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A Compare of Fuzzy Logic and Entropy Models: A Case Study of Assessment Analysis of Geohazard Susceptibility in Jianshi County of Qingjiang River Basin

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Abstract

Fuzzy logic model and entropy model are useful for the geohazard susceptibility zonation in Jianshi County of Qingjiang River Basin. In this paper, the same impact factors were chosen and the geohazard samples were considered in two cases with quantitative analysis method. The first case 162 geohazards chosen as samples and the other one all of 182 geohazards chose as samples. The authors completed the susceptibility zonation in the two different cases using the two models in order to analysis the effects of the two models. The results of the two models in different cases were almost the same in space, except small differences in some areas. The entropy model was more accurate for the analysis of relationship between impact factors and geohazards, but not stable for different geohazard samples. The fuzzy logic model was better for less geohazard samples. According to the analysis process, it was found that the fuzzy γ operation was the best which was defined in terms of the fuzzy algebraic product and the fuzzy algebraic sum. The results of fuzzy logic model were most useful when γ was 0.20. The fuzzy logic model and entropy model were useful for the geohazard susceptibility which was scientific and useful for the government to manage the geohazards and make the preliminary development plans.

Keywords: *Fuzzy logic model; entropy model; geohazards susceptibility; quantitative analysis; GIS*

1. Introduction

In the 21st century, most of researches on geohazards susceptibility used different statistics or logic methods with GIS (Geographical Information System) technology [1-6]. The geohazard susceptibility could be calculated by the probability of geohazard occurrence in space over a background of geo-environmental conditions. The analysis aim has been transitted from qualitative analysis to quantitative analysis. Many methods and techniques were used to estimate the geohazard susceptibility in order to get an accuracy result, such as statistical methods based on the physical and classification models [5-9].

In recent years, with the development of GIS technology, the researchers focused on the quantitative analysis on basis of some physical and conceptual model to build mathematical model in order to improve the accuracy [5-10]. There were many

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quantitative analysis methods, including entropy model, evidential belief functions, fuzzy logic model, likelihood ratio, logistic regression and artificial neural network models and so on. Some methods had been applied in different areas on basing of the probability and numerical statistics to make the degree of disorder impact factors into a system [5, 9, 11-12] In this paper, entropy model and fuzzy logic model were selected to complete the geohazard susceptibility zonation and compare the two methods with each other in order to find out the advantages and disadvantages in each method.

Entropy model had been applied in different fields. The applications of entropy have focused on water management, energy utilization, landscape analysis, urban ecosystem and the quality of economic growth [13-15]. The entropy approach was beginning to apply in the geosciences in recent years. Some experts used the entropy approach to analysis geological data in order to obtain more accurate and scientific results [11, 16-22]. It is a good method to analyze the susceptibility of geohazards according to the mass data investigated to get more information and connection with different impact factors.

Fuzzy logic model was introduced by Zadeh [23] and had been used to many fields due to the advantages of analyzing disorder natural process or phenomena with mathematical methods. On basis of the characters, the different classes of impact factors graded can be characterized by a membership function which assigns to each object a grade of membership ranging between zero and one. The spatial objects on a map are considered as members of each impact factor in geohazard susceptibility mapping [24-26]. Generally, the different impact factors could be quantified according to the occurrences of geohazards in each impact factor. On basis of the characters, the fuzzy logic model could be used to complete the geohazard susceptibility zonation according to the probability of occurrences with statistical methods depending on spatial and mathematical characters.

In this paper, according to the field investigation data, quantitative analysis calculation was made by the entropy and fuzzy logic models with GIS technology. On basis of the results of the two models, the advantages and disadvantages would be found out. It can provide a reference to the formation mechanism of geohazard and estimation of geohazard susceptibility in the future [2-4, 18, 23, 27].

2. Study Area and Data

2.1. Study Area

Jianshi County is located in the Qingjiang River Basin, the Center of China. The study area is about 2667 km^2 and extends from latitude 30°01′to 30°56′ North and from longitude 109°30′ to 110°10′ East (Figure 1). The landscape is tectonic erosion corrosion middle-mountain and low-middle-mountain. In this area, the geological features and conditions are extremely complex, which are characterized by steep mountains, criss-cross ravines, about the difference of 1877m and an average slope of 25°.The weather is dry in winter and wet in summer, which is influenced by the subtropical monsoon climate. Human engineering activities are frequent in Jianshi County. There are several large projects, such as Shuibuya Project in Qingjiang River, Yi-wan Railway, Hu-rong High Way and Natural Gas Pipe and so on. These projects lead to a large number of immigrants and reconstruction which are followed by unreasonable engineering site, road cut slope, blasting vibration, the excavation and mining, *et al.* The human activities aggravate the occurrences of geohazard further.

