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

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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: maximum 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 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 7 August 2010, a large debris-flow occurred at Zhouqu County, Gansu Province, Northwestern China, which took about 1765 lives of people living on the densely urbanized fan (Tang et al., 2011). On 11 January 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, abundant mass movements cause a high level of potential risk to the urban centers and transportation systems (Pellicani

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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). Southwestern of China is one of the most affected regions by catastrophic events, due to the complicated geological condition and earthquakes (e.g., the Wenchuan earthquake on 12 May 2008 and Lushan earthquake on 20 April 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 the 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 and usually they are widespread in mountainous areas. In order to reduce their impact, scientists are working on forecasting the occurrence of shallow landslides. According to the different scale of the study area, two categories can be distinguished: 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 on regional studies over larger areas, the method used in early warning systems to forecast shallow landslide occurrence is frequently based on statistical and empirical models relying on one or two parameters from of the rainfall events, e.g. rainfall intensity and duration, or antecedent precipitation. Empirical rainfall thresholds have already proven their value to forecast the occurrence of landslides, and are frequently used in operational warning systems (Baum and Godt, 2009; Guzzetti et al., 2007b; Keefer et al., 1987; Segoni et al., 2014). There are five types of methods to obtain the threshold line for rainfall-induced shallow landslide: (i) precipitation intensity-duration thresholds, e.g. Keefer et al. (1987), Guzzetti et al. (2007a), Cannon et al. (2008) and

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Segoni et al. (2014). (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).

Various critical threshold values and equations have been proposed for different regions, such as Seattle, on the West Coast of the USA (Baum and Godt, 2009), the 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. (2014) presented a mosaic of several local rainfall thresholds instead of a single regional value. 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 rainfall thresholds strongly depend on the local physiographic, hydrological and meteorological conditions (Guzzetti et al., 2007a). They suffer as well from the lack of necessary resources for provision of continuous support or expansion of services. The application of these methods in other regions is therefore very difficult. Presently, most mountainous regions in China lack available rainfall records and landslide occurrence information, which makes it difficult to establish rainfall thresholds for landslides 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. This 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.

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2 Study area

The Huangshan study area is located in Anhui Province, Eastern China (Fig. 1), and covers an area of 9807 km^2, most of which are tablelands and mountains, with elevations ranging from 1000 m to 1873 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 °C, although this is strongly dependent on the altitude, especially above 1000 m a.s.l. The total annual rainfall ranges from 1500 to 3100 mm, most of which is falling on the southern slopes from May to October.

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 separates the mountains from 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 consist 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. The flow diagram of this approach is described in Fig. 3. Several ways have been used in this study to collect

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additional data for the analysis, such as contained in technical reports and documents produced by national scientific communities and government agencies.

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 (Fig. 3). 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. 4).

In this period more than 100 landslides were recorded but some of them were not triggered by rainfall; some were triggered by human activities and were not included in the database for the study. This also applies to some events with unclear dates of occurrence. As a result only 50 landslides with accurate dates of occurrence and rainfall records were collected in the data sets. More than 50 rainfall historical events with no landslide occurrence were also used during the analysis.

3.2 The probabilistic and empirical model

As mentioned in the Introduction, several parameters related to rainfall thresholds 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. Its applicability 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 available database: the maximum hourly rainfall intensity (I_h: $\mathrm{mm\,h^{-1}}$) and the accumulated precipitation (R_t: mm). According to Jan et al. (2002), the beginning of each rainfall event is defined at the moment that the rainfall intensity is more than $4\,\mathrm{mm\,h^{-1}}$, and the end is when the rainfall intensity is less than 4 mm for

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a period lasting 6 h. With this definition, I_h and R_t can be calculated easily from the rainfall record.

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. 5). Subsequently, following the method proposed by Jan et al. (2002) and modified by Zhuang et al. (2014), the rainfall thresholds for shallow landslide can be determined as follows.

3.2.1 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. 5. 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 (PRO = 0 %). For a safer consideration, the probability is defined as PRO =10 %, as shown in Fig. 5.

