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Rainfall threshold analysis and integrated landslide susceptibility mapping: application to landslide management in Wudu county, China

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Abstract The main purpose of this study is the analysis of rainfall thresholds and landslide susceptibility mapping in order to assist the prediction, mitigation and management of slope instability in the Wudu county in China. Firstly, the rainfall thresholds were assessed using the Antecedent soil water status (ASWS) model based on landslides induced by multi-temporal rainfall events in the Wudu county. Secondly, three separate susceptibility maps were produced using historic landslide inventories, and inventories reflecting single landslide triggering events, i.e. earthquake and heavy rain storms. The separate maps were combined to illustrate the maximum landslide probability of all three landslide susceptibility maps. The results show that rainfall thresholds could be applied to forecast rainfall-induced landslides, and the integrated landslide susceptibility map could be used for planning of spatial development as well as emergency response actions.

Keywords landslides, susceptibility, rainfall thresholds, GIS, China

Introduction

China is possibly the country with the world's most serious geological disasters. Each year the direct economic losses of geologic disasters accounts for over 20% of the total losses from all natural disasters. Hereby, landslides are the most important sudden processes of all geological hazards in China's mountains. Nationwide the landslide related direct and indirect economic losses account for more than 20 billion Yuan (approximately 2 billion EUR) every year (Hu & Tang 2005). According to the inventories of the China Institute of Geo-Environment Monitoring, there were a total number of 102,804 geological disasters nationwide in 2006, of which 88,523 (86%) were landslides. In 2007 there were 25,364 entries nationwide, of which 15,478 (61%) were landslide events. In 2008, 14,350 landslides were recorded from a total number of 26,580 geological disasters, which accounts for 54%.

These numbers underline the importance of disaster prevention and relief for the reduction of economic losses. Therefore, landslide risk mapping and scientific predictions are important tools. Furthermore, 90% of landslides and debris flows in China are directly induced by or related to rainfall as the triggering or a preconditioning factor (Li et al. 2004). Landslides induced by rainfall occur frequently and cause great harm to human beings. As in numerous countries in the world, also in China landslides are a serious geological disasters which have to be addressed by various organizations and institutions including also national, regional and local governments (Keefer et al. 1987, Brabb & Harrod 1989, Guzzetti 2000, Keefer & Larsen 2007).

The empirically determined rainfall-induced landslide threshold is a very important methodology in reducing the risk posed by the landslide hazard (Guzzetti 1998. Aleotti 2004, Wieczorek & Glade 2005). Therefore, great efforts have been made on the study of regional rainfall induced landslides forecasting models in recent years. The relationship beween rainfall characteristics and landslide occurrence is very complex and is affected by for example slope conditions and the type of vegetation, but also by precipitation type, total rainfall amounts and the antecedent rainfall conditions.

Most landslide-triggering rainfall models use triggering rainfall, and rarely consider other meteorological factors such as temperature, wind direction and radiation, or topographical factors such as the relative slope position and slope curvatures. There is no generally accepted method for rainfall-induced landslide forecasting, and each threshold model is commonly developed for its specific purpose.

The Wudu county covers 4,683 km^2 and is located in the Qinling Mountains and is surrounded by the Qinghai-Tibet Plateau, the Loess Plateau and the Sichuan Basin as the three major geomorphic units. Due to its geophysical conditions, the area is one of China's most severely landslide affected regions (Scheidegger & Ai 1987). In addition to the soft and erodible lithologic formations, the area is tectonically active and frequently experiences earthquakes. Moreover, the increase of urbanization and the reconstructions following the Wenchuan earthquake increased the landslide frequency, and also amplified the impact of landslides occurrences on society. In the past 10 years, several large landslide disasters occurred. For example, the Gansu mudslide which took place on August 8^{th} 2010 only 30 km away from the Wudu study area, was caused by heavy rainfall and killed more than 1,478 people.

