Development of a new rainfall-triggering index of flash flood warning-case study in Yunnan province, China

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Abstract

Flash floods, characterized by rapid, short-duration, and high-velocity flows, are the major causes of property damage and casualties worldwide. Flash flood warning is one of the key measures to prevent flash floods. Relying upon rain gauge data and official statistics of flash flood events with casualties, this study proposes a new rainfall triggering index, \( \beta \), defined as the ratio of accumulated rainfall to intraday rainfall, which effectively divides floods into events triggered by heavy intraday rainfall (\( 0 < \beta \leq 5 \)) and those triggered by high cumulative rainfall (\( \beta > 5 \)). Then, historical disaster events were used to evaluate the performance of the proposed index. Results reveal that: (1) when \( 0 < \beta \leq 5 \), the intensity–duration (I–D) curve method is more desirable, and the simulation result has a high correlation coefficient (\( r = 0.95 \)) with the measured result; (2) when \( \beta > 5 \), the rainfall triggering index (RTI) method is more suitable (\( r = 0.8 \)); (3) the cumulative critical rainfall using the RTI method ranges from 50 to 400 mm. This paper stretches the thought of flash flood warning method and provides the reference for flood-prone regions.

KEYWORDS

antecedent accumulated rainfall, flash flood, RTI, Yunnan
According to the “NWS Glossary”, flash floods are rapid rises of water in “a stream or creek above a predetermined flood level, beginning within six hours of the causative event”. Flash floods are mainly caused by short-duration and high-intensity rainfalls, generally occurring in watersheds smaller than 260 km² (Davis, 2001; Georgakakos & Hudlow, 1984; Hong, Adhikari, & Gourley, 2012; Tang, Clark, Papalexiou, Ma, & Hong, 2020). In this article, flash floods include river floods, rainfall-induced landslides, and debris flows. Flash floods are one of the most devastating and fatal disasters in the world (Spitalar et al., 2014; Tang et al., 2017). For instance, from 2007 to 2015, 28,826 flash flood events happened in the United States, 10% of which resulted in an average loss of $1 million per property (Gourley et al., 2016). From 2000 to 2015, 935 deaths per year due to flash floods, accounting for 73% of all flood fatalities in China (Ma et al., 2018). Around 2,764 fatalities in Europe during 1950–2005 were attributed to flash floods, that is, 49 casualties per year on average (Barredo, 2007). Additionally, climate change studies have projected an intensified hydrologic cycle under future emission scenarios, which will result in more extreme rainfall events, thus exacerbating the flash floods severity (Beniston et al., 2012). However, the research on the main key technologies of flash flood prevention is still in the exploratory stage. How to accurately predict local heavy rainfall and improve defence capabilities is a critical and challenging issue.

In order to monitor and predict flash floods, huge efforts have been undertaken to explore the factors that induce flash floods, including rainfall (e.g., accumulated rainfall, duration of rainfall, and instantaneous rainfall), soil moisture, topographic slopes, sediment transport, etc. (Grillakis et al., 2016; Norbiato, Borga, Esposti, Gaume, & Anquetin, 2008). In Taiwan, numerous flash floods are mainly initiated during the peak hours of rainfall events (Huang, Chan, & Lee, 2015). In Eastern Pyrenees in Spain, high intensity and short duration rains without antecedent rainfall trigger mostly flash floods (Corominas & Moya, 1999). But in the United States, flash floods usually only occur after significant antecedent rainfall and moderate to long-duration rainfall (Baum & Godt, 2010). Soil moisture is another important controlling factor of flash floods (Lacava et al., 2005). For example, highly saturated soil impedes quick infiltration of precipitation, resulting in the generation of more surface runoff. When estimating the critical rainfall that initiates flash floods, it is essential to distinguish between antecedent rainfall and intraday rainfall. Hence, in the article, we presented a new rainfall triggering index, $\beta$, defined as the ratio of accumulated rainfall to intraday rainfall.

At present, the most widely used dynamic flash flood warning method is Flash Flood Guidance (FFG), which was established by the US National Weather Service (NWS) in the late 1970s (Mogil, Monro, & Groper, 1978). FFG generally refers to the amount of rainfall (i.e., thresholds) required to produce bank-full conditions on small streams at a given duration. The issuing flash flood warnings require comprehensive consideration of flood risk by comparing the measured or predicted cumulative rainfall with the rainfall threshold for the same period. Meanwhile, spatial soil moisture is estimated in real-time by the operational lumped hydrological model suitable for catchments on a scale of 1,000 km² (Gourley, Erlingis, Hong, & Wells, 2012). Many previous studies are dedicated to improving FFG, and the FFG generation (LFFG, FFPI, GFFG, and DFFG) have emerged and gained specific applications (Clark, Gourley, Flamig, Hong, & Clark, 2014). However, the hydrological models involved in this method are suitable for the large watersheds, and take into account almost all influencing factors, resulting in high data requirements. Hence, the prediction accuracy of hydrological models is still limited.

