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# DEBRIS FLOW AND LANDSLIDE FORECAST BASED ON GIS AND DOPPLER WEATHER RADAR IN LIANGSHAN PREFECTURE

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## ABSTRACT

Debris flow and landslide forecast is an important means of disaster reduction. This paper took Liangshan Yi Autonomous Prefecture, Sichuan Province as the study area. Analyzing distribution rules of debris flow and landslide under different underlying surface's conditions, it used the extension theory to erect to debris flow forecasting model and the information content analysis method to erect the landslide forecasting model. These models obtained 3 hours' forecasting precipitation by processing some Doppler weather radar products. The debris flow and landslide forecasting system in Liangshan Prefecture based on GIS was put into use in Liangshan Meteorological Observatory and could provide the future 3 hours' debris flow and landslide forecast. Experimental results showed that the forecasting results have fine reliabilities.

***Key words**: debris Flow, landslide, forecast, GIS, Doppler Weather Radar*

## INTRODUCTION

Debris flow and landslide are the common disasters in mountain regions. The two disasters have very strong relativities. Almost all debris flows, introduced by strong rain, take place with landslides (Tan *et alii,* 1994; C. *et alii*, 1997). Debris flow and landslide introduced by strong rain often burst in a sudden, so debris flow and landslide forecast has become an important means of disaster reduction. However, it is very difficult to forecast debris flow and landslide accurately because of their complicated formations mechanism. The past forecasting researches mainly studied critical precipitation of debris flow and landslide taking place. Tan Wanpei found out the critical precipitation distribution rules in 35 different debris flow ditches by cluster analysis methods (Tan *et alii*, 1989). According to the relationship between the mean diurnal precipitation intensity and its duration, Wilson established the precipitation isolines and applied it in the debris flow and the landslide forecast in San Francisco America (Wilson, 1997). Corominas studied the relationship between the precipitation and landslides in Liobregat River basin and obtained the critical precipitation of debris flow taking place in this region (Corominas *et alii*, 1999). Bell established the critical precipitation coefficient of debris flow and landslide in Durban region of South African (Bell *et alii*, 2000). Having studied the relationship between the precipitation and debris flows in Piedmont region of northeast Italy, Pietro Aleotti determined the critical precipitation of debris flows in this region (Pietro *et alii*, 2004). All of these methods forecast debris flow and landslide to take place or not to by analyzing and erecting statistical relationship between the precipitation and debris flow and landslide events. Since not sufficiently considering the function of underlying surface, it is very difficult to determine the critical precipitation value of debris flow and landslide in some large regions,.

This paper took Liangshan Yi Autonomous Prefecture, Sichuan Province as the study area. Analyzing the conditions of debris flow and landslide formation, debris flow and landslide forecasting models were erected respectively. The debris flow and landslide forecasting system was developed on the GIS platform in the study area. The system processed some Doppler weather radar products to obtain importing forecasting precipitation.

## GENERAL SITUATION OF STUDY AREA

### *STATUS OF PHYSICAL GEOGRAPHY*

Liangshan Yi Autonomous Prefecture situates at the Southwest of Sichuan province. It is located between longitudes 100°15' E and 103°53' E and latitude 26°03' N and 29°27' N. It covers a total area of 60,100 km$^2$. The study area lies between the first ladder and the second ladder of China's terrain. The highest elevation is 5958m and the lowest is only 305 m. Since the study area situates at the boundary between eastern platform region and western geosyncline region and lies on the junction of the Pacific tectonic domain and Tethyan tectonic domain, geologic structures are complicated, new tectonic movements are intense, and seismic activities is frequent. Many issues of different direction's breaks are developed, which demonstrates the geologic history is complicated and the rock mass has been destructed by the tectonic movements many times. The study area locates at the medium section of Kang-Dian old land and many stratum are exposed. There are many kinds of exposed rocks from the most ancient Presinian such as metasandstone, slate, and phyllite to Tertiary sequence such as Xigeda strata. Yushu- Kangding-Dongchuan earthquake belt influence the study area greatly. The seismic intensity of Anning River Valley in the middle of the study area is VIII~IX degree.