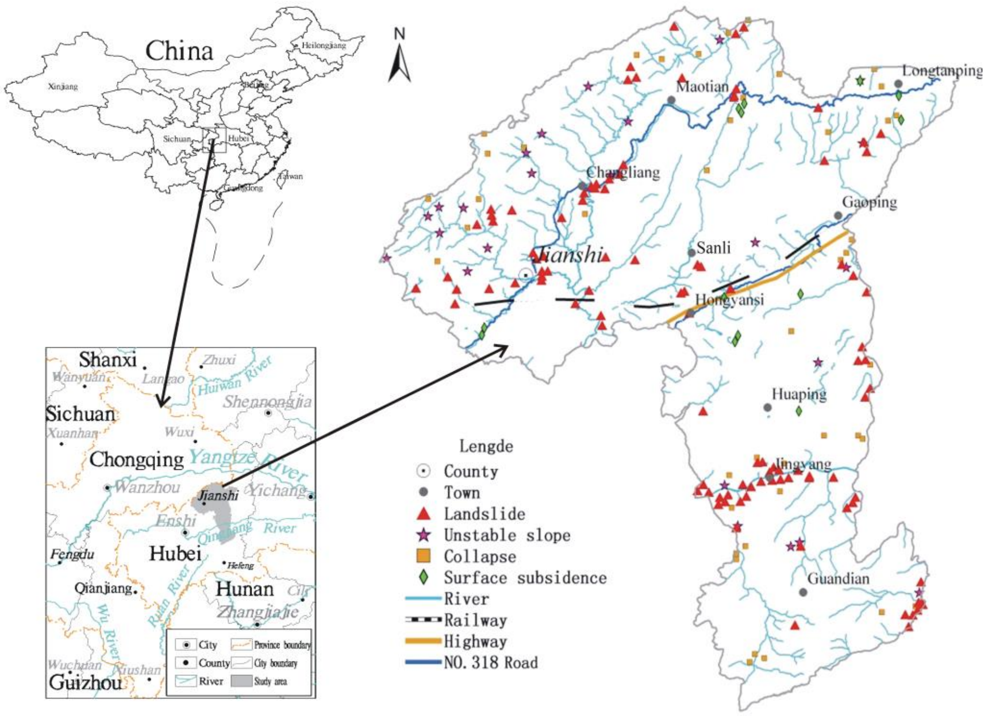


Figure 1. Positions and Types of Geohazards in Jianshi County

Due to the special natural, geographical environment, geological formation and the human engineering activities, geohazards develop in this county, mainly landslides, collapse and unstable slopes. The positions and types of geohazards are given in Figure 1. In the study area, the total number of geohazards is 182, including 102 landslides, 43 collapses (including unstable rocks), 24 unstable slopes and 13 surface subsidences. Collapse and landslide are dominant geohazard.

2.2. Data Selection

According to previous studies [3-6, 12, 18, 23, 28-31], combined with the actual situation in Jianshi County, seven individual factors were selected as the geohazards susceptibility zoning control factors, including slope height, slope type, geotechnical engineering rock group type, the distance from river or valley, geological structural conditions and human engineering activities impacts.

In order to complete the susceptibility zonation, the basic data were mainly collected and from field survey (hydro-geological maps, engineering geological maps, geographic traffic maps and remote sensing data). Most data were collected from the projection “Qingjiang River Basin Geological Disasters Detailed Survey”, and others were from the field survey. Some data of Jianshi County was in Table 1. The scopes of geohazards were extracted from the remote sensing imageries. The total projection area of geohazards was about 1.8480 km^2.

Table 1. Data of Study Area

Data	Scale	Date	Data	Scale	Date
Engineering geological map	1:50000	2010	P6	5.8m	April 13, 2008
Geohazards distribution map	1:50000	2010	ALOS	2.5m	June 17, 2009
Geographic map	1:50000	2000	ASTER	15m	July 5, 2008
Traffic and location map	1:100000	2010	Geology map	1:200000	1978

3. Methodology

3.1. Entropy Model

Entropy model was used to carry out quantitative analysis based on the contribution of influential factors on the formation of geohazards by calculating their contributions to the geohazard failure to determine the damage of such factors on the geohazards' bodies. This would not only reflect the statistical laws of geohazards, but also could be performed simply and easily [3-4, 11-12, 18-21, 23, 32-33]. The calculation principle and the process are shown in the equations below.

In this model, the occurrence of geohazards was considered to be related to both quantity and quality of information that is obtained in the process of forecast, and shall be measured based on the information entropy model, namely:

$$I(Y, x_1, x_2, x_3 \dots x_n) = In \frac{P(Y, x_1, x_2, x_3 \dots x_n)}{P(Y)} \tag{1}$$

where: $I(Y,x_1,x_2,x_3,\dots,x_n)$ mean the information entropy provided by factors combination $x_1,x_2,x_3,\dots,x_n$ for geohazards, $P(Y,x_1,x_2,x_3,\dots,x_n)$ mean the probability of geohazards under the conditions of factors combination $x_1,x_2,x_3,\dots,x_n$, $P(Y)$ mean the probability of geohazards.

According to conditional probability operation, equation (1) could be further calculated as:

$$P(Y, x_1, x_2, x_3 \dots x_n) = I(Y, x_1) + I_{x_1}(Y, x_2) + \cdots + I_{x_1, x_2, x_3 \dots x_{n-1}}(Y, x_n) \tag{2}$$

where: $I_{x1}(Y,x_2)$ mean the information entropy provided by factor x_2 with the existence of factor x_1.

The establishment process of information entropy model was as follows:

i) Calculation of the information entropy value $I(x_i|H)$ provided by factor x_i for the geohazards event (H), namely:

$$I(x_i \mid H) = In \frac{P(x_i \mid H)}{P(x_i)} \tag{3}$$

where: $P(x_i|H)$ mean the probability of factor x_i occurrence in the conditional zoning of geohazards, $P(x_i)$ mean the probability of factor x_i occurrence in the zone.