Traditional flash flood prediction relies on statistical methods, such as Soil Water Index (SWI) (Albergel et al., 2008), Rainfall Triggering Index (RTI) (Chen, Lio, & Hsu, 2017), intensity–duration (I–D) (Cannon, Gartner, Wilson, Bowers, & Laber, 2008), etc. Initially proposed by Wagner, SWI is a method of estimating soil moisture profiles from surface observations. It has only one parameter related to penetration time, which makes it easy to apply in practice. However, it is difficult to obtain the SWI parameters regardless of the centralised calculation and distribution of people (Albergel et al., 2008; Saito & Matsuyama, 2015). RTI method focuses on the antecedent conditions, using the product of rainfall intensity ($I$) and effective accumulated rainfall ($R_t$) to predict flash flood, which has been applied in Taiwan for more than 10 years (Jan & Lee, 2004). RTI is primarily used to determine the upper and lower critical warning lines. It requires a small amount of input data and is specifically suitable for flash floods. However, RTI is affected by the antecedent rainfall calculation using the deduction coefficient of “t” days and the rainfall division, resulting in a higher false alert rate in some rainfall patterns (Carpenter, Sperflage, Georgakakos, Sweeney, & Fread, 1999). Regarding rainfall thresholds, I–D, first proposed by Caine (1980), is widely used to describe the empirical relationship between rainfall duration ($D$) and average rainfall intensity ($I$) (Guzzetti, Peruccacci, Rossi, & Stark, 2007). At present, this method has been applied to local, regional, and global scales (Caine, 1980; Cannon et al., 2008; Hong, Adler, & Huffman, 2006). Indeed, such thresholds neglect the role of hydrological processes occurring along slopes and concentrate predominately on the final rainfall characteristics leading to flash
floods. Moreover, the method does not consider the antecedent conditions and rainfall intensity variations.

Therefore, the main objectives of this study are: (1) to propose a new rainfall trigger index $\beta$ to distinguish dominant disaster triggering factors; (2) to develop flash flood warning methods characterised by different triggers in combination with RTI and I–D. $\beta$ can effectively separate the effect of accumulated rainfall and intraday rainfall on triggering flash floods. The combination of RTI and I–D methods can potentially improve early warning accuracy. This study will contribute to further enhance national disaster prevention and mitigation capacity, and provide a decision-making basis for the country to formulate flood prevention and disaster reduction plans.

2 | STUDY AREA AND DATA

2.1 | Study area

Yunnan Province ($20^\circ$8′–29°16′N, 97°31′–106°12′E) is located in southwest China with an area of 383,210 km$^2$. In 2017, Yunnan Province had a population of about 46 million, and a gross domestic product (GDP) of $0.24$ billion, with an annual growth rate of 9.5%. It is situated in a low-latitude plateau, of which 94% is mountain and plateau. 39% of the mountainous areas have slopes greater than 25°, and the kastanozem accounts for more than 50% of the province, increasing the frequency of flash floods (Figure 1). Meanwhile, jointly influenced by the East Asian summer monsoon and the Indian summer monsoon, the spatiotemporal distribution of precipitation varies greatly. Precipitation mainly takes place from May to October, accounting for 85–95% of the total amount in the whole year. Precipitation peaks are especially notable from June to August, often causing flash floods. For two consecutive years (2014 and 2015), the numbers of flash floods and deaths in Yunnan Province are the highest in China, with the death toll accounting for about 22.2% of the national total. According to previous studies on the relationship between geological disasters and precipitation (Xie, Cheng, & Fan, 2005; Zeng et al., 2016), the cumulative critical rainfall in northwestern Yunnan is 35–200 mm, 50–200 mm in the southwest, and 100–300 mm in the east.