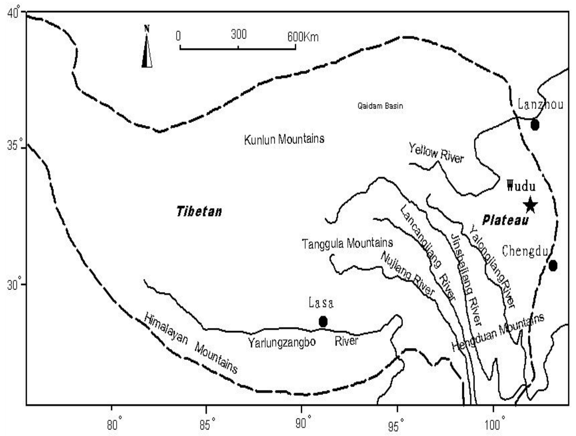

Figure 1 Location of the Wudu study area.

Landslide inventory and landslide triggering factors

In the Wudu region, landslide triggering factors include high magnitude earthquakes, high intensity rainfall events and human activities such as construction works. The combination of geophysical susceptibility and potential triggering conditions cause a frequent occurrence of landslides and debris flows. Landslide inventories were constructed by a combination of field investigation and SPOT 5 and ALOS remote-sensing image data analysed by visual interpretation, image classification and texture analysis.

The historical rainfall-induced landslide database of the Wudu region has its basis in survey documents of the two former government departments, which has been working on geo-hazard survey plan since 1999; one being the Ministry of Land and Resources of the People's Republic of China; another being the Longnan First Station for Landslide and Debris Flow Forecasting and Warning System of the Upper Reaches of the Yangtze River, which was constructed in 1991. Within this period of 1995-2003, a total number of 826 rainfall landslides have been reported. In 2003, seven successive rainfall events induced 290 landslides and 360 debris flows. The inventories of the Ministry of Land and Resources lists 187 historic landslides, and additional 374 landslides which were triggered by the Wenchuan earthquake.

In China, the landslide classification differs from the categorisation by Cruden & Varnes (1996) and primarily differs landslide based on material composition (Liu & Yan 2002). Within the Chinese classification, the landslides in the Wudu region can be divided into the four types, i.e. colluvial landslides, loess landslides, loess - mudstone landslides and bedrock landslides.

A database of landslide predisposing factors was constructed accounting for landslides before and after the Wenchuan earthquake. Data were stored in a resolution of 30×30m and include digital orthophoto maps (DOM), digital elevation model (DEM) and derived topographical parameters (e.g. altitude, slope, aspect, profile curvature, plan curvature), geology (the map scale of lithological properties and fault characteristics is 1:200,000), land use (1:100,000) and further layers including road network and rivers. The triggering factors of the Wenchuan earthquake were collected from the USGS database and include the Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and the Modified Mercalli Intensity (MMI). The triggering factors of the rainfall dataset were extracted from the daily precipitation records from several rain stations in the region.

Calculation of the landslide-inducing rainfall threshold

Antecedent Daily Rainfall Model and the Threshold Approach

The calculation of rainfall threshold is one of the methods being adapted to aid the mitigation of the effects caused by landslides (Glade et al. 2000, Jakob & Weatherly 2003). The probability of landslide occurrences for different rainfall events is useful for landslide risk management and important information for organisations which have to deal with landslides. Institutions such as insurance companies or regional governmental bodies can use these landslide probability figures to define the appropriate level of either preparedness or, combined with risk analysis, estimated possible average costs resulting from landslide damage (Glade et al. 2000).

Landslide triggering rainfall threshold models can be divided into three categories: approaches assessing the triggering rainfall characteristics based on for example rainfall intensity and duration conditions, approaches incorporating antecedent soil water conditions (e.g. the ASWM), and models also reflecting geological factors in addition to rainfall characteristics.

The study on rainfall models aims to analyse and determine the relation between landslide occurrence and triggering rainfall characteristics. Earlier threshold studies mainly focussed on the establishment of an empirical formula between landslide occurrence and the total rainfall (Lume 1975; Brand et al. 1984, Fukuzono 1985, Keefer et al. 1987). Glade (2000) summarised three models for determining landslide thresholds: daily rainfall model, antecedent daily rainfall model, and antecedent soil water content model. These approaches and consequent advancements are basically the major models that scholars currently adopt to determine the rainfall threshold inducing landslides (Glade 2000). Brand et al. (1984) concluded that most landslides were induced by the magnitude of the short period rainfall intensity, and that these landslides were synchronous with the maximum hourly rainfalls. The hourly rainfall was thus put forward as the threshold of disastrous landslides, and was given priority to facilitate landslide forecasting, (Brand et al. 1984).

