007a). As well, they suffer from the lack of necessary resources for provision of continuous support or expansion of services. The application of these methods in other regions is very difficult from a practical point of view. It is, therefore, so important and urgent to find a simple and suitable approach for the definitions of warning thresholds through study of fundamental process mechanisms and analysis of relationships between rainfall and landslides. Presently, most mountainous regions in China lack available rainfall records and landslide occurrence information, which makes it much more difficult to establish a rainfall threshold for landslide forecasting in a short period of time.

This paper presents the results of a recent study on rainfall thresholds for shallow landslides at a regional scale to overcome the aforementioned difficulties: the thresholds are determined with rigorous statistical techniques from two rainfall parameters. The paper contains (i) the description of a method to calculate rainfall thresholds from limited available data and time; (ii) the application and improvement of the rainfall threshold for landslide early warning in a case study.

2 Study area

The Huangshan study area is located in Anhui Province, Eastern China (Fig. 1), and covers an area of 9,807 km^2, most of which are tablelands and mountains, with elevations ranging from 1,000 m to 1,873 m above sea level (a.s.l.) and some areas between the mountains with elevations lower than 500 m a.s.l. The Huangshan region has a population of 1.47 million (in the year 2012). In the mountainous areas, the general climate is moist monsoonal and subtropical with an average yearly temperature of 15.5-16.4℃, although this is strongly dependent on the altitude, especially above 1,000 m a.s.l. The total annual rainfall ranges from 1,500 to 3,100 mm, most of which is falling on the southern slopes from May to October.

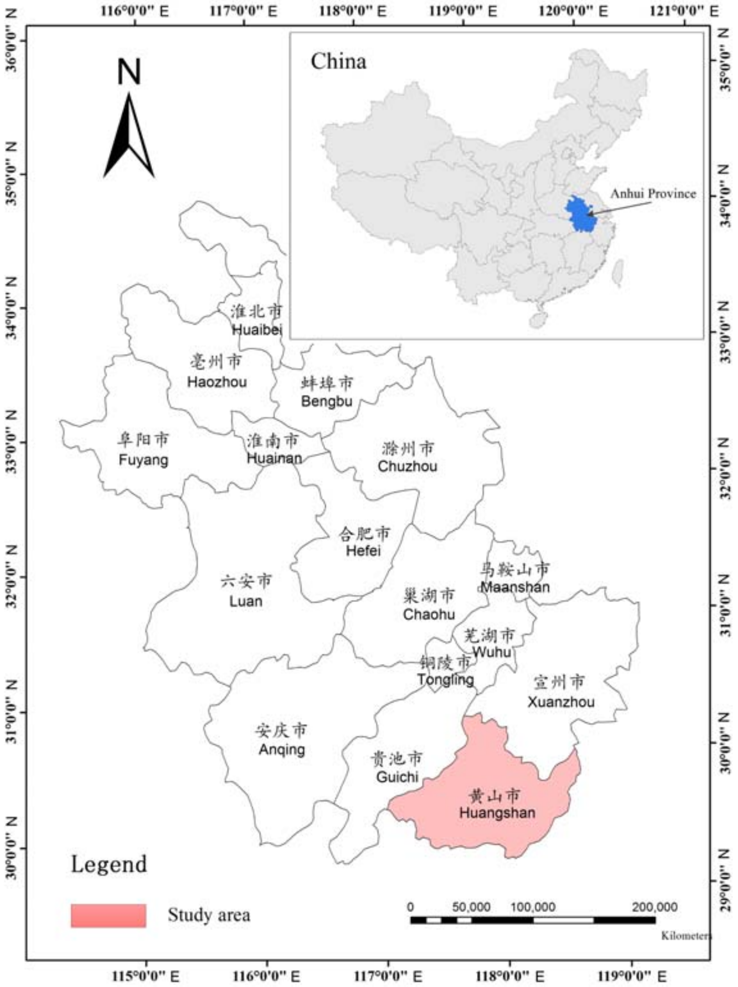

Figure 1. Location of the Huangshan region. The inset map shows the location of Anhui province in China.

