A Real-time Prediction Method for Regional Rainfall-induced Geo-hazards in Post-earthquake Region of Wenchuan Earthquake

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ABSTRACT: After years of the Wenchuan earthquake took place in 12 May, 2008, rainfall has been the most major triggering factor of geohazards in the earthquake stricken areas. As a random event, geohazards including landslides and debris flows occurrence are affected by environmental factors and triggering factors, as a result the hazard degree should be a variational value varying from the regional random precipitation triggering factor and regional geohazards susceptibility assessment environmental factors. According to geohazards mechanism, the probability based method of assessing the variational hazard degree of regional geohazards is proposed by the combination of probability of daily precipitation and susceptibility assessment. The prediction model is established by the analysis of geology and hydrology factors of the study area, which is incorporating with the analysis of geohazards occurrence data and the corresponding precipitation data. Then, the method is applied in earthquake region of Chengdu City, 8 km away from the epicenter of Wenchuan earthquake, Sichuan province. The validity of the prediction method is verified by evaluating the hazard degree of regional geohazards in Chengdu city on September, 24, 2008 and July, 17, 2009. It is found that the occurrence location and occurrence time of the two geohazards from prediction coincide with those from measurement. As a result, this variational hazard degree assessment model for regional geohazards demonstrates a useful application of a new predictive method and provides a basis for the prediction of time and space of regional Rainfall-induced geohazards.

1. INTRODUCTION

The prediction of geohazards is very difficult because the factors affecting slope stability are various, and virtually most are closely interconnected. Factors affecting the slope stability can be divided into two sorts: environmental factors and external triggering factors(Au et al.1998, Ding et al. 2004, Qiao et al. 2009, Yang et al. 2010). Environmental factors mainly include geological condition and geomorphology. External triggering factor chiefly provides external dynamic condition for geohazards. Both environmental factors and triggering factors affect the occurrence of geohazards. Environmental factors or intrinsic variables determining hazards include bedrock geology, topography, slope gradient, slope aspect, elevation, and engineering properties of the slope material, land use pattern, and drainage patterns. Triggering factors or extrinsic variables include heavy rainfall, earthquakes, and volcanic activities. Although the probability of landslide occurrence depends on both environmental factors and triggering factors, the former possess a special distribution which can be proposed by the regional geohazards assessment zonation (Qiao et al. 2004, Wang et al. 2010), the latter possess a temporal distribution which is changing over time and more difficult to handle in modeling practice. Therefore, for geohazard prediction, “hazards zonation mapping” is often conducted in which the extrinsic variables are not considered in determining the probability of geohazards occurrence (Dai et al. 2001), or directly overlay the annual contour map of precipitation which regrets the differences and randomicities of rainfall in space and time.

During the past years, with the emergence of Geographic Information System (GIS) capabilities and a rapid increase in computational power and decrease in cost of computational facilities, rainfall threshold value approaches to regional geohazards prediction have been developed, which have resulted in successful geohazards prediction for rainfall induced geohazards in some areas (Wang et al. 2010, Ding et al. 2004, Yang et al. 2010).

Although the methods described above have been useful in practical applications, there remain certain limitations. For example, geohazards is not necessarily occurrence as exceed the threshold value, and threshold value can not show how much degree of the occurrence probability when the threshold value is exceeded largely (Qiao et al. 2009, Yang et al. 2010).

In this research, a geohazards prediction map was prepared by considering the extrinsic variable of rainfall in addition to the intrinsic variables. The probability based prediction method of regional geohazards is proposed by the combination of geohazard zonation and probability of regional precipitation occurrence. The prediction model is established by the analysis of geology and hydrology factors of the study area, which is combined with the analysis of geohazards occurrence data and the corresponding precipitation data.

