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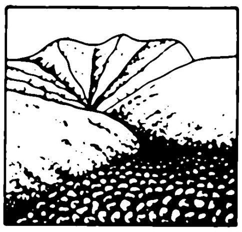

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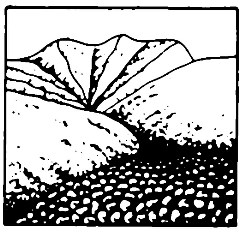

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При создании логотипа конференции использован рисунок из книги С.М. Флейшмана «Селевые потоки» (Москва: Географгиз, 1951, с. 51).
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A study on the integrated regional meteorological forecast and warning model for geological hazards

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Исследование интегрированного регионального метеорологического прогноза и модели предупреждения геологических опасностей

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Информационная модель адаптирована для того, чтобы интегрировать возможности естественных наук для расчета уязвимости от геологических опасностей. Комбинация метеорологических наблюдений за осадками и логистических расчетов использована для моделирования возможности формирования опасных процессов и предупреждения об опасностях, вызванных ливневыми дождями. Модель использует численные прогнозы осадков по точкам сетки в качестве динамического входа и предсказывает вероятности возникновений геологических опасностей по той же самой сетке. Сопоставление модели с наблюдаемыми данными на 2004 год показывает, что 80 % геологических опасностей года были идентифицированы как «достаточно вероятные, чтобы выпустить сообщение о предупреждении».

An information model is adopted to integrate factors of various geosciences to estimate susceptibility to geological hazards. Further combining of the dynamic rainfall observations, logistic regression is used for modelling the probabilities of geological hazard occurrences, upon which hierarchical warnings for rainfall-induced geological hazards are produced. The forecasting and warning model takes numerical precipitation forecasts on grid points as its dynamic input, and forecasts the probabilities of geological hazard occurrences on the same grid. Validation of the model with observational data for the year 2004 shows that 80% of the geological hazards of the year have been identified as “likely enough to release warning messages”.

1 Introduction

Geological hazards such as landslide, debris flow and landslip are affected by various geographical, geological and environmental factors. In addition to them, rainfall is always a dominant triggering factor. According to a general survey covering all counties (cities) in China carried out by the Ministry of Land and Resources, rainfall accounts for not only all the debris flows, but 90% landslides and 81% landslips as well.

In recent years, remote sensing technology had provided abundant observational data which are almost continuous in space; meanwhile GIS had been able to effectively integrate observational data with various physical properties and spatial-temporal scales, to represent the spatial patterns of attributes concerning rainfall-induced geological hazards (Atkinson & Massari, 1998; Dai & Lee, 2002, 2003; Ohlmacher & Davis, 2003). On the other hand, numerical weather forecasting technology had been able to provide precipitation forecasts for future 1–7 d in raster data format, with high spatial resolution of 0.5–5 km. These technological developments have provided objective facilities to construct occurrence probability model for rainfall-induced geological hazards with dynamic forecasting ability. The work reported here adopts Logistic regression to construct Regional Integrated Meteorological Forecasting and Warning Model for Geological Hazards (abbreviated to RIMFWMGH) with dynamic forecasting ability. In the development of such a model, particular efforts had been made to address the following two existing issues:

1) Spatial analysis of hazard-triggering precipitation. Precise retrieve of the historical triggering rainfall at the very site where a hazard had occurred is a crucial point in the model development. Former works simply use nearby rain gauge records to represent, by which triggering precipitations are often underestimated. An effective spatial analysis technique, the thin-plate smoothing splines method, is adopted in this work to retrieve historical hazard-triggering precipitations as precise as possible.

