

Quantitative assessment on the influence of rainfall on landslides in Jianshi County of Qing River Basin, China

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Abstract Rainfall is one of the main inducing factors of landslide disaster. Based on many years of landslide monitoring data and rainfall data of Jianshi County, 66 landslides occurred from 2002 to 2008 were chosen, which is about 52.38 % of the total 126 landslides in the whole area. There are 13 landslides with deformation or displacement over twice, this is about 19.70 % of 66 landslides chosen. According to analysis the correlation between rainfall and landslides with the geostatistics method, the critical rainfall and effective rainfall are determined. Using the Bayes statistical inference model to improve the probability model, the probabilities of landslide early warning system zones are determined. The landslide early warning model is established on basis of the result of landslide susceptibility, rainfall model and probabilistic model with ArcGIS software. The probability value (T) is from 0.002168 to 0.909062. The whole county is divided into four grades of landslide early warning system. The data of second deformation or displacement of 13 landslides induced by the rainfall are used to validate the model. Totally, the result of landslide early warning model is scientific and reliable. The rainfall data of eight landslides are in line with the model and in the range of level IV/V. The accuracy is about 61.54 % according to the relationship between landslide and rainfall. The distributions of 11 landslides are located in the level V zone and

the accuracy is 84.62 % according to the relationship between landslide early warning result.

Keywords Landslides · Rainfall · Early warning system · Geostatistics · Jianshi County

Introduction

The occurrence and development of the landslide is a complex physical process. The landslide is produced by a variety of internal and external forces (Chen et al. 2008; Donati and Turrini 2002). The internal forces are geological environmental factors such as landform, river cutting, formation lithology, geological structure, among others. External forces such as rainfall, earthquake and human engineering activities trigger occurring of landslides. According to the statistical analysis of sudden landslides in southern China, it is found out that about 65 % of the total landslides are induced by rainfall. This means sudden landslides are mainly the impacts of rainfall. The correlation between landslides and rainfall is high (Liu 2007; Guinau et al. 2005; Ohlmacher and Davis 2003). Therefore, considering the rain as the direct inducing factor of landslide can be one of the effective methods for setting up a landslide early warning system.

At present, the research concepts of landslide early warning system are widespread. With the development of technologies, the research methods are also diverse (Liu 2007; Ma and Chen 2007; Guo and Lin 2001; Van Westen et al. 2008). The main research contents can be divided into three types, such as time forecast, space forecast and strength forecast (Liu et al. 2004). There are three types of main research models for early warning systems. They include the statistical models, the theoretical models and

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the coupling of statistics and theory model. The early warning models can be divided into three types, such as implicit statistics warning method, display statistics warning method and dynamic early warning method (Liang et al. 2013; Van Westen et al. 2008). Countries such as Japan, USA, Puerto Rico, Brazil, Venezuela, and Italy have studied the geohazards early warning system with the coupling of statistics and theory model using dynamic early warning forecast method. Until now, the forecast precision can reach hours for landslides real-time forecast induced by rainfall in some countries and regions, including Hong Kong, USA, Japan and Italy et al. (Barnd et al. 1984; David et al. 1987; Miyagi et al. 1998; Wang et al. 2002; Prete et al. 1998).

The monitoring network system of rainfall is advanced and rainfall data is relatively completed over a long period of time. The detailed information on investigation of the landslides' development characteristics is in place. The evaluation/assessment methods and technologies of susceptibility and vulnerability are impeccable.

According to comparisons and analysis at home (China) and abroad, the relatively mature methods of landslide early warning system, mainly are divided into three categories.

1. In order to obtain the rainfall threshold, it needs to analyze the relationship between landslide and rainfall. The statistical analysis character between rainfall intensity and landslide occurring time is an effective method to analyze rainfall thresholds of landslides triggered. But the method is simply to analyze the critical rainfall of a 24-h rainfall process, and not to give full consideration to the antecedent rainfall (Caine 1980; Cardinali et al. 2006; Jacob et al. 2006; Guzzetti et al. 2008).

2. Using logistic regression models, it is necessary to consider the rainfall as a dynamic variable and the geological conditions as surface static variables. It establishes the models of relationship between rainfall and landslides (Dai and Lee 2003; Xu et al. 2006; Chang et al. 2008; Jiao et al. 2010; Peng et al. 2010). Due to the limitations of the arrangement of monitoring equipment, it leads to less equipment or uneven equipment in many areas. In this case, the data accuracy of rainfall is restricted. The real-time observation curve of rainfall is not possible to obtain and the analysis of threshold of rainfall is limited. The probability model, including rainfall and landslide, is an effective method to complete the landslide early warning system (Dai et al. 2002; Guri et al. 2008). Using geo-statistics method to analyze antecedent rainfall before the occurred landslides, it can obtain the cumulative rainfall and estimate the impact of rainfall. It could determine the different rainfall thresholds on the landslides with different depths, and the influences of the frequencies and amplitudes (Inagaki and Sadohara 2006; Chang et al. 2011).

Using the coupling analysis of rainfall as dynamic variables and geological background conditions as static variables, it can realize the probability model of landslide early warning system (Thomas et al. 2000; Collison et al. 2000; Chen and Lee 2003; Liu 2004; Van Westen 2004; Chen et al. 2005; Chen and Cong 2006; Li and Yang 2006; Yin et al. 2007; Gabi and Michael 2008; Wu et al. 2008; Zhou et al. 2008; Zhang et al. 2009; Qiao et al. 2009; Melchiorre and Frattini 2012). At the same time, every country has been or is currently setting up the real-time landslide monitoring and early warning system. They begin to do the research on not only the statistical characteristics between rainfall and landslides, but also the mechanism and process of landslides (Au 1993, 1998; Dai et al. 1999; Inversion 2000). They introduce a rainfall infiltration model to analyze the relationship between the landslide and critical rainfall intensity. They continuously modify the forecasting model and parameters, to improve the accuracy of evaluation and prediction precision (Matsushi et al. 2006; Gao and Yin 2007).

3. Considering the influences of rainfall on the surface and the hydrogeological conditions of the geotechnical engineering, it is useful to estimate the slopes' stabilities with the slope stability model. Based on the principle of interaction between soil and water, rainfall increases the water content of the sliding zone, and reduces the friction of the sliding zone and loose soil. Meanwhile, rainfall infiltration increases water content and the gravity of the landslide, which leads to increasing the downward force of the sliding body (Greco et al. 2013; Lee et al. 2013). Considering the influences of the hydrogeological process of landslides, but not giving full consideration of the hydrogeological and engineering geological conditions, the application is limited. Therefore, some scholars try to consider the rainfall as a variable and use the numerical simulation technologies and methods of hydrogeology and engineering geology to complete the landslide early warning system (Wu and Sidle 1995; Montgomery et al. 1998; Neri' et al. 1999; Wilkinson et al. 2002; Hong et al. 2005; Salciarini et al. 2006; Versace and Capparelli 2008; Montrasio et al. 2009; Zhou and Li 2009; Xu and Li 2009; Zhang et al. 1998; Tong 2004).

On the basis of the susceptibility, or risk zoning, research results and the real-time rainfall monitoring system, this paper completes the landslide early warning system. According to the analysis of the relationship between landslide and rainfall, it estimates critical rainfall and cumulative rainfall model, and constructs the landslide early warning model. With the GIS spatial analysis function, it realizes the possibility model of a landslide early warning system and understands the occurrences and developments of landslides.

Study area

Jianshi County is located in the southwest of Hubei province. It lies between 109°30' and 110°12', longitude, East and 30°00' to 30°50' latitude, North (Fig. 1). The study area covers an area of about 2667.74 km². The landscape is tectonic erosion corrosion middle-mountain and low-middle-mountain. In this area, the geological features and conditions are extremely complex, which are characterized by steep mountains, criss-crossing ravines, about the difference of 1877 m and an average slope of 25°. The weather is dry in winter and wet in summer, which is influenced by the subtropical monsoon climate. The distribution of rainfall is uneven, and the heavy rain often happens in the summer. According to rainfall data, from 1997 to 2008, the average annual rainfall is about from 1200 to 2100 mm. The maximum annual rainfall is 2887.1 mm (Tanmuya precipitation station, 1998). The maximum monthly rainfall is 922.3 mm (Tanmuya precipitation station, July, 1998). The maximum daily rainfall is 236.3 mm (Sanliba precipitation station, July 13, 1997). Maximum number and rainfall intensity are in July. The rainfall during May to July is around 61 % of the total rainfall in the whole year. The complex natural geological

environment and climate conditions contribute to the formation of geohazards.

