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GIS-Based Risk Assessment of Debris Flow Disasters in the Upper Reach of Yangtze River

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Abstract: This paper discussed theory and methodologies of debris-flow risk assessment and established an implementation process according to indicators of debris-flow hazard degree, vulnerability, risk degree, etc. Among these methodologies, historical and potential hazard degree was comprehensively considered into hazard assessment and hazard index was presented to indicate the debris-flow hazard degree. Regarding debris-flow vulnerability assessment, its statistical data and calculating procedure were based on the hazard-degree regionalization instead of administrative divisions, which improved the assessing scientificity and precision. These quantitative methodologies integrated with Geography Information System (GIS) were applied to the risk assessment of debris flows in the upper reach of Yangtze River. Its results were in substantial agreement on investigation data and the actual distribution of debris flows, which showed that these principles and methodologies were reasonable and feasible and can provide basis or reference for debris-flow risk assessment and disaster management.

Key words: debris flow; risk assessment; principles and methodologies; geography information system; upper reach of Yangtze River

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0 Introduction

Debris-flow disasters are natural disasters usually occurring in mountain areas every year, and there are many debris-flow disasters occurred all around the world. China is one of the countries in which debris-flow disasters hit most frequently. In China, there are about 950 counties and towns around 31 provinces, cities and municipalities, where more than 80 thousand of debris flow gullies are scattered, 8 500 gullies of which are serious. The active area is about 4.3×10^6 km^2 in which the strong active area is above 1.3×10^6 km^2[1]. In recent decades, the direct average economic loss caused by debris-flow disasters amounts to several billion yuan(RMB) and the death number nearly thousand[2]. Moreover, the increasing human economicand social activities as well as the over-demand of natural resources by human beings and continuing damages over natural environment make the mountainous disasters such as debris flows more serious and more frequent than ever. In order to scientifically and economically organize the debris-flow control engineering, the primary task is to learn basic knowledge and make debris-flow risk assessment, namely, assess the possibility, hazardousness, vulnerability of debris flow.

Risk assessment was put forward much earlier, but it was not until 1990s that the special study on debris-flow risk assessment and analysis began to develop all over the world, with the action project of "International Mitigation Hazard for a Decade". This subject was also a front and rising research field in the world. Chinese scientists followed this tendency and carried out study on debris-flow disaster risk. While till at the end of 20th century some Chinese scholars[3-8] began to study debris-flow risk assessment. All these studies gradually formed a embryonic form of debris-flow risk assessment and enriched its contents and methodologies.

1 Debris-Flow Risk Assessment Principle

1.1 Basic Concept and Assessment Models

The concept of risk is the theoretic basis of debris-flow risk assessment, but there has been no universal definition of risk[9-14]. This paper adopted the definition of risk by the United Nations Department of Humanism Affairs (UNDHA), namely, "Risk is the expectation loss value of human life and property and economic activity caused by a certain natural hazard in a certain area and in a given time." Its assessment model is:

$$R = H \times V \tag{1}$$

where R is disaster risk; H is hazard which means the probability that a potential hazard occurred in a specific area and in a given time, expressed as a value between 0(no danger) and 1(complete danger or high danger); V is vulnerability which means the loss to element at risk as a result of the occurrence of a specific hazard with a certain intensity, expressed as 0 to 1(0 no loss, 1 complete loss).

This is similar to that of Varnes[11]:

$$R_t = f(E, R_s) = g(E, H, V) \tag{2}$$

where E is element at risk which means the objects threatened by a specific hazard in a specific area, including population, properties, infrastructures, economic activities, etc; R_s is specific risk which means the loss as a result of specific hazard phenomena; R_t is total risk which means the expectation loss value of casualties, property damage and economic activity devastated caused by a certain hazard.

Hazard degree which is the function of the hazard scale and frequency (probability) reflects the natural attribute of disasters. Vulnerability which is the function of the hazard-affected bodies, population, property, economy and environment reflects the social attribute of disasters. Risk degree is the combination of natural and social attribute of disasters and can be expressed as the product of the hazard and vulnerability.