The study area belongs to the subtropics plateau monsoon climate zone. The climate can be classified as dry and wet seasons. The vertical climate difference is obvious. The mean diurnal precipitation is about 1000 mm and the precipitation in rainy season (May to October) accounts for 84-95%, especially, the precipitation in the flood season (June to August) accounting for about 60% of a year. The monthly mean precipitation is more than 200 mm.

In a word, the geology, terrain and precipitation in the study area provide pretty basic conditions for debris flow and landslide growth. And then the study area is one of the most serious debris flow and landslide disaster regions in China.

### *DEBRIS FLOW AND LANDSLIDE DISTRIBUTION IN THE STUDY AREA*

There are 1105 debris flow valleys and 533 great landslide points found in the study area. There are a lot of debris flows (Fig. 1) and landslides (Fig. 2) in most of counties. These two kinds of disasters mainly distribute in the Intermediate Belt of big terrain, the fault zone and the earthquake belt with rivers cutting intensely, great relative height and rich precipitation. These regions provide plenty of matter, energy and rain for debris flow and landslide taking place.

Although, there are a little of debris flows introduced by melting glacier water and landslides in-


*Fig. 1 - Distribution of debris flows in study area*

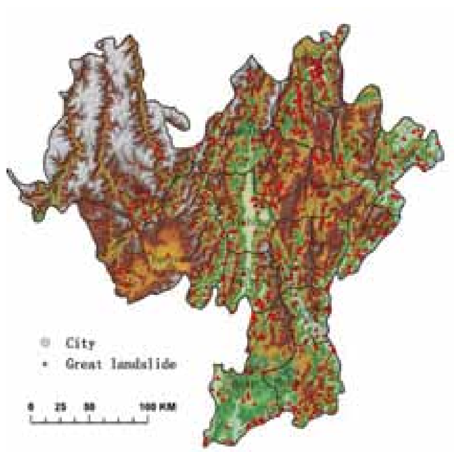


*Fig. 2 - Distribution of great landslides in study area*

troduced by other factors, most of debris flows and landslides are related with high rainfall. Rain is the primary factor introducing debris flows and landslides. Therefore, most of debris flows and landslides in the study area take place in wet seasons (May to October), especially in June to September.

## DEBRIS FLOW AND LANDSLIDE FORECASTING MODELS

### *THE FORECAST UNIT DIVISION*

In order to analyze and operate forecast data conveniently, the study area was divided into many same size units. The appropriate units are beneficial to the accuracy of debris flow and landslide forecasting. The oversized units could not express the real situation of small terrain units or small valleys. Too small units maybe only partly express circumstances of debris flow valleys and landslide points. These two cases could result in wrong positives or wrong negatives to forecast.

The related research (Wei *et alii*, 1999) indicated that the areas of more than 80% debris flow valleys were within 10 $km^2$, and the areas of approximate 85% active landslide points were within 10,000 $m^2$. Therefore, a debris flow forecasting unit was divided into 3km×3km, and a landslide forecasting unit was 100m×100m.

### *THE EXPRESSION OF FORECAST RESULT*

The current debris flow and the landslide forecast is probability forecasting, however, restricted by the complicating formation of debris flow and landslide and the precision of basic data, it is impossible to accurately determine definite probabilities forecasting. So possibilities forecasting are expressed by different probability intervals which often have five levels (Wei *et alii*, 2004). From first level to fifth level, the probability intervals are <0, 0.2>, <0.2, 0.4>, <0.4, 0.6>, <0.6, 0.8>, and <0.8, 1>. Among these levels, from third level to fifth level express bigger probabilities with yellow, orange, and red.

### *THE DEBRIS FLOW FORECASTING MODEL*

The debris flow forecasting model was established on basis of element theory and extension set theory of Extenics (Cai, 1999; Cai *et alii*, 2000). Fuzzy mathematics is used to transform qualitative indexes to quantificational indexes. The evaluating indicators in each unit would be chosen around the three basic factors (material, energy, and rain) of debris flow formation.

