

Vulnerability Assessment of Ecological Environment Based on Set Pair Analysis Model

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ABSTRACT

Vulnerability Assessment of Ecological environment is the main pre-technology work of regional Ecological environment protection, pollution control, engineering construction of ecological restoration and exploitation of water resources. According to the characteristics of uncertainty and fuzziness of the Vulnerability Assessment index of Ecological environment, combined with the unique ecological environment in Yunnan province, based on set pair analysis theory and entropy value method, connection degree of set pair analysis is used to describe the assessment objects and assessment standard of the same, different and opposite degree. A new Vulnerability Assessment model of Ecological environment is built based on set pair analysis method, and the model is applied to Vulnerability Assessment of Ecological environment of the yunnan province. The assessment results show that: the most area of Vulnerability Assessment of Ecological environment belong to medium level in Yunnan province, Vulnerability Assessment of Ecological environment of xishuangbanna is low, and the regional Ecological environment system structure is stable. Research and assessment conclusion are basically identical with the local actual conditions of ecological environment. The research can provide technical guidance and theoretical evidence for the regional ecological environment protection, ecological restoration and management etc.

Keywords: Ecological environment; Vulnerability; Set pair analysis; Connection degree; Assessment.

1. INTRODUCTION

Human activities continue to pose influence on environment and climate change, result in a destruction of regional ecological system. Ecological environment becomes more and more vulnerable, even human beings have been threatened. Vulnerability of ecological environment is defined as sensitivity to external interference and the restoring capacity of nature under certain time and space. It is a common result of natural attributes and human activities. The research on Ecological environment vulnerability has been a hot issue of the research about global environment change, it not only provides scientific instructions on reconstructing the ecological environment, but also holds significance to promoting the sustainable development of the economy and the society. The assessment of ecological environment vulnerability is an important aspect of the research on Ecological environment vulnerability. Currently, methods such as Fuzzy Comprehensive Assessment, Principal Component Analysis, Multi-objective Analysis and

Background Analysis take the lead, but each method has its own limitations. For Fuzzy Comprehensive Assessment, much useful indicator information is lost. Principal Component Analysis can only be applied to study the spatial difference of a fixed year in a specific region. The principle component analysis is the simply linear composition of original variables that is hard to define clearly. Multi-objective Analysis fails to consider interdependence or interaction between indicators. Background Analysis is limited to static historical background, it disconnects resources, society and environment. In terms of system evolution, assessment method is determined on the basis of attribute value and indicators, in order to reflect the evolution mechanism of the ecological environmental system. Set pair method is an effective way to study the connection between certainty and uncertainty of objects. It focuses on similarities, diversities and inverse of things, the method is easy, operable and clear definitions, this method can make up for previous methods. Thus, this paper employs set pair method to evaluate Ecological environment vulnerability and compute the weight of indicators

based on utility value of indicators reflected by information entropy. It analyzes the samples by their certainty and uncertainty, and makes quantitative assessment on how indicators influence the vulnerability of ecological environment.

2. ASSESSMENT MODEL BASED ON SET PAIR ANALYSIS MODEL

2.1. Set Pair Analysis Method

Set pair analysis theory was initially proposed by Zhao Keqin in 1989 for dealing with uncertainty. It has been widely used in assessment, planning, prediction and management. Its core lies in that certainty and uncertainty are in the same system where certainty is divided into "similarity" and "inverse" and uncertainty is divided into "diverse". It transforms uncertainty to arithmetic operations by connecting similarity, diverse and inverse.

(1) Set pair connectivity

Set pair refers to a pair of sets with certain connections. According to set pair analysis theory, properties of the pair, namely, set A and B are subject to the analysis. The connectivity of two sets is:

$$\mu = \frac{S}{N} + \frac{F}{N}i + \frac{P}{N}j = a + bi + cj \quad (1)$$

Where, μ is the connectivity; N is the number of properties. S is the number of common properties of two sets. P is the number of inverse properties of two sets. F is the number of uncertainties, and its value is $F = N - P - S$. S/N is the similarity degree of set A and B, noted as a . F/N is the diversity degree, noted as b . P/N is the inverse degree, noted as c , there is $(a + b + c = 1)$. i is the diverse coefficient. In section $[-1, 1]$, similarity and inverse take up a certain proportion in the diversity degree. j is the inverse coefficient, usually taken as -1 .