1.2 Index System of Debris-Flow Risk Assessment

In comparison with research findings of interfacing disciplines, we consider the index of debris-flow risk assessment as a tool to measure and describe casualties, economic losses and social impact caused by debris flow. It is a language or measurement to describe or measure the situation of debris flow disasters, which consists of several characteristic groups with interrelationship and a certain logical structure, namely, the index system of debris-flow risk assessment[15]. Index system of debris-flow risk assessment can be divided into different levels and aspects as Table 1. According to the research range, debris-flow risk assessment can be divided into site-specific risk assessment, area risk assessment and regional risk assessment. Site-specific risk assessment on debris-flow disasters refers to the assessment on a gully or gully group or several neighboring debris-flow gullies which have integrated activity process and damage objects. Area risk assessment and regional risk assessment are the assessments on disasters such as debris-flow disasters in a valley, a region or a larger natural, administrative region and its characteristics are as following: the area is large, conditions that cause a disaster are complicated, elements causing disaster are various, the types of disaster-affected objects are different, etc. Moreover, many elements are fuzzy and uncertain on high degree. Therefore, the index adopted is more likely to be the comparative index and the quantifying level of assessment results is comparatively low.

1.3 Technologic Process of Debris-flow Risk Assessment

The basic principle of debris-flow risk assessment goes in this way that according to the probably temporary, spatial and intensity values of disaster-causing elements, the various probable damage and loss values of population and soc-economic system are assessed, and then risk expectation of debris-flow disasters are obtained. According to this principle, debris-flow risk assessment can be summarized as the following six aspects (Fig.1):

ⓐ Study the formation factors of debris-flow disasters, and determine assessment objects and methods.

ⓑ Collect and analyze the information of assessment essentials, and establish an integrated disaster database by GIS and other technologies.

ⓒ Make hazard assessment, and decide the hazard

Table 1 Index system of debris-flow risk assessment

		Elementary Indices	Secondary Indices	General Indices
Hazard	Historical disasters	Density, scale, frequency	Active intensity, probability	Hazard degree and scope
	Formation factors	Topography(gradient, slope), geology (lithology, fault), physiognomy((altitude difference, cutting density),meteorology(temperature, precipitation, rainfall intensity), hydrology(soil humidity, runoff, groundwater level), vegetation(coverage, type), human activities(slope cultivation, engineering excavation and filling, discarded soil ,waste residue),etc.	Topography, geology, physiognomy, meteorology , hydrology, vegetation, human activities, etc.	
Vulnerability	Population	Number, density, mortality, vulnerable ratio of population	Amount of disaster-effected population	Amount, density and loss rate of population, economy and property, resources and environment endangered by debris-flow disasters
	Economy and property	GDP, output value and growth rate of every industry, house, pine-line engineering, infrastructure, indoor property, equipment and special facilities	Value and density of economy and property endangered by disasters	
	Resources and environment	Amount and value of Territorial resources, mineral resources, water resources, biological resources; ecological environment	Value of resources and environment endangered by debris-flow disasters	
Failure loss	Historical damage	Casualties, economy and property ,damage amount and degree of prevention engineering in different hazard areas	Casualties; damage degree, value, amount and intensity of various wealth property and resource property	Loss expectation (casualties or property losses)
	Predictive damage	Scope and hazard degree of assessed areas; qualities ,value and failure-loss rate of disaster-effected elements; types, qualities, investment, efficiency and coverage of various prevention measures		