There were 182 geohazards at the end of 2009, including 126 landslides, 43 avalanches and 13 surface collapses. Landslides count for around 70 % of the total geohazards in the whole county. The geohazards are mainly concentrated in two periods. The number of geohazards has increased by 30 % from 1997 to 1999, and by 53 % from 2007 to 2008. There are 10 precipitation stations and the data are exact.

During the study, the basic data are mainly collected from field survey (hydrogeological maps, engineering geological maps, geographic traffic maps and remote sensing data). Most data are collected from the projection “Qing River Basin Geological Disasters Detailed Survey”, and others from the field survey. Some topographic maps of Jianshi County and Jingyang Town are 1:10 000. The scale of engineering geology map, geohazard distribution map and geographic map is 1:50,000. Traffic and location map is 1:100,000. The scale of geology map is 1:200,000. In order to obtain information about human engineering activities in Jianshi County, such as road construction and water conservation facilities construction, as well as spatial distribution and projection ranges of geohazards, the P6

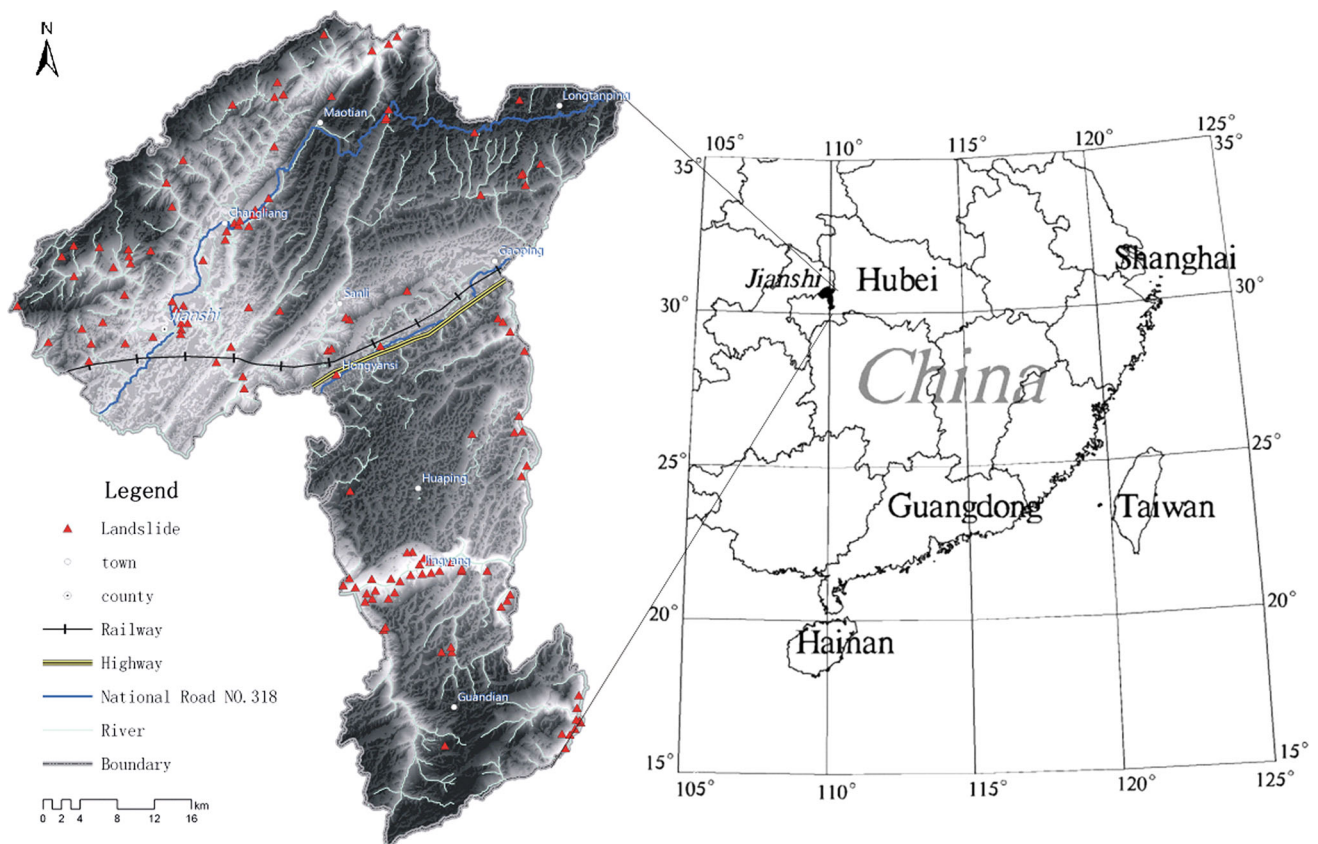


Fig. 1 The location of Jianshi County and the landslide distribution in the area

(April 13, 2008), ALOS (June 17, 2009), ASTER (July 5, 2008) and WorldView-1 data of Jingyang Town (September 11, 2009) are specially purchased. The resolution of P6 imagery is 5.8 m, ALOS is 2.5 m, ASTER is 15 m and WorldView-1 is 0.5 m. The rainfall data is from 2002 to 2008.

Methodology

Framework of the early warning system

According to the survey data of all landslides, especially the geo-exploration data of two typical landslides (Magantang and Huojiaping landslides), it completed the analysis of the landslide mechanism and background to evaluate the landslide susceptibility zoning in Jianshi County. Based on the analysis of the water content in rock and soil mass, landslide stability coefficient, the previous cumulative rainfall and 24-h rainfall in the future, the landslide early warning model is established (Inagaki and Sadohara 2006; Christian et al. 2010; Chang et al. 2011; Liang et al. 2013). However, it is difficult to accurately obtain the water content data and stability coefficient of geotechnical rock in a wide range. Therefore, this study used the background conditions and the rainfall characters to complete the early warning model and discover the landslides' trends (Van Westen et al. 2008; Chang et al. 2011; Greco et al. 2013).

Based on the previous research, 66 geohazards induced dominantly by rainfall with detailed records, which are closely related to the rainfall, are chosen from the total 126 landslide in the whole county. The correlation coefficients of landslides and rainfall were calculated in Statistical Package for Social Sciences (SPSS 16) software. Establishment of the statistical relationship between time–space distributions of landslides and rainfall enabled to determine the characteristic value of effective rainfall. One of the characteristics included the threshold value in the future which depends on the cumulative effective rainfall model and 24 h of rainfall (Inagaki and Sadohara 2006; Christian et al. 2010; Chang et al. 2011; Liang et al. 2013; Lee et al. 2013; Greco et al. 2013). Finally, the coupling analysis of the background and rainfall, completed the procedure for quantitative assessment of the landslide early warning system.

The analysis of background information conditions is according to geographical and geological landforms, slope structure types, lithology, structure, hydrogeological conditions and human engineering activities. Through establishment and analysis of entropy model, the authors complete the landslide susceptibility zones in Jianshi

County. The sum of 66 typical landslides were selected for the correlation analysis between rainfall and landslides to determine the rainfall characteristic value and the threshold of effective rainfall (Song et al. 2004; Miao et al. 2007; Shi et al. 2007; Chang et al. 2011; Lee et al. 2013). According to correlation analysis between rainfall and landslide susceptibility zones, the probability factors and frequency factors of landslide at different susceptibility levels are determined through analysis and probability distribution table of landslide at different rainfall levels as well as landslide early warning zones (Song et al. 2004; Inagaki and Sadohara 2006; Miao et al. 2007; Shi et al. 2007; Christian et al. 2010; Chang et al. 2011; Liang et al. 2013; Lee et al. 2013; Greco et al. 2013). The specific methods are as follows:

1. Using remote sensing imagery, it can interpolate the scopes of 126 landslides. The data are the samples of information entropy model.
2. Using ArcGIS spatial analysis technology, it obtains vector data, such as the geographical and geological landforms, slope structure types, lithology, structure, hydrogeological conditions and human engineering activities and so on. It can calculate the weights of these impact factors. Through spatial analysis calculation, the landslide susceptibility zoning map is completed (Kayastha 2012; Wang et al. 2012; Bijukchhen et al. 2013).
3. By analyzing the correlations between rainfall data and landslide data in Jianshi County, effective rainfall and critical rainfall of landslides in Jianshi County are determined (Inagaki and Sadohara 2006; Van Westen et al. 2008; Christian et al. 2010; Chang et al. 2011; Liang et al. 2013).
4. Through the analysis of relationship between rainfall and landslides, it can complete quantitative precipitation probability table and determines the level of different rainfall landslide probability (Liu et al. 2004; Inagaki and Sadohara 2006; Chang et al. 2011; Lee et al. 2013; Greco et al. 2013).
5. Coupling of the rainfall and landslide susceptibility, using spatial analysis function, the landslide early warning system is established and the map is completed.

