Evaluation method of ecological environment vulnerability and its application

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Abstract: The Karst area in Chongqing is typical eco-environmental vulnerable area, where farmland is insufficient and degeneration of soil is serious, ability of enduring the natural calamities is vulnerable. Consequently, coordination between development of social economy and eco-environment is inferior, and sustainable developmental ability is feeble. The Karst area of Chongqing in China as a study case , this paper picks up 13 influencing factors of eco-environment vulnerability to be assessment indicators, containing earth surface of carbonate rock salt, area of mountainous region, area of slopping upland farming, degree of rock desertification(classified by gently, moderately, seriously), forest coverage, loss area of water and soil, soil erosion modulus, slip volume density, cultivation index, farmland area per capita, agriculture population density, subsequently, uses analytic hierarchy process(AHP) to endow index weight, and sets up assessment model by using fuzzy mathematics method to analyze and evaluate the eco-environment vulnerability of Karst area, finally, conducts the rank divisions towards the assessment results. Results indicate: there are 3 potentially vulnerable counties, 10 gently vulnerable counties, 6 moderately vulnerable counties and 6 seriously vulnerable counties among the 25 Karst counties in Chongqing.

Key-Words: - Karst counties; eco-environment vulnerability; fuzzy mathematics; Chongqing

1 Introduction

China is one of most growing countries of the world Karst landform [1]. Total area of national Karst reaches to 1.37 million km^2, approximately occupies 1/7 of national territory total area; once the buried limestone is concerned about, the area reaches to 2 million km^2 and approximately occupies 1/5 of national territory total area. West south Karst area, that takes Guizhou Province as center mainly spreading over Yunnan, Guizhou, Guangxi, Sichuan and Chongqing, is approximately 550,000 km^2, occupying 15.97% of national Karst area. It's one of the biggest and most intense growing areas of Karst around global Karst pieces [2]. Meanwhile, the total population is beyond 3.9 billion in the area, nearly 1/2 of national impoverished population musters in the region, so it's a main impoverished area in China. The restoration and reconstruction of degeneration Karst ecosystem is always key point to which government management and scientific researchers have paid more attention [3-5]. In recent years, information technology has played a more and more important role in environment protection fields. Spatial information technology, especially GIS, have become a more significant instrument for environment management and analysis in scientific research. At present, GIS technology has been widely applied in natural resources management and eco-environment assessment [6-9]. But used-work was mainly focused on the Guizhou, Yunnan and Guangxi pronvice in China [10-11], only preliminary study on restoration and reconstruction of degenerating Karst ecosystem in Chongqing was presented [12-13]. This paper picks up 25 karst counties of Chongqing as the examples, and applies quantity classification method to establish an evaluation index system by reasonably selecting ecological environmental frailty influencing factors. In the index system, indexes are endowed weight by analytic hierarchy process (AHP); then, an evaluation model is established by fuzzy mathematical generalization; finally, GIS-based rank division is accomplished. The present work is orientated to explore quantitative evaluation method of ecological environment frailty of Karst area in Chongqing and rank the ecological environment frailty, aims to provide the basis for restoration and reconstruction of degeneration Karst ecosystem, utilization of land structure optimization in Chongqing.

2 Study area

The Chongqing Karst area (containing carbonate rocks clamp detritus petrographic area)is about 41,400 km^2, accounting for 51% of the whole rural

area, mainly disseminates in Nanan, Banan, Beibei, Yubei, WanSheng, Qijiang, Nanchuan, Jiangjin, Yongchuan, Chengkou, Wuxi,Wushan, Zhongxian, Yunyang, WanZhou,Shizhu, Fengdu, Fengjie, Fuling,Wu Long, Pengshui, Qianjiang, Yongyang, Xiushan, Kaixian(Fig.1). Similar to Mediterranean Sea, it belongs to subtropics exposed dissolved Karst landscape with Karst marshland - mound peak corroded - erosion, which is characterized as karst marshland, funnel and Karst knoll, low-middle Mountain. In the pure stratum(entirety is phenol salt crag area), the Karst is foliation distribution, also growth is positive; in the inter-bedded stratum, Karst often takes on the belt-shaped distribution; in the m-stratum, the Karst distribution only appears several isolated bands or fragments. Within urban area, land resource in limestone mountainous area is primarily stone hillside; hypsography is big; terrain is steep; geological function of endo-exo agent is intensive; mountains are interlock-distributed among canyons, peak clumps and marsh lands. These characteristics demonstrate that water and soil resource easily drain in the area, water loss and soil erosion are serious, vegetation appears reverse succession, coverage of forest is low, capability of conservation water is bad, and ability of ecological environment anti-interference is reduced. As a result, a vicious circle of "population increase- cultivated land grow-forest degeneracy-land petrified" is generated.