FIGURE 1  Map of Yunnan Province, with elevation (m) and the number of people dead and missing as a result of flash flood disasters (2011–2016) overlaid as different triangles
2.2 | Data

In the article, the flash floods refer to events accompanied by death or missing of people. The daily precipitation data are obtained from the China Meteorological Administration station (CMA). One day refers to the time from yesterday at 08:00 a.m. to today at 08:00 a.m. We only consider days with flood occurrences. If a disaster occurs in an area without a monitoring station, the data from the nearest monitoring station is employed as a substitute. Rainfall level is defined by CMA, categorising into light rain (0–25 mm), heavy rain (25–50 mm), and rainstorm (>50 mm). The division of rainfall events adopts Taiwan’s RIT method, that is, for six consecutive hours, the hour with rainfall greater than 4 mm is taken as the start time, and the hour with rainfall less than 4 mm is taken as the end time. The intraday rainfall refers to the cumulative rainfall at the beginning of rainfall (>4 mm for 6 hr) to the monitoring time. Topographic information was derived from the 1:250,000 scale digital elevation model (DEM) in the Yunnan Province. From 2011 to 2015, there were 112 flash flood events in Yunnan Province, with 237 deaths and missing. These disaster data come from almost all the open-access official materials from the Ministry of Water Resources, Ministry of Civil Affairs, Ministry of Land and Resources, CMA, and some Yunnan local government, etc.

3 | METHODOLOGY

3.1 | Relationship between rainfall intensity and rainfall duration

Flash floods caused by heavy rainfall is related to $I$ (rainfall intensity) and $D$ (duration). The $I$–$D$ thresholds are often used to predict flash floods occurrence (Aleotti, 2004; Guzzetti et al., 2007; Rosi et al., 2015) with the formula shown below:

$$I = \alpha D^{-\gamma} \quad (1)$$

where $I$ is the rainfall intensity, in mm/hr; $D$ is the rainfall duration, in hr; $\alpha$ and $\gamma$ are empirical parameters defined employing statistical analyses.

Generally, a $\gamma$ smaller than one indicates that the sensitivity of $I$ is dominant over $D$ in the empirical threshold model. In this article, we only focus on critical thresholds calculated using the $I$–$D$ method, which is derived by examining rainfall characteristics. It is usually obtained by drawing the minimum horizontal line to the rainfall intensity ($Y$-axis) and duration ($X$-axis). Rainfall characteristics in different regions trigger different levels of flash floods.

3.2 | Comprehensive warning of rainfall intensity and effective accumulated rainfall

Considering flash floods are usually caused by peak rainfall, RTI is defined as the product of $I$ (rainfall intensity) and $R_a$ (the effective accumulated rainfall) at the time of flash flood occurrence (Yin, Yu, Yin, Wang, & Xu, 2015). Flash floods risk increases with increasing RTI, and the equations are as follows:

$$\text{RTI} = I \times R_a \quad (2)$$

$$R_a = R_0 + Pa \quad (3)$$

$$\text{PA} = \sum_{i=1}^{n} \alpha^i R_i \quad (4)$$

$$\text{RTI}_p = \text{RTI}_{10} + \left( \frac{P-0.1}{0.8} \right) \left( \text{RTI}_{90} - \text{RTI}_{10} \right) \quad (5)$$

where $R_0$ is the intraday rainfall; $R_i$ is the amount of the antecedent $i$ day’s rainfall; $Pa$ represents the antecedent effective rainfall; $i$ represents the antecedent day number from 1 to 10; $\alpha$ is the weighting factor, and $P$ indicates the flash floods risk. RTI$_p$ refers to the estimation of RTI corresponding to different occurrence probability $P$ in a linear distribution model. The highest RTI of the historical rainfall event is defined as the upper critical (denoted as RTI$_{90}$); similarly, the lowest RTI is defined as the lower critical (denoted as RTI$_{10}$).

Based on Equations (2), (4), and (5), the RTI of different rainfall events with different cumulative probabilities can be calculated statistically in conjunction with the recorded flash flood events, and then the flash flood threshold is obtained to distinguish the corresponding flash flood probability. The detailed description of this method is as follows:

1. Sort the RTI of rainfall events in descending order, and use the Weber to calculate the RTI$_{10}$ with a cumulative probability of 10%. If the newly calculated minimum RTI is less than RTI$_{10}$, update RTI$_{10}$.
2. Subtract the portion below RTI$_{10}$, and then re-take the RTI$_{90}$ with a cumulative probability of 90% by Weber method.
3. Calculate other occurrence probability with linear probability distribution between RTI$_{10}$ and RTI$_{90}$.