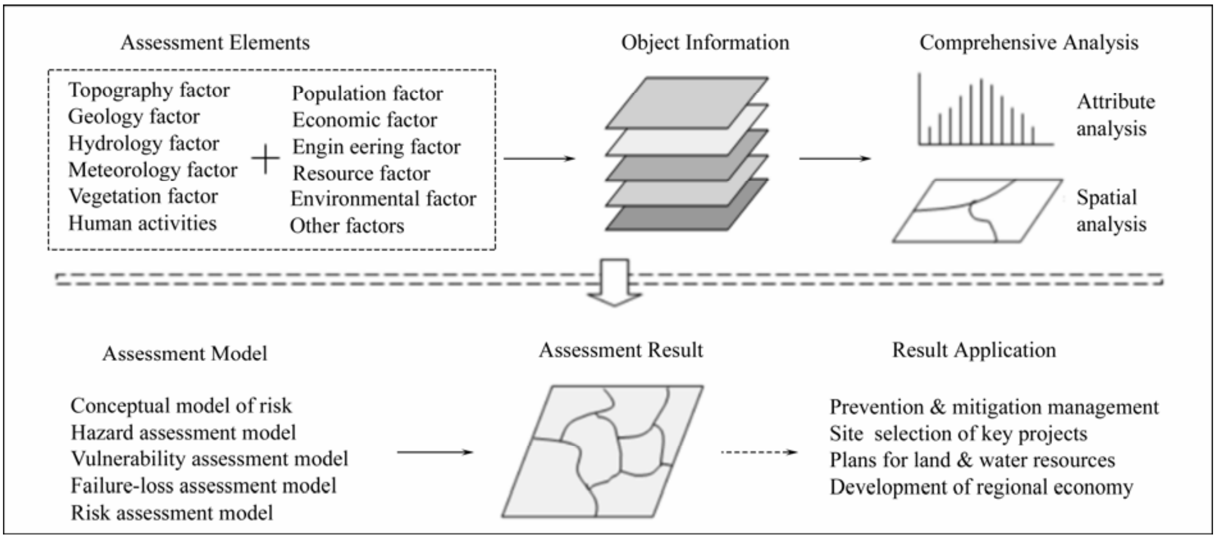

Fig.1 Process of debris-flow risk assessment

activity density, intensity, frequency of occurrence and location and scope of probable area at risk.

ⓓ Make vulnerability assessment, and make sure of the quantities and the loss rate of lives, properties, socioeconomic, infrastructures and land resources probably caused by debris-flow disasters.

ⓔ Establish risk-assessment models to analyze risk level and degree of debris-flow disasters at risk area.

2 Contents and Methodologies of Debris-Flow Risk Assessment

2.1 Hazard Assessment

Debris-flow hazard assessment is the basis of debris-flow risk assessment, which is focused on natural attributes of debris flow disaster and is used to assess hazard degree of debris-flow activities and determine the probable scale and range of debris-flow disaster by comprehensively analyzing activity degree, movement conditions and formation factors of debris-flow disaster. It mainly includes historical hazard assessment and potential hazard assessment. Regarding historical hazard assessment, its basic elements include hazard scale, activity frequency and hazard density and its general expression of assessment mode is as following:

$$H_{\mathrm{h}} = f(M, P, D) \tag{3}$$

where H_{h} is historical hazard index; *M*, *P* and *D* are respectively hazard scale, frequency and density, which are determined by normalizing actual data.

The potential hazard assessment is to evaluate the activity probability of debris flows in the future by analyzing degree of hazard activity conditions. Now comprehensive fuzzy assessment model is often used. Its general expression is as following:

$$H_{\mathrm{t}} = k_i \sum_{i=1}^{n} (w_i x_i) \tag{4}$$

where H_{t} is potential hazard index to debris flow; k_i is discrimination or correction coefficient, x_i is index to debris-flow activity condition, which is determined by normalized data; w_i is activity condition weight of debris flow, which is determined by the method combining correlation analysis and expert judgement. Hazard assessment model of debris flow is as following:

$$H = mH_{\mathrm{h}} + nH_{\mathrm{t}} \tag{5}$$

where *H* is hazard index of debris flow; H_{h} and H_{t} are respectively historical hazard index and potential hazard index; *m* and *n* are respectively historical hazard weight and potential hazard weight, in which $m + n = 1$.

2.2 Vulnerability Assessment

Vulnerability assessment is premise of debris-flow risk assessment, which is focused on socioeconomic attributes of disaster and is used to assess socioeconomic loss by disaster. Its basic elements contain personnel density, cost of work, resource value, environment value and production value density, etc. The vulnerability assessment model for regional debris flows[16] is as follows:

$$\begin{cases} V = [0.5(FV_1 + FV_2)]^{0.5} \\ FV_1 = \begin{bmatrix} 0.25\log V_1, V_1 < 10\,000 \\ 1, V_1 \geqslant 10\,000 \end{bmatrix} \\ FV_2 = \begin{bmatrix} 0.002\log V_2, V_2 < 500 \\ 1, V_2 \geqslant 500 \end{bmatrix} \\ V_1 = P + G + B \cdot A/100 \\ V_2 = (a + b + c) \cdot D/3 \end{cases} \tag{6}$$

where V_1 is property index (in 100 million yuan(RMB); *P* is capital asset investment for the past 15 years (in 100 million yuan(RMB)); *G* is the current year gross domestic product (in 100 million yuan(RMB); *B* is the basic price of land resource yuan(RMB/m^2); *A* is land area (km^2); V_2 is population index; a is the ratio of population who are older than 65 or younger than 15; *b* is the ratio of population with no more than primary education; *c* is the ratio of agricultural population (%); *D* is population density (person/ km^2); FV_1 is the normalized value of V_1 (0 to 1); FV_2 is the normalized value of V_2 (0 to 1) and *V* is regional debris flow vulnerability degree, which is normalized value of vulnerability (0 to 1).