3 Evaluation method

3.1 Elaborating the evaluation method

The Karst environment is a unique ecological environment system, where energy circulation and variation of carbon matter are extremely intense and prompt [14]. The system has a series of ecological frailty characteristics, including low environmental capacity, small creature amount, high variation sensitivity of ecosystem, weak ability of anti-interference, inferior stability. Karst environment vulnerability are so sophisticated that it's necessary to establish a unified evaluation index system for quantizing the vulnerability degree of different Karst areas, then one could have a whole objective understanding and evaluation for the integral Karst ecological environment frailty. As mentioned above, the paper initiating from natural disturbance and human disturbance of Chongqing Karst area, takes 13 influencing factors as evaluation indexes, which consists of earth surface of carbonate rock salt, area of mountainous region, area of sloping upland farming, degree of rock desertification(classified by gently, moderately, seriously), forest coverage, loss area of water and soil,

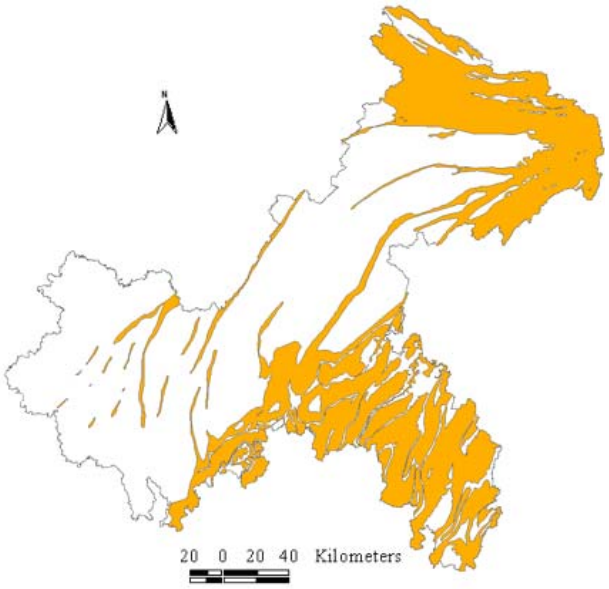

Fig.1 Spatial distribution of Karst geomorphy coverage in Chongqing

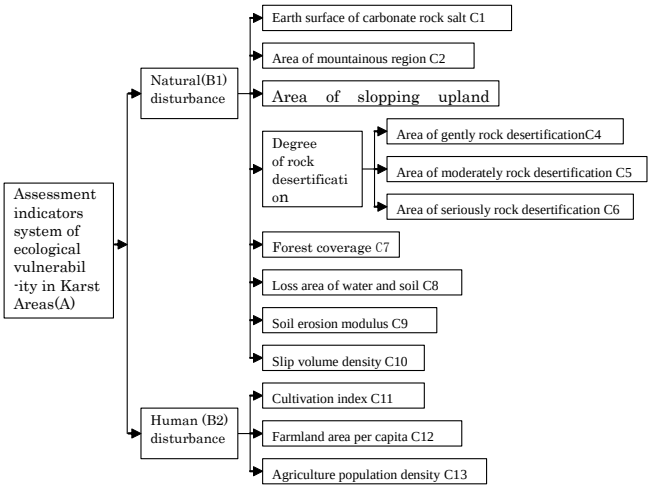

Fig.2 Assessment indicators system of ecological vulnerability in Chongqing Karst Areas

Table 1 Grading standard for assessment indicators of ecological vulnerability in Karst Areas