Expression (3) was just the theoretical model. Following sample frequency calculation was often used in practice:

$$I(x_i \mid H) = In \frac{N_i / N}{S_i / S} \tag{4}$$

where: N_i mean the number of geohazards units distributed within factor x_i, N mean the total number of geohazards units distributed within the study area, S_i means units number of factor x_i within the study area, and S mean total number of units within the study area.

ii) Calculation of the total information entropy I_i provided by n types of factors within the evaluation units:

$$I_i = \sum_{i=1}^{n} I(x_i, H) = \sum_{i=1}^{n} In \frac{N_i / N}{S_i / S} \tag{5}$$

where: I_i mean the total information content of the evaluation units, n mean the number of influence factors.

iii) Calculation of the total information entropy I_i, as the aggregative indicator of the evaluation unit in influential the occurrence of geohazards, the larger value it had, the more likely geohazards was to happen, and the higher risk of such geohazards. When I_i had a positive value, it would accelerate the geohazards.

iv) Substituted the calculation results of entropy into the evaluation model and used ArcGIS to carry out spatial analysis calculation to obtain the susceptibility index values of each area.

3.2 Fuzzy Logic Model

Fuzzy logic model was based on the frequency ratio, which was calculated according to the membership function. The relationship of fuzzy logic model was not only the spatial but also the quantitative relationship between the geohazards and the impact factors [23-26, 34-35]. The frequency ratio of geohazards could be obtained according to the statistical analysis of the observed geohazards in a certain impact factor. On basis of the frequency ratio, the probability of occurrence of geohazards could be completed by the fuzzy logic operators. The susceptibility zones of geohazards of each area could be obtained by the ArcGIS spatial analysis function according to the probability. The ratio was carried out by the percentages of geohazards in each impact factor and the impact factor in the whole study area.

The frequency ratio was defined as:

$$W_{ij} = \left(\frac{r_{ij}}{r}\right) = \left(\frac{N_{ij}}{N} \times \frac{S}{S_{ij}}\right) \tag{6}$$

Where: W_{ij} was the frequency ratio of a certain class I of parameter j, r_{ij} was the geohazard density within class I of parameter j, r was the geohazard density within the entire map, N_{ij} was the area of geohazards in class I of parameter j, S_{ij} was the area of class I of parameter j, N was the total of geohazards in the entire map, and S was the total area of the entire map.

The frequency ratio was higher; the relationship between geohazard and the factors was higher. Then, the frequency ratio was normalized between 0.00 and 1.00 to create the fuzzy membership value.

$$f_{ij} = W_{ij} / \max(W_{ij}) \tag{7}$$

Where: f_{ij} was the fuzzy membership value of class i of parameter j.

There were five operators in the fuzzy logic model, including fuzzy AND, fuzzy OR, fuzzy algebraic product, fuzzy algebraic sum and the fuzzy γ operator.

The fuzzy AND operator was equivalent to a logical intersection operation (Boolean AND), defined as:

$$f_{and} = \min(f_a, f_b, f_c, \cdots) \tag{8}$$

where: f combination was the combined fuzzy membership function, f_a was the membership value for factor a at a particular location, f_b was the membership value for factor b at a particular location, etc.

The fuzzy OR was equivalent to the logical union operation (Boolean OR), defined as:

$$f_{or} = \max(f_a, f_b, f_c, \cdots) \tag{9}$$

The fuzzy algebraic product was defined as:

$$f_{ap} = \prod_{i=1}^{n} f_i \tag{10}$$

where: f_i was the fuzzy membership function of the i^{th} map and i = 1,2,...,n maps were to be combined.

The fuzzy algebraic sum was complementary to the fuzzy algebraic product and defined as:

$$f_{as} = 1 - \prod_{i=1}^{n} (1 - f_i) \tag{11}$$

The fuzzy γ operation was defined in terms of the fuzzy algebraic product and the fuzzy algebraic sum as:

$$f = f_{as}{}^{\gamma} \times f_{ap}{}^{1-\gamma} = \left(\prod_{i=1}^{n} f_i\right)^{\gamma} \times \left(1 - \prod_{i=1}^{n}(1 - f_i)\right)^{1-\gamma} \tag{12}$$

where: γ was a parameter chosen in the range [0,1]. In the fuzzy γ operation, when γ was 1 the combination was equal to the fuzzy algebraic sum, and when γ was 0 the combination was equal to the fuzzy algebraic product.

4. Results

4.1 Calculation Results

The calculation results of entropy model and fuzzy logic model were shown in Table 2. These factors played a decisive role in the formation and development of such geohazards as landslide, collapse, etc., and were the dominant control conditions to geohazards.

4.2 Susceptibility Zones

Entropy Model:

A chi-square test also could be performed in order to test the statistical significance and effectiveness of the geohazard susceptibility test [12, 27, 31]. It reflected the differences between the observed geohazards and expected geohazards. For the hypothesis, the appearances of geohazard were purely due to the chance. In this case, the chi-square values of grid in observed geohazards and excepted geohazards with or without geohazard should be almost the same. If the chi-square values were different greatly, the hypothesis was wrong.

In this paper, the observed number of girds with and without geohazards for each of the four susceptibility classes was determined from the map, and the expected number of grids for the same was estimated from the observed values using excepted probabilities. The chi-square values of 162 geohazards and 182 geohazards without geohazards were much smaller than with geohazards respectively (Table 3). It suggested that the geohazards susceptibility map was considered statistically significant.