3 A Case Study

3.1 Introduction of Study Area

The above assessment models were used to assess the risk of debris-flow disasters in the upper reach of Yangtze River, involving 373 counties, cities and districts of 8 provinces and 1 municipality, whose total administrative areas was 1 254 343.5 km^2. The area of 980 573.0 km^2 was assessed because the assessed areas on the fringe sections only covered part area of the above provinces and cities. The debris-flow distribution of each province and municipality was as follows: 181 cities and counties in Sichuan province, 42 in Chongqing municipality, 48 in the north of Yunnan province, 53 in the north of Guizhou province, 5 in the eastern of Tibet Autonomous Region, 15 in the southern of Ganshu province, 16 in the western of Hubei province, 6 in the southwestern of Shaanxi, 9 in the southwestern of Qinghai (deadline to December, 2005). Despite extensive investigations and researches into debris flows in the upper reach of Yangtze River since last century, regional research was still uneven and there remained still many areas short of data, due to large areas, complicated natural conditions, wide distribution and large amount of debris flows. Therefore, it was impossible to assess the risk of debris flows from direct data. In viewing of this, we adopted the GIS-based methods to assess the debris-flow risk in the upper reach of Yangtze River.

3.2 Risk Assessment of Debris Flow

3.2.1 Debris-flow hazard assessment

According to hazard assessment model of debris flow(Equations (3),(4) and (5)) combined with GIS technique and debris-flow formation conditions, 8 main factors, such as stratum (X_1), lithology (X_2), geological structure (X_3), slope grade (X_4), aspect (X_5), altitude (X_6), landuse (X_7), climatic and meteorological factors (X_8), etc, were chosen, and hazard grade was calculated in index-weight model (each index times its weight and then plus together), the formula is as follows:

$$H = \sum_{i=1}^{8} (k_i X_i) \tag{7}$$

Among which correlative assessment index can be gotten from remote sensing method, field investigation and calculation of digital topography map. After standardized, the indexes were input into Eq.(7), and the result was showed in Fig.2.

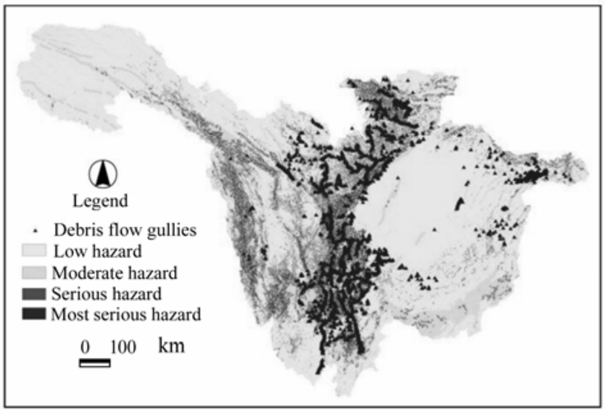

Fig.2 Hazard assessment of debris flows in the upper reach of Yangtze River

3.2.2 Debris-flow vulnerability assessment

The socioeconomic data of study area were not complete, and the detailed data were distributed among many relevant departments which were difficult to collect. Therefore, vulnerability assessment can be made only based on the acquired data at present. 8 indexes were chosen, such as population density, death rate, GDP, output of the primary industry, output of the second industry, output of the third industry, route value and land value, etc. Each of their weight scores was gotten according to multifactor analysis and level analysis. Then the weight scores were calculated in Eq.(6) and the results were shown as Fig.3.