2. PREDICTION MODEL AND PROGRESS

The prediction model is an overlay process of calculation the internal and external event-controlling factors together.

$$\boldsymbol{P_{AL}=P_{A(L\backslash R)} * P_R} \tag{1}$$

$$\boldsymbol{P_{A(L\backslash R)} = P_{(L\backslash R)} * P_{DL}} \tag{2}$$

$$\boldsymbol{P_{(L\backslash R)}} = \frac{1}{1+e^{-P}} \tag{3}$$

Where P_{AL} is the probability of the regional geohazards, $P_{A(L\backslash R)}$ is the rainfall induced conditional probability of geohazards, P_R is rainfall probability, P_{DL} is geohazards spatial probability in different degree of hazards, $P_{(L\backslash R)}$ is the rainfall time probability of triggering geohazards.

The analysis is carried out by the following steps (Figure 1): On the one hand, geohazards spatial probability ($\boldsymbol{P_{DL}}$) map of different degree of hazards should be proposed on basis of regional geohazards hazard assessment and zonation, which represents the environmental factors of geohazards; on the other hand, firstly obtain the rainfall distribution map which based on the real time forecast precipitation data offered by the Meteorological Department, then the rainfall induced probability of geohazards $\boldsymbol{P_{(L\backslash R)}}$ which represents the external triggering factors of geohazards, is determined based on the rainfall distribution map, afterwards rainfall conditional probability $\boldsymbol{P_{A(L\backslash R)}}$ is defined by combining the rainfall time probability of triggering geohazards $\boldsymbol{P_{(L\backslash R)}}$ and geohazards spatial probability ($\boldsymbol{P_{DL}}$) of different degree of hazards, finally, the probability of the regional geohazards occurrence P_{AL} is determined by rainfall probability $\boldsymbol{P_R}$ and rainfall conditional probability $\boldsymbol{P_{A(L\backslash R)}}$ according to the conditional probability law. This method can reflect the combination of comparative constant environmental factors and random variable precipitation in the study area.