(2) Indicator connectivity

The assessment of Ecological environment vulnerability is the analysis that combines indicators and standards of certainty, indicators and attribute variations of uncertainty. The attribute of assessment indicators and the assessment standard form a set pair. Suppose there are N indicators, among which S are superior to the standard, and P are inferior to the standard, and F are in between. Compute the connectivity between samples according to formula (1) and get the rough idea of Ecological environment vulnerability. Ecological environment vulnerability at the same grade but in different regions may vary from each other. Thus, it is necessary to continue the set pair analysis.

There are two types of indicators of regional Ecological environment vulnerability, namely, the bigger-the superior, and the smaller-the superior.

For the bigger -the superior indicators, the connectivity is:

$$\mu_{sk} = \begin{cases} 1 + 0i + 0j & x \in [S_1, +\infty) \\ \frac{S_2 - x}{S_2 - S_1} + \frac{x - S_1}{S_2 - S_1}i + 0j & x \in [S_2, S_1) \\ 0 + \frac{S_3 - x}{S_3 - S_2}i + \frac{x - S_2}{S_3 - S_2}j & x \in [S_3, S_2) \\ 0 + 0i + 1j & x \in [0, S_3) \end{cases} \quad (2)$$

For the smaller-the superior indicators, the connectivity is:

$$\mu_{sk} = \begin{cases} 1 + 0i + 0j & x \in [0, S_1) \\ \frac{S_2 - x}{S_2 - S_1} + \frac{x - S_1}{S_2 - S_1}i + 0j & x \in (S_1, S_2) \\ 0 + \frac{S_3 - x}{S_3 - S_2}i + \frac{x - S_2}{S_3 - S_2}j & x \in (S_2, S_3) \\ 0 + 0i + 1j & x \in (S_3, +\infty) \end{cases} \quad (3)$$

Where, S_1, S_2, S_3 is respectively the threshold of indicator grade. Subscript k indicates that it is the k -th indicator. Subscript s is the s -th object. x is the real value of the k -th indicator of the s -th object.

2.2. Weight of Indicator

Information entropy method determines the weight according to the amount of information an indicator provides. According to the theory of information, acquiring entropy means losing information. The more orderly the system is, the smaller the entropy and the more the information, and vice versa. Thus, entropy can be used to evaluate the effectiveness of all information and allocate weights to indicators. Weight of indicator is computed as below:

(1) Construct the judgment matrix R

Suppose there are m objects for assessment. Each object has n indicators, the judgment matrix is:

$$R = (r_{st})_{m \times n} \quad (4)$$

Where, r_{st} is the attribute value of the t -th indicator of the s -th object.

(2) Normalization

Normalize the judgment matrix R and get the normalized judgment matrix B .

For the bigger-the superior indicator, it is computed as:

$$b_{st} = \frac{r_{st} - r_{\min}}{r_{\max} - r_{\min}} \quad (5)$$

For smaller-the superior indicator, it is computed as:

$$b_{st} = \frac{r_{\max} - r_{st}}{r_{\max} - r_{\min}} \quad (6)$$

Where, b_{st} is the element of normalized matrix B .

r_{\max}, r_{\min} are the best and worst under the same indicator.

(3) Compute the entropy of an indicator

According to the definition of entropy in the theory of information, the entropy of an indicator is defined as:

$$H_i = -\left(\sum_{s=1}^m f_{st} \ln f_{st}\right) / \ln m \quad (7)$$

Where, there is $f_{st} = b_{st} / \left(\sum_{i=1}^m b_{st}\right)$, obviously, when

$f_{st} = 0$, $\ln f_{st}$ is meaningless. So we need to adjust f_{st} by:

$$f_{st} = (1 + b_{st}) / \sum_{s=1}^m (1 + b_{st}) \quad (8)$$

(4) Compute the entropy coefficient

The entropy coefficient of each indicator is computed as:

$$W = (w_i)_{1 \times n} \quad (9)$$

Where, $w_i = (1 - H_i) / \left(n - \sum_{i=1}^n H_i\right)$, and $\sum_{i=1}^n w_i = 1$