Factor	Index number	Vulnerable grade				
		Potentially vulnerable?	Gently vulnerable?	Moderately vulnerable?	Seriously vulnerable?	Extremely vulnerable?
Natural disturbance	C_1	10.55	30.35	50.15	69.95	89.74
	C_2	24.65	41.07	57.49	73.91	90.33
	C_3	14.57	28.31	42.05	55.79	69.53
	C_4	0.91	2.83	4.71	6.59	8.47
	C_5	4.22	11.15	18.08	25.01	31.94
	C_6	4.45	13.28	22.11	30.94	39.77
	C_7	38.91	32.73	26.55	20.37	14.19
	C_8	44.63	53.27	61.91	70.55	79.19
	C_9	2279.3	3233.9	4188.5	5143.1	6097.7
	C_{10}	3.23	9.66	16.09	22.52	28.95
Human disturbance	C_{11}	29.48	40.47	51.45	62.44	73.43
	C_{12}	5.04	4.05	3.06	2.07	1.08
	C_{13}	107	197	287	377	467

soil erosion modulus, slip volume density, cultivation index, per capita farmland area, density of agriculture population, to establish an evaluation index system(shown in Fig.2).

3.2 Evaluation standard

At present, there is no unified classification standard and evaluation basis to ecological environment frailty of Karst area [15]. The paper divides frailty rank of index into 5 frailty ranks (potentially frail, gently frail, moderate frail, seriously frail, extreme frail) according to D-value division between maximum value and the minimum of each index. Evaluation standard includes forward-index (bigger the index value is, bigger the frailly is) and negative-index (smaller the index value is, bigger the frailly is). Forward-index adopts the value attained by adding minimum value of each index to half of D-value division as standard value of potentially frailty, adopts the value attained by minimum value of each index minus half D-value division as limited value of extremely frailty, the middle three ranks are equally divided; negative-index is reverse.

3.3 Evaluation model

3.3.1 Endow index weight

Because various indicators play different roles in the index system, their influencing extent to ecological environment are different. And weighting evaluation method is usually utilized to definite the influence discrepancy. At present, a lot of researches on weight definite question have been carried on, among them weight is defined according to either researcher's experience and subjective judgment or all kinds of mathematics methods [16]. This paper uses analytic hierarchy process (AHP) to determine index weight of ecological environment frailty in Chongqing Karst. AHP is a simple systematic engineering method to quantitatively analyze non-quantitative objects. It cannot only fully consider the researcher's subjective judgment during the quantitative and/or qualitative analysis, but also express the complex system in a hierarchic structure from interrelation between inside and outside of the system, which contributes to make the decision-making process systemic, numerical and modeling by analyzing step by step. Due to its ability of assigning proper weights to various factors of complex systems, AHP is also called as an analytic multi-level value process. As a complex system with multi-subjects and multi-levels, eco-environment system is suitable to employ AHP as evaluation method. The detailed analytic process is as follow:

①Establish comparison matrix B2 Layer B is broken down into Layers C to establish the pair-wise comparison matrix. Relative importance of C_1, C_2 …,C_{13} is analyzed by Delphi method, also so-called Expert Judgment. During the research, we invite experts with ecological backgrounds to give the relative importance of each factor, respectively, and then universally analyze all the opinions, and finally, gain the rank of relative importance for each factor. The established comparison matrix of human disturbance is seen in Table 2.

Table 2 comparison matrix of human disturbance

B_2	C_{11}	C_{12}	C_{13}
C_{11}	1	5/9	1/3
C_{12}	9/5	1	3/5
C_{13}	3	5/3	1

②Calculate the product of every row M_i

$$M_i = \prod_{j=1}^{m} C_{ij} \ (i=1,2,...,m) \quad (1)$$

③Get the cubic root of M_i

$$\beta_i = M_i^{\frac{1}{m}} \quad (2)$$

④Get the weight of C11，C12 and C13

$$w_i = \frac{\beta_i}{\sum_{i=1}^{m} \beta_i} \ (i=1,2,...,m) \quad (3)$$

w_i =(0.1386,0.2733,0.5881)

⑤Calculate the maximum eigenvalue

$$\lambda_{\max} = \frac{1}{m} \sum_{i=1}^{m} \frac{(Bw)_i}{w_i} \ (\lambda_{\max}=3.0651) \quad (4)$$

⑥ Use CR to carry on consistent test, when $CR \leq 0.10$,it means that the consistence of this matrix is acceptable.

$$CR=CI/RI \quad (5)$$

$$CI = \frac{\lambda_{\max} - n}{n-1} = 0.03256$$

In the equation, RI is average random consistence index, when m=3, RI=0.58, in this research, CR(random consistence index)=0.0561 ≤ 0.10, Weight of assessment indicators for human disturbance is acceptable.(Table 3)