3.2.2 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. 5. The area above the red line represents combinations of R_t and I_h with a 100 % probability of landslide occurrence (PRO = 100 %). For a safer consideration, the probability is defined as PRO =90 %, as shown in Fig. 5.

3.2.3 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. 5). The algorithm for each probability line is shown in Eq. (1).

$$R_t + aI_h = C, \quad (1)$$

where R_t is the accumulated precipitation (mm), I_h is the hourly rainfall intensity ($mm\,h^{-1}$) and C is a numerical constant.

According to Eq. (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}. The relation between the value C and the probability of landslide occurrence (PRO) can be calculated by Eq. (2).

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

Equation (2) can be changed to Eq. (3) for a better understanding.

$$C = C_{min} + (C_{max} - C_{min}) \cdot \mathrm{PRO}^2 = C_{min} + \Delta C \cdot \mathrm{PRO}^2 \tag{3}$$

Then, a line for each probability for shallow landslide occurrence can be drawn in the graph by Eq. (3), as shown in Fig. 6.

3.2.4 Modification and application in Huangshan region

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

$$W = R_t \cdot I_h, \tag{4}$$

where R_t is the accumulated precipitation of one rainfall event (mm), I_h is the maximum hourly rainfall intensity ($mm\,h^{-1}$). So, the W represents a combination of the influence from both rainfall factors on landslide occurrence.

Based on the results from Eq. (4), the lowest 3–5 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. 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 Eq. (5).

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

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

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

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

There are 16 points of landslides in the area that occurred where PRO = 10–50 % (C_{10-50}), as shown in Fig. 6, and 38 points in the area where PRO = 10–90 % (C_{10-90}). The ratio between C_{10-50} and C_{10-90} is 42 %, which is less than 50 % but it is still reliable enough for initial application. When more data come available, they will make the method 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 landslides in the Huangshan region are defined. A corresponding four color-coded scale (Blue, Yellow, Orange and Red) of warning levels is shown in Fig. 7.

Figure 7 shows 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 serious possibility of landslide occurrence in the near future, leading to a requirement to inform the local authorities and population to pay attention to the rainfall development. The probability in the orange area is 50–90 %, indicating that there is a serious possibility of landslide occurrence in the near future. Therefore, countermeasures and recommendations need to be discussed, e.g. to avoid that people enter 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 ($I_h > 4\,\mathrm{mm\,h^{-1}}$) must be determined first, then 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. 8), which is also helpful for the improvement of the preliminary rainfall threshold curves. On 30 June 2013, a heavy rainstorm occurred in the Huangshan region, from 8.30 to 10.30 in the morning. The total cumulative rainfall reached 207.5 mm, and the hourly maximum rainfall intensity reached 83.5 $\mathrm{mm\,h^{-1}}$, 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.

Figure 8 shows that the rainfall started at midnight of 29 June 2013, and the hourly rainfall intensity became more than 4 $\mathrm{mm\,h^{-1}}$ at 5 a.m. in the morning of 30 June. 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 a.m. is located in the blue area in Fig. 8).

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Due to the fast increase of the rainfall intensity, the yellow area was left shortly after 7 a.m., and the 8 a.m. point is very close to the red line. At 9 a.m., the point is outside the diagram area, due to the fact that the rainfall intensity exceeded all historical records. At 10 a.m. the point is down in the diagram again in the red zone. Field investigations after the rainstorm have shown that the catastrophic landslides and debris flows mainly occurred between 8 and 10 a.m. If the alert message had informed the local people before 8 a.m., less persons would have been killed or hurt.

5 Discussion and conclusion

Landslides, induced by rainfall cause significant harm both in terms of human casualties and economic losses in vast mountainous areas in China. Thus, 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 maximum hourly rainfall intensity and the accumulated precipitation as the two rainfall factors to overcome these difficulties. The Huangshan region was selected as study area for the explanation of this methodology. The results of this application show that it is indeed a suitable approach for landslide.

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 limited only for the Huangshan region. These limitations must be considered before applying the methodology to other areas. 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 reliable approach in the future.