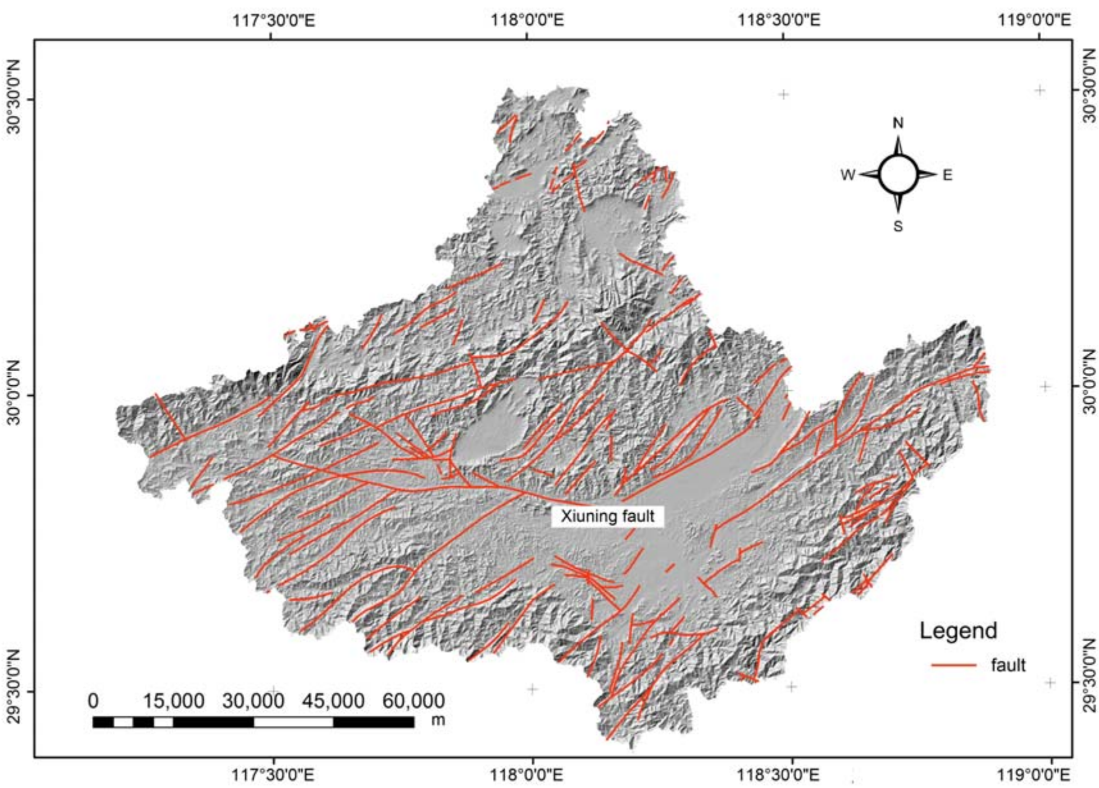

Figure 2. Faults distribution of the Huangshan region with a DEM background.

The landslide-prone areas lie between the Southern Yangtze Block (South of the Yangtze Plate) and the transitional segment of the Jiangnan uplift belt. The main fault zones are NE- and EW-trending which determine the local tectonics and topography, and one fault called as Xiuning fault is inferred to separate the mountains and the hilly parts and plains, as shown in Fig. 2 (Ju et al. 2008). The rocks in the study area range from Late Precambrian to Upper Triassic in age and consisting mainly of granite, dolomite, limestone, sandstone, slate and shale. The complicated geological condition, the numerous heavy rainfall events and the numerous human activities in the area caused numerous landslides, leading to catastrophic economic losses and large numbers of fatalities in recent years.