2.3. Set Pair Analysis Model Based on Entropy

First of all, use the assessment standard of Ecological environment vulnerability and formula (1) to compute the connectivity μ_s of the object s . Then, use formula (2) and (3) to analyze the set pair and get the connectivity μ_{sk} of the k -th indicator. Use formula (4)-(9) to compute the weight vector of each indicator. The set pair analysis model based on entropy coefficient is constructed as:

$$\mu'_s = \mu_s \sum_{i=1}^n (w_i \mu_{si}) \quad (10)$$

Normalize the component of μ'_s in terms of similarity, diversity and inverse and can get $\overline{\mu'_s}$. We can judge the grade of the object by comparing a , b and c . If there is $\max[a, b, c] = b$, then the object is of grade II.; if there is $\max[a, b, c] = a$ and $a + b \geq 0.7$, the object is of grade I; otherwise, it is of grade II. If $\max[a, b, c] = c$, and $a + b \geq 0.7$, the object is of grade III; otherwise, it is of grade II.

3. EXAMPLE APPLICATION

3.1. Introduction of the Region

Yunnan Province locates in Southwest of China, and it is the typical mountain-ravine landform. Separated by Yuanjiang valley and the gully valley at the south range of Yunling Mountain, the northwest of Yunnan is higher than the southeast. There stands Gaoligong Mountain, Nuijiang River, Nushan Mountain, Lancangjiang River, Yunling Mountain and Jinshajiang River from west to east. Mountains cover 84% of the total area, plateau and hills, 10%, and basin and river valleys, 6%. Yunnan Province is 200m above sea level, with the highest altitude reaching 6740m and the lowest altitude, 76.4m. Influenced by topography and the climate, this region presents the phenomenon of "hot in the north and cool in the south". The most prominent feature about the ecological environment in Yunnan Province is that it is complicated with clear wet and dry seasons. Natural resources are unevenly distributed. Regional eco system is degraded and turns fragile, resulting in lower capacity of production and restoration. Natural disasters such as soil and water erosion and cultivation at hilly land, flooding in rain season and drought in the spring, earthquake, landslide, etc., all take its toll on the stability of the ecological environment in Yunnan Province.

3.2. Constructing Assessment Indicators

Currently, there is no complete or unified assessment index system for Ecological environment vulnerability. Indicators for vulnerability assessment are selected often according to region characteristics and relying on experience of researchers and experts, thus there is much subjectivity. According to the theory of system evolution, the vulnerability of regional eco-system is subject to resources, geography and climate, etc. The evolution of eco-system is driven by sub-system and overall system. Thus, social economy, ecological environment, system coordination and real situation stand as assessment standards for constructing indicators of vulnerability of ecological environment. Reliability, completeness, dynamism and operability need to be taken into account. Based on these rules, we determine 10 indicators of Ecological environment vulnerability, namely, population density, land reclamation coefficient, water production module, forest coverage rate, sewage treatment rate, water resources carrying index, per capita water resources, per capita GDP, natural population growth rate and water use ratio of river, as is shown in Table 1. The attribute value of each indicator is shown in Table 2.

Table 1. Indicator system of Ecological environment vulnerability in Yunnan province

Indicator code	Indicator	Unit	Meaning/ Calculation method
T ₁	population density	person/km ²	Number of people / Land area
T ₂	land reclamation coefficient		Arable land / land area
T ₃	water production module	m ³ /km ² •a	Total regional water / regional land area•year
T ₄	forest coverage rate	%	Forest area / land area
T ₅	sewage treatment rate	%	Sewage treatment capacity / total volume of sewage
T ₆	water resources carrying index		Reflecting the support capacity of regional socio-economy and ecological environment
T ₇	per capita water resources	(m ³ /person)	Total water resources/ total number of people
T ₈	per capita GDP	(Yuan)	GDP/ total number of people
T ₉	natural population growth rate	(%)	Increasing the number of people / Average population
T ₁₀	water use ratio of river	(%)	River water consumption / average runoff