Table 2. Results of Different Impact Factors with Entropy Model and Fuzzy Logic Model with Different Samples Including 162 and 182 Geohazards

Types	162 geohazard		182 geohazards		Domain pixels	Percent of domain (%)	162 geohazards			182 geohazards		
	Geohazard pixels	Percent of geohazard (%)	Geohazard pixels	Percent of geohazard (%)			Entropy values (I)	Frequency ratio (f)	Fuzzy membership values (W)	Entropy values (I)	Frequency ratio (f)	Fuzzy membership values (W)
Elevation, h-(m)												
h<600	11827	28.478209	11827	25.740592	261130	3.915813	1.984116	7.272618	1.000000	1.8830463	6.573499	1.000000
600<h≤900	13106	31.557910	13501	29.386414	1727928	25.911394	0.197141	1.217916	0.167466	0.1258496	1.134112	0.172528
1000<h≤1200	7415	17.854563	11415	24.846005	1722221	25.825814	-0.369115	0.691346	0.095061	-0.038678	0.962061	0.146354
h>1200	9182	22.109319	9201	20.02699	2957324	44.346979	-0.696045	0.498553	0.068552	-0.794964	0.451598	0.0687
Slope angles, p-(°)												
12<p≤18	6154	14.818204	10154	22.101299	916237	13.739564	0.075577	1.078506	0.981108	0.4753568	1.608588	1.000000
6<p≤12,18<p≤30	19299	46.470022	19478	42.396012	2819046	42.273412	0.094649	1.099273	1.000000	0.002896	1.0029	0.623466
30<p≤36	4653	11.203949	4887	10.637094	804507	12.064101	-0.073968	0.928702	0.844832	-0.125887	0.881715	0.54813
p≤6,p>36	11424	27.507826	11424	24.865594	2128813	31.922923	-0.148854	0.861695	0.783877	-0.249839	0.778926	0.48423
TOBIA coefficient (p)												
p≤0.7	3797	9.142788	4931	10.732865	2289449	34.331763	-1.323106	0.266307	0.127687	-1.16276	0.312622	0.153634
0.7 <p≤0.9	12522	30.151698	13801	30.039397	2438142	36.561511	-0.192755	0.824684	0.395414	-0.196486	0.821613	0.403771
0.9 <p≤1.0	25211	60.705514	27211	59.227739	1941012	29.106726	0.735065	2.085618	1.000000	0.7104207	2.034847	1.000000
Geotechnical engineering rock group												
Loosen rocks and soils	1735	4.177703	2221	4.834251	30132	0.451849	2.224169	9.245799	1.000000	2.370134	10.698826	1.000000
Soft-hard clastic rocks	5401	13.005057	5813	12.652635	994902	14.919197	-0.137311	0.8717	0.094281	-0.164783	0.848077	0.079268
Hard clastic rocks	3088	7.435589	4372	9.51614	469824	7.045314	0.053915	1.055395	0.114149	0.3006266	1.350705	0.126248
Soft-hard carbonate rocks	17528	42.205634	19023	41.405655	2585512	38.771419	0.08487	1.088576	0.117737	0.0657341	1.067943	0.099819
Hard carbonate rocks	13778	33.176017	14514	31.59132	2588233	38.812222	-0.156908	0.854783	0.092451	-0.205853	0.813953	0.076079
Geological structure, l-(km)												
influence scope of the faults (l≤1)	8432	20.303395	9817	21.367782	1117837	16.762686	0.191633	1.211226	1.000000	0.2427289	1.274723	1.000000
influence scope of the faults (l>1)	33098	79.696605	36126	78.632218	5550766	83.237314	-0.043469	0.957462	0.79049	-0.056914	0.944675	0.741083
Distance to river or valley, l-(m)												
50<l≤350m	16215	39.044065	16314	35.509218	1357798	20.361056	0.651067	1.917585	1.000000	0.5561683	1.743977	1.000000
l≤50m, 350<l≤550m	8411	20.252829	11602	25.253031	1075887	16.133619	0.227389	1.255318	0.654635	0.448041	1.565243	0.897513
550<l≤800m	3989	9.605105	5012	10.90917	934212	14.009111	-0.377413	0.685633	0.35755	-0.250104	0.77872	0.446519
l>800m	12915	31.098001	13015	28.328581	3300706	49.496214	-0.464753	0.628291	0.327647	-0.558025	0.572338	0.32818
Human activities(road),l-(km)												
the influence scope of road (l ≤ 1)	20009	48.179629	22214	48.351218	2222816	33.332559	0.368402	1.445422	1.000000	0.3719568	1.45057	1.000000
the influence scope of road (1< l≤ 2)	6397	15.403323	7012	15.26239	1586111	23.784757	-0.434462	0.647613	0.448044	-0.443653	0.641688	0.442369
the influence scope of road (l>2)	15124	36.417048	16717	36.386392	2859676	42.882685	-0.163431	0.849225	0.587527	-0.164273	0.84851	0.584949
primeval forest	--	--	--	--	--	--	--	--	--	--	--	--

Table 3. Results for the Chi-square Test with Different Samples

Susceptibility zones	Low	Medium	High	Very High	Total
162 geohazards with entropy model					
Observed number of grids					
Without geohazard	2650829	1988122	1325415	662707	6627073
With geohazard	5419	9018	9923	17170	41530
Total	2656248	1997140	1335338	679877	6668603
Expected number of grids					
Without geohazard	2639636	1984681	1327032	675724	6627073
With geohazard	16612	12459	8306	4153	41530
Total	2656248	1997140	1335338	679877	6668603
Chi-square values					
Without geohazard	47.46	5.97	1.97	250.76	306.16
With geohazard	7541.73	950.36	314.80	40799.97	49606.86
Total	7589.19	956.32	316.77	41050.73	49913.01
182 geohazards with entropy model					
Observed number of grids					
Without geohazard	2650067	1987685	1324787	660121	6622660
With geohazard	6181	9455	10551	19756	45943
Total	2656248	1997140	1335338	679877	6668603
Expected number of grids					
Without geohazard	2649064	1986798	1324532	662266	6622660
With geohazard	18377	13783	9189	4594	45943
Total	2656248	1997140	1335338	679877	6668603
Chi-square values					
Without geohazard	0.38	0.40	0.05	6.95	7.77
With geohazard	8093.94	1359.04	201.88	50040.54	59695.40
Total	8094.32	1359.43	201.93	50047.49	59703.17

Note: the size of grid is 20m×20m.