2) Representation and integration of factors of geosciences. Under the conditions of rich remote sensing data and various factors of geosciences, another crucial point in the model development is to analyze the statistical correlations between occurrence probability of geological hazard and factors with various attributes, and then represent these correlations farthest in proper forms. Only through proper representations of the correlations between factors of geosciences and geological hazard, can rainfall and factors of geosciences be effectively integrated in the model, which enables the model to faithfully reflect the statistical correlations between occurrence probability of geological hazard and factors, and to make realistic forecast for occurrence probability of geological hazard. In this work, Information Model is adopted to integrate factors of geosciences that have significant driving effects on geological hazard occurrence, to provide a synthetic representation of hazard susceptibility distribution as the background of the occurrence of rainfall-induced geological hazard.

The above issues addressed, Logistic regression is used to combine the dynamic rainfall condition with the static hazard susceptibility distribution, to model the occurrence probability of rainfall-induced geological hazard. This solution addresses by a great extent the problem of effective combination of dynamic rainfall condition and static hazard susceptibility distribution. The RIMFWMGH is finally constructed.

2 Regional integrated meteorological forecast and warning model for geological hazards

2.1 Model design

RIMFWMGH is the core of the operational system of meteorological forecast and warning for geological hazards at the Central Meteorological Observatory. With the 24-hour numerical precipitation forecasts and historical observations inputted, the system makes hierarchical forecasts for geological hazards on grid points covering the whole country. The numerical forecasts and daily observations are updated everyday, which are the dynamic inputs of the system. Geological, geographical and environmental factors concerning the geological hazards are the relatively static background. Accordingly, the model predictors consist of two parts, representing the dynamic rainfall input and the static background. Logistic regression is applied to integrate the two parts of predictors to model the occurrence probability of rainfall-induced geological hazard.

The development of RIMFWMGH is a two-stage procedure. Stage 1: using Logistic regression to build the hazard occurrence probability model with respect to historical hazards. The historical daily precipitations at hazard sites retrieved through spatial analysis of rain gauge records serve as dynamic rainfall input of the model. Since currently the warning system operates only for rainy season (from May to September), historical hazard and rainfall records during rainy seasons are taken only. Factors of geosciences sampled at hazard sites are integrated by Information Model to serve as the relatively static background of hazard occurrence. Stage 2: sampling factors of geosciences at grid points, then integrating them by Information Model to serve as the relatively static background of the forecasting area. Historical precipitations at grid points are retrieved through spatial analysis, together with numerical precipitation forecasts at same points to constitute the dynamic input of the model. The occurrence probability model for geological hazards with inputs from grid points constitutes the RIMFWMGH, which forecasts the occurrence probabilities of rainfall-induced geological hazards at grid points in the forecasting area, and by translating them releases the hierarchical warning messages.

2.2 Choices of model predictors

1) Rainfall predictors.

Both the short-term heavy rainfall and the continuous rainfall for several days can trigger geological hazards of different types. Short-term heavy rainfall can be represented by 24-hour precipitation of the day. For the continuous rainfall lasted for several days, because of runoff and evaporation, total precipitation infiltrating the rock mass is less than the sum of successively observed daily rainfall amounts, therefore the effect of the previous days' rainfall on the hazard occurrence is evaluated by the previous working precipitation instead, which is formulated as follow:

$$R_w = \sum_{i=1}^{n} k^{i-1} R_i$$

where R_w is the previous working precipitation, R_i is the previous ith day's precipitation, k is the damping coefficient which is set to 0.8 and n is the total number of days which is set to 14. Since the great variation of the climate over China, hazard-triggering precipitation varies in space accordingly. Therefore, either the daily precipitation or the working precipitation is actually expressed in the relative form in the model, which is the ratio of daily or working precipitation to the long-term averaged annual precipitation. In addition, in case that neither the 24-hour precipitation of the day nor the previous working precipitation is heavy, the continuity of the previous rainfall can also contribute to the triggering of hazards. Thus the number of wet days during the previous 14 days is taken as a triggering factor into account in the model.

2) Information model for geological hazard susceptibility assessment.