Table 2. The attribute value of each indicator of every region

No.	Region	population density	land reclamation coefficient	water production module	forest coverage rate	sewage treatment rate	water resources carrying index	per capita water resources	per capita GDP	natural population growth rate	water use ratio of river
1	Kunming	321.76	0.78	30.83	45.00	91.7	5.62	958.30	19283.15	5.80	0.49
2	Qujing	209.37	0.81	46.01	40.30	35.6	0.98	2197.58	7579.38	7.00	0.15
3	Yuxi	153.67	0.85	29.04	62.00	68	3.85	1889.74	25903.81	5.60	0.19
4	Zhaotong	226.99	0.86	56.40	30.10	30.8	0.50	2484.56	4416.09	9.00	0.06
5	Chuxiong	98.69	0.82	22.17	60.50	60	1.00	2246.09	8046.37	4.70	0.14
6	Honghe	141.59	0.75	66.43	43.00	54.4	0.40	4691.72	6659.35	6.90	0.08
7	Whenshan	114.00	0.76	51.16	48.00	35	0.26	4487.24	4137.84	7.40	0.06
8	Xishuangbanna	56.95	0.87	53.39	75.00	46.6	0.26	9374.68	8919.39	6.50	0.06
9	Dali	128.27	0.82	34.95	57.00	66	0.80	2724.44	7828.53	5.20	0.20
10	Baoshan	135.53	0.81	82.52	60.00	36.8	0.26	6088.68	5685.52	5.90	0.07
11	Dehong	106.01	0.87	122.86	55.00	51	0.15	11589.17	6477.90	7.60	0.07
12	Lijiang	60.86	0.82	39.13	64.00	66.5	0.22	6430.53	5156.44	4.50	0.08
13	Diqing	16.88	0.86	54.00	72.00	25.6	0.04	31986.85	4991.90	6.50	0.01
14	Lincang	107.91	0.84	70.33	60.00	28.9	0.19	6516.96	4582.85	6.40	0.06

Table 3. Assessment grading standards of each indicator

Grading	population density	land reclamation coefficient	water production module	forest coverage rate	sewage treatment rate	water resources carrying index	per capita water resources	per capita GDP	natural population growth rate	water use ratio of river
I	<25	<0.2	>30	>70%	>70%	>1	>3000	>6000	<3%	<0.2%
II	25-100	0.2-0.4	10-30	30%-70%	30%-70%	0.5-1	1700-3000	3000-6000	3%-7%	0.2%-0.4%
III	>100	>0.4	<10	<30%	<30%	<0.5	<1700	<3000	>7%	>0.4%

3.3. Assessment Standard

The selection of assessment standard of Ecological environment vulnerability is key to vulnerability assessment. For a specific region, all types of eco-system have their own ideal state. But sometimes, they can be degraded to a low quality state. The “ideal” state, normal state and the “least ideal state”, combined with indicator features can form a series of indicator standards. The grade of regional Ecological environment vulnerability should meet the requirement of regional planning on the function of eco-system, and reflect regularities and possibilities of different eco-system types and natural conditions. Otherwise,

there may be conflicts under major constraints (e.g. the system is controlled by some indicators or there are weaknesses), which is a departure of objective result. According to natural conditions, geology, resources and environment of Yunnan Province, this paper prepares three grades (see table 3) for the assessment of regional Ecological environment vulnerability. The greater the grade is, the more vulnerable the environment. Grade I means that the ecological environment is the least vulnerable. Grade II indicates that the ecological environment is mediocrelly vulnerable and Grade III indicates that the ecological environment is the most vulnerable.

3.4. Vulnerability Assessment

Based on the model, compute the connectivity of set pair according to formula (1). That is:

$$\begin{aligned}\mu_1 &= \frac{4}{10} + \frac{2}{10}i + \frac{4}{10}j, \mu_2 = \frac{3}{10} + \frac{4}{10}i + \frac{3}{10}j; \\ \mu_3 &= \frac{3}{10} + \frac{5}{10}i + \frac{2}{10}j, \mu_4 = \frac{2}{10} + \frac{4}{10}i + \frac{4}{10}j; \\ \mu_5 &= \frac{2}{10} + \frac{6}{10}i + \frac{2}{10}j, \mu_6 = \frac{4}{10} + \frac{3}{10}i + \frac{3}{10}j; \\ \mu_7 &= \frac{3}{10} + \frac{3}{10}i + \frac{4}{10}j, \mu_8 = \frac{5}{10} + \frac{3}{10}i + \frac{2}{10}j; \\ \mu_9 &= \frac{5}{10} + \frac{2}{10}i + \frac{3}{10}j, \mu_{10} = \frac{3}{10} + \frac{4}{10}i + \frac{3}{10}j; \\ \mu_{11} &= \frac{4}{10} + \frac{2}{10}i + \frac{4}{10}j, \mu_{12} = \frac{3}{10} + \frac{5}{10}i + \frac{2}{10}j; \\ \mu_{13} &= \frac{5}{10} + \frac{2}{10}i + \frac{3}{10}j, \mu_{14} = \frac{3}{10} + \frac{3}{10}i + \frac{4}{10}j.\end{aligned}$$