From Table 3, according to the chi-square test, it was found that chi-square values of 162 and 182 geohazards were almost the same, and the numerical difference was very small. In this case, it showed that there were no differences of statistical significance and effectiveness of the geohazard susceptibility assessment between 162 geohazards and 182 geohazards. The chi-square vale of 182 geohazards smaller than the value of 162 geohazards, it showed that the statistical significance and effectiveness of 182 geohazards was better than the ones of 162 geohazards.

20 geohazards were selected randomly in order to validate entropy model in Jianshi County. The effective result (162 geohazards) of entropy model was good and the confidence coefficient was 0.7499 [12]. The rationality and scientificness of the entropy model had been validated in western part of Hubei province. Therefore, on basis of the same concept and mathematical model, the analysis of geohazard susceptibility assessment with 182 geohazards was rationality and scientific. In this paper, the 182 geohazards of the whole county were considered as samples and the susceptibility zonation was calculated with entropy model. The confidence coefficient was 0.6863, smaller than the value of 162 geohazards.

Fuzzy Logic Model:

In this paper, the frequency ratio was calculated for all types of geohazards background impact factors according to the areas of the geohazards in the impact factors. The fuzzy membership values were calculated by normalizing the ratio values into the range of 0~1[36]. The results are shown in Table 4.

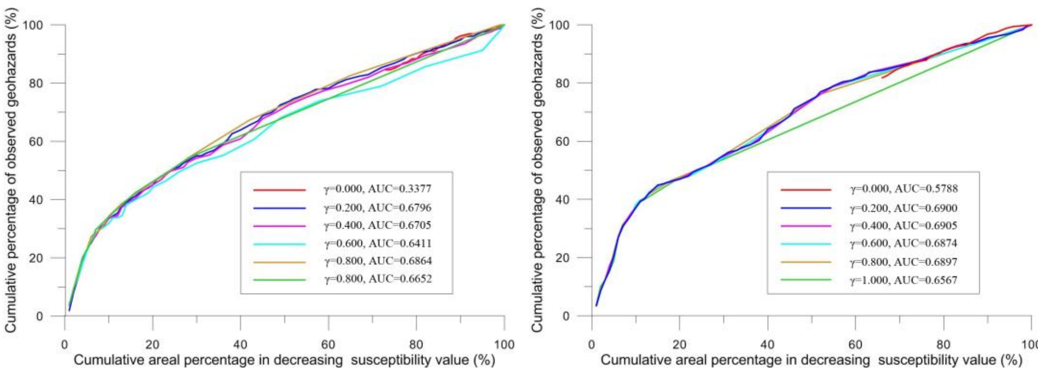
The fuzzy membership values were weighted as the different classes of impact factors, and the geohazard susceptibility index values of each grid were calculated according to the equation (7) with the spatial analysis function of ArcGIS. In order to find out the best methods, the parameter γ in equation (7) were calculated as 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0.The operator enable a compromise between the increasing tendencies of fuzzy SUM and the decreasing effect of the fuzzy Product [26, 37]. The statistics of the geohazards susceptibility index values for 162 geohazards and 182 geohazards were shown in Table 4.

Table 4. Statistics of the Geohazard Susceptibility Index Values

γ	Max	Min	Mean	Std dev.	AUC(%)
182 geohazards					
0	1.000000	0.963567	0.995499	0.008471	33.77
0.1	0.886340	0.352895	0.484294	0.065780	68.03
0.2	0.785598	0.129244	0.239678	0.067145	67.96
0.3	0.696307	0.047334	0.120817	0.053450	67.58
0.4	0.617164	0.017336	0.062106	0.039000	67.05
0.5	0.547017	0.006349	0.032595	0.027464	65.81
0.6	0.484843	0.002325	0.017483	0.019091	64.11
0.7	0.429736	0.000852	0.009591	0.013247	61.82
0.8	0.380892	0.000312	0.005384	0.009230	68.64
0.9	0.337600	0.000114	0.003093	0.006478	68.69
1.0	0.299228	0.000042	0.001818	0.004587	66.52
Entropy model	5.403262	-3.472008	-0.687634	1.269101	68.63
162 geohazards					
0	1.000000	0.994237	0.998833	0.001840	57.88
0.1	0.968327	0.425206	0.530041	0.067828	68.65
0.2	0.848219	0.181848	0.285806	0.078370	69.00
0.3	0.718327	0.077771	0.156905	0.070049	68.75
0.4	0.638217	0.033260	0.087887	0.057418	69.05
0.5	0.552982	0.014224	0.050335	0.045599	68.53
0.6	0.489213	0.006083	0.029540	0.035983	68.74
0.7	0.431872	0.002602	0.017797	0.028599	68.56
0.8	0.386215	0.001113	0.011024	0.023066	68.97
0.9	0.338019	0.000476	0.007028	0.018949	66.18
1.0	0.310287	0.000204	0.004614	0.015876	65.67
Entropy model	4.890346	-3.986272	-0.722090	1.179769	74.99

The AUC (area under the curve) values mean the confidence coefficients of different models. From Table 4, the AUC values of entropy model were higher than the ones of fuzzy logic model. The differences between 162 geohazards and 182 geohazards conformed to the more the number of samples in statistical analysis, the lower the degree of confidence coefficient. In some degree, the differences mean the entropy model was unstable and the accuracy of entropy model depended on the characters of samples, including the spatial and attributive characteristics.