The loosing materials reserve is the best factor expressing the physical conditions, but it is impossible to obtain the accurate material reserve in each forecasting unit. The loosing materials reserve is only evaluated by its producing causes which mainly including stratum-rock property *(X1)*, fault density *(X2)* and land use *(X3)*. The energy condition includes relative height and slope which expresses the conversions from potential energy to kinetic energy.

Since forecasting units have the same size, relative height is well correlated with slope in an unit. To decrease calculation, the relative height *(X4)* is chosen to express the energy factor. Precipitation *(X5)* and precipitation intensity *(X6)* are chosen as evaluation indexes of rain condition, the former provides sufficient water source, and the latter provides dynamic condition by forming formidable surface runoffs or big interstitial hydraulic pressures.

In different cases of 6 predictors, there are different probabilities $B_j$ $(j=1, 2, \dots, 6)$ of debris flow taking place. In order to judge Bj under different combinatorial conditions $R(X_1, X_2, \dots, X_6)$ of predictors, the standard matter-element model is set up firstly.

$$R_0 = \begin{bmatrix} B_1 & X_1 & x_1 \\ B_2 & X_2 & x_2 \\ \vdots & \vdots & \vdots \\ B_6 & X_6 & x_6 \end{bmatrix} \quad (1)$$

where $x_1, x_2, \dots, x_6$ are the values of $X_1, X_2, \dots, X_6$.

Then the correlation degree, between any combinatorial state ($R$) of six factors and the probability ($Bj$) of debris flow happening, can be calculated. The correlation degrees of six factors under $R$ and $B_j$ are assumed as $K(x)$.

$$K(x) = \frac{\rho(x, X_0)}{D(x, X_0, X)} \quad (2)$$

where $X_0 = \langle a\ b \rangle$ $X = \langle c\ d \rangle$ $X_0$ $X$ $X_0$ is the classical region, and $X$ is limited the region,

$$\rho(x, X_0) = \left| x - \frac{a+b}{2} \right| - \frac{1}{2}(b-a)$$

$$D\ (x, X_0, X) = \begin{cases} \rho(x, y) - \rho(x, X_0), & x \notin X_0 \\ -1, & x \in X_0 \end{cases}.$$

Assuming the correlation degree under $R$ and $Bj$



 

is K*j*(P), and then

$$K_j(P)=\sum_{i=1}^{6}\alpha_i K_j(x_i) \tag{3}$$

where $\alpha_i$ is the weight of $X_i$ relative to other factors; $K_j(x_i)$ is the correlation degree under $X_i$ and $B_j$.

According to the principle of most subjection degree, the probability of debris flow happening can be worked out by Formula (3). If $K_k(P)$ is equal to

$$K_k(P)=\max_{k=1,2,\Lambda,m} K_j(P)$$

the probability of debris flow taking place is Bk under state R.

## *THE LANDSLIDE FORECAST MODEL*

Landslides introduced by rain are the results of rain acting on underlying surfaces with different conditions. Then complex underlying surfaces may be looked as the integrity. Firstly, analyze the sensitivities of landslides to underlying surfaces with different conditions. Secondly, analyze the probability of landslide taking place while different precipitation acting on different underlying surfaces. At last determine the probability.

## *SENSITIVITY ANALYSIS OF LANDSLIDE IN FORECASTING UNIT*

The sensitivity of landslide was evaluated by the information content analysis method. There are so many environmental factors restricting and influencing landslides happening, and different factors have different effects. Essential conditions of material, energy and free-face must be provided while landslides happening. The material condition refers to the distributing condition of material easily participating in the formation of landslides. There is no effectual method to directly obtain the distributing condition material in large regions , so only those factors influencing broken degree of rocks can be chosen to evaluate material conditions. The primary factors include stratum-rock property, fault density, earthquake activity, land use, and etc.. Land use mainly expresses the surface cover and the influence of human activity. Landslides taking place need some certain slope. Based on good relativity between slope and relative height in same size units, relative height was chosen to express the energy condition. Both river erosions and side slopes excavation could produce free faces. Among the formations of excavation to side slope, road construction is the most widespread. Therefore, the distance from a unit to rivers and roads is chosen to express the free face condition.