3 Materials and methodology

The methodology used in this study mainly consisted of two components: (i) collect landslide and rainfall records and (ii) analyze the relationship between rainfall and landslide occurrence with probabilistic and empirical methods. Several ways have been used in this study to collect additional data for the analysis, such as contained in technical reports and documents produced by the national scientific communities and government agencies. The parameters and analysis model are mainly referenced from previous researchers, but which have been improved in this paper to present a more simple and suitable approach for shallow landslide early warning in mountainous areas.

3.1 Landslide and rainfall data

Detailed landslide and rainfall datasets are the foundation for the analysis of the relationship between rainfall and landslide occurrence. The landslide inventory and rainfall data provided in this paper are mostly the result of field investigations immediately after landslide occurrence, and were validated by the local geological and environmental monitoring station in the Huangshan region during the period 2007-2012 (Fig. 3). Most of the shallow landslides are located in the mountainous region, but some ones located in the plain areas where usually river banks are, always occurred in a rainstorm.

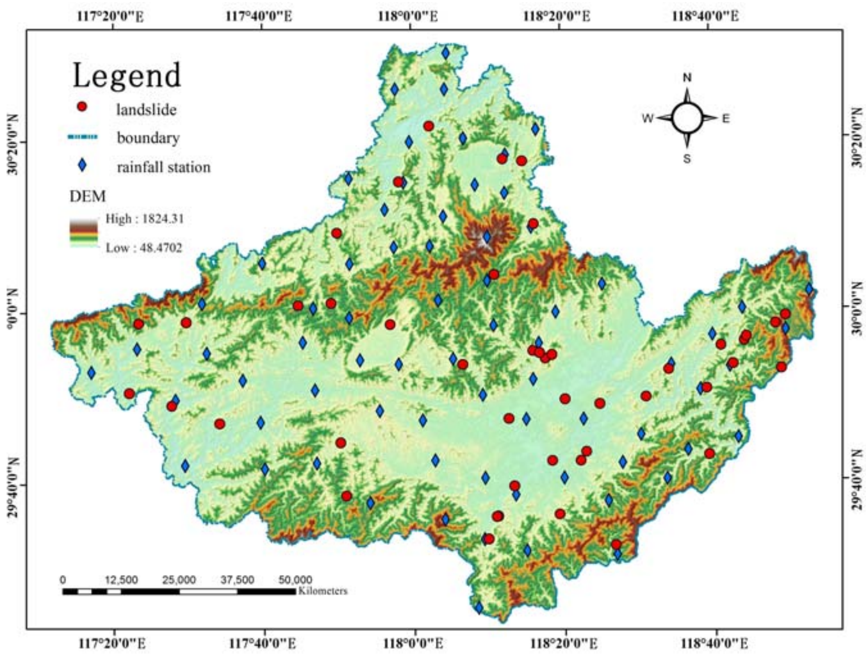

Figure 3. Location of rainfall-induced shallow landslide in the Huangshan region (2007-2012)

In this period more than 100 shallow landslides were recorded but some of them were not triggered by rainfall. Some landslides were triggered by human activities factors and were not included in the study. This also applies to some events with unclear dates of occurrence. As a result, there are only 50 landslides with accurate dates of occurrence and rainfall records collected in the data sets, and typical examples are shown in Table 1. Meanwhile, in order to study the relationship between rainfall and shallow landslide occurrences, more than 50 rainfall historical events with no landslide occurrence also were collected to be used during the analysis.