Geohazard susceptibility assessment

Based on the consistency of the conditions and mechanism of geohazards' formation, leading to the simultaneous occurrence and regionality of geohazards, the geohazard statistics become the theoretical basis for entropy model analysis. According to the investigation

and analysis of geohazards, and through detailed survey of typical geohazards, the geohazards-inducing factors are divided into static factors and dynamic factors. The static factors include lithology, structural conditions, slope structure, topographic slope and aspect, elevation distribution, etc. The dynamic factors include seismic activity, rock weathering and erosion, river valley development, human engineering activities, weather conditions, etc. According to previous studies (Liu 2004; Shi et al. 2007; Kayastha 2012; Bijukchhen et al. 2013), combined with the actual situation in Jianshi County, seven individual factors are selected as the geohazard susceptibility zoning control factors, including slope height, slope type, geotechnical engineering rock group type, the distance from river or valley, geological structural conditions, and the impacts of human engineering activities. 162 landslides, about 89.01 % of the total geohazards, are used to analyze impact factors with the entropy model, and the correctness of the model is proven by the other 20 landslides (the total area of geohazards is about 0.1868 km²), about 10.99 % of landslide located in 10.11 % of the areas of landslides.

On basis of the field survey data, the impact factors are chosen and graded. The entropy model is employed to the compute values of different impact factors quantitatively with ArcGIS. All impact factors are weighted based on the calculation results of the entropy model. The result of assessment susceptibility is calculated by different impact factors and reclassified into very high, high, medium, and low susceptibility zones as 10, 20, 30, and 40 % of the total area of Jianshi County, respectively. The percentages are 41.34, 23.90, 21.71, and 13.05 % of the total areas of 162 geohazards and 26.70, 43.52, 23.02, and 6.76 % of the total area of 20 validated geohazards in very high, high, medium, and low susceptibility zones, respectively. There is a significant consistency between the result and validated result. According to the success rate curve the overall success rate is about 75 %. The result of assessment of landslide susceptibility in Jianshi County is useful for the landslide early warning system.

Rainfall models

On basis of the analysis of the landslides’ mechanism and background conditions, the landslides are triggered by rainfall including different stages of the rain period. The cumulative effective rainfall is a prerequisite condition and 24-h of rainfall in the future is an inducing condition. In this case, it is very important to establish the cumulative effective rainfall model and threshold of rainfall.

Cumulative effective rainfall

The development and occurrence of landslides are a gradual process, and the rainfall infiltration has a delayed effect on the landslides’ bodies. For example, small landslides occur in the middle or later periods of a heavy rainfall process and large landslides occur in the late stage of a rainfall or after several days. In most cases, the landslides in some regions occur together after a heavy or continuous rainfall. Based on the above two characteristics of landslides, it is possible to determine characteristic values of the continuous rainfall process. According to analysis the correlation between the rainfall and landslides, it determines the reasonable rainfall process model and carries out the values of cumulative effective rainfall (Thomas et al. 2000; Van Westen 2004; Van Westen and Getahun 2003; Liu et al. 2004; Van Westen et al. 2005; Inagaki and Sadohara 2006; Chang et al. 2011; Lee et al. 2013; Greco et al. 2013).

According to the analysis of the comprehensive effect of the water content and the rainfall in the future, it can predict the stability trend of landslide which is affected by the rainfall and realize the early warning system. The effective rainfall model is selected (Crozier and Eyles 1980; Thomas et al. 2000; Inagaki and Sadohara 2006; Chang et al. 2011).

$$r_{a_0} = kr_1 + k^2r_2 + \dots + k^n r_n \tag{1}$$

where: r_{a_0} means antecedent rainfall, based on maximum regional rainfall values (mm) for 0 day; k means attenuation coefficient of antecedent accumulation rainfall, in this paper the value of k is 0.5 and the antecedent cumulative rainfalls of 15 and 4 days are shown in Table 2; n means number of days before the 0 day for comprehensive discussion.

1. According to the monitoring data of 10 weather stations in Jianshi County, there was no record of 15 days rainfall duration and the longest duration rainfall of every station was shown in Table 1, respectively. The antecedent cumulative rainfall of 4 and 15 days are almost the same. Therefore, the rainfall duration within 15 days is used to carry out the probability of landslides under different rainfall duration conditions.
2. Based on the previous work, the attenuation coefficient of antecedent cumulative rainfall is 0.5. The antecedent daily rainfall is carried out by the daily rainfall during last 30 days. The rainfall and the cumulative rainfall are shown in Table 2.

It obtains the cumulative rainfall and the maximum daily rainfall of the 66 landslides from 1 to 15 days,

Table 1 Statistics of max rainfall and rainfall duration frequency in JianShi county from 1999 to 2008

Year	Max rainfall in 24 h (mm)	Max rainfall duration (days)	Rainfall duration (times)				
			3 days	4 days	5 days	10 days	15 days
1999	112.60	7	45	23	13	0	0
2000	112.30	8	47	25	15	0	0
2001	66.90	10	39	22	11	1	0
2002	65.20	11	67	45	28	0	0
2003	60.70	8	53	29	15	0	0
2004	67.50	9	32	16	8	0	0
2005	141.00	8	39	15	12	0	0
2006	90.20	10	35	20	13	1	0
2007	86.80	10	48	25	12	1	0
2008	199.00	9	48	25	13	0	0
Average	100.22	9	45.3	24.5	14	0.3	0

30 days and a continuous cumulative rainfall in Jianshi County during 2002–2008. Using SPSS16 to analyze the correlation between such characteristic values of process rainfalls and 66 landslides, the correlation coefficients are shown in Table 3.

In Table 3, when the correlation coefficient is positive, it means the occurrence and development of landslides are influenced by the daily rainfall. Some coefficients of the daily rainfall are positive, including the 1, 2, 3, 4, 13 and 15 days. The other coefficients are negative. From 1 to 4 days, the positive coefficients mean that the effects of the daily rainfall accelerated the occurrence of landslides. The cumulative rainfalls of 4 days are almost the same as the ones of 15 days. In this case, the rainfalls of 4 days are considered as the threshold values of cumulative rainfall. The correlation coefficient of 4-day rainfall is larger than the one of 5-day or more than 5-day rainfall. Therefore, the cumulative rainfall of 4 days is chosen as the characteristic value of the process rainfall (Inagaki and Sadohara 2006; Chang et al. 2011; Lee et al. 2013; Greco et al. 2013).

Threshold of rainfall

On the basis of research methods at home and abroad, the method of China Geological Survey is effective and accepted. The early warning method is effective with the parameters such as the cumulative rainfall from 1 to 15 days, daily rainfall, and the effective rainfall. According to analysis of the data of rainfall and landslides in Jianshi County, the antecedent cumulative effective rainfall is determined. The landslide early warning model adopts 4-day cumulative rainfall and the 24-h rainfall in the future to calculate and determine the cumulative effective rainfall value. According to the data of 66 landslides and rainfall data from 2002 to 2008, it obtains the data of 4-day

antecedent cumulative effective process rainfall and 24-h rainfall in the future in order to find out the threshold of rainfall. The scatter diagram of 24-h rainfall and 4-day cumulative effective process rainfall is shown in Fig. 2.

The quantity of 24-h rainfall is more than 5 mm, and peak value of landslides appears when the rainfall is more than 10 mm or 21 mm (shown in Fig. 2). On the basis of the complexity of factors of landslides, when the rainfall is <0.3 mm, the author suggests the landslides' occurrences have nothing to do with the rainfall. The antecedent effective cumulative rainfall is more than 10 mm in 4 days and the peak value of landslide appears when rainfall is more than 20 mm. When the rainfall is <20 mm in 4 days, the author suggests that the landslides' occurrences are not influenced by the rainfall.

The smaller the rainfall is, the larger the discreteness is (Fig. 2). In this case, there is not enough evidence to confirm the influence of rainfall on the landslides. Therefore, it is necessary to analyze the 24-h process rainfall and 4-day antecedent effective cumulative rainfall together in order to complete the early warning system.

Through analyzing the rainfalls of 24 typical landslides in Jianshi County, the deformation or development of 21 landslides appears with the changes of rainfall at 4, 6, 8 and 9 days and 24 landslides with the changes of rainfall at 12 days, especially 4 landslides with large rainfall changes (Christian et al. 2010; Inagaki and Sadohara 2006; Chang et al. 2011). In this case, it validates the landslides are influenced by the 4-day antecedent effective cumulative rainfall and 24-h process rainfall.