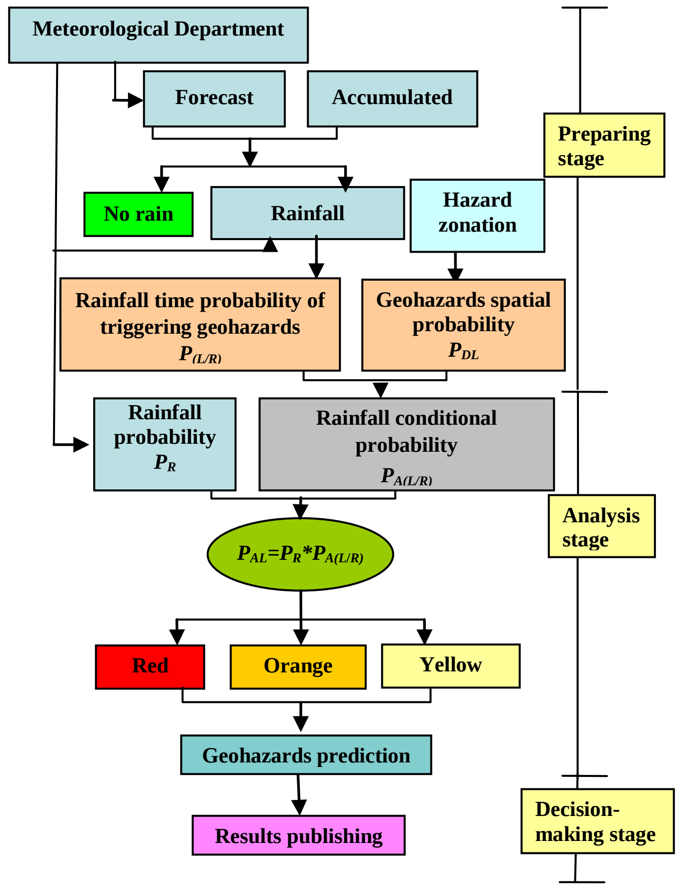

Figure 1. Flow chart of regional rainfall-induced geohazards prediction method

3. CASE STUDY

3.1 Regional setting

This study area focused on the city of Chengdu located in the central part of Sichuan province. The area was hit by the 8 ms Wenchuan earthquake and great damage was made on this region. The study area covers about 12390 km^2 with a north latitude range of 30°05' to 31°26', and an east longitude range of 102°54' to 104°53'. The geomorphology of the area is primarily that of the lowest terrace of the Minjiang River. From the southeast to the northwest, landscapes gradually change from relatively flat Plain, to Hill, to Middle Mountains, and finally to High Mountains. Elevation in the study area ranges from a minimum of 387 m a.s.l. to a maximum of 5364 m a.s.l. with a 5000 m relative height difference. About 63.6% of the study area is mountainous; the Plain accounts for 36.4%. Tectonically the area is located along the transitional belt between the Chengdu plain and the Longmenshan Mountains and Longquanshan Mountains, belonging to the Cathaysian structural system. It also belongs to the Yangtze para-platform and the Qinghai-Tibet quasi-geosynclinal area. There are two major pressure-shear faults with a northeast orientation crossing the area, the Hongkou-Yinxiu and Guanxian faults. The study area is underlain by rock varying in age from the Proterzozoic to the Quaternary, except for the Ordovician. The thickness of the crust is approximately 20000 m. The strata include igneous rocks, metamorphics, carbonates, carbonates intercalated with clastics, sandstones, mudstones interbeded with carbonaceous shales, as well as unconsolidated Quaternary deposits. The region is drained by the Minjiang River. The study area is situated in the subtropical humid monsoon climate zone, with an annual average temperature of 16.7°. The annual average precipitation is about 1234.8 mm, with the highest value being 1605.4 mm in 1978. Rainfall is mostly concentrated in the period between June and September. From a spatial distribution perspective, the study area shows a trend of decreasing precipitation from southeast to northwest, where the average precipitation is about 1800 mm (Figure 2).

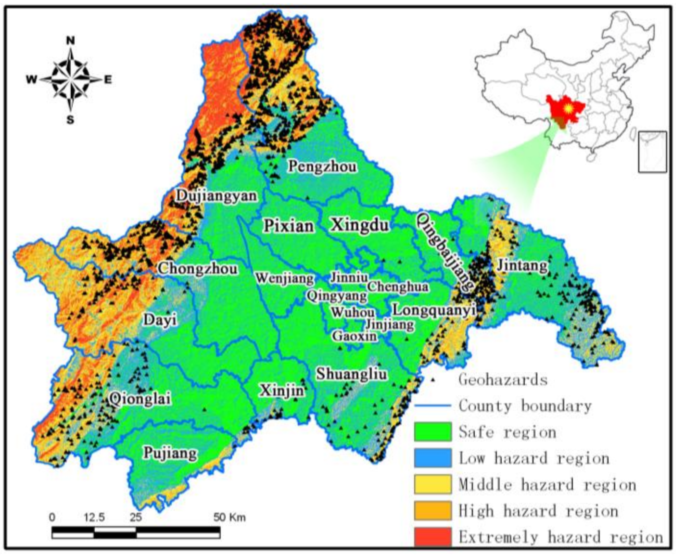

Figure 2 Location and spatial probability map of study area

3.2 Regional hazard zonation

During the past ten years, various approaches to geohazards zonation have been developed, According to Varnes (1984), landslide hazard in a given area can be assessed in terms of probability of occurrence of a potentially damaging landslide event within a specified period. Geohazard zonation is a fundamental tool for disaster management activities in mountainous terrains. The modeling was performed within a geographical information system (GIS), to derive a hazard zonation map, Thematic maps representing various factors (e.g., slope gradient, slope aspect, geomorphology, lithology, surface roughness, and so on) that are related to geohazards activity were generated, using field data and GIS techniques, rainfall-induced geohazard events of the 2 years (2008 and 2009) after Wenchuan earthquake were used to assess the geohazards spatial probability (PDL) on regional scales of different degree of hazards .