In the current research of geology-meteorology models, the area of rainfall and related landslide statistics are of relevance (Guzzetti 1998; Aleotti 2004).

For parts of counties of Sichuan province a statistical analysis of cumulative rainfall and landslides showed that within a storm with a total rainfall larger than 200mm, a daily rainfall greater than 110mm is sufficient to trigger numerous landslides (Huang & Lin 2002). Dai & Lee (2003) considered the impact of rainfall on landslide for Hong Kong. They analysed for different periods the relationship between rolling 24h rainfall and landslide occurrences in order to determine the probability of landslide events. Liu et al. (2004) divided China into 7 major areas and 28 warning areas on the basis of geological and climatic conditions. Based on a statistic analysis of the amount and distribution of rainfall 15 days prior to the landslide occurrence, the forecast and warning criteria for each area were determined. Zhang et al. (2005) based the statistical analysis on 153 landslides and related precipitation in the Chongqing region. They determined a significant relation between landslide occurrence, daily rainfall and accumulated antecedent rainfall. Chen et al. (2005) combined information from historical landslides with landslide monitoring data and obtained landslide probability models using a statistic analysis. In each susceptibility class the rainfall in the forthcoming 24hours was the main factor.

Researchers in Hong Kong first classified man-made slopes into the four categories: soil cut slopes; fill slopes, retaining walls and rock cut slopes. For each category, the landslide frequencies at various rainfall totals were determined and applied for a landslide forecast (Pun et al. 2005). Li & Yang (2006) selected data on 28 landslides triggered by a rainfall event in August 2003 in Yucheng District of Ya'An city. The established rainfall threshold considered both the daily precipitation at day of landslide occurrence and the three days accumulated rainfall before. Wang & Sassa (2006) combined static variables and rainfall conditions (e.g. cumulative precipitation, maximum daily precipitation in of six or seven days) and performed a landslide hazard assessment. Ding et al. (2006) suggested a new method for spatio-temporal prediction on the basis of overlapping geological condition and rainfall factor by analysing the forming conditions of rainfall-induced landslides. Jia et al. (2008) used 722 entries of historical landslide data from the period 2002 to 2008 and select the corresponding rainfall data from 161 gauges in Shenzhen. They evaluated the static factors (lithology, slope, elevation, aspect, distance to drainage, distance to fault, vegetation index, and human engineering activity index) by the information value model. Subsequently, they analysed the dynamic factor (rainfall in 24 h prior to landslide occurrence, the rainfall in 24-48 h prior to landslide occurrence and the rainfall in 48-72 h prior to landslide occurrence) by binary logistic regression model Finally, they set up a static and dynamic factors-coupled forecasting model for Shenzhen by generalized additive model. Qiao et al. (2009) calculated rainfall and movement frequency for the Muchuan landslide and were able to establish a landslide warning system based on the probability of future rainfall.

Glade (2000a) used the parameter of daily rainfall for the analysis of landslide triggering and non-triggering conditions. Minimum rainfall threshold below which never landslides were recorded and maximum threshold above which always landslide were observed, were identified. It was confirmed that the antecedent rainfall is of major importance for landslide initiation in many areas. It is argued that the daily rainfall model can not accurately reflect the relation between landslides and rainfall for some regions. Instead the cumulative precipitation, the intensity and the duration of rainfall should be used to determine respective thresholds.