In a forecasting unit, there are seven predictors including stratum-rock property($A_1$), fault density($A_2$), land use($A_3$),earthquake activity ($A_4$), relative height ($A_5$), the distance to rivers($A_6$) the distance to roads($A_7$). Assuming each predictor($A_{ij}$=*1,2,...,7*) has its different state *Aij* (j=1,2,3,....r), and under different states of these seven predictors, landslides taking place(B) are possible. The importance of A*ij* to B can be expressed by information quantity.

$$I_{A_{ij}}\rightarrow B=\lg\frac{P(B/A_{ij})}{P(B)} \tag{4}$$

where $I_{A_{ij}}\rightarrow B$

is the information quantity of B under state $A_{ij}$, $P(B/A_{ij})$ is the probability of *B* under state *Aij,* and *P*(*B*) is the general probability of B. When the value of

$$I_{A_{ij}}\rightarrow B$$

is greater, the predictor Ai under the state $_j$ can provide greater information quantity to *B*, and then landslides will take place more easily.

Assuming

$$I=\sum_{i=1}^{n}\lambda_i I_{A_{ij}}\rightarrow B \tag{5}$$

where $\lambda_i$ is the weight of predictor $A_i$. I is the total information quantity. *I* is bigger, and then landslides takes place more easily.

Because it is difficult to determine $P(B/A_{ij})$, the probability of landslides taking place while Ai under state j, and $P(B/A_i)$, the general probability while Ai under the combinatorial state, the formula (4) have to be changed into the formula (6) according to the probability multiplication theorem.

$$I_{A_{ij}}\rightarrow B=\lg\frac{P(A_{ij}/B)}{P(A_{ij})}\qquad (i=1,2,3,\Lambda,7) \tag{6}$$

To simplify computation, while sample volume is enough, the probability can be replaced by frequency. Then the formula (6) is changed into the formula (7).

$$I_{A_{ij}}\rightarrow B=\lg\frac{N_{ij}/N}{S_{ij}/S}\qquad (i=1,2,3,\Lambda,7) \tag{7}$$

where $N_{ij}$ is the number of units where landslides taking place while $A_i$ under state *j*, $S_{ij}$ is the number of units with Ai having state *j*, *N* is the total number of units landslides taking place, and *N* is the total number of units in study area.

### *THE PROBABILITY OF LANDSLIDES TAKING PLACE WHILE RAIN ACTING ON*

Landslide is the result of rain acting on underlying surface. When the sensitivity of landslide to underlying surface is determined, the probability of landslide with different precipitation could be evaluated. The total information quantity I of seven predictors and precipitation P are the final predictors of landslide forecast.

The probability $B_j$ (*j=1,2*) of landslide is different under different combination states of *I* and *P*. In order to determine Bj under different combination state *R* ( *I,P*) , a standard element model about the probability of landslide can be constructed as formula (8) firstly.

$$R_0 = \begin{bmatrix} B_1 & \mathrm{I} & m_1 \\ B_2 & \mathrm{P} & m_2 \end{bmatrix} \quad (8)$$

where $m_1$ is the value of *I* and $m_2$ is the value of *P*.

The same to computation of the correlation degree in debris flow forecast model, the correlation degree $K_j(R)$ of the probability $B_j$ under state *R* could be computed as formula (9).

$$K_j(\mathrm{R}) = \sum_{i=1}^{2} \alpha_i K_j(m_i) \quad (9)$$

where *αi* is the weight of mi, $K_j(m_i)$ is the correlation degree of mi to *Bj*.

if $K_k(\mathrm{R}) = \max_{k\in\{1,2,\Lambda,j\}} K_j(\mathrm{R})$

and then the probability of landslide under state *R* is determined as $B_k$.