This study adopted the contributing weight model developed by QIAO (2004 and 2009) and Wang (2010) to assess the seismically induced landslide hazards of study area. The GIS-based pixel-by-pixel analysis first evaluates and then weights the event-controlling parameters. At last, they are combined to yield a composite value that can be used for decision making for a specific objective. The geohazards spatial probability (P_{DL}) map and parameter maps incorporated into the model that related to the probability of geohazards occurrence were converted into raster data format with a resolution of 25×25m^2 pixels.

3.3 Rainfall-induced probability

The geohazards occurrence mechanism is extremely complicated, which is formed under the interactions of various internal and external dynamic factors. To study the relationship between rainfall and geohazards, geohazards and rainfall data of the following two years after 5.12 earthquakes in 2008 in the study area are collected in this paper. Research shows that daily rainfall and cumulative rainfall in a rainfall period is most closely related with geohazards occurrences, For instance, Figure 3 shows during the two years (2008 and 2009) after the earthquake, geohazards concentrate in June, July and September (amount to 88.8%), the highest(amount to 34.4%) being occurred in July and September; correspondingly, the monthly distribution of precipitation in 2008 and 2009 indicates that July and September are the wettest month in tthe following two years of 5.12 earthquake in 2008 because there are continuous concentrated rainfall process in 24 September 2008 and 17 July 2009, which triggered mass of debris flows and landslides. In contrast, less heavy rain in August lead to low frequency of geohazards, and the precipitation in June triggered considerable number of geohazards just next to the 5.12 earthquake in 2008.

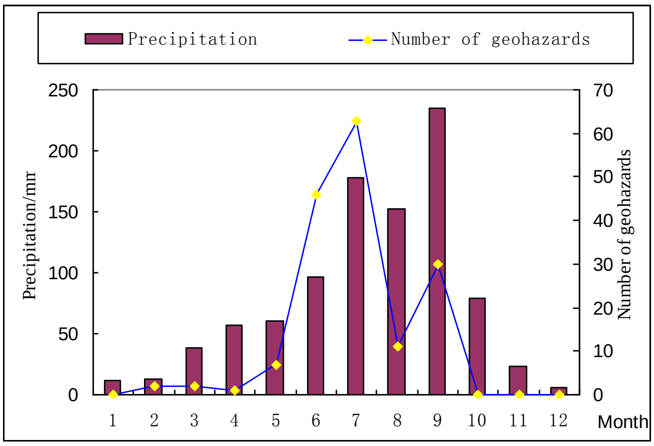

Figure 3 Distribution of geohazards and rainfall after earthquake

The relation between rainfall and geohazards has been well examined in the past, rainfall intensity and duration, cumulative rainfall event, and antecedent rainfall were the most commonly investigated variables. In this section, we analyse the correlation between rainfall and geohazards by statistics of daily precipitation type in each day before 10 days of geohazards occurred (Figure 4).