Table 1. Typical shallow landslides triggered by rainfall in the Huangshan region

Name	Location (Lon, Lat)	Time	Hourly rainfall intensity (mm/h)	Accumulated precipitation (mm)
Shacun	(117.9664, 30.2511)	2007 - 07 - 10	47.1	268.8
Dawu	(118.3710, 29.7078)	2008 - 06 - 10	29.2	305.6
Xiacun	(118.4139, 29.8182)	2008 - 06 - 18	8.0	194.6
Zaotai	(118.8294, 29.9871)	2008 - 06 - 27	15.0	105.2
Fenghuangshan	(118.0000, 30.3256)	2008 - 08 - 01	12.2	203.4
Zhoulintian	(118.2922, 29.9009)	2009 - 07 - 28	13.5	243.8
Yaojiapeng	(118.3231, 29.6038)	2010 - 07 - 10	27.1	260.2
Banxizu	(117.7440, 30.0129)	2010 - 07 - 15	27.9	463.9
Jinzhu	(118.5683, 29.8837)	2011 - 06 - 09	20.7	204.7
Yuelingwu	(118.5169, 29.8311)	2011 - 06 - 10	15.3	270.7
Yinshan	(118.6564, 29.7175)	2011 - 06 - 15	16.2	440.6
Linlangkeng	(118.2808, 29.9186)	2011 - 06 - 19	12.7	323.8
Hulingcun	(118.7113, 29.8937)	2012 - 06 - 26	14.5	111.4
Lucun	(117.9750, 30.0154)	2012 - 08 - 08	14.1	23.6
Hongxing	(118.1850, 29.8042)	2012 - 08 - 11	8.7	189.7

3.2 The probabilistic and empirical model

As mentioned in the Introduction, there are several parameters related to rainfall thresholds, which have been applied successfully in some regions. In the Huangshan region, it is very difficult to obtain a reliable rainfall threshold value for landslide early warning due to the limited availability of data. In order to overcome this problem, a trial method was developed first. Then, its practicability and expandability will be investigated with new data collected in the near future. Two rainfall parameters were selected to obtain the threshold equation in a simple way from the currently available database: the hourly rainfall intensity (I_h: mm/h) and the accumulated precipitation (R_t: mm). Generally, the accurate time of landslide occurrence always is not for sure during a rainstorm. According to Jan et al. (2002), therefore, maximum hourly rainfall intensity in a rainfall record is calculated as the triggering parameter for rainfall threshold study. The accumulated precipitation is a total sum of rainfall amount for 7 days including that day of rainstorm occurrence for a consideration of antecedent effective rainfall.

The beginning of each rainfall event is defined at the moment that the hourly rainfall amount is more than 4 mm/h, and the end is when the hourly rainfall amount is less than 4 mm/h, and which should be lasting for 6 hours at least. After such definition, I_h and R_t can be calculated in a real time way from the rainfall record. Meanwhile, R_t and I_h can be plotted in a graph with x and y axes. Rainfall records accompanied by or without landslide occurrences can be shown in this graph (Fig. 4). Subsequently, following the method proposed by Jan et al. (2002) and which has been applied successfully in Shanxi Province, China for forecasting landslide occurrence by Zhuang et al. (2014). Thus, improvements and modifications have been presented in this study, and then the rainfall thresholds for shallow landslide can be determined as follows:

A. the lower envelope of landslide occurrence

Draw a line with a gradient (-a) under the lowest points which represent landslide occurrences under such rainfall condition. This is shown with a blue line in Fig. 4. The area between the blue line and the x and y axes defines combinations of R_t and I_h with a zero probability of landslide occurrence. Generally, there will be provided a coefficient with ten percent for a conservative consideration. Then, the probability of landslide occurrence is defined as PRO=10%.

B. the upper envelope of landslide occurrence

Similarly, a line with the same gradient can be drawn above the highest points representing combinations of R_t and I_h without occurrence of landslides, as shown with a red line in Fig. 4. The area above the red line represents combinations of R_t and

I_h with a 100% probability of landslide occurrence. The same coefficient has been considered to the upper envelope, then PRO=90%.

C. the algorithm for each probability line

In the area between the lower envelope (blue line) and the upper envelope (red line), probability lines can be defined by the same method (Fig. 4). The algorithm for each probability line is shown in Equation 1.

$$R_t + aI_h = C \qquad (1)$$

where R_t is the accumulated precipitation (mm), I_h is the hourly rainfall intensity (mm/h) and C is a numerical constant.