3.3 | $\beta$ index

Among the historical flash flood events used in this study, rainy days (<4 mm) and rainstorm days
(>50 mm) accounted for 69.4% and 27.7%, respectively, indicating that accumulated rainfall is the dominant factor triggering most flash floods. Meanwhile, Figure 2 also shows that the majority of flash floods are caused by accumulated rainfall. When the intraday rainfall is greater than 50 mm, the relationship between intraday heavy rainfall and cumulative rainfall is almost linear. Therefore, the disasters are classified into two categories: antecedent rainfall-induced and intraday heavy rainfall-induced. In the practical application, the risk is usually considered high when rainfall reaches 100 mm, while rainfall less than 25 mm is considered non-risk. Zhao et al. (2011) suggested that the ideal situation for triggering the flash floods is at least one order of magnitude difference between the intraday heavy rainfall and the antecedent rainfall. Meanwhile, combined with the trial-and-error method, the actual disaster analysis revealed that the antecedent rainfall ($R_0$) is five times of the intraday rainfall ($R$). Therefore, we can define the disaster index, $\beta = R/R_0$, where $\beta$ is the antecedent rainfall divided by the intraday rainfall from 2011 to 2015. When $0 < \beta < 5$, the dominant factor inducing flash flood is the intraday heavy rainfall; when $\beta > 5$, it is the antecedent rainfall. Both the RTI and I–D methods are long-term practical applications, where the former focuses on accumulated rainfall, while the latter focuses on rainfall on the current day. Therefore, when $\beta > 5$, the RTI method is mainly employed for early warning; $0 < \beta < 5$, mainly used I–D method for early warning.

In the actual surface runoff events, by analyzing the influence of rainfall characteristic factors on the early warning threshold, a trigger factor $\beta$ is proposed, and different warning methods are selected for different dominant rainfall trigger factors, thereby improving the early warning accuracy. Figure 3 shows the distribution of $\beta$ in Yunnan Province at the county level. The larger $\beta$ is concentrated in the eastern part of Yunnan Province, such as Qujing County and Zhaotong County. Smaller $\beta$ are mainly distributed in central Yunnan Province, such as Chuxiong et al. The $\beta$ shows a downward trend from northeast to southwest. Moreover, $\beta$ ranges from 3.5 to 17.6, of which less than 5 is about 8%, indicating that the flash flood is mainly caused by intraday rainfall, and the I–D method should be adopted for early warning; the other 92% is greater than 5, indicating that the main factor inducing flash floods is cumulative rainfall, and RTI method should be used for early warning. Regardless of the RTI method or the I–D method, the focus is on the rainfall factor, and the factors such as topography, slope, and soil are not fully considered. Therefore, when issuing the flash flood warning, the flash flood potential index (FFPI) should be considered comprehensively.

FFPI is mainly derived from the slope, land use, forest cover, and soil type, ranging from 1 to 10, which enable the forecasters to determine whether a catchment has high or low susceptibility with flash floods. The greater the FFPI value, the greater the flash flood risk. In considering whether to issue a flash flood warning, areas with low FFPI are excluded because of the low risk of flash floods, which is effective for reducing false alarms. According to Figures 3 and 4, FFPI and $\beta$ values are higher in eastern Yunnan and lower in southwest Yunnan. However, in the central region where $\beta$ is small and FFPI is large, there is no significant correlation between FFPI and $\beta$; perhaps because FFPI mainly considers static factors, while $\beta$ is a dynamic rainfall factor. Thus, both FFPI and $\beta$ should be considered when issuing a warning.

**Figure 2** Relationship between intraday rainfall and accumulated rainfall for flash flood events

**Figure 3** The distribution of $\beta$ in the county level over Yunnan
4 | RESULTS AND DISCUSSION

4.1 | Early warning method for the disaster caused by accumulated rainfall

4.1.1 | Relationship between antecedent effective rainfall and intraday rainfall

In this study, since $\beta > 5$ accounts for more than 90% of flood events, the antecedent accumulated rainfall ($Pa$) is the key factor. Therefore, the following part focuses on using the RTI method to predict flash floods. The first is to determine the parameter $\alpha$ related to factors such as antecedent rainfall, the flash flood type, and underlying surface conditions. $\alpha = 0.78$, which is a measured value in Jiangjia Gully, Yunnan Province (Cui, 2003). The effect of the previous $i$-day rainfall on the intraday rainfall decreased with the increase of $i$ (Fedora & Beschta, 1989), and $i$ is as follows: 13, 12, 10, 9, 7, 6, 5, 3, 2, 1. First, $Pa$ is calculated based on Equation (4). Then, with $Pa$ as the independent variable and $R_0$ as the dependent variable, the linear function ($Y = aX + b$), exponential function ($Y = ae^{bX}$), logarithmic function ($y = alnx + b$), and power function ($Y = aX^b$) are fitted by regression analysis. Results are shown in Table 1, where the linear function is better than the other three, and the correlation between $R_0$ and $Pa_{10}$ is the best. The correlation coefficient, $r = 0.80$, indicating that the fitting relationship is propitious to the early warning of this pattern. The relationship between $R_0$ and $Pa$, $R$, and $Pa$ is shown in Equations (6) and (7):

\begin{align*}
R_0 &= 0.2Pa - 5 \quad (6) \\
R_t &= R_0 + Pa = 1.2Pa - 5 \quad (7)
\end{align*}

where $R_0$ (mm) is the intraday rainfall, $R_t$ is the accumulated rainfall, and $Pa$ (mm) is the antecedent accumulated rainfall.