Discriminant analysis of rainfall

It is reasonable to determine the level of landslide early warning system according to probabilities of landslides induced by the 4-day antecedent effective rainfall and 24-h

Table 2 Antecedent daily rainfall and antecedent cumulative rainfall data of 15 days before the landslide occurrences

No.	Landslide code	Antecedent daily rainfall (mm)								
		15 days	14 days	13 days	12 days	11 days	10 days	9 days	8 days	7 days
1	JY1-9	0	1.2	25.5	0.6	3.1	9.5	0	0	0
2	JY1-9	0.5	16.5	0.5	0	0	0	0	0	0
3	TS1-11	0	0	0	23.9	0.3	0	1.5	0	0
4	GP1-6	0	0	0	0	0	9	0	0	14.6
5	CLX1-2	0	0	0	0	0	5.3	0	0	0
6	HP1-2	0	0	0	0	0	0	0	0.4	9.8
7	MT1-4	28.6	15.2	0.8	12.5	47.6	9.9	0	0	1.1
8	LP1-6	2.6	5.5	0	0	2.6	0	0	0	40.5
9	CLX1-10	0	0	5.2	7.3	7.8	0	8.2	0	0
10	JY1-10	0	0.5	2.6	0	12.7	7.9	0	0	1
11	CLX1-9	14.1	3.5	0	0	0	2.1	15.1	30.2	18.4
12	HP1-1	3	11.1	0	0	0	0	0	1	0
13	JY1-18	9.8	0	0	5.6	0.4	0	0.6	0	0
14	GD1-2	11.2	43.3	0	0	0	0.3	0	0	20
15	GD1-17	8.2	8.3	33.9	2	0	11.2	43.3	0	0
16	GD1-18	8.2	8.3	33.9	2	0	11.2	43.3	0	0
17	YZ1-5	0.9	0	43	0	0	27.2	0.3	0	0
18	YZ1-6	2.6	5.3	0.8	2.7	0	0	0	0	18.4
19	JY1-6	0	0	0	0	6.5	0	0	0	0
20	TS1-10	0	11.2	0.3	19.8	3.2	0	41.8	0.4	72.2
21	SL1-2	61	2	29	0	0	0	0	0	0
22	LP1-9	1.5	43.6	1.3	0	12	5.7	67.1	0.4	0
23	LP1-10	12.2	63	119.6	8.3	0	11.5	44.9	0	0
24	HP1-4	36.9	71	10.8	0	3.6	38	0	0	0
25	JY1-25	0	0	0	0	6.5	0	0	0	0
26	JY1-26	4.5	5.1	0	0	0.2	5.3	4.2	1.6	0
27	JY1-16	0	0	0	29.2	10.1	15.3	0	3.2	7.6
28	JY1-17	0	0	0	0	0	0	0	0	0
29	JY1-27	0	0	29.2	10.1	15.3	0	3.2	7.6	2.1
30	JY1-36	36.9	71	10.8	0	3.6	38	0	0	0
31	SL1-7	0	0	0	19.5	0	0	0	0	3
32	JY1-12	36.9	71	10.8	0	3.6	38	0	0	0
33	JY1-13	0	0	29.2	10.1	15.3	0	3.2	7.6	2.1
34	JY1-24	0	0	0	0	6.5	0	0	0	0
35	SL1-1	0	0	1.5	4	0	0	0	0	0
36	LP1-8	42.6	3.3	14.3	0	0	0	0	0	0
37	YZ1-1	0	0	0	8.5	58	7.5	16	0	0
38	YZ1-4	23.5	3	0	1	2.5	7	0	0.5	0
39	YZ1-11	0	0	3.5	9	6	0	20.5	1.5	0
40	HYS1-2	0	0	31	1.5	0	4	22.5	28.5	10
41	HYS1-4	24	0	2.5	14.5	0	0	13.5	11	13
42	TS1-1	0	11.2	0.3	19.8	3.2	0	41.8	0.4	72.2
43	TS1-2	64.6	2.7	2.3	0	0	0	0.2	8.7	34.1
44	SL1-3	0	0	0	0	0	9.5	10	2.5	0
45	SL1-4	21	0	0	0	7	53	0	0	0
46	GD1-3	0.4	2.4	0	0.6	5.3	11	2.1	1	0.3
47	GD1-4	0.4	2.4	0	0.6	5.3	11	2.1	1	0.3

Table 2 continued

No.	Landslide code	Antecedent daily rainfall (mm)								
		15 days	14 days	13 days	12 days	11 days	10 days	9 days	8 days	7 days
48	GD1-5	0.4	2.4	0	0.6	5.3	11	2.1	1	0.3
49	GD1-7	47.4	0	0	0	0	13.2	0	0	0.4
50	GD1-16	0	0	4.9	0	4	0	0	0	2.3
51	JY1-30	0	0	3.5	8	0.5	16.5	0.5	0	0
52	JY1-32	14	0	0	0	0	10	21.5	0	0
53	JY1-19	26.3	0	2.6	4.7	0	0	0	0	0
54	GD1-8	0.4	2.4	0	0.6	5.3	11	2.1	1	0.3
55	GD1-9	0.4	2.4	0	0.6	5.3	11	2.1	1	0.3
56	HP1-5	29.5	0.5	8	6	0	0	0	0	1
57	JY1-7	0	0	0	0	0	0	3.5	0	0
58	JY1-8	0.5	16.5	0.5	0	0	0		0	0
59	JY1-11	0	0	0	0	0	34.5	2.5	0	0
60	JY1-14	29.5	0.5	8	6	0	0	0	0	1
61	JY1-15	29.5	0.5	8	6	0	0	0	0	1
62	JY1-20	0.3	0	0	3.4	15	2.6	48.7	0	0
63	JY1-21	26.3	0	2.6	4.7	0	0	0	0	0
64	MT1-5	0	0.5	57	0	0	32.8	0	0	0
65	MT1-6	1.8	2.4	46.5	0.1	0	0	0	0	0
66	HP1-8	0	0	0	0	0	34.5	2.5	0	0

No.	Antecedent daily rainfall (mm)							Antecedent cumulative rainfall (mm)		Date/YYMMDD
	6 days	5 days	4 days	3 days	2 days	1 days	0 days	4 days	15 days	
1	0	0	5.5	0	0	5.6	0	3.1438	3.1579	02/11/1
2	0	0	9	19	86.5	46.5	27	47.8125	47.8136	08/7/5
3	0.1	0	0	12.8	0	0	0.3	1.6000	1.6105	03/6/12
4	5.3	0	0	1.8	45.9	1.6	0	12.5000	12.7057	04/5/4
5	35.8	0	0.5	1.6	0	0	0	0.2313	0.7958	04/7/2
6	3.7	33.9	0	57.5	5	0	0	8.4375	9.6328	04/6/1
7	33.6	0	9	2.9	34.1	5.9	0.1	12.4000	12.9715	04/7/5
8	0.5	0	0	0	17.4	41.5	0.2	25.1000	25.4259	05/6/6
9	0	0	4.1	5.9	7.8	8.7	16.9	7.2938	7.3160	05/5/22
10	1.3		0.8	3.8	1.4	3.7	0.4	2.7250	2.7674	05/4/1
11	0	10	0	2.1	48	1	10.2	12.7625	13.3689	06/7/6
12	0	0	0	0	0	16.8	8.1	8.4000	8.4047	06/4/5
13	0	0	0	0	0	10.2	9.8	5.1000	5.1030	06/5/5
14	0	0	22	0	0.3	0	0.4	1.4500	1.6095	07/7/5
15	0	0.3	0	0	20	0	22	5.0000	5.1103	07/7/1
16	0	0.3	0	0	20	0	22	5.0000	5.1103	07/7/1
17	0	0	0	0.8	0	27.6	1	13.9000	13.9324	07/5/22
18	0	0	0	0	3.1		0.9	0.7750	0.9199	07/5/10
19	5.4	20.5	2	0	0	0	5.3	0.1250	0.8532	07/3/1
20	0	0	3.2	0	19.9	16.1	5.7	13.2250	13.8794	07/7/30
21	0	0	3	14.5	134.5	70	9.5	70.6250	70.6305	07/7/5
22	24.7	0.1	3.1	4.7	9.6	0	3.9	3.1813	3.7172	07/8/1
23	0	0.7	0	0	7.1	11.8	26.4	7.6750	7.8166	07/7/1
24	3.1	0	0	12.1	0	0	17.1	1.5125	1.6066	07/7/1
25	5.4	20.5	2	0	0	0	5.3	0.1250	0.8532	07/3/1