According to equation 1, there must be two constants C_{min} and C_{max}, corresponding to the lower envelope and the upper envelope respectively. There is an uncertain value C in the area between the C_{min} and C_{max}. Relation between the value C and the probability of landslide occurrence (*PRO*) can be calculated by equation 2.

$$\frac{C - C_{\min}}{C_{\max} - C_{\min}} = \left(\frac{PRO - 0}{1 - 0}\right)^2 = PRO^2 \qquad (2)$$

Equation 2 can be changed to equation 3 for a better understanding.

$$C = C_{\min} + (C_{\max} - C_{\min}) \times PRO^2 = C_{\min} + \Delta C \times PRO^2 \qquad (3)$$

Then, a line for each probability for shallow landslide occurrence can be drawn in the graph by equation 3, as shown in Fig. 4.

D. modification and application in Huangshan region

While drawing the first probability line (blue line), the gradient (-a) is an uncertain parameter, dependent on experts' experiences or on historical data sets (Jan et al. 2002). To deal with this problem, another parameter (W) has been defined in this study as shown in equation 4.

$$W = \sqrt{(R_t)^2 + (I_h)^2} \qquad (4)$$

where R_t is the accumulated precipitation of one rainfall record (mm), I_h is the hourly rainfall intensity (mm/h). So, the *W* represents a combination of the influence from both rainfall factors on landslide occurrence.

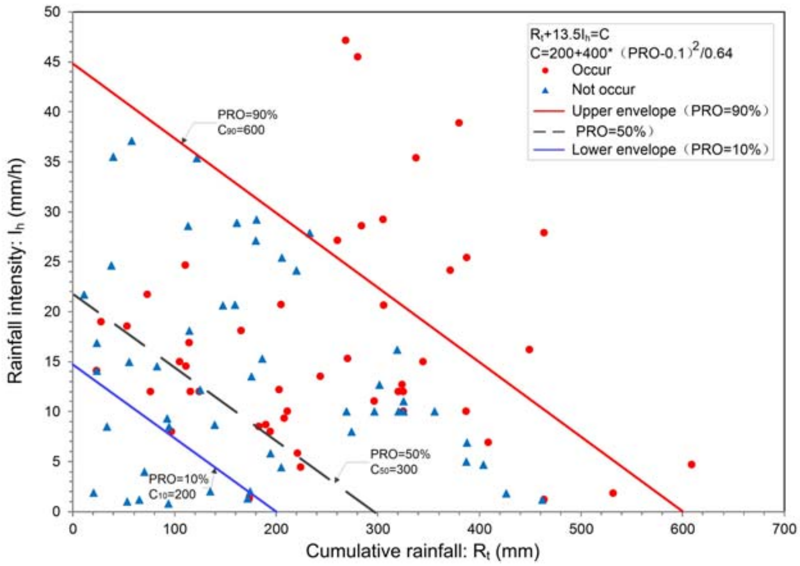

Figure 4 R_t-I_h graph for occurrence and non-occurrence of landslide events in the Huangshan region based on historical rainfall data. The red points and blue triangular points indicate occurrences and non-occurrences.