In this study, the Information Model is applied to integrate the geological and environmental elements to assess the risks on sites where hazards occurred as the static background of the forecast and warning model. Information Model has been widely used in geological hazard risk assessment. It takes the studied area as a whole to evaluate the effect of a factor in a certain state on the hazard occurrence at a spatial unit. The area in this study is the China mainland with spatial unit set to 1 km^2. Let S be the total number of units in the studied area, S_{i,A_i} be the number of units where the state of the ith factor is A_i, N be the number of units where geological hazards occurred, N_{i,A_i} be the number of units with hazards occurred where the state of the ith factor is A_i. For each unit where the state of the ith factor is A_i, the contribution of the factor to the hazard susceptibility at the unit, or the Information of the factor, is

$$I_{i,A_j} = \ln\left(\frac{N_{i,A_i} / N}{S_{i,A_i} / S}\right) \quad (i = 1,2,\cdots,n)$$

The sum of all the contributions of factors to the hazard susceptibility at the unit, or the total Information of the unit, is

$$I = \sum_{i=1}^{n} I_{i,A_i}$$

The larger the total Information I, the higher the hazard risk for the unit.

This study uses elevation, slope gradient, height difference, fault density, seismic intensity, rock mass classification and land use data. Information of each factor and the total Information at each unit are calculated. The total Information at a hazard site is defined by the total Information at the unit where the site locates. Consequently, the total Information of all the hazard sites is obtained and is used as the static part of the model representing the influences of geological and environmental factors on hazard occurrences.

3) Logistic regression.

Logistic regression belongs to the family of Generalized Linear Models (McCullagh & Nelder, 1989). In terms of the geological hazard forecast model, the response is the probability p_i for the ith case of hazard occurrence that is defined on [0, 1], whereas the predictors are the geological and environmental factors that are defined on (-∞, +∞). In order to build the regression, a link function is introduced to map [0, 1] onto (-∞, +∞). Specifically,

$$\ln(\frac{p_i}{1-p_i}) = \beta_0 + \sum_{j=1}^{m} \beta_j x_{i,j} \qquad (i = 1, \ldots n)$$

where $\beta_j (j = 0,....m)$ are model parameters, $x_{i,j} (j = 1,....m)$ are *m* predictors corresponding to the *i*th case of hazard occurrence and $\mu_i (i = 1,....n)$ is the response to predictors valued for the *i*th case. Model parameters can be estimated by the Maximum Likelihood method.

2.3 Integrated meteorological forecast and warning model for geological hazards

In this study, precipitation and hazard records on wet days for rainy seasons during the period from 1990 to 2004 are used as observational data, in which data for the period from 1990 to 2003 are used for model fitting, data for 2004 are used for model validation. Predictors are selected as the same day precipitation, previous 14 days' working precipitation, number of wet days for the previous 14 days and total Information.

The ANOVA results show that all the above predictors are significant at the level 0.001. For the standard errors of the fitted parameters it can be seen that the highest one is taken for the total Information, which is only 1/7 of the fitted value. All the results show that these factors are significantly correlated with the probability of hazard occurrence and thus are proper predictors of the model.

3 Conclusion

The integrated meteorological forecast and warning model for geological hazards developed in this study shows that it is feasible to integrate the meteorological, geological and environmental elements into a single model, which improves the meteorological warning practices. Logistic regression is a powerful tool to implement the idea. Statistical tests and validations by new data show that the model is capable to forecast and warn for geological hazards, and is suitable for meteorological warning system operations.

The retrieving of historical precipitations at sites where geological hazards occurred is one of the difficulties that must be overcome, and is a part that still needs improving in the future. Thin plate smoothing splines are used in this study for spatial analysis of historical precipitations at hazard sites. This method can take factors affecting the spatial pattern of rainfall such as elevation into account and thus greatly improve the interpolation accuracy. This method can satisfy the needs from the forecast and warning system operations, and has great potential of further improvement.

Information Model is a simple and effective method for hazard risk assessment. The current problem affecting the model performance is that the spatial resolutions of remote-sensed data are not in agreement with the spatial scale of hazard events so that the data cannot reflect the actual status of the site. To further improve the interpretation and classification of remote-sensed data is crucial for a better performance of Information Model.

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