Table 2 continued

No.	Antecedent daily rainfall (mm)							Antecedent cumulative rainfall (mm)		Date/Y YMMDD
	6 days	5 days	4 days	3 days	2 days	1 days	0 days	4 days	15 days	
26	0	0	2.2	0	0	34.8	7.3	17.5375	17.5577	07/9/1
27	2.1	12.5	0.8	0	0	0	0	0.0500	0.5723	07/5/2
28	0	0	0	0	0	0.3	0	0.1500	0.1500	07/12/2
29	12.5	0.8	0	0	0	0	0	0.0000	0.2862	07/5/1
30	3.1	0	0	12.1	0	0	17.1	1.5125	1.6066	07/7/1
31	16.5	1	0	52	0	0	28.5	6.5000	6.8173	07/5/14
32	3.1	0	0	12.1	0	0	17.1	1.5125	1.6066	07/7/1
33	12.5	0.8	0	0	0	0	0	0.0000	0.2862	07/5/1
34	5.4	20.5	2	0	0	0	5.3	0.1250	0.8532	07/3/1
35	46	0	0.5	0	0	0	0	0.0313	0.7512	07/4/7
36	0	0	4.4	13.8	132.2	73.9	13.1	72.0000	72.0032	08/7/5
37	0	0	0	0	0	0	11.5	0.0000	0.0690	08/7/1
38	0	2	0	0	0	0	0	0.0000	0.0737	08/6/6
39	25.5	60	33	8.5	4	0.5	21.5	4.3750	6.6999	08/7/27
40	0	0	0	0	7.5	0	0	1.8750	2.1165	08/8/23
41	1.5	6	0	0	1	11	11	5.7500	6.1364	08/11/6
42	0	0	3.2	0	19.9	16.1	5.7	13.2250	13.8794	08/7/30
43	0	0	0	21.1	6.2	0	0	4.1875	4.4907	08/7/16
44	0	0	0	0	0	0	0	0.0000	0.0386	08/4/7
45	16	0	0	0	0	0	0	0.0000	0.3058	08/5/18
46	0	0	0	0	1	9.3	0	4.9000	4.9240	08/4/9
47	0	0	0	0	1	9.3	0	4.9000	4.9240	08/4/9
48	0	0	0	0	1	9.3	0	4.9000	4.9240	08/4/9
49	0.3	0	17	30	19.2	0	0	9.6125	9.6346	08/9/1
50	6.6	5.9	0.3	0	0	0	0	0.0188	0.3268	08/3/1
51	0	0	0	0	0	0	9	0.0000	0.0197	08/7/1
52	0	6	58.5	1.5	0	0	7.5	3.8438	4.0834	08/5/12
53	0	0	0	0	0	13.5	14.3	6.7500	6.7523	08/5/1
54	0	0	0	0	1	9.3	0	4.9000	4.9240	08/4/9
55	0	0	0	0	1	9.3	0	4.9000	4.9240	08/4/9
56	14	0	0	0	0	10	21.5	5.0000	5.2299	08/5/3
57	0.5	3	0	0.5	1.5	51.5	2	26.1875	26.2959	08/10/4
58	0	0	9	19	86.5	46.5	27	47.8125	47.8136	08/7/5
59	0	7.5	0	1	0	0	0	0.1250	0.3979	08/6/1
60	14	0	0	0	0	10	21.5	5.0000	5.2299	08/5/3
61	14	0	0	0	0	10	21.5	5.0000	5.2299	08/5/3
62	0	0	0	0	0	0	3.7	0.0000	0.1058	08/7/1
63	0	0	0	0	0	13.5	14.3	6.7500	6.7523	08/5/1
64	0	0	0	1.8	2.4	46.5	0.1	24.0750	24.1140	08/5/24
65	13.8	41.5	6.5	0	0	0	0	0.4063	1.9247	08/6/5
66	0	7.5	0	1	0	0	0	0.1250	0.3979	09/6/1

process rainfall, not only to just consider the rainfall. Based on the standard of the risk level of landslide early warning system provided by the Ministry of Land and Resources and China Meteorological Administration (Liu et al. 2004), the risk level of Jiashi County is completed and shown in

Table 2. The discriminant analysis of rainfall had been applied successfully in the Three George Area.

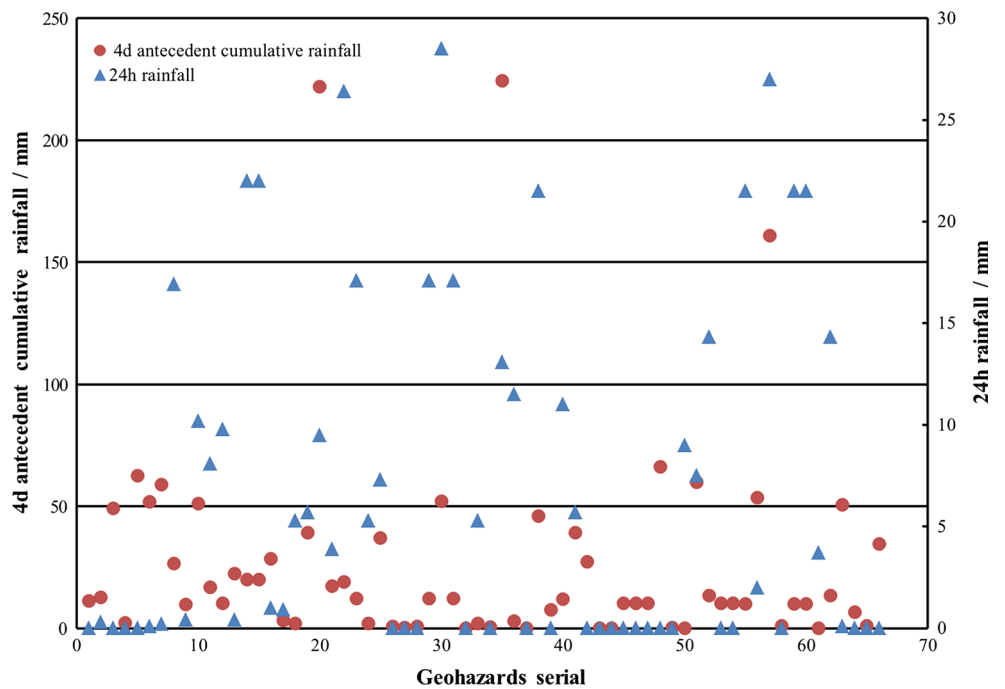
On the basis of the risk standard of rainfall, this study uses 2-D comprehensive discriminant analysis method of 24-h process rainfall in the future and 4-day

Table 3 Correlation of landslides and different rainfall conditions

No.	Characteristic value	Correlation coefficient of the daily rainfall	Correlation coefficient of the cumulative rainfall
1	1-day rainfall	0.9210	0.9160**
2	2-day rainfall	0.9140	0.9870**
3	3-day rainfall	0.2660*	0.9680**
4	4-day rainfall	0.0680	0.9570**
5	5-day rainfall	-0.1170	0.9100**
6	6-day rainfall	-0.1640	0.8690**
7	7-day rainfall	0.0640	0.8500**
8	8-day rainfall	-0.0610	0.8390**
9	9-day rainfall	-0.0720	0.7680**
10	10-day rainfall	-0.1850	0.7580**
11	11-day rainfall	-0.1470	0.7280**
12	12-day rainfall	-0.1300	0.6990**
13	13-day rainfall	0.1000	0.6760**
14	14-day rainfall	-0.0250	0.5970**
15	15-day rainfall	0.2980*	0.6220**
16	30-day rainfall	-0.0041	0.1790**
17	A continuous accumulative rainfall	-0.0024	0.0157**

* Correlation is significant at the 0.05 level; ** Correlation is significant at the 0.01 level

Fig. 2 Scatter diagram of 24-h process rainfall and 4-day antecedent effective cumulative rainfall



antecedent effective cumulative rainfall and establishes the indicators and decision table of landslide early warning system in Jianshi County (Song et al. 2004; Miao et al. 2007; Peng et al. 2010). The result is shown in Table 4.

Probability model

It obtains statistical data and the analysis results of the 24-h process effective rainfall and 4-day antecedent effective cumulative rainfall depending on the rainfall data of 66

landslides from 2002 to 2008. The aim is to complete characteristics analysis of distribution of rainfall. Based on the standard of rainfall level and the result of landslide susceptibility zone, it can calculate the risk probabilities in the different landslide susceptibility zones which are influenced by the different intensities of 24-h process rainfall and 4-d antecedent effective cumulative rainfall together. According to landslide warning system probability model, the landslide susceptibility zones, the 24-h process effective rainfall and 4-day antecedent effective cumulative rainfall are rasterized, respectively, with ArcGIS. Using the spatial analysis function of ArcGIS, the probability and the distribution characteristic of landslides are completed. The risk levels of landslide early warning system are completed.