In spite of these limitations, we can conclude that the presented method to establish threshold lines from limited data sets facilitates 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.

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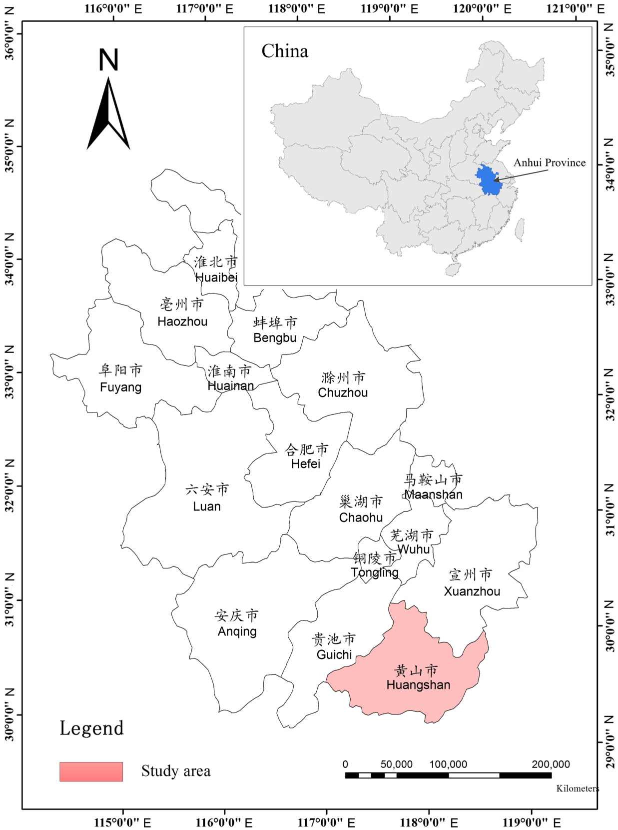

Figure 1. Location of the Huangshan region. The inset map shows the location of Anhui province in China.

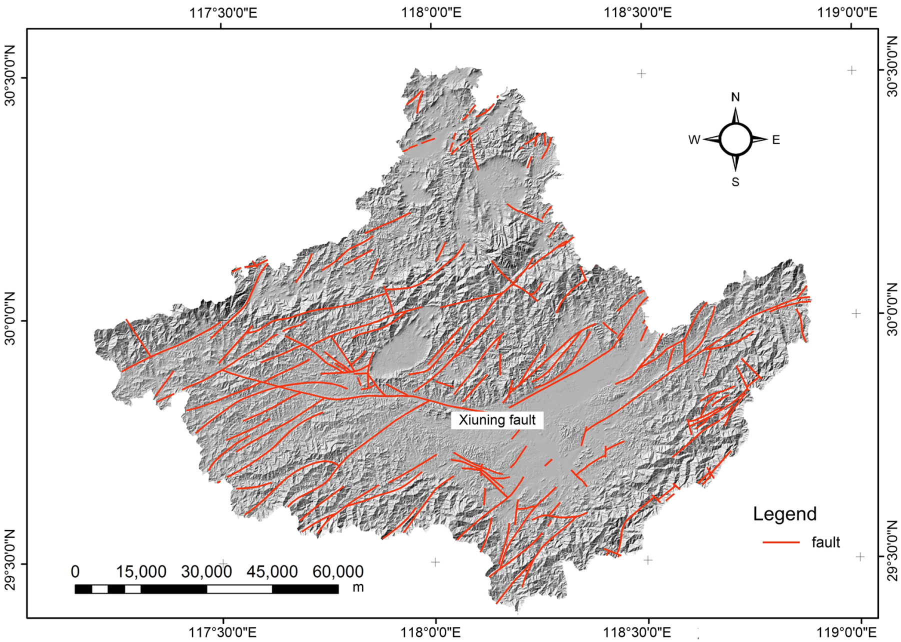

Figure 2. Faults distribution of the Huangshan region with a DEM background.