## SYNTHETICAL RESULT OF DEBRIS FLOW AND LANDSLIDE FORECAST

Due to promulgating the disaster forecasting grade to public not pointing out debris flow or landslide, forecasting results of debris flow and landslide must be processed synthetically. The size of a debris flow forecasting unit is bigger than that of a landslide forecasting unit, so the size of final outputting should be 3km ×3km.

A unit of 3km × 3km can be divided into 900 units of 100m × 100m, and then to landslide forecast, the value of every outputting unit adopts the greatest forecast grade among its 900 units of 100m × 100m. The greater grade between the debris flow result and the landslide result is the final synthetic result in a unit.

## PARAMETER DETERMINING IN FORECAST MODELS

### *PARAMETER DETERMINING IN THE DEBRIS FLOW FORECASTING MODEL*

After extracting the information quantity of underlying surface factor in every forecasting unit where debris flow ditches locate, the distribution rule of debris flow ditches in every underlying surface factor can be analyzed. When the number of tests is bigger, the frequency is closer to the probability. There are 7159 units in the study area, so the probability can be replaced by the frequency like formula (10).

$$p_i = \frac{N_i}{S_i} \quad (10)$$

where $p_i$ is frequency of debris flow ditches having the underlying surface factor *i*, $N_i$ is the number of debris flow ditches having the underlying surface factor *i*, and $S_i$ is the number of units having the underlying surface factor *i*.

Fig. 3 is frequencies of debris flow ditches appearing in the units with different relative heights. When the relative height is below some value, the relative height is greater and the frequency of debris flow taking place is greater. The reason is that the topographical condition is more propitious to debris flow taking place with the relative height increasing. But when the relative height is over some value, the tendency is re-

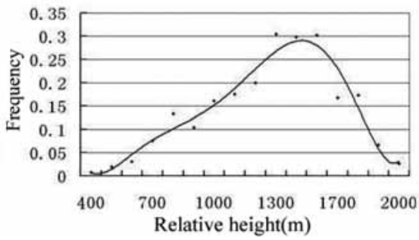


*Fig.3 - frequencies of debris flow ditches in different relative heights*

 

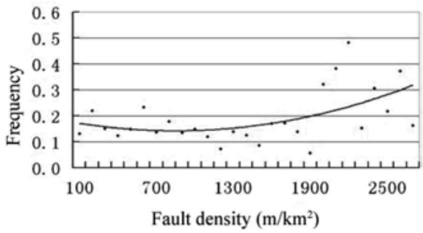


*Fig. 4 - frequencies of debris flow ditches in different fault densities*

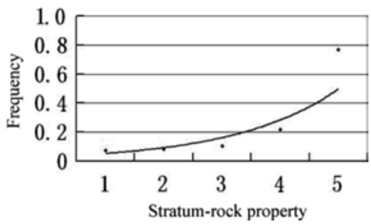


*Fig. 6 - frequencies of debris flow ditches in different stratum-rock properties*

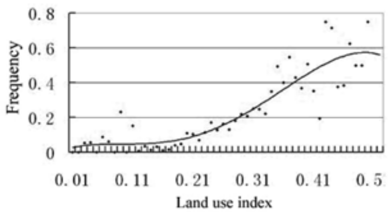


*Fig. 5 - frequencies of debris flow ditches in different land use indexes*

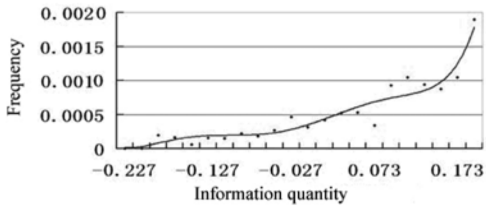


*Fig. 7 - Frequencies of landslides in different total information quantities*

verse. With the slop increasing, it is difficult to reserve loosing solid matter in slope-faces

Fig. 4 is frequencies of debris flow ditches appearing in the units with different fault densities. The fault density is greater, which makes loosing solid matter's forming condition better, and the frequency of debris flow taking place is greater.

Fig. 5 is frequencies of debris flow ditches appearing in the units with different land use indexes (WEI *et alii*, 2008). The land use index is greater, which makes the loosing solid matter's forming condition better, and the frequency of debris flow taking place is greater.