Table3 Weight of human disturbance factor(B_2)

Index	C_{11}	C_{12}	C_{13}
Weight	0.1386	0.2733	0.5881

Similarly, weight of assessment factor for natural disturbance is gotten. (Table 4)

Table4 Weight of assessment indicators for natural disturbance (B_1)

Index	C_1	C_2	C_3	C_4	C_5
Weight	0.1819	0.0454	0.1363	0.0228	0.0683
Index	C_6	C_7	C_8	C_9	C_{10}
Weight	0.1363	0.0909	0.1061	0.1060	0.1060

3.3.2 Calculation of eco-environment frailty

Ecological environment frailty has some fuzziness in the Karst area. That is to say, concrete ecological environment should be confirmed to be neither absolutely frail nor absolutely stable, membership relationship of varying extent only is proposed relative to some frail standard. Therefore, vulnerability evaluation for Chongqing Karst area may be dealt as a fuzzy problem. Membership degree to some level frailty is mainly calculated by establishing membership function according to current value of evaluation index (Table 3).

The evaluation index is divided into forward-index and negative-index, their membership degree formula are different. For forward-index, its formula is as follows:

$$x_i < s_{i,1},\ r_{i,1}=1,\ r_{i,2}=r_{i,3}=r_{i,4}=r_{i,5}=0; \quad (6)$$

$$s_{i,j} \le x_i \le s_{i,j+1},\ r_{i,j+1}=\frac{x_i - s_{i,j}}{s_{i,j+1}-s_{i,j}},\ r_{i,j}=1-r_{i,j+1};(j=1,2,3,4) \quad (7)$$

$$x_i > s_{i,5},\ r_{i,5}=1,\ r_{i,1}=r_{i,2}=r_{i,3}=r_{i,4}=0; \quad (8)$$

Calculation method of negative-index membership degree is similar to that of forward-index, its formula is as follows:

$$x_i > s_{i,1},\ r_{i,5}=1,\ r_{i,1}=r_{i,2}=r_{i,3}=r_{i,4}=0; \quad (9)$$

$$s_{i,j} \ge x_i \ge s_{i,j+1},\ r_{i,j+1}=\frac{x_i - s_{i,j}}{s_{i,j+1}-s_{i,j}},\ r_{i,j}=1-r_{i,j+1};(j=1,2,3,4) \quad (10)$$

$$x_i < s_{i,5},\ r_{i,1}=1,\ r_{i,2}=r_{i,3}=r_{i,4}=r_{i,5}=0; \quad (11)$$

Using above formula, relational matrix between assessment indexes with frailty is gotten. Then assessment model of eco-environment frailty is

$$R_{i,j}=\begin{pmatrix} r_{11}r_{12}r_{13}r_{14}r_{15} \\ r_{21}r_{22}r_{23}r_{24}r_{25} \\ \cdots\cdots\cdots\cdots \\ r_{i1}r_{i2}r_{i3}r_{i4}r_{i5} \end{pmatrix} \quad (12)$$

$$U_j = wi \cdot R_{i,j} \quad (13)$$

In usual case, the biggest membership degree principle was employed to analyze the fuzzy assessment result after accomplishing the assessment model, but this method had some limitation that unreasonable appraisal result would be possibly obtained if the difference among judgment objects with different rank membership degrees was not large. In order to lessen the limitation by assessment model and access the essence, the paper applied the weighted average principle for obtaining the membership rank, and analyzed result vector of fuzzy synthesis assessment.

$$B^* = \frac{\sum_{j=1}^{5} U_j^k \cdot j}{\sum_{j=1}^{5} U_j^k} \quad (14)$$

Where, $r_{i,j}$ is relative membership degree of the *i*th index to *j*th level standard; x_i is current value of the ith index; $s_{i,j}$ is standard value of the ith index to *j* level frailty rank; wi is the index weight coefficient of *i*th index; U_j is frailty of the *j*th level standard; B* is the frailty, *j* is the frailty rank; *k*=2, the objective is to control the role of bigger U_j.

According to formulas of fuzzy evaluation(6)~(14), the paper firstly carries on frailty evaluation for natural disturbance and human disturbance; then, takes evaluation result as evaluation factor; finally, obtains integrated rank division of ecological environment frailty in Chongqing 25 karsts counties (Fig .3).