4.1.2 | Comprehensive effect of rainfall intensity and effective cumulative rainfall

Based on data from 112 flash flood events, the RTI was firstly calculated following Equations (2)-(4), and then sorted from large to small according to the occurrence time. For specific calculation, please refer to Jan & Lee (2004). The results are shown in Figure 5. The flash flood probability is mainly concentrated in 10–90%. First, events with flash flood probability less than 10% are deleted; then, when the flash flood probability occurrence is $P$, RTI$_P$ is calculated using the linear distribution model (Equation (5)). Figure 6 presents the potential for flash flood occurrence. When RTI is greater than the upper margin line (RTI$_{90}$), the rainfall is more likely to trigger the flash flood; when the RTI falls below the lower margin line (RTI$_{10}$), the rainfall is less likely. Given the practical experience, RTI$_{50}$ was selected as the reference for flash flood warning. The total effective cumulative rainfall at the rainfall intensity $I = 10 \text{ mm/h}$ was regarded as a flash flood warning indicator. Finally, with a step size of 50 mm, from 50 to 400 mm, the rainfall threshold was divided into eight intervals to further evaluate the flash floods possibility.

Combining with empirical cumulative rainfall, FFRI risk, and $\beta$ distribution, Figure 7 demonstrated the critical cumulative rainfall distribution in Yunnan Province, indicating that the cumulative rainfall of a single event is between 50 and 200 mm; while in some areas such as in Zhaotong, Nujiang, Qujing, the cumulative rainfall is higher than 300 mm. Regarding Figure 1, in high-altitude areas, the cumulative rainfall threshold is relatively high; mainly because the area may not be suitable for human habitation, reducing the severity of the disaster to a certain extent.

4.2 | Early warning method for the disaster caused by intraday heavy rainfall

Many previous studies have demonstrated that most of the rainfall thresholds for possible flash flood occurrences are the rainfall intensity ($I$) versus rainfall duration ($D$) (Guzzetti et al., 2008; Aleotti, 2004). When $\beta < 5$, the intraday heavy rainfall is the dominant factor causing
The $I-D$ curve mainly considering the intraday rainfall is more suitable for such a disaster mode. Both $I$ and $D$ are defined as the average rainfall intensity and duration from the start of a rainfall event to the occurrence of a flash flood. Based on the rainfall station data, the general formula is fitted as follows:

$$I = 16D^{-0.7} \quad (8)$$

where $I$ (mm/hr) is the rainfall intensity; $D$ (h) is the duration.

Figure 8 shows the relationship between $D$ and $I$, and the correlation coefficient, $r = 0.95$, indicating that the fitting relationship is propitious to the early warning of this pattern. If the rainfall intensity and duration are near
or exceed the trend line, the flash flood is more likely to occur, and the monitoring and timely warning forecast should be strengthened. For shorter durations, the difference is the greatest and decreases with duration, mainly due to the adoption of the smaller flash flood datasets in this study. The results presented above, namely the relationship between rainfall intensity ($I$) and duration ($D$), are important information for assessing flash floods in China.

5 | CONCLUSIONS

Based on historical flash flood events, the article proposes a rainfall trigger index $\beta$, which achieves the purpose of selecting early warning methods depending on trigger factors. The specific conclusions obtained are as follows: (1) $\beta$ is defined as the cumulative rainfall divided by the daily rainfall, where the critical threshold is 5, and the county-level $\beta$ distribution map of Yunnan Province is obtained; (2) when $\beta > 5$, flash floods are triggered mainly by accumulated rainfall, and the fitting relationship is: $R_0 = 0.2 \text{ Pa·d}^{-1}, r = 0.8$; RTI baseline warning value is RTI 50 in 50 mm steps from 50 to 400 mm. Meanwhile, the cumulative distribution map of county-level precipitation in Yunnan Province was further obtained. When $0 < \beta \leq 5$, the dominant factor inducing flash floods is intraday heavy rainfall, and the fitting relationship is $I = 16D^{-0.7}$, and $r = 0.95$. This study innovates the early warning ideas relying on the traditional experience methods, and we will further refine this early warning threshold in combination with physical mechanisms, establishing the foundation for application to the ungauged area.

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DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study are included in this article.

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