Fig. 6 is frequencies of debris flow ditches appearing in the units with different stratum-rock properties. According to the hardness and weather-resistant ability, the stratum appearing in study area can be divided into five grades. With the hardness and weather-resistant ability decreasing, which makes loosing solid matter forming and accumulating easily, then debris flow may take place easily.

According to the four trending figures, threshold values of the four underlying surface factors can be determined in every grade in the debris flow forecasting model.

### *PARAMETERS DETERMINING IN THE LANDSLIDE FORECAST MODEL*

The information quantity of every underlying surface factor in landslide forecast can be computed by formula (7). The total information quantity of underlying surface factors in every unit can be obtained by formula (5).

Fig. 7 is frequencies of landslides appearing in the units with different total information quantities. With the information quantity increasing, the frequency of landslide taking place is greater. According to this, the threshold value of the total underlying surface factors information quantities can be determined in every grade in the landslide forecast model.

## PRECIPITATION OBTAINING AND ANALYZING

### *FORECASTING PRECIPITATION PRODUCTS PROCESSING*

Doppler weather radar could quickly catch strong convective weather process and obtain high precision inspecting and forecasting precipitation products. The space resolution is 1 km. The radar provides products dBZ (21#) and VIL (57#). From these two products, forecasting precipitation and one-hour rainfall intensity could be obtained. Methods are as follows.

Product 21# and 57# must be processed by geometry transformation with formula (11) firstly.

$$\begin{cases} X = Ax + By + C \\ Y = Dx + Ey + F \end{cases} \tag{11}$$

where X and Y are ground coordinate, x and y are the coordinates of the image, and A, B, C, D, E and F are transforming parameters (KANG-TSUNG, 2004).

Choose no less than three points (control points) whose ground coordinates known in the Doppler weather radar images. Put image coordinates and ground coordinates of control points into formula (5), transform equations into standard form, and then calculate least-square solutions of six transforming parameters (A, B, C, D, E and F). The six transforming parameters could be used to set up mapping relationship between radar image coordinates and ground coordinates

Among the forecasting precipitation and one-hour rainfall intensity, dBZ (21#) accounts for 2/3, and VIL (57#) accounts for 1/3. Then the two products plus weighted participate in calculation. The forecasting precipitation and one-hour rainfall intensity will be objective.

*ANTECEDENT PRECIPITATION PROCESSING*

Antecedent precipitation is a part of the rainfall factors in debris flow forecast. It is provided by precipitation database. Antecedent precipitation must be considered attenuation and then transformed into effective antecedent rainfall (SENOO *et alii*, 2008) to act in debris flow precipitation. The transforming method adopts the follow formula (12) (1985).

$$R_a = \sum_{t=1}^{20} a_t R_t \qquad (12)$$

where $R_t$ is the observational precipitation of $t$ antecedent day, $a_t = 0.5^{t/T}$ is the attenuation rate of rainfall and $T$ is the half life of rainfall. Values of $T$ are different in different regions.

*THE FORECASTING SYSTEM APPLYING CASES*

The debris flow and landslide forecasting system was put into use in Liangshan Meteorological Observatory in Sichuan province in June, 2006.

*CASE 1*

There was an extremely big debris flow disaster in Yanyuan County in the study area on July 14, 2006. The debris flow took place at about 23. This was the only one debris flow aroused by rainstorm in the region in 2006.