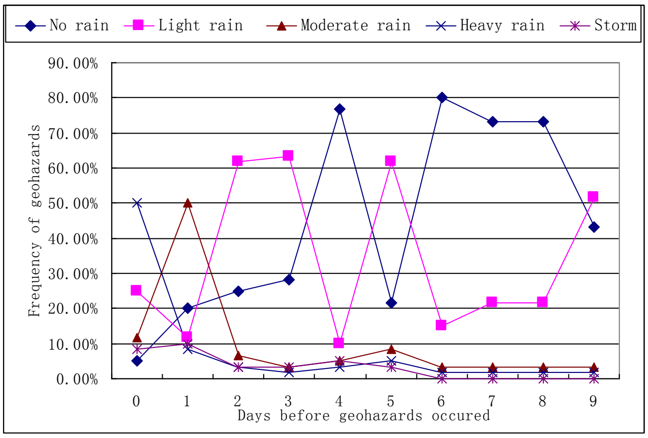

Figure 4 Comparison of everyday rainfall before geohazards

The curve of no rain show a growing trend from the intraday to ten days before the occurrence of geohazards, which proved that precipitation is the trigger factor of geohazard, and the quantity of geohazards has direct ratio with rainfall and its time interval. The curve of light rain(0-10mm) type has the largest proportion of frequency in two, three and five days before the occurrence of geohazards indicates that light rain type has the most contribution to antecedent accumulated rainfall, which has delayed about 2 days on triggering the hazards. Figure 4 also shows that the moderate rain (10-25mm) type has the largest proportion of frequency in one day before the occurrence of geohazards, which indicates that moderate rain type has delayed for about one day on triggering the hazards. The curve of heavy rain (25-50mm) type has the largest proportion of frequency (50%) in the intraday of hazards occurrence and show a reducing trend from the intraday to ten days before the occurrence of geohazards, which indicated that heavy rain is very possible to trigger geohazards in the intraday. Figure 4 shows the storm is also be prone to trigger geohazards in the intraday, but the frequency (less than 10%) is much lower than heavy rain. 83.3% heavy rain happened from the intraday to ten days before the occurrence of geohazards, and the frequency is much higher than storm rain (16.7%), which have a relation with 1/3 geohazards before the 8 ms earthquake.

It would be concluded that the storm is no longer the most immediate trigger factor of geohazards comparing with in other geohazards susceptible region (for example in the Three Gorges area) and in the study area before earthquake. So it is likely that following the ground shaking, the critical amount of precipitation and the daily rainfall intensity necessary to initiate geohazards was reduced compared with values before the earthquake.

By concluding and analyzing data of geohazards occurred in some districts and counties of earthquake hit region, it is discovered that rainfall are the most crucial factor controlling the occurrence of the geohazards , especially after the earthquake. Only in 2010, 1453 geohazards (including 1032 landslides, 180 rockfalls and 185 debris flows) were induced by the rainfall, and cause 73 people killed and 37 missing. Moreover, in Zhouqu County, Gansu province and Qingping County Sichuan province, great damage was caused by rainfall-induced debris flow in August. According to investigations and statistics 90% geohazards after earthquake occurred in rainy season, consequently, it can be said that rainfall, especially heavy rainfall or rainstorm is one of the uppermost factor for inducing geohazards following the megaseism.

According to the binary logistic analysis of the daily precipitation data and geohazards with occurrence time data, the rainfall time probability of triggering geohazards $P_{(L/R)}$ can be determined as follow equations:

$$P(L/R)=\frac{1}{1+e^{-P}} \qquad (4)$$
$$=\frac{1}{1+e^{-(0.071*R_0+0.037*R_1+0.020*R_2-3.038)}}$$

Where Ri is the daily precipitation of i days before prediction. e is mathematic constant, and P is the coefficient defined by the Binary logistic analysis with hazard and precipitation data.

In September 26, the daily precipitation is as much as 72.6 mm, the prediction rainfall distribution map in September 26 of the study area can be interpolating as the 10×10 km raster map, according to rainfall distribution raster map, by using Eq. (4) , the rainfall time probability of triggering geohazards map $P_{(L\backslash R)}$ can be calculated as Figure 5.

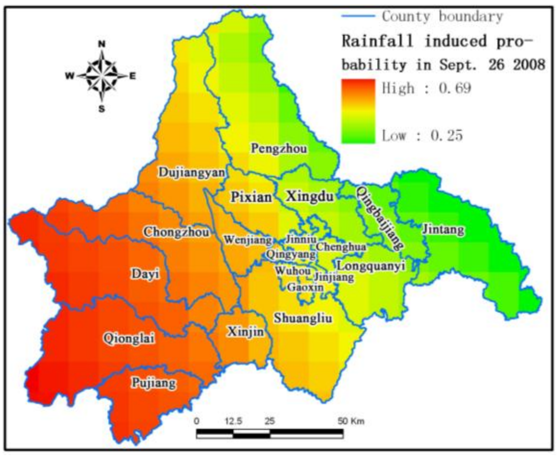

Figure 5 Rainfall tine probability of triggering geohazards map in September 26, 2008 of Chengdu city