Probability model of impact factors

According to previous studies (Shi et al. 2007; Peng et al. 2010; Kayastha 2012; Wang et al. 2012; Bijukchhen et al. 2013), the landslide susceptibility zonation is completed depending on the 126 landslides in Jianshi County. Using ArcGIS software, the landslide susceptibility result is reclassified with the method (Kayastha 2012; Bijukchhen et al. 2013). Combining with the landslide data and rainfall data, it completes the statistical analysis of landslides and calculates the landslide occurrence probability in different susceptibility zones (Table 5).

It completes the statistical analysis of the 24-h process rainfall and the 4-day antecedent effective cumulative

rainfall from 2002 to 2008. There are 66 landslides induced by rainfall in 2557 days (from 2002 to 2008). There are 1061 occurrences of rainfall in the total 2557 days. There are 756, 157, 68, 37 and 43 in different classes of rainfall intensities, respectively. The numbers of landslides in different classes of rainfall intensities are 29, 7, 11, 10 and 9 mm, respectively. The probabilities of landslides induced by daily rainfall can be calculated (Table 6).

There are 1951 times of effective precipitation of 4-day rainfall duration in the total 2557 days. The numbers of effective precipitation of 4-day rainfall duration are 1235, 514, 126 and 76 in different classes of rainfall intensities, respectively. The numbers of landslides induced by the rainfall are 20, 0, 19 and 27, respectively. The rainfall probabilities of quantitative analysis are completed (Table 7).

Establishing the probability model

In this study, the authors consider the different characteristics of landslides affected by the 24-h process rainfall and the 4-day antecedent effective cumulative rainfall. The methods of geohazard comprehensive rainfall probabilities which are provided by the Shi Jusong Team and Song Qiguang Team in the Three Gorges Reservoir are referenced (Song et al. 2004; Shi et al. 2007). Based on the above researches and the characteristics of rainfall in Jianshi County, the authors put forward the landslide quantitative comprehensive rainfall probability model in

Table 4 Discriminant analysis of 24-h rainfall and accumulative rainfall for landslide in early warning system

Grade	24-h rainfall in the future (mm)					
	Effective accumulative rainfall(mm)	≤0.3	0.3–5	5–10	10–21	≥21
≤10		I	I	II	III	IV
10–20		II	II	III	IV	IV
20–50		III	III	IV	V	V
≥50		IV	IV	V	V	V

Table 5 Landslide probability values (H) in different susceptibility assessment zones

Susceptibility zones	Low	Medium	High	Very high
Susceptibility index (a)	$a < -1.1829$	$-1.1829 \leq a < -0.169$	$-0.1691 \leq a < 0.8079$	$a \geq 0.8079$
Landslide probability (H)	0.10	0.30	0.60	0.80

Table 6 Probabilities of landslides induced by 24-h rainfall

Rainfall (mm/d)	≤0.3	0.3–5	5–10	10–21	≥21
Rainfall times	756	157	68	37	43
Landslide times	29	7	11	10	9
Probability	0.038360	0.044586	0.161765	0.270270	0.209302

Table 7 Probabilities of landslides induced by the effective precipitation of 4-day rainfall duration

Rainfall (mm/4 days)	≤10	10–20	20–50	≥50
Rainfall times	1235	514	126	76
Landslide times	20	0	19	27
Probability	0.016194	0	0.150794	0.355263

Jianshi County [modified from Song et al. (2004) and Peng et al. (2010)].

$$Y = 0.50 \times Y_{24\text{ h}} + 1.63 \times Y_{4\text{ days}} \tag{2}$$

where Y means the quantitative comprehensive rainfall probability; $Y_{24\text{ h}}$ means the probability of 24-h process rainfall in the future; $Y_{4\text{ days}}$ means the probability of effective precipitation of 4-day rainfall duration.

On the basis of Tables 4, 6 and 7, the authors established the discriminant table, as follows:

According to the quantitative comprehensive rainfall probability model, using spatial analysis function of ArcGIS, the comprehensive rainfall probability is completed depending on the factor of different weights of the 24-h process rainfall and effective precipitation of 4-day rainfall duration. The spatial and calculating distribution characteristics of the quantitative comprehensive rainfall probability are clear (Song et al. 2004; Peng et al. 2010).

The complex geoenvironment and most of landslides are induced by the rainfall in Jianshi County which leads to the large potential area of landslide, especially in the very high, high and medium susceptibility zones. In these areas, the probability of landslides which are induced by the rainfall is very high (Table 8). However, it is not given enough attention because the correlation between the landslides and the rainfall is neither very clear, nor is it quantitatively analyzed in this study area. Therefore, it is very important to analyze and predict the probabilities of landslides in the large potential areas in practice. In this study, on the basis of the quantitative probability of landslide induced by the rainfall, it realizes the landslide probability model which is determinate by the threshold.

The aim is to avoid the unnecessary loss. The landslide risk probability can be considered as the prior information value of the Bayes statistical inference model. The comprehensive Bayes probability model will be modified by the information value of rainfall probability model. It can realize the landslide early warning system with Bayes probability model (Strahler 1980). The Bayes probability model is as follows.

$$T = \left(1 + e^{\ln \frac{1-Y}{Y} - \ln \frac{H}{1-H}} \right)^{-1} \tag{3}$$

where T means the probability values of landslide early warning system; H means the probability values of landslide occurring in different susceptibility zones; Y means the comprehensive probability values of the 24-h process rainfall and effective precipitation of 4-day rainfall duration.

The results of Bayes probability model were shown in Table 9 and would be classified as four classes: very high, high, medium and low landslide zones of early warning system.

Results and discussions

Results

According to the Bayes probability model of landslide early warning system, under the aid of spatial analysis technology in ArcGIS, it completes the quantitative calculation of the landslide early warning system. It obtains the distribution map of the probabilities. Using cluster analysis function of SPSS16, and it could complete the classification of the landslide early warning system according to results of the susceptibility zonation, landslide data and rainfall data. The probability of landslide induced by the rainfall is from 0.002168 to 0.909062. The result is classified by the definition method (Bijukchhen et al. 2013). The threshold values of different landslide early warning system levels are in Table 10 and Fig. 3.

Using spatial analysis function, it realizes the landslide early warning system according to landslide monitoring

Table 8 Probability discriminant analysis of 24-h rainfall and accumulative rainfall for landslide in early warning system

Grade	24-h rainfall in the future probability				
	≤0.3 mm	(0.3–5 mm)	(5–10 mm)	(10–21 mm)	(≥21 mm)
Effective accumulative process rainfall probability	0.038360	0.044586	0.161765	0.270270	0.209302
0.016194 (≤10 mm)	0.0455762 (I)	0.048689 (I)	0.107279 (II)	0.161531 (III)	0.131047 (IV)
0.03696 (10–20 mm)	0.019180 (II)	0.022293 (II)	0.080883 (III)	0.135135 (IV)	0.104651 (IV)
0.150794 (20–50 mm)	0.264974 (III)	0.268087 (III)	0.326677 (IV)	0.380929 (V)	0.350445 (V)
0.355263 (≥50 mm)	0.350445 (IV)	0.601372 (IV)	0.659961 (V)	0.714214 (V)	0.683730 (V)

Table 9 Results of Bayes probability model in Jianshi County

Probability	0.1 (Low, $a < -1.1829$)	0.3 (Medium, $-1.1829 \leq a < -0.169$)	0.6 (High, $-0.1691 \leq a < 0.8079$)	0.8 (Very high, $a \geq 0.8079$)
0.0455762 (I)	0.005278	0.020055	0.066841	0.160377
0.019180 (II)	0.002168	0.008311	0.028497	0.072546
0.264974 (III)	0.038513	0.133823	0.350963	0.590497
0.350445 (IV)	0.141972	0.389579	0.503971	0.856253
0.048689 (I)	0.005655	0.021464	0.071298	0.169935
0.022293 (II)	0.002527	0.009677	0.033071	0.083582
0.268087 (III)	0.039107	0.135680	0.354599	0.594342
0.601372 (IV)	0.143559	0.392667	0.503199	0.857842
0.107279 (II)	0.013176	0.048979	0.152726	0.324635
0.080883 (III)	0.009683	0.036344	0.116608	0.260355
0.326677 (IV)	0.051150	0.172138	0.421215	0.659943
0.659961 (V)	0.177394	0.454086	0.487847	0.885889
0.161531 (III)	0.020957	0.076267	0.224190	0.435220
0.135135 (IV)	0.017065	0.062761	0.189873	0.384615
0.380929 (V)	0.063994	0.208679	0.479975	0.711091
0.714214 (V)	0.217331	0.517153	0.472107	0.909062
0.131047 (IV)	0.016481	0.060709	0.184483	0.376264
0.104651 (IV)	0.012820	0.047703	0.149171	0.318584
0.350445 (V)	0.056556	0.187798	0.447292	0.683350
0.683730 (V)	0.193682	0.480926	0.481144	0.896345

Table 10 Results of different landslides in early warning system

Risk zone	Area (km ²)	Probability (T)	Level (percentage of area)
Low	1067.10	0.217331 ~ 0.389579	II (40.00 %)
Medium	800.32	0.389579 ~ 0.590497	III (30.00 %)
High	533.55	0.590497 ~ 0.711091	IV (20.00 %)
Very high	266.75	0.711091 ~ 0.909062	V (10.00 %)

data and the coupling of rainfall and geology background data. The whole county is divided into four classes, namely very high (V), high (IV), medium (III) and low (II) landslide of early warning system zones. In most cases of rainfall, it is very important to prevent landslides in level IV and V zones. The total area of level IV and V is 800.32 km², which is around 30 % of the total area of the whole county.