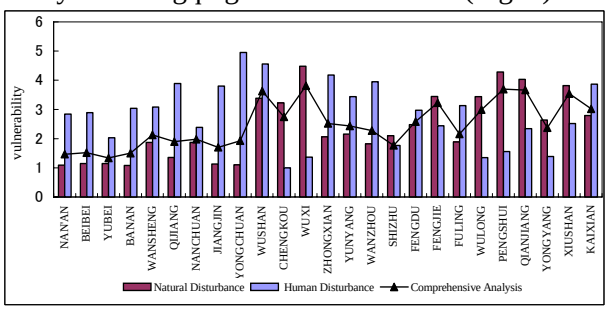

Fig. 3 Evaluation results of ecological vulnerability of 25 karst counties in Chongqing

3.3.3 GIS-based rank division

The paper applies ArcView software as evaluation tool, carries on rank division according to weighted average principle (potentially vulnerable: B * < 1.5; gently vulnerable: 1.5 <= B * < 2.5; moderately vulnerable: 2.5 <= B * < 3.5; seriously vulnerable: 3.5 <= B * < 4.5; extremely vulnerable: B * >= 4.5). Rank division of natural disturbance and human disturbance are shown in Fig.4 and Fig.5, respectively. Rank division of eco-environmental comprehensive vulnerability of 25 Karst counties in Chongqing is shown in Fig.6.

4 Result

The comprehensive rank division results indicate that there are 3 potentially vulnerable areas, 10 lightly vulnerable areas, 6 moderately vulnerable areas, and 6 seriously vulnerable areas in the 25 Karst areas of Chongqing.

I Potentially vulnerable area includes 3 areas (Nanan, Yubei, and Banan). Its area is 3561.11km^2, accounting for 5.26% of total area. The region is

mainly composed of cross-belt of city and countryside, where rural ecosystem and agricultural ecosystem are coexisted, natural environmental condition is relatively superior, earth surface of carbonate rock salt is slight (<13.51%), status of forest and vegetation is better, peasant's income is stable, development level of economy is higher. However, runoff of ground surface is rich, intensity of rain is big, soil erosion is serious (area > 40.31%), soil erosion (modulus >3239.33t/ km^2.a) is moderate, the geological disasters frequency occur (primarily landslide and danger crag), so it belongs to potentially vulnerable area.

Ⅱ Gently vulnerable area includes 10 areas (Beibei, Qijiang, Jiangjin, Yongchuan, Wan Sheng, Nanchuan, Shizhu, Yunyang, Fuling andWanzhou), the area is 23931.04km^2, accounting for 35.34% of total area. In this region, natural environmental condition is better, forest coverage is higher, and it has the obvious function of self-control water source and accumulation and regulation of hydrology. However, mountainous area is big, rainfall is big and centralized, and soil erosion is serious. In addition, the humanity activity is frequent, index of cultivation is higher, and land reserve resource is insufficient. So this region belongs to mild vulnerability.

Ⅲ Moderately vulnerable area includes 6 areas (Fengjie, Kaixian, Zhongxian, Chengkou, Fengdu and Wu Long), its area is 19, 318 km^2, accounting for 28.52% of total area. In this region, geologic structure is complex, slope stability is bad, landslide risk is big (landslide bulk density> 134,800 m^3/km^2). And, intensity of soil corrosion is high(average mold is 4,973 t/ km^2.a), soil layer is superficial, land productive is low, chemical fertilizer is emphasized instead of organic fertilizer, agriculture strongly depends on chemical fertilizer, agricultural pollution is serious, potential harm to environment is big; also, drought and flood disasters are frequent, agricultural production is extremely unstable, economical development is slower. So this region belongs to moderate vulnerability.