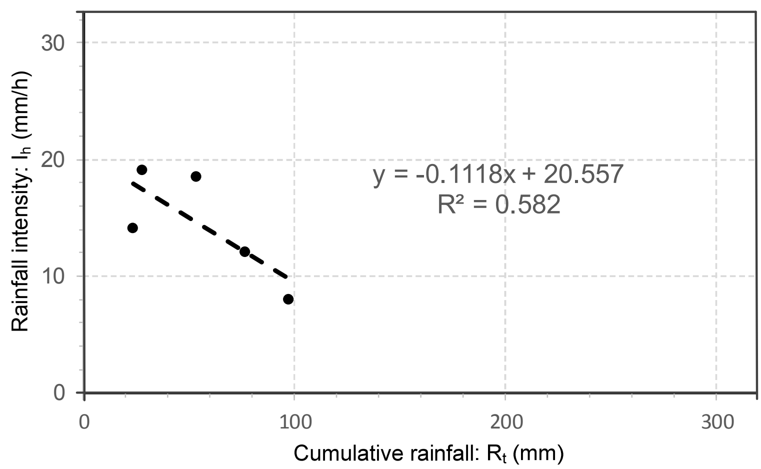

Figure 5 Improved method to ensure the gradient of the lower envelope

Based on the results from equation 4, the lowest five available points of rainfall records with landslide occurrence in a descending sequence, can be selected to determine the gradient (-a) of the lower curve by the least squares method, as shown in Fig. 5. For a safe landslide early warning in Huangshan region, the probability of the lower curve is defined as *PRO*=10% (C_{10}), and the probability of the upper curve is defined as *PRO*=90% (C_{90}). Each probability line between them can be calculated with equation 5.

$$C = C_{10} + (C_{90} - C_{10}) \times \frac{(PRO - 0.1)^2}{0.64} \quad (5)$$

When *PRO*=10%, in Fig. 4, the formula of the lower curve is R_t+13.5I_h=200, thus C_{10}=200; and when *PRO*=90%, the formula of the upper curve is R_t+13.5I_h=600, thus C_{90}=600. Then, equation 5 can be modified into equation 6.

$$C = 200 + 400 \times \frac{(PRO - 0.1)^2}{0.64} \quad (6)$$

where *PRO* is between 0.1 and 0.9. Based on equation 6, each probability line for rainfall-induce landslide occurrence can be drawn in the graph.

There are 8 points of landslides in the area that occurred where *PRO*=10% - 50% (C_{10-50}), as shown in Fig. 4, and 30 points in the area where *PRO*=10%-90% (C_{10-90}). The ratio between C_{10-50} and C_{10-90} is 26.7%, which is less than 30% indicating that the points located in such area showing the low possibility of landslide occurrence, which also proves it is reliable enough for initial application. When more data come available, they will make it more accurate and more suitable for shallow landslide early warning.

4 Example of Application

According to the national standard, a four-level early warning scheme (Zero, Outlook, Attention and Warning) for rainfall-induced shallow landslide in the Huangshan region is defined. Additionally, in order to improve the effectiveness of an EWS, the response of the population living in this study area needs to take into consideration. Referencing from the successful examples, e.g. Baum and Godt (2009); Guzzetti et al. (2007b); Segoni et al. (2014a); Frigerio et al. (2014). A corresponding four color-coded scale (Blue, Yellow, Orange and Red) of warning levels shown in Fig.4, Fig. 6 and Table 2. In a real-time early warning system, the points calculated from the rainfall monitoring data in 1 hour per circle, which can be draw a tendency line in the early warning graph (Fig. 6).

Table 2. Recommended warning levels and responses

Warning level	Definition	Response
I	The point calculated from real-time rainfall monitoring data is in the **blue** area.	**Zero**: but data are checked daily. Monthly monitoring bulletin.
II	The point calculated from real-time rainfall monitoring data is in the **yellow** area.	**Outlook**: data are checked daily. Weekly monitoring bulletin.
III	The point calculated from real-time rainfall monitoring data is in the **orange** area.	**Attention**: data are checked more frequently. Daily monitoring bulletin. Authorities and experts are alerted. Preparing for alarm.
IV	The point calculated from real-time rainfall monitoring data is in the **red** area.	**Warning**: data are checked even more frequently. Two monitoring bulletins per day. Local population is alerted.