The spatial distribution of the IV level regions is mainly around V level regions. The landslides are easily induced by the rainfall in the area, because the regions are influenced by human engineering activities. The area is about 533.55 km², which accounts for 20 % of the total area of the whole county.

Based on the analysis of the above data, it put forward the principle of landslide early warning system. Firstly, when the 24-h process rainfall value is bigger than 10 mm or the 4-day effective accumulative rainfall is bigger than 20 mm, it is

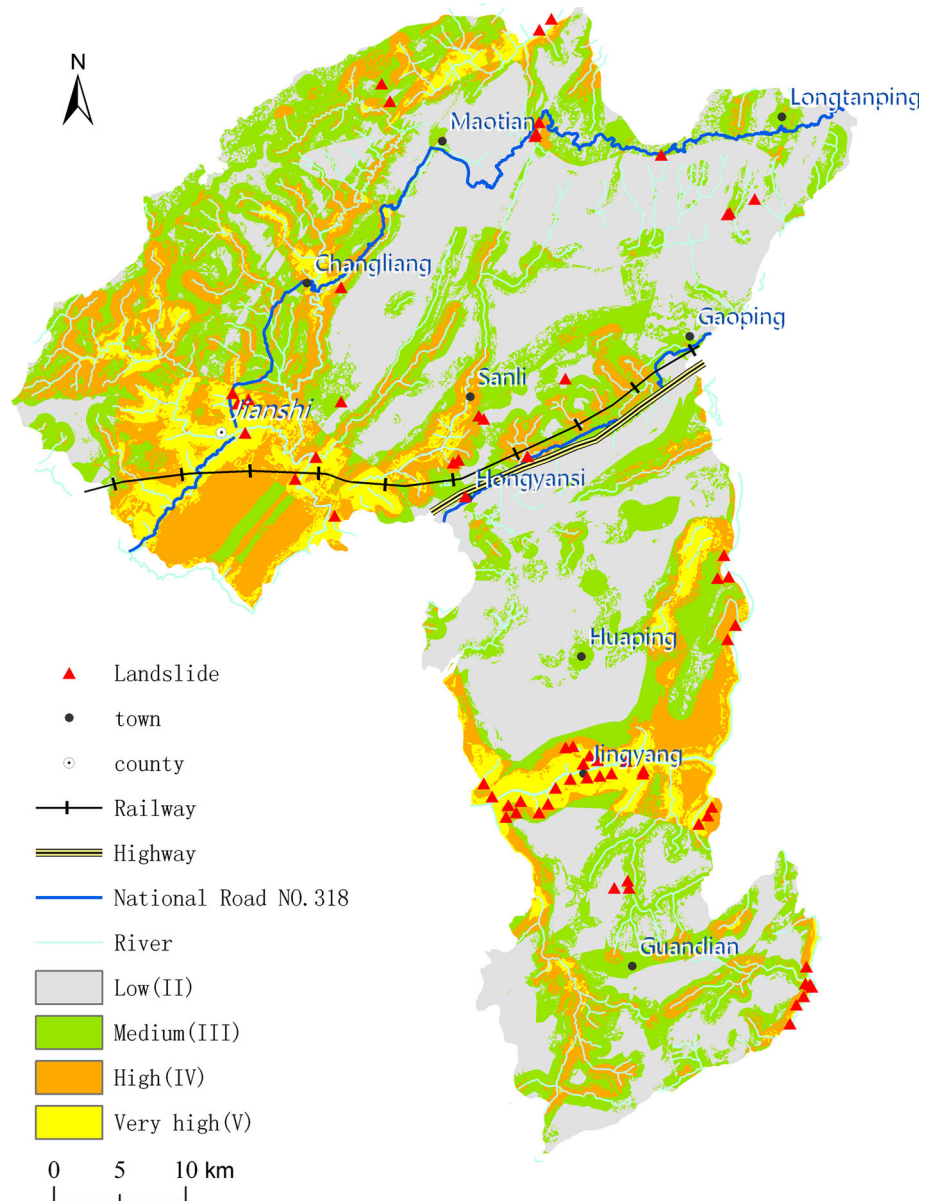
necessary to predict the warning level forecast in level IV zones and warning forecast level forecast in level V zones. Secondly, when the 24-h process rainfall value is bigger than 21 mm or the 4-day antecedent effective cumulative rainfall is bigger than 50 mm, it is necessary to predict the warning level forecast in level II and III zones and warning level forecast in level IV and V zones.

Result validation

According to analysis of the data of the 66 landslides, 13 reactivating landslides are selected according the data from 2002 to 2008. The recurrences of landslides deformation or displacement are induced by the rainfall. The 13 landslides are used to validate the result of the landslide early warning system (Table 11; Fig. 4).

According to the statistical analysis and probability results of landslides induced by rainfall, 13 landslides are

Fig. 3 Landslide susceptibility assessment zones with early warning system in Jianshi County



induced by the rainfall. The warning and forecast result of 8 landslides whose rainfall characteristics are in line with the level V and IV is good and the other 5 landslides not very exact, including 2 in level III, 2 in level II and 1 reoccurrence with 1.10 mm in 24-h process rainfall and 11.40 mm in effective precipitation of 4-day rainfall duration. In all possibility, there is something inaccurate in the records of rainfall. According to the distributions of landslides in the result, 11, 1 and 1 landslides are in the very high region, high region and medium susceptibility assessment region, respectively. There are 11 landslides in the high susceptibility zones and only 2 in the low susceptibility zones. The accuracies of rainfall characteristics and spatial distribution characteristics of landslide early warning system are 61.54 and 84.62 %, respectively. The

data reliability of 13 landslides is good, except rainfall data of 1 landslide having some errors.

On the basis of the results of calculation and analysis, it suggests that the susceptibility result is the determining influence factor to the early warning system and the rainfall is a dominant inducing factor.

Discussions

Bayes probability model

This work gives a method of early warning systems for rainfall-related landslides in the Qing River basin on basis of the geohazard susceptibility assessment. The key point is given to the system the rainfall (inducing factor) and

Table 11 Recurrences of landslides induced by the rainfall from 2002 to 2008

No.	Landslide	First occurring time	Information of landslide recurrences			Susceptibility	Probability (T)	Warning forecast level
			Second occurring time	24-h process rainfall	4-day antecedent cumulative rainfall			
1	YZL-5	2007.5.25	2008.5.9	0.50	40.50	High	0.62317	IV
2	YZL-6	2007.5.10	2008.6.9	0.50	34.00	High	0.62317	IV
3	CLX1-2	2004.7.2	2008.6.10	1.00	35.50	Low	0.15051	II
4	JY1-6	2007.3.1	2008.5.3	21.50	10.00	High	0.34320	III
5	CLX1-10	2005.5.22	2008.6.10	1.00	35.50	Low	0.15051	II
6	TS1-10	2007.7.30	2008.7.1	31.70	0.00	High	0.34320	III
7	TS1-11	2003.6.1	2008.7.4	147.10	205.30	High	0.93883	V
8	HP1-2	2003.6.1	2007.8.1	5.50	24.00	High	0.67470	IV
9	JY1-17	2007.12.2	2008.10.4	2.00	53.50	High	0.91315	V
10	JY1-18	2006.5.1	2007.3.4	0.80	21.00	High	0.62317	IV
11	JY1-27	2007.5.1	2008.3.7	1.10	11.40	High	0.24464	III
12	JY1-9	2002.11.1	2008.7.5	27.00	161.00	High	0.93883	V
13	JY1-12	2007.7.1	2008.6.9	0.00	40.00	High	0.91210	V

susceptibility assessment (geological mechanism) which is more important. The early warning system is on basis of the susceptibility assessment and weather prediction input data and detect extreme events with considerable lead time. It can provide early information which improves the setup of emergency and recovery procedures.