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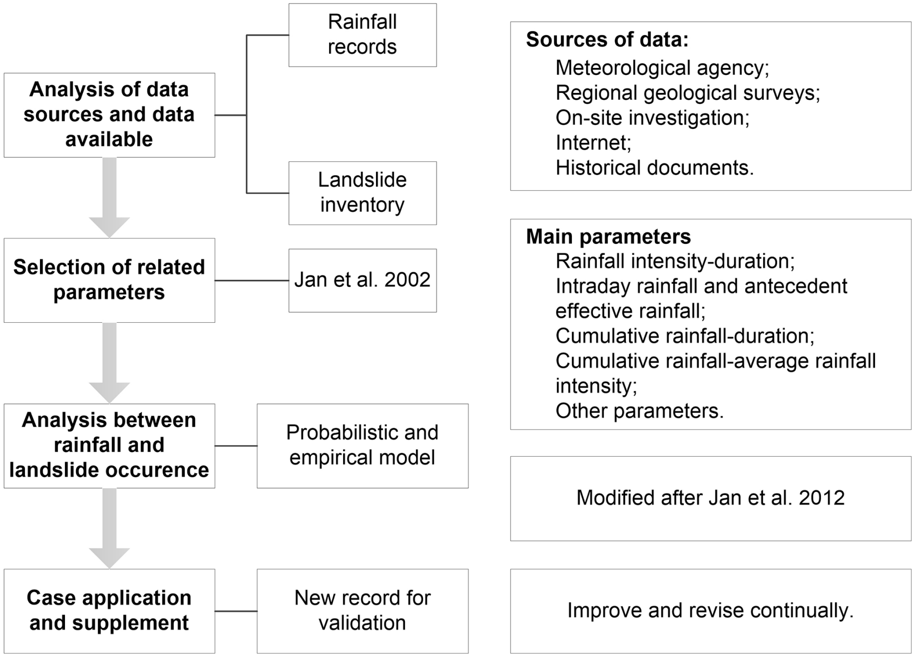

Figure 3. Flow chart illustrating the procedure to determine rainfall thresholds.

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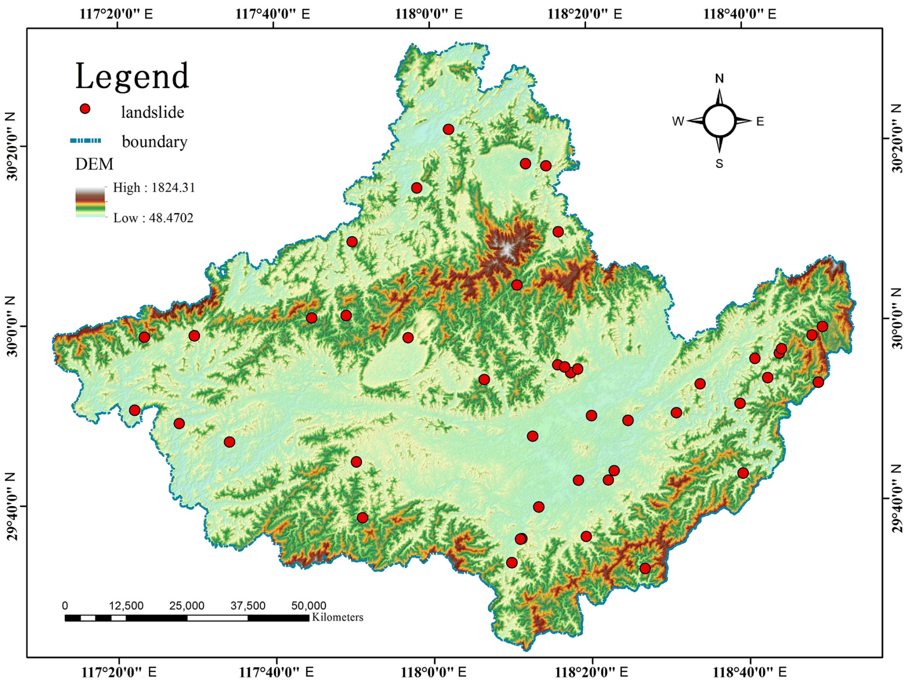

Figure 4. Location of rainfall-induced shallow landslide in the Huangshan region (2007–2012).