The AUC values of 162 geohazards were higher than the values of 182 geohazards in fuzzy logic model. In order to analysis the stability of the fuzzy logic model, the authors compared the AUC when the parameter γ in equation (7) were calculated as 0, 0.2, 0.4, 0.6, 0.8 and 1.0 (Figure 2). From the figures, it obviously showed the curves of 162 geohazards with small contact ratio and the curves of 182 geohazards with good contact ratio except γ=1.0. It suggested that the stable of fuzzy logic model was better if the geohazards were enough. On basis of the above analysis, the stable of fuzzy logic model was good for the susceptibility analysis.



a b

Figure 2. Success Rate Curves of Fuzzy Logic Models

(a: including 162 geohazards, b: including 182 geohazards)

Not only 162 geohazards but also 182 geohazards in fuzzy logic model, when γ=0.2, the AUC values were almost the highest and the standard deviation were the biggest values (Table 4). In statistics, when the value of standard deviation was bigger, it suggested that the data contained a greater amount of information, and the result was better representative and more reliable. In this case, the authors considered when the γ =0.2, the fuzzy logic model was the best in the study. In this case, the authors used γ=0.2 to complete the susceptibility assessment with fuzzy logic model. The results of 162 geohazards and 182 geohazards were also classified into four classes, including low, medium, high and very high susceptibility zones. Chi-square test also could be performed in order to test the statistical significance and effectiveness of the geohazard susceptibility test [5, 12, 27].

In this paper, the chi-square values of 162 geohazards and 182 geohazards with geohazards were much bigger than without geohazards respectively. It showed that the geohazards susceptibility map was considered statistically significant [5, 12]. The chi-square vale of 182 geohazards smaller than the value of 162 geohazards, it suggested that the statistical significance and effectiveness of 182 geohazards was better than the ones of 162 geohazards (Table 5).

Table 5. Results for the Chi-square Test with Different Samples

Susceptibility zones	Low	Medium	High	Very High	Total
162 geohazards with fuzzy logic model					
Observed number of grids					
Without geohazard	2648325	1986047	1328283	664418	6627073
With geohazard	7923	11093	7055	15459	41530
Total	2656248	1997140	1335338	679877	6668603
Expected number of grids					
Without geohazard	2650829.2	1988121.9	1325414.6	662707	6627072.7
With geohazard	16612	12459	8306	4153	41530
Total	2656248	1997140	1335338	679877	6668603
Chi-square values					
Without geohazard	2.37	2.17	6.21	4.42	15.16
With geohazard	4544.83	149.77	188.42	30779.11	35662.12
Total	4547.20	151.93	194.63	30783.53	35677.28
182 geohazards with fuzzy logic model					
Observed number of grids					
Without geohazard	2650067	1987685	1324787	660121	6622660
With geohazard	6181	9455	10551	19756	45943
Total	2656248	1997140	1335338	679877	6668603
Expected number of grids					
Without geohazard	2649064	1986798	1324532	662266	6622660
With geohazard	18377	13783	9189	4594	45943
Total	2656248	1997140	1335338	679877	6668603
Chi-square values					
Without geohazard	3.04	0.12	0.67	8.60	12.44
With geohazard	3796.74	632.25	49.58	24596.63	29075.20
Total	3799.78	632.37	50.25	24605.23	29087.63

Note: the size of grid is 20m×20m.

4.3 Results and Discussions

Results:

According to analysis results of fuzzy logic model, in this paper, the entropy model and fuzzy logic model (γ=0.2) were employed to calculate the susceptibility values for the Jianshi county with ArcGIS spatial analysis function. All influencing factors were weighted based on calculation results of entropy model and fuzzy logic model [5, 6, 9]. The spatial analysis of entropy model was completed based on ArcGIS, obtaining the distribution range of unit value. The values of susceptibility assessment were shown in table 6 and figure 3. Statistical data of 162 geohazards showed that the Eigen-values of entropy model were 4.1340 and 1.1950 which were bigger than the ones of fuzzy model (3.7224 and 1.1950) in very high and high susceptibility zones respectively. The data of 182 geohazards had the same characters which the values of entropy model (4.1250 and 1.2580) were bigger than the values of fuzzy logic model (3.3317 and 1.0735) in very high and high susceptibility zones respectively. The unit geohazards Eigen-values of very high susceptibility zones of geohazards with entropy model were greater than the Eigen-values with fuzzy logic model.