3.2.3 Debris-flow risk assessment

The natural attribute of disaster-causing bodies and the social attribute of disaster-affected bodies are comprehensively considered into the risk assessment of debris flows, and risk degree is expressed as the product of the two attributes. We determined that the weight coefficient of risk index which represented natural attribute of debris flow disasters was equal to 0.70 by means of the multifactor analysis and synthetic analysis, and that the weight coefficient which represented vulnerability index

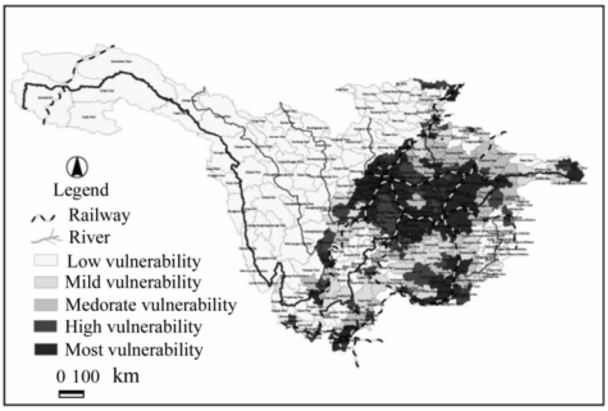

Fig.3 Vulnerability assessment of the upper reach of Yangtze River

of social attribute of debris flow disasters was equal to 0.30. In addition, the product of graded value and weight coefficient of the natural attribute index was regarded as row value, and the product of graded value and weight coefficient of the social attribute index was regarded as column value. Thus these two values together formed a 2D table. Then each corresponding items was added up together respectively, a series of synthetic parameters which assess risk zonation of debris flow were gained, whose values were between 1.0 and 4.3. The criteria of debris-flow risk zonation were: the value from 1.00 to 2.01 was considered as low risk area (namely, safety area), 2.01-2.61 was considered as moderate risk area, 2.61-3.31 was high risk area, and 3.31-4.31 was most high risk area. According to the above, the zoning map of debris-flow risk assessment in the upper reach of Yangtze River was made (Fig.4).

Based on the integrated risk assessment of debris-flow disasters in the upper reach of Yangtze River, the most high risk area was 16 956.4 km^2, accounting for 1.7% of the whole study area; high risk area was 79 898.2 km^2, accounting for 8.2% of the whole study

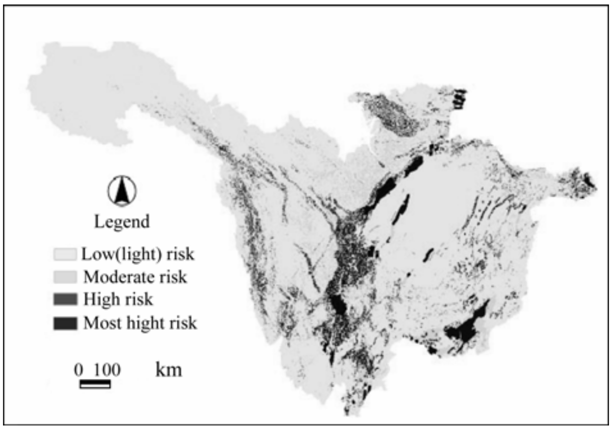

Fig.4 Risk assessment of the upper reach of Yangtze River

area; moderate risk area was 120 435.7 km^2, accounting for 12.3%; low or light risk area was 763 282.8 km^2, accounting for 77.8%. The risk assessment outcomes were in substantial agreement on investigation data and reflected the actual distribution of debris flows, which showed that theory and methodologies of debris-flow risk assessment discussed in this paper were reasonable and feasible. Therefore, these risk assessment principles and methodologies have a certain sense of application and can provide basis or reference for debris-flow risk assessment and disaster management.

4 Conclusion and Discussion

This work gets the following opinions of risk assessment on debris flow disasters:

① Historical hazard degree and potential hazard degree were comprehensively considered into debris-flow hazard assessment and the hazard index was adopted to reflect debris-flow hazard degree, thus improving the scientificity and operation of debris-flow hazard assessment to some extent.

② Debris-flow vulnerability assessment was based on the zonation of debris-flow hazard degree instead of administrative divisions to make data processing and analysis, which improved the precision of vulnerability assessment.

③ The amount and value of objects threatened by debris flow, failure loss and disaster-mitigation validity of debris-flow control engineering were considered into failure-loss assessment, and the ratio of failure loss was presented to indicate the degree of failure loss by debris flow, thus making loss assessment more reasonable.

④ It is a new methodology and trend in hazard sciences to assess risk of debris flow disasters by applying geography information system (GIS) which can quantitatively analyze and integrate all kinds of evaluating indicators in a better way.

⑤ This work discussed theory and methodologies of debris-flow risk assessment and got some quantitative assessment models which were applied and validated in the upper reach of Yangtze River. However, it did not resolve all critical problem of debris-flow risk assessment, due to complicacy of disasters. Certainly the quantitative assessment models need to be developed unceasingly.

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