It can be seen in Fig. 4 and Table 2, that the probability of landslide occurrence in the blue area is less than 10%, indicating that landslides are very unlikely to occur. At this probability level, no warning will be given to the local authorities or the population, but general inspection and regular rainfall monitoring must be carried on, and experts must be informed to pay attention to the variation of rainfall. The probability in the yellow area is 10% - 50%, indicating that there is a possibility of landslide occurrence in the short term future, leading to a requirement to inform the local authorities and population to pay attention to the rainfall variation. The probability in the orange area is 50% - 90%, indicating that there is a serious possibility of landslide occurrence in the short term future. Therefore, countermeasures and recommendations need to be discussed, e.g. to avoid going to the threatened area. The probability in the red area is more than 90%, indicating that there is a very great chance of landslide occurrence in the next hours. Therefore, local people must be alerted to evacuate the threatened area or avoid to go to there, and keep a safe distance.

When a rainfall happens, the starting time of the critical rainfall event ($I_h > 4$ mm/h) must be determined first, then with the values of the accumulative rainfall (R_t) and the rainfall intensity (I_h) can be calculated from the rainfall record and plotted in the graph (Fig. 6). The corresponding alert level can be read from the diagram in a consistent and completely automated way in a landslide early warning system. To demonstrate the application of the above-mentioned method, we present a heavy rainfall record as a case study (Fig. 6), which is also helpful for the improvement of the preliminary rainfall threshold curves. On June 30, 2013, a heavy rainstorm occurred in the Huangshan region, mainly concentrated in two hours from 8:30 to 10:30 in the morning. The total cumulative rainfall is reached 207.5mm, and the hourly maximum rainfall intensity is reached 83.5 mm/h, which is likely to happen less than once in a century in this area. Triggered by this heavy rainstorm, many shallow landslides and debris flows occurred, which caused the death of 4 persons, the disappearance of 2 persons and a great economic loss.

Fig. 6 shows that the rainfall started at midnight of June 29, 2013, and the hourly rainfall intensity became more than 4 mm/h at 5 o'clock in the morning of June 30. From this moment onwards, points with R_t and I_h have been calculated every hour and plotted into the diagram (The first point at 7.00 a.m. is located in the blue area in Fig. 6). Due to the fast increases of the rainfall intensity, the yellow area was left shortly after 7 o'clock, and the 8 o'clock point is very close to the red line. Incredibly at 9 o'clock, the point is outside the diagram area, due to the fact that the rainfall intensity exceeded all historical records. At 10 o'clock the point is down in the diagram again. Field investigations after the rainstorm have shown that the catastrophic landslides and debris flows mainly occurred between 8:00 and 10:00 o'clock. If the alert message had been informed the local people before 8:00 o'clock in the morning, less persons would have been killed or hurt.