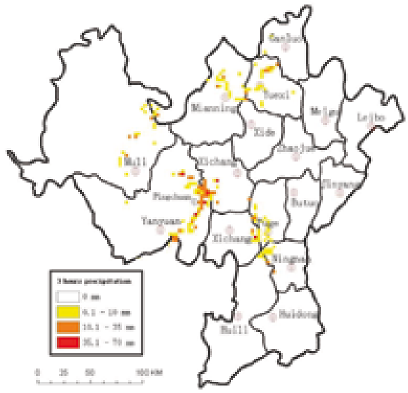

*Fig.8 - 3 hours' forecasting precipitation at 22 July 14, 2006*

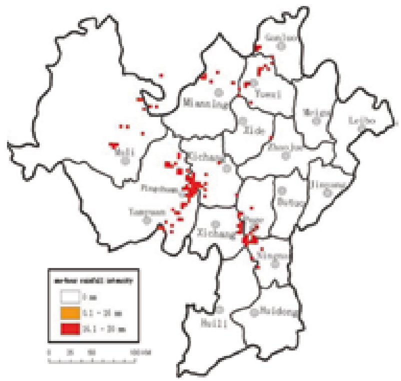

*Fig. 9 - 3 hours' forecasting one-hour rainfall intensity at 22 July 14, 2006*

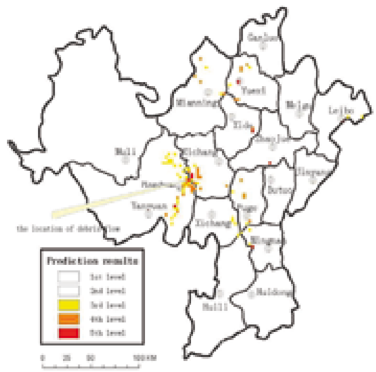

*Fig. 10 - Forecasting map of debris flow in study area at 22 July 14, 2006*

The forecasting system calculated 3 hours' forecasting precipitation (Fig. 8) and one-hour rainfall intensity (Fig. 9) by Doppler weather radar inspecting data at 22, July 14, 2006. And then the system produced 3 hours' disaster forecast (Fig. 10). The


*Fig.11 - 3 hours' forecasting precipitation at 23 Sep. 17, 2008*

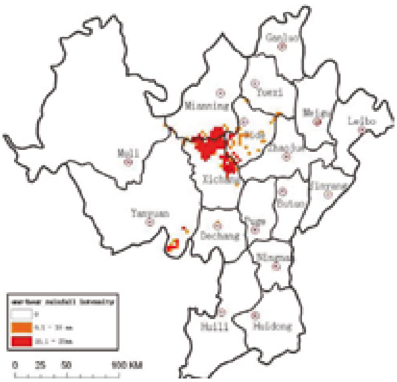


*Fig.12 - 3 hours' forecasting one-hour rainfall intensity at 23 Sep. 17, 2008*

result where debris flow took place was forth grade (itsprobability was in the range from 0.6 to 0.8). This indicated that the forecasting result was reliable.

*CASE 2*

There was a big debris flow disaster in Xichang County in the study area on September 18, 2008. The debris flow took place at 5 past 0.

The forecast system calculated 3 hours' forecasting precipitation (Fig. 11) and one-hour rainfall intensity (Fig. 12) by processing Doppler weather radar inspecting products at 23, September 17,2008.

And then the system produced 3 hours' disaster forecast (Fig. 13). Most of the regions where debris flow took place were forth grade and fifth grade (its probability was in the range from 0.6 to 1).

## CONCLUSIONS

Through studying the methods of debris flow and landslide forecasting and analyzing the results,


*Fig. 13 - Forecast map of disasters in study area at 23 Sep. 17, 2008*

a number of conclusions can be summarized as follows:

- The method of debris flow and landslide forecasting, which was based on fuzzy mathematics, extension theory and information content theory by analyzing debris flow and landslide forming factors and relationship of the two, could resolve the problems of debris flow and landslide forecasting perfectly.
- Owing to complications of debris flow and landslide forming, it was very difficult to forecast exact probability of debris flow and landslide. So it was more preferable and practical to use five probability ranges to express debris flow and landslide forecasting results.
- Doppler weather radar inspecting rain has its characters such as data updating fast, high resolution and continual space. These characters could provide powerful means of inspecting and forecasting precipitation, and they could improve the accuracy of debris flow and landslide forecasting.
- The forecasting system was put into use in study area and obtained favorable effects. However the density of precipitation observation stations was very low, Doppler weather radar in study area was set up not so long and accumulation data was not long enough, so accuracy of debris flow and landslide forecasting needed to be improved.

## ACKNOWLEDGEMENTS

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