By adopting the GIS raster calculation tool, then rainfall conditional probability $P_{A(L\backslash R)}$ of study area can be defined by combining the rainfall time probability of triggering geohazards map $P_{(L\backslash R)}$ and geohazards spatial probability (P_{DL}) map, after that, the probability of the regional geohazards occurrence map P_{AL} can be determined by rainfall probability P_R (supposed as high as 90%) and rainfall conditional probability map $P_{A(L\backslash R)}$, the result is showed in Figure 6.

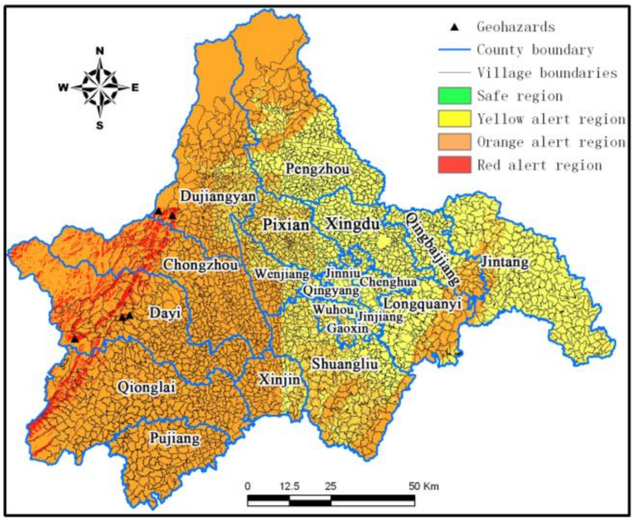

Figure 6 Predictive regional geohazards occurrence map in September 26, 2008 of Chengdu city

Finally, according to the frame work showed in Figure 1, four prediction potential hazard classes were identified on the probability of the regional geohazards map, and color was assigned as follows: safe (green); yellow alert; orange alert; and red alert. It can be concluded from Figure 6 that the red alert areas are mainly distributed in the southwest segment of Longmenshan mountain region, administratively including of Qionglai County, Dayi County, Chongzhou County, and south of Dujiangyan County, where prevention measures should be carry out. The orange alert areas are mainly distributed in the immense mountainous region of north segment of Longmenshan Mountain and Longquanshan Mountain regions, and the rest of the plain of the central part and some relatively gentler rainfall parts of the eastern mountains of areas in Chengdu city is proposed as yellow alert and safe areas.

3.4 Verification

The factual state of geohazards occurrence in September 26, 2008 is adopting to verify the probability of the regional geohazards map reliability, the storm centre in September 24 to 26, 2008 which hit Wenchuan earthquake region was concentrating in the northern part, therefore the damage is milder in Chengdu city comparing with the Beichuan county, all 5 geohazards was taking place in the red alert area in the probability of the regional geohazards map in the study area including 2 debris flows in Longchi town and Qingchengshan town in Dujiangyan county, 1 landslide and 2 rockfalls in dayi county. Field investigation also carried out and the prediction results are still consistent with the field observations.

4. CONCLUSION

In this study, the probability based prediction method of regional geohazards is proposed by the combination of geohazard zonation which represents the geo-environmental factors and probability of regional precipitation occurrence which represents triggering factors. The city of Chengdu and surrounding area was selected as study area, because of its damage in the 8 ms earthquake and high rainfall-induced geohazard activity after Wenchuan earthquake.

The prediction results are consistent with the field observations, and the case history in September 26, 2008 also identifies the probability model to be effective in regional rainfall-induced geohazard prediction.

This model demonstrates a useful application of a new methodology and provides a basis for the predictions of time and space of regional Rainfall-induced geohazard including debris flows, landslides, its results can provide the research reference for the future hazard management and damage prevention of geological and land use authorities.

5. ACKNOWLEDGMENTS

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