Caine (1980) analyzed the available data and presented equations for landslides as a combination of intensity and cumulative precipitation for different areas. Guidicini & Iwasa (1987) developed the statistic relation between landslide events and rainfall for nine areas of Brazil. Ayalew (1999) analyzed 64 landslides and rainfall characteristics in Ethiopia, and worked out the relation between landslide occurrence probability and rainfall in Ethiopia. Crozier & Eyles (1980), Crozier (1999), and Glade et al. (2000) attempted an approach to link soil moisture conditions to the occurrence of landslides. These authors developed the antecedent soil water status (ASWS) model, a conceptual model that estimates soil moisture on a daily basis. This requires detailed soil characteristics data and meteorological information including rainfall, air temperature and potential evaporation. This model calculates the landslide occurrence probability, named the soil water content index, considering a variety of parameters (Glade 2000b). The ASWS model analyses the soil water balance including a drainage factor to account for the excess precipitation over a period of days prior to the day of the landslide event. A decay function for the loss of water through drainage and evapotranspiration is obtained by analysing hydrograph recession curves (Glade et al. 2000). Crozier (1999) calibrated the ASWS model in the Wellington area, New Zealand, using rainfall and landslide information for a severe landslide event occurred in 1974, and successfully predicted days with landslides and days without landslides for an 8-month period in 1996. Despite its proven capability, the model has not been implemented in a landslide warning system (Wieczorek & Glade, 2005). Glade et al. (2000) applied probability determination to refine landslide-triggering rainfall thresholds using an empirical "Antecedent Daily Rainfall Model". Based on the study of the antecedent soil water content model, the landslide stability distribution model has been developed as a substitution (Borga et al. 1998, Crosta et al. 2004).

Correlation of landslides and daily precipitation

The Antecedent Daily Rainfall model was applied to the landslides induced by the 2003 rainfall events in the Wudu county. All daily precipitation records of the year 2003 were combined with the available landslide information. Due to missing local soil information, the decay constant *k* (representing the outflow of the regolith) was set as 0.84 and the *rn* (maximum regional precipitation on the *n*-th day before landslide occurrence) is 10 days. By applying the ordinary logistic regression model, the relation between landslide occurrence and daily rainfall was determined. Both datasets were used as input for the logistic regression algorithm to calculate the correlation of landslides to daily precipitation (*ro)* and antecedent daily precipitation (*ra*). The probability between landslide occurrence and rainfall magnitude was obtained in the Wudu County by the following equation:

$$\log(\frac{p}{1-p}) = -5.257 + 0.222 r_0 + 0.314 r_a$$

where *p* is the landslide occurrence probability at day 0, *ro* and the antecedent days *ra* with ro is the daily precipitation at day of landslide occurrence and *ra* is the antecedent daily precipitation for a specified period prior to day of landslide occurrence.

Combination of daily and antecedent rainfall

Applying the equation to the Wudu County resulted in figures which illustrate how the combination of decayed 10 day antecedent daily rainfall and the magnitude of daily rainfall at day 0 influence landslide initiation. The resulting regional figures are presented in Fig. 2 and give a generally negative relationship between antecedent conditions and daily rainfall, indicating that with increasingly wet antecedent conditions, less rainfall is required to trigger landslides on a given day. After exceeding a given threshold, the soil is so saturated from antecedent rainfall, that no rainfall is required to trigger landslides. Thus, such an initiation is purely based on internal factors (such as positive pore water pressures) and not on external forces (such as additional precipitation). In contrast, exceeding a daily rainfall of 20mm always leads to landslides; this is independent for the antecedent rainfall conditions.

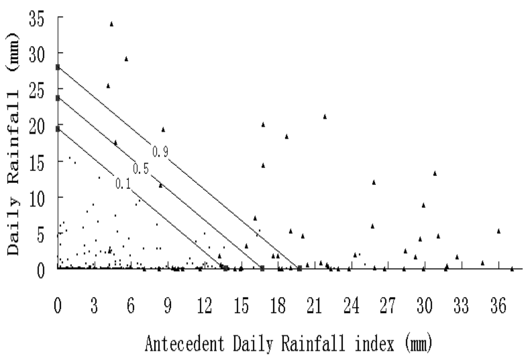

Figure 2 The Antecedent Daily Rainfall Model applied to rainfall-triggered landslides and precipitation in 2003 (Large triangle dots relate to rainfall which triggered landslides, and small square dots relate to rainfalls which did not trigger landslides).