As far as the susceptibility assessment, it has been applied successfully in Jianshi County in 2014. The antecedent rainfall, including the cumulative rainfall, daily rainfall and even the rainfall duration and so on, are being considered during the process of a landslide, to make the mechanism clearer. The Bayes Probability Model including the rainfall and geological mechanism of landslides, it is on the basis of the geology with consideration to the different rainfall durations and influences according to the actual situation in the area. The major disadvantage of the Bayes probability model is the estimation method of probability in different susceptibility assessment zones and rainfall intensity area. The probability values are calculated in different areas, respectively. The probability computation of early warning system is not continuous and the result is not very good. The prior rainfall and landslide data impact the prediction accuracies.

In the next step, it is very important to collect the data from 2009 to 2014, including rainfall data and landslide data to make up the early warning system, to improve the accuracies and come into service.

The inducing factors of landslides

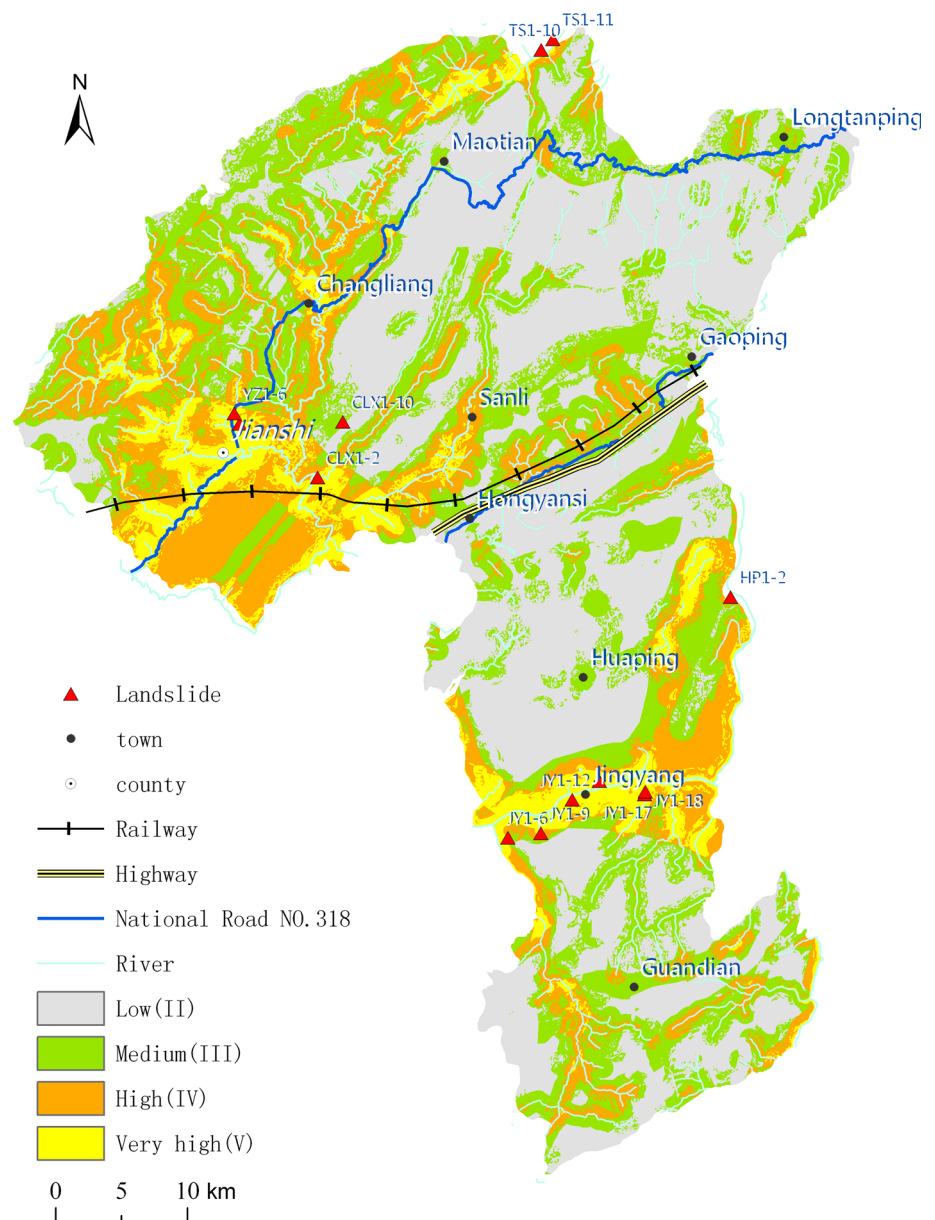
The authors obtain the data of structure types and compositions of 66 landslides induced by rainfall in order to make the relationship between the landslides and rainfall

more clear. There are 60 tractive landslides and 6 push-type landslides according to the landslide types. There are 32 fragment stone landslides, 31 soil landslides and 3 rock landslides according to the components of landslide. There are 29 carbonate rock landslides, 23 clastic rock landslides, 7 loosen soil landslides and 3 unknown nature landslides according to the stratum lithologies. There are 5 landslides with pore water and 61 landslides with fissure water and karst water according to the groundwater types. There are 24 dip slope landslides, 18 oblique slope landslides, 10 transverse slope landslides, 11 reverse slope landslides and 4 unknown type landslides according to the slope structure types. There are 31 hard rock landslides, 26 soft-hard rock landslides and 7 hard siliceous rock landslides.

The next is to analyze the relationship between landslides and the rainfall which includes the 24-h process rainfall and effective precipitation of 4-day rainfall duration.

1. The relationship between the effective precipitation of 4-day rainfall duration and 24-h process rainfall is different. Landslides induced directly by the 24-h process rainfall are low in number, including 9 landslides, for instance LP1-9, LP1-9, YZ1-4, GD1-1, GD1-2, GD1-9, JY1-7, JY1-11, JY1-14 and JY1-36. The other landslides are influenced more greatly by the effective precipitation of 4-day rainfall duration.
2. The different natural components of landslides influence the period of rainfall infiltration. According to the statistic analysis data, it suggests that the periods of soil landslides and fragment stone landslides are different which are influenced by the effective accumulative rainfall. The period of soil landslides is

Fig. 4 Validation of landslide recurrences (13 landslides) induced by the rainfall from 2002 to 2008



concentrated in 5–7 days and the period of fragment stone landslides is about 4 days. The first one is a little longer than the later one.

3. The variation of groundwater recharge types of landslides leads to inconsistent effects which are influenced by the rainfall infiltration process. The landslide early warning system time is influenced by the rate of rainfall infiltration, which is determined by the different groundwater types. In this case, the landslide warning and forecast time is influenced by the groundwater directly. The time of landslides which are induced by the effective rainfall is shortened in the karst water especially. The landslides are directly, to some extent, influenced by the types of underground

water, such as karst water, pore water and fissure water. The karst water shortens the time of rainfall infiltration before landslides. 7 landslides with karst water occurred at 1–2 days after the rainfall, while 9 landslides with pore water occurred at 6–9 days after the rainfall. The time of rainfall infiltration before landslides with fissure water varies from 2–3 days (27 landslides), 4–5 days (8 landslides) to 5–6 days (4 landslides) or remains unclear (11 landslides).

4. The relationship between the rainfall infiltration and landslide types, slope structure types and geotechnical engineering rock group is not clear, but the three impact factors are the most determinant conditions of landslide formation.

Conclusions

On basis of the statistical analysis of the relationship between the 66 landslides and the rainfall, it analyzes the 24-h process rainfall and 4-day effective cumulative rainfall of the 66 landslides to obtain the threshold values. It completes the coupling of the geological background conditions and rainfall information and the application research of landslide early warning system in Jianshi County.

The comprehensive probability model of rainfall is improved on the basis of the predecessors' research results. According to the recurrence of 13 landslides during the period from 2002 to 2008, the model is validated and the method is optimized. The validated result shows the accuracy of comprehensive rainfall model is up to 61.54 % and the accuracy of spatial distribution characteristic of coupling of the geology background conditions and rainfall is as high as 84.62 %. It can therefore be seen that the method of landslide early warning system is significant and effective.

The application of landslide early warning system is on the basis of landslide susceptibility zonations. According to the study, it discovers that early warning result is influenced by the susceptibility result directly. The probability values of different susceptibility zones are in a large region and leads to different results of landslide early warning system. Therefore, it is necessary to improve the susceptibility zonation methods in order to obtain more accurate early warning results. In the further work, the simulation methods of hydrology and engineering geology will be used to analyze the landslide early warning model.

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