Ⅳ Serious vulnerable area includes 6 areas (Pengshui, Wushan, Wuxi, Qianjiang, Yongyang, Xiushan), its area is 20,911 km^2, accounting for 30.88% of total area. In this region, middle-low mountain area occupies above 96% of breadth area, earth surface of carbonate rock salt is large (> 50%), especially above 90% in Wuxi, Qianjiang and Yongyang. Forest coverage is low, biodiversity is reduced, soil erosion area is broad (> 63.08%). The soil is mainly composed of yellow soil and calcareous soil, because of big slope and centralized rain, rainstorm runoff is seriously, it belongs to intensively erosion area

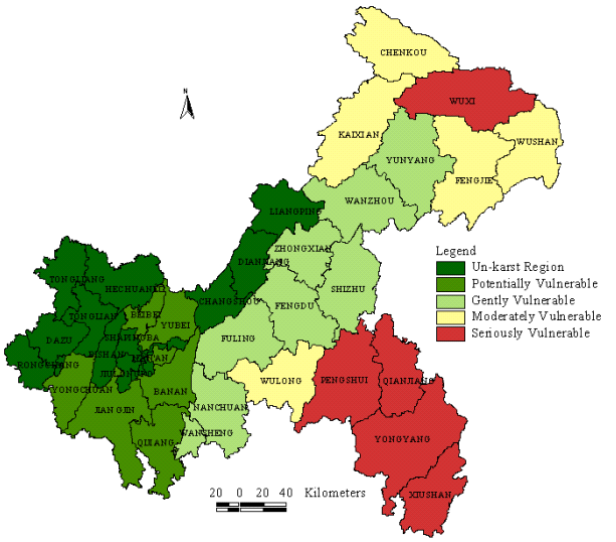

Fig.4 Rank division figure of natural disturbance vulnerability of 25 karst counties in Chongqing

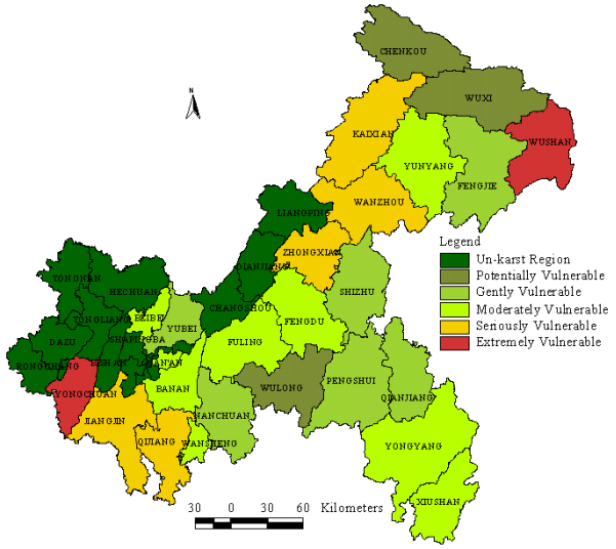

Fig.5 Rank division figure of human disturbance vulnerability of 25 karst counties in Chongqing

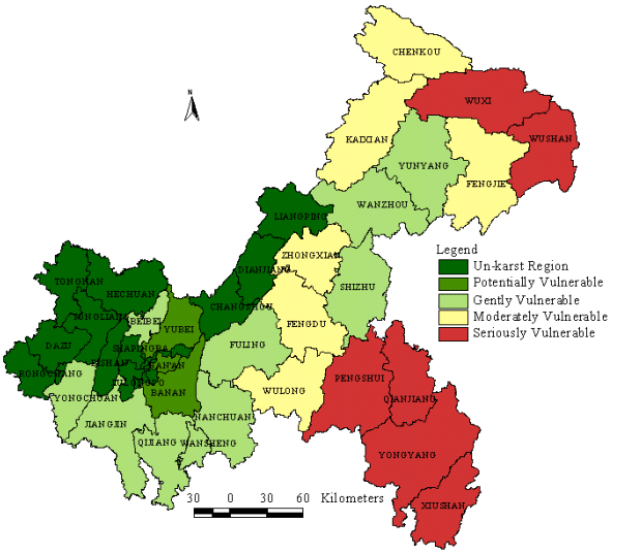

Fig.6 Rank division figure of eco-environmental comprehensive vulnerability of 25 karst counties in Chongqing

(modulus >4739t/km^2.a). The land desertification is seriously, land area above moderate sensitivity accounts for 53%, highly sensitive area approximately occupies 23.4%. Moreover, topography is rugged, transportation is unenlightened, contradiction of human-land is serious, particularly proportion of dry slope farming is big (> 44.07%), economy is backward. So this region belongs to serious vulnerability.

5 Conclusion

（1）The paper takes 25 karsts areas in Chongqing as examples, sets up a set of comprehensive and scientific index system by reasonably selecting influence factors of ecological environmental frailty of karst area, defines an objective and accurate graduation standard, uses analytic hierarchy process method to quantize weight of each index, then establishes fuzzy mathematical evaluation model, constructs judgment matrix, finally, carries on frailty rank division based on the GIS technology. It provides a reference for restoration and reconstruction of degeneration karst ecosystem and optimization of land utilization structure in Chongqing.