Table 6. Correlation Table of Geohazard Susceptibility Zonation and Geohazards

Susceptibility	Susceptibility values	Number of grid	Percentage of area a (%)	Grid number of geohazards	Percentage of geohazards b (%)	Unit geohazard Eigen-value b/a
162 geohazards						
Entropy model						
Very High	0.7726~4.9862	679877	10	17170	41.34	4.1340
High	-0.1539~0.7726	1335338	20	9923	23.90	1.1950
Medium	-1.1833~-0.1539	1997140	30	9018	21.71	0.7237
Low	-3.0241~-1.1833	2656248	40	5419	13.05	0.3263
Total		6668603	100	41530	100	1.0000
Fuzzy logic model						
Very High	0.3928~0.8482	679877	10	15459	37.22	3.7224
High	0.2969~0.3928	1335338	20	7055	16.99	0.8494
Medium	0.2490~0.2969	1997140	30	11093	26.71	0.8904
Low	0.1818~0.2490	2656248	40	7923	19.08	0.4769
Total		6668603	100	41530	100	1.0000
182 geohazards						
Entropy model						
Very High	0.8079~5.0921	679877	10	18952	41.25	4.1250
High	-0.1691~0.8079	1335338	20	11559	25.16	1.2580
Medium	-1.1829~-0.1691	1997140	30	9593	20.88	0.6960
Low	-3.1473~-1.1829	2656248	40	5839	12.71	0.3178
Total		6668603	100	45943	100	1.0000
Fuzzy logic model						
Very High	0.3215~0.7856	679877	10	15224	33.14	3.3137
High	0.2549~0.3215	1335338	20	9864	21.47	1.0735
Medium	0.2087~0.2549	1997140	30	10831	23.57	0.7858
Low	0.1292~0.2087	2656248	40	10024	21.82	0.5455
Total		6668603	100	45943	100	1.0000

Note: the size of grid is 20m×20m.

The very high and high susceptibility zones of 162 geohazards and 182 geohazards were about 65.24% and 66.41% of the total area employing entropy model and about 54.21% and 54.61% of the total area employing fuzzy logic model. The area percentages of entropy model were higher than the percentages of fuzzy logic model and the area percentages of 162 geohazards were lower than the percentages of 182 geohazards respectively. According to the table, the entropy model was better than the fuzzy logic model, especially highlight the concentrated area of geohazards. Obviously, the results of different models were almost same in the space, but different in some areas.

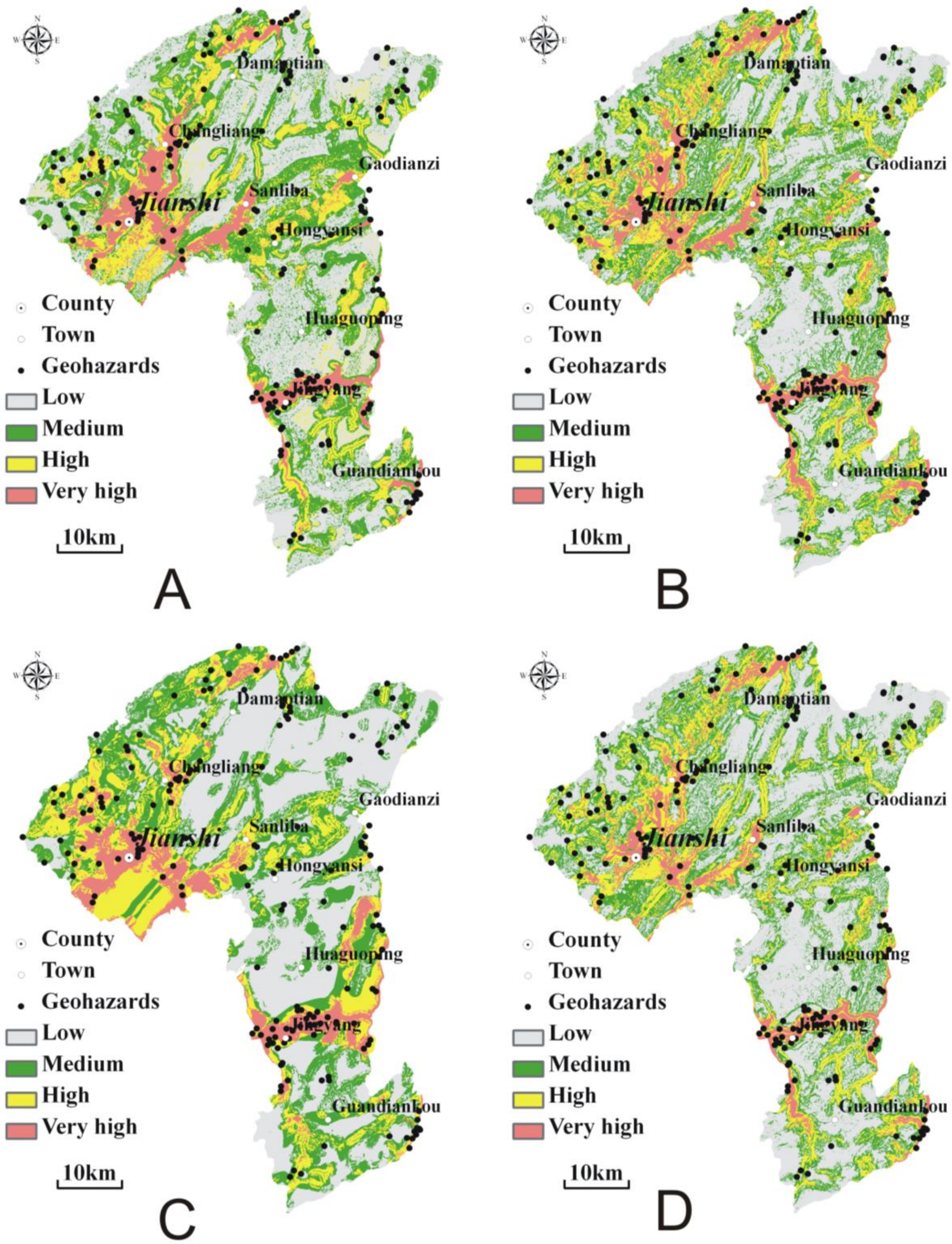


Figure 3. Results of Fuzzy Logic and Entropy Models with Different Numbers of Geohazards

(A: result of fuzzy logic model with 162 geohazards; B: result of fuzzy logic model with 182 geohazards; C: 1result of entropy model with 162 geohazards; D: result of entropy model with 182 geohazards)

Comparison of Entropy and Fuzzy Logic Model:

In this paper, fuzzy logic model and entropy model were employed to complete the geohazard susceptibility zonation in Jianshi County of Qingjiang River Basin. The results of different models were almost the same in the space, except some small areas. The two models were useful for the analysis of geohazard susceptibility.