Compare the connectivity of 14 objects, we can see 8, 9 and 13 are the least vulnerable; 1, 4, 11, 14 are the most vulnerable. 1 and 11, 2 and 10, 7 and 14 and 9 and 13 are in the same grade. Even though the vulnerability degree of the ecological environment in different regions is of the same grade, it doesn't mean the vulnerability degree of the ecological environment is of the same value. To better evaluate the connection between indicator value and the grade, we continue the set pair analysis.

Take object I as an example, compute the connectivity of indicators about the grade according to formula (2) and (3):

According to formula (4) to (9), compute the weight of indicators $W = (0.065, 0.131, 0.090, 0.119, 0.108, 0.133, 0.099, 0.125, 0.073, 0.055)$. Compute the average connectivity of the object according to formula (10):

$$\mu'_1 = 0.182 + 0.015i + 0.136j$$

Normalize it and we can get:

$$\bar{\mu}'_1 = 0.547 + 0.045i + 0.408j$$

Similarly, compute the average connectivity of other objects:

$$\begin{aligned}\bar{\mu}'_2 &= 0.233 + 0.231i + 0.536j, \bar{\mu}'_3 = 0.310 + 0.303i + 0.388j; \\ \bar{\mu}'_4 &= 0.075 + 0.541i + 0.383j, \bar{\mu}'_5 = 0.210 + 0.515i + 0.275j; \\ \bar{\mu}'_6 &= 0.123 + 0.491i + 0.386j, \bar{\mu}'_7 = 0.168 + 0.231i + 0.584j; \\ \bar{\mu}'_8 &= 0.725 + 0.084i + 0.191j, \bar{\mu}'_9 = 0.369 + 0.085i + 0.547j; \\ \bar{\mu}'_{10} &= 0.200 + 0.326i + 0.475j, \mu_{11} = 0.382 + 0.058i + 0.560j; \\ \mu_{12} &= 0.399 + 0.179i + 0.423j, \mu_{13} = 0.563 + 0.025i + 0.412j; \\ \mu_{14} &= 0.177 + 0.083i + 0.740j.\end{aligned}$$

We can hereby judge the grade of the vulnerability and compare it with the result obtained by Fuzzy Comprehensive Assessment. We can see that most ecological environments in the region are mediocly

vulnerable. The vulnerability of Xishuangbanna is the lowest and the eco-system functions well with a good coordination and structure. It is in line with the real Diqing and Lijiang obtained through this method is different from that through fuzzy comprehensive assessment. It may be because some information is lost during indicator selection or there exist minor differences in the grading standard.

4. CONCLUSIONS

(1) Conducting vulnerability assessment of ecological environment is significant to environment planning, ecological restoration project and the exploitation of water resources in the region. It provides instructions on preventing the ecological environment from degraded and is sign cant to reduce the vulnerability.

(2) According to features of society, economy, natural conditions, geological conditions, resources and ecology, this study constructs an assessment index system for Ecological environment vulnerability. Set pair analysis method is applied to the assessment. Arithmetic operations and the concept of connectivity are introduced to describe the uncertainty. Entropy is used to evaluate the effectiveness of all information in order to determine the weight of indicators. Set pair analysis model is established for comprehensive assessment on Ecological environment vulnerability.

(3) Assessment result shows that regional ecological environment is mediocly vulnerable. Xishuangbanna is the least vulnerable with a stable ecological system. Sub-regions in Yunnan Province are supposed to take active measures to prevent environment from degradation and boost the sustainable development of the region.

(4) Set pair analysis method is new try to the vulnerability assessment of ecological environment in Yunnan province. But there are still limitations, for example, the selection of indicators and the determination of grading standard have some subjectivity, leaving room for improvement.

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