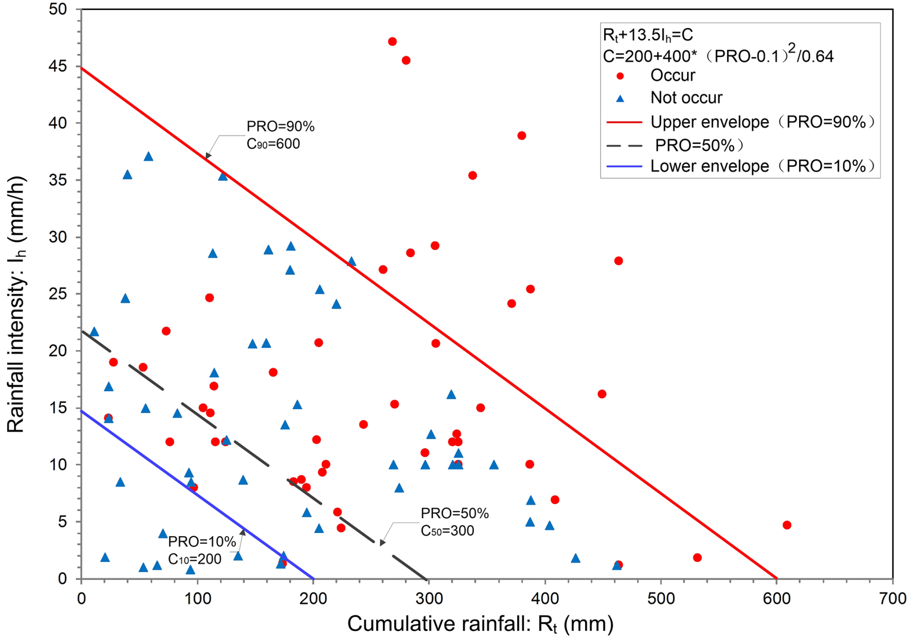

Figure 5. r_t–I_h graph for occurrence and non-occurrence of landslide events in the Huangshan region based on historical rainfall data. The red points and blue triangular points indicate occurrences and non-occurrences.

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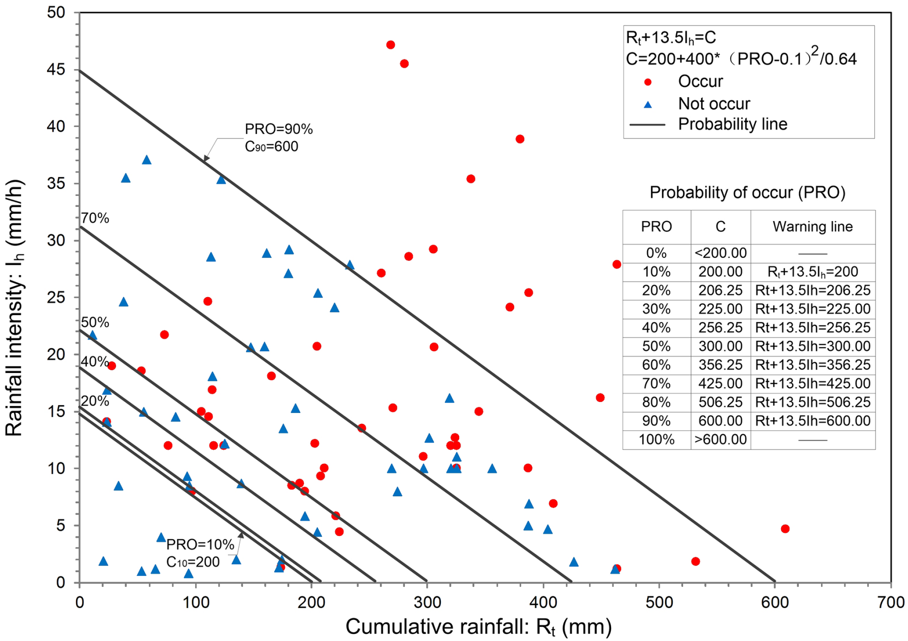

Figure 6. Several probability lines in Huangshan region based on the proposed approach.