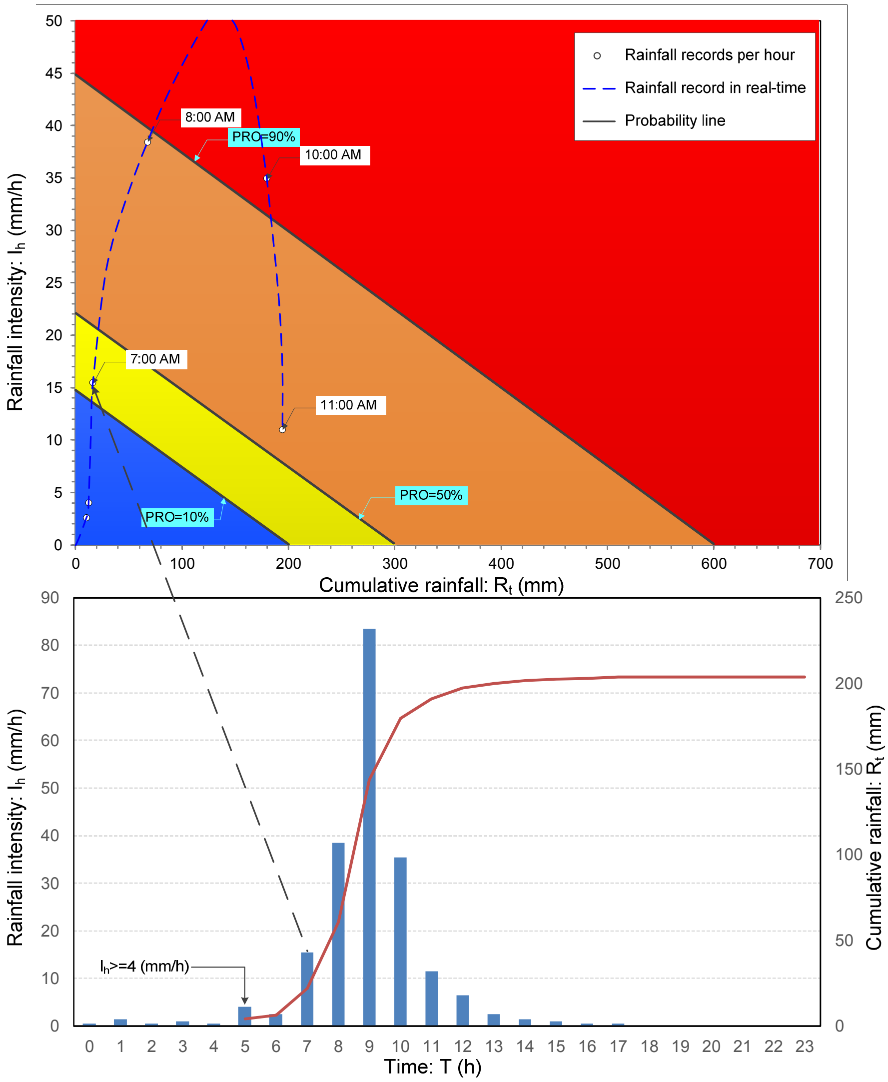

Figure 6 Application of the methodology in the Huangshan region (rainstorm of June 30, 2013)

In previous early warning system of this region, there was only a single value (150 mm) of cumulative rainfall to be the warning threshold. The warning message should be sent at 9:00 o'clock approximately. Therefore, there would be 2 hours earlier to send the alert message compared to the improved method presented in this paper (Outlook in yellow area, as shown in Fig. 6). We can conclude that the threshold lines facilitate the prediction of occurrences of rainfall-induced shallow landslide, which is useful for landslide prevention and mitigation at an early stage. Moreover, the rainfall threshold curves can be improved when more data are collected in the future.

5 Discussion and Conclusion

Landslides induced by rainfall cause significant harm both in terms of human casualties and economic losses in the vast mountainous areas in China. So, there is an urgent need for effective measures for landslide early warning and mitigation. However, problems were always met during studies to define regional rainfall threshold values due to the lack of available rainfall and landslide data. Based on the result of previous research by other authors, we selected in this paper the hourly rainfall intensity and the accumulated precipitation as the two rainfall factors in order to overcome these difficulties. The Huangshan region was selected as the study area for the explanation of this methodology. The results of this application show that it is indeed a suitable approach for shallow landslide triggered by rainfall.

However, when using this method, one has to be aware of some limitations and restrictions. The basic limitation is that rainfall thresholds inevitably just represent a simplification of the relationship between rainfall and landslide occurrence (Reichenbach et al. 1998). Usually, when a landslide happens, there are more than one causative factors and the analysis is a complex procedure. The second issue is that the rainfall thresholds presented in this paper, have a usage limitation for only the Huangshan region. These limitations must be considered before applying the methodology to another area. Therefore, the determination of rainfall threshold values for landslide early warning must be regarded as a long-term research activity before it can be used as a more reliable approach in the future.

In spite of these limitations, this method to establish rainfall threshold values from limited datasets, provides a way to improve and modify the method by collecting new data during subsequent studies to reduce the losses caused by this type of natural disaster.

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