（2）The paper carries on quantitative evaluation for ecological environment of 25 karst counties in Chongqing using suggested index system and evaluation method, ecological environmental vulnerability is relatively divided into four gradations, there are 3 potentially vulnerable counties, 10 gently vulnerable counties, 6 moderately vulnerable counties and 6 seriously vulnerable counties. The evaluation results basically conform to actual situation of ecological environment vulnerability in Chongqing karst. In addition, evaluation method for ecological environment vulnerability of karst area is reasonable and feasible.

Acknowledgments

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References:

[1]Yuan, D.X.Karst environmental system, Proceeding of the international geographical Union Study Group,Man's Impact on Karst,1989.

[2]Li,Y.B., Hou,J.Y., Xie, D.T..The recent development of research on Karst ecology in Southwest China. *Scientia Geographica Sinica*,Vol. 22,No.3,2002,pp.365-370.(in Chinese).

[3]Gogu, R., Dassargues, A.. Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. *Environment Geology*,Vol. 39,No.6,2000,pp.549-559.

[4]Enrico, F., Laura, G.V.. Evaluation of environ -mental degradation on northern Ethiopia using GIS to integrate vegetation, geomorphological, erosion and socio-economic factors,*Agriculture Ecosystems & Environment*.2002,pp.313-323.

[5]Weltzin, J. F., McPherson, G. R., Implications of precipitation redistribution for shifts in temperate avanna ecotones, *Ecology*,Vol.81,No.7,2002,pp. 1902-1913.

[6]Van H.,A., Wiedemann, T., A monitoring tool for the provision of accessible and attractive urban green spaces,*Landscape Urban Plann*.No.63,2003,pp. 109–126.

[7]Matejicek, L., Benesova, L., Tonika, J., Ecological modeling of nitrate pollution in small river basins by spreadsheets and GIS, *Ecol. Model*,No.170,2003,pp. 245–263.

[8]Ron,S.,Jakka, J.,A GIS-based multi-scale approach to habitat suitability modeling, *Ecol.Model*,No.169,2003, pp.1-15.

[9]Arampatzis, G., Kiranoudis, C.T., Scaloubacas, P., et.al.,A GIS-based decision support system for planning urban transportation policies,*European Journal of Operational Research*,No.152,2004,pp.465-475.

[10]Chen, H.Y., Yang,Y., Hu,X.H., et al,Effective utilization of rain water resources in Karstic Mountain Region-Taking Maguan underground reservoir in Puding of Guizhou as a case, *Journal of Natural Resources, Vol.*16,No.6,2001,pp.505-510(in Chinese).

[11]Qin,X.Q., Qiang,Z.C.,An assessment of eco-environmental vulnerability in Karst counties of Guanxi, *Earth and Environment*,Vol.33.No.2, 2005,pp.45-51(in Chinese).

[12]Li,Y.B.,Gao,M., Xie,D.T.,et. al.,Land types and evaluation on Karst Mountain Regions of Chongqing, *Southwest China Journal of Agricultural Sciences*,Vol.17,No.6,2004,pp. 50-754(in Chinese).

[13]Guan, D. J., Su, W. C.,Study on GIS-based eco-environmental vulnerability assessment of KARST region in Chongqing, *Carsologica sinica*,Vol.25,No.3,2006,pp.211-219(in Chinese).

[14]Su,W.C.,Zhu,W.X.,Xiong, K.N., Stone desertification and eco-economics improving model in Guizhou Karst mountain. *Carsologica.Sinica*, Vol.21, No.1, 2002,pp.19-25(in Chinese).

[15]Tian,Y.P., Liu,P.L., Zheng,W,W.,Vulnerability assessment and analysis of hilly area in Southern China: a case study in the Hengyang Basin. *Geographica lResearch*,Vol.24,No,6,2005,pp. 843 -852.(in Chinese).

[16] Xiao, R.B., Ouyang, Z.Y., Wang, X.K., Sensitivity of rocky desertification and its spatial distribution in south western China,*Chinese Journal of Ecology*,Vol.24,No.5,2005,pp. 551-554(in Chinese).