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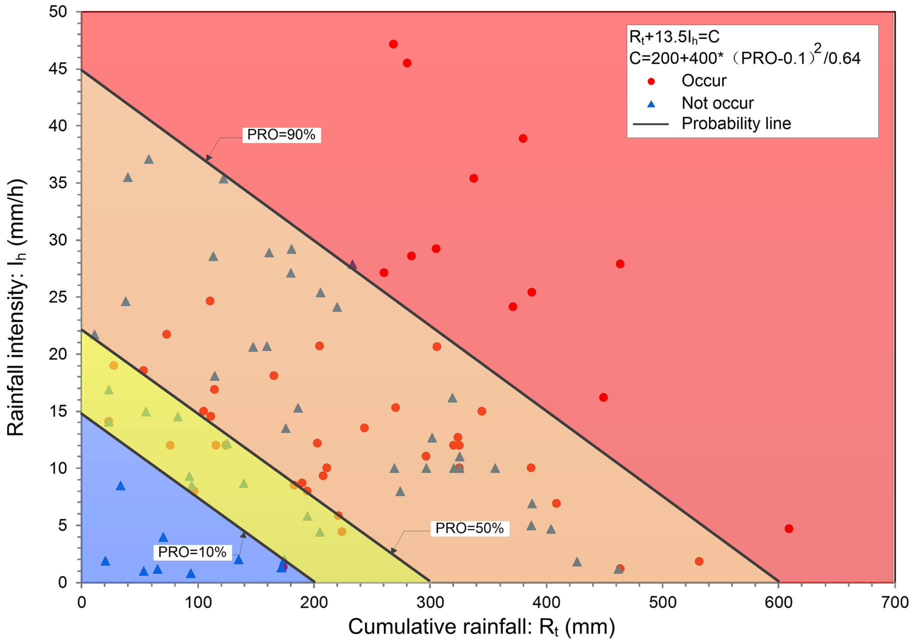

Figure 7. Probability lines for landslide occurrence in the Huangshan region based on the proposed method.

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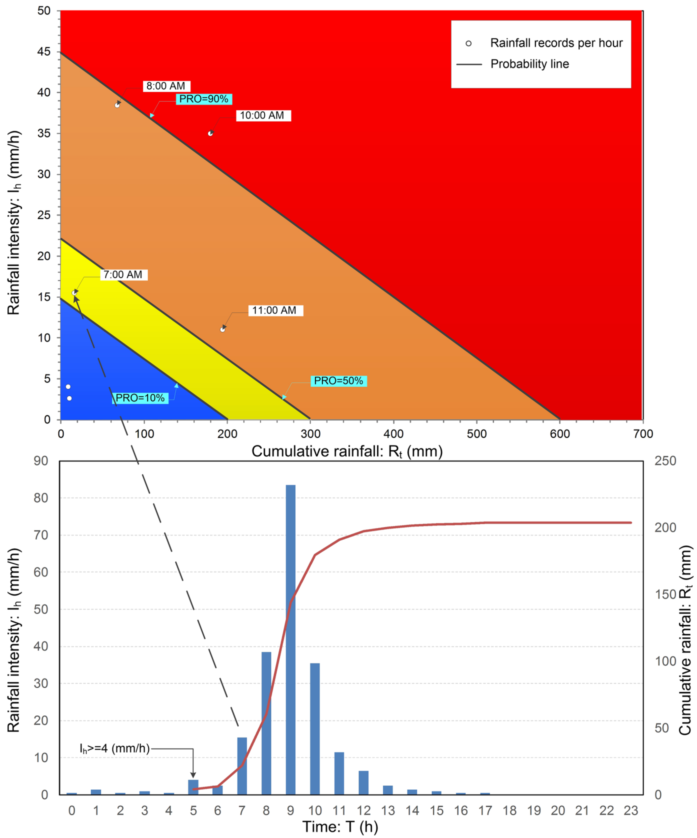

Figure 8. Application of the methodology in the Huangshan region (rainstorm of 30 June 2013).

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