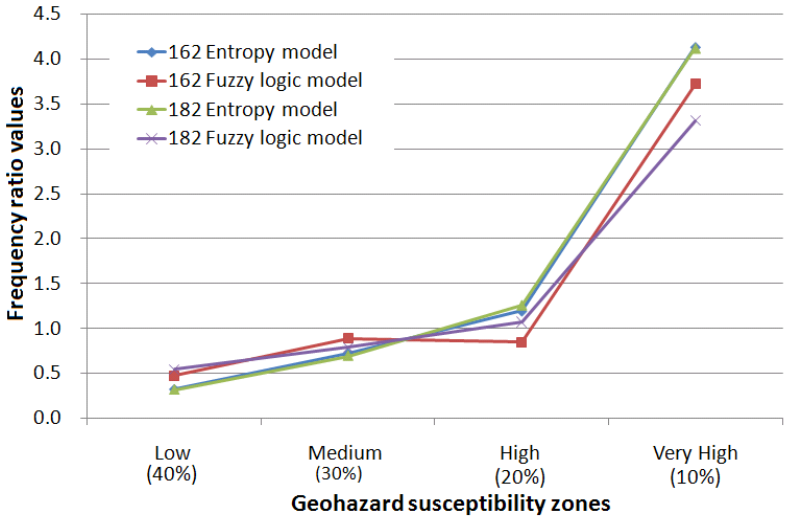


Figure 4. Frequency Ratio Plots of Geohazard Susceptibility Zones of Fuzzy Logic Model and Entropy Model

From Table 6 and Figure 4, statistical data showed that the frequency ratio values of 162 geohazards were bigger than the ones of 182 geohazards and the ones of entropy model were bigger than the ones of fuzzy logic model in very high and high susceptibility zones except the frequency ratio value of 162 geohazards smaller than the one of 182 geohazards with fuzzy logic model. However, the characters of frequency ratio values were inversed in the low and medium susceptibility zones. Totally, the frequency ratio values of fuzzy logic model and entropy model were almost the same in each susceptibility zone respectively.

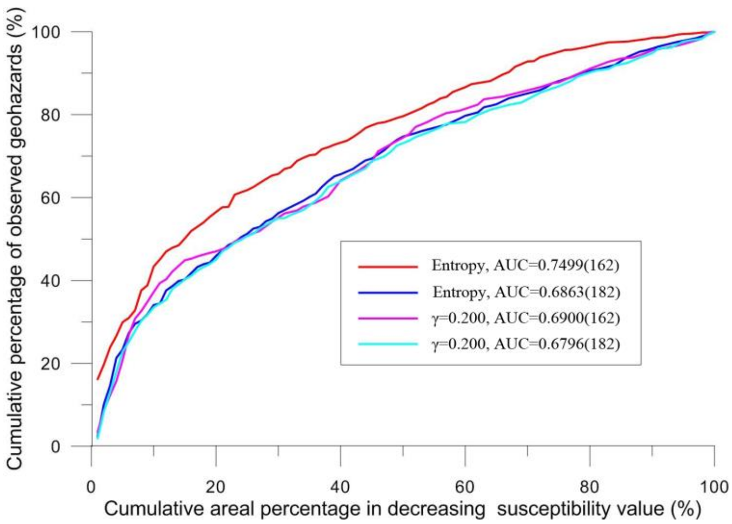


Figure 5. Success-rate Curves of Fuzzy Logic and Entropy Models

The AUC values of 162 geohazards were bigger than the ones of 182 geohazards. The curve of 162 geohazards was above the one of 182 geohazards, obviously the two curves of entropy model much different. In this case, it suggested that the entropy model was not stable with different samples (Fig.5). However, the two curves of fuzzy logic model were almost the same. It suggested that the fuzzy logic model was stable and not influenced by the number of samples. Basing on the above analysis, the fuzzy logic model was suitable for the geohazard susceptibility zonation in Jianshi County. The two models of geohazard susceptibility zonation would provide references of preliminary development planning purposes.

5. Conclusions

In this study, the entropy model and fuzzy logic model were based on the statistical analysis with ArcGIS software. The models were both quantitative analysis and assessment of geohazard susceptibility zonation. The authors used the entropy model and fuzzy logic model to finish the geohazard susceptibility zonation with different numbers of geohazards (162 geohazards and 182 geohazards). Generally, the results of different geohazards with the two models were almost the same in the space. It suggested that the two models were useful for Jianshi County. However, there were different advantages and disadvantages in the two models.

In the case of entropy modeling, it could accurately analyze the characteristics of geohazards on different influence factors according to the statistical data of geohazards [11-12]. The entropy model would be influenced by the number and spatial character of geohazards. However, it analyzed the probability of geohazards in terms of their formation mechanisms and obtains the major controlling factors quantitatively.

The fuzzy logic model could be used to complete the geohazard susceptibility zonation with a few geohazards. In some degree, it would get a general relationship between the geohazards and impact factors. According to the analysis process, it was found that the fuzzy γ operation was the best and most useful when γ was 0.20. It was easy to find out the determine impact factors.

Generally, on basis of the formation mechanisms of geohazards, the fuzzy logic model and entropy model were useful for the geohazard susceptibility zonation which was consistent with the field investigations.

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