Integrated landslide susceptibility mapping

Logical Regression (OLR) model

Because of the complex nature of rainfall or earthquake triggers, current technology cannot accurately predict the time of slope failures. Therefore, most local and regional authorities and land use planners rely on landslide inventory and susceptibility maps to develop emergency rescue plans and land use assessment (Fell et al. 2008). Both qualitative and quantitative methods have been used in the process of creating landslide susceptibility maps (Aleotti and Chowdhury 1999, Guzzetti et al. 1999). The qualitative method was widely used during the late 1970s by engineering geologists and geomorphologists. The quantitative methods, however, became popular in the last few decades largely because of its numerical expressions of the relationship between controlling factors and landslides, assisted by the advances in computer and geographic information system (GIS) technology (Chung et al. 2002, Van Westen et al. 2003, 2008, Bell and Glade 2004, Glade 2005, Guzzetti et al. 2005, Bai et al. 2008, Bai et al. 2009, Bai et al. 2010a, Bai et al. 2010b, Bai et al. 2011).

The Ordinary Logical Regression (OLR) has been applied for landslide susceptibility mapping extensively (Atkinson & Massari 1998, Bai et al. 2010a, b). The algorithm of logistic regression applied maximum likelihood estimation after transforming the dependent variable into a logic variable representing the natural log of the odds of the dependent occurring or not. In this way, the logistic regression estimates the probability of a certain event occurring (Atkinson & Massari 1998).

The landslide susceptibility analysis using the logical regression model includes four main steps: (1) splitting the dataset and resampling; (2) multi-collinearity diagnosis; (3) implementation of LR models; and (4) validation and evaluation of the model results. In the study, the continuous data like average annual precipitation and the distance were not categorized into binary format, and directly input to the logistic regression for the analysis. The categorized parameters such as lithology, land use and aspect were applied as a dummy variable in the logistic regression model with respect to each class of the respective categorized parameter. The last category is used as the default reference category.

Integrated landslide susceptibility mapping

In this study, for rainfall event based landslide susceptibility mapping, variables such as the average annual precipitation during 1971-2009, aspect, lithological units, elevation, distance to river and land use were selected for statistical significance.

For Wenchuan earthquake landslide susceptibility mapping, variables such as aspect, plan curvature, elevation, land use and peak ground acceleration were selected for statistical significance.

For historic landslide susceptibility mapping, variables such as the average annual precipitation during 1971-2009, aspect, elevation and land use were selected for statistical significance.

In this study, an equal interval method to generate the different classes was applied. The three types spatial susceptibility map was divided into the four classes level 1 (very low), level 2 (low), level 3 (medium) and level 4 (high) respectively. The integrated landslide susceptibility score in this pixel is maximum landslide probability of three landslide susceptibility at that pixel (Fig. 3).

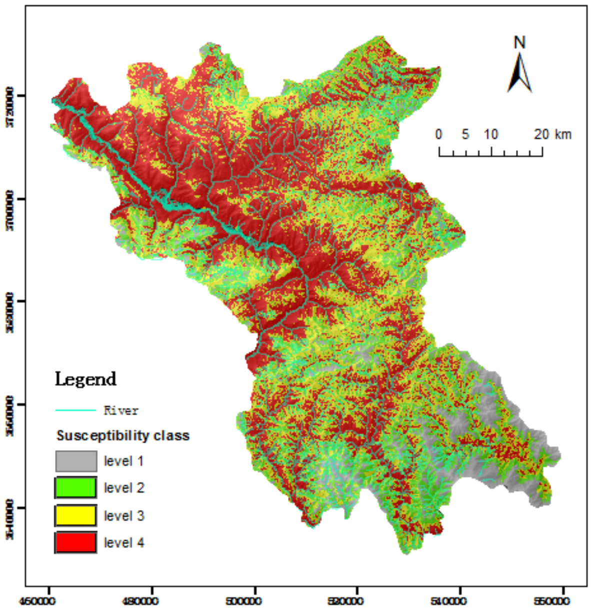

Figure 3 The integrated landslide susceptibility score mapping.

Conclusions

We propose a logistic regression model within a GIS-framework for landslide susceptibility analysis in areas prone to rainfall and earthquake triggered landslides. A quantitative method based on ASWS and logistic regression including effective antecedent rainfall is suggested. The historic, earthquake and rainfall three separate susceptibility maps were produced. The integrated landslide susceptibility score in this pixel is maximum landslide probability of three landslide susceptibility at that pixel.

Results show, that the rainfall thresholds has the potential to be applied to rainfall forecasts and the integrated landslide susceptibility map could be used for land use planning in this region as well as for emergency planning by the responsible local authorities.

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