VULNERABILITY OF ASSESSING WATER RESOURCES BY THE IMPROVED SET PAIR ANALYSIS

by

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Climate change has tremendously changed the hydrological processes with global warming. There are many uncertainties in assessing water resources vulnerability. To assess the water resources vulnerability rationally under climate change, an improved set pair analysis model is established, in which set pair analysis theory is introduced and the weights are determined by the analytic hierarchy process method. The index systems and criteria of water resources vulnerability assessment in terms of water cycle, socio-economy, and ecological environment are established based on the analysis of sensibility and adaptability. Improved set pair analysis model is used to assess water resource vulnerability in Ningxia with twelve indexes under four kinds of future climate scenarios. Certain and uncertain information quantity of water resource vulnerability is calculated by connection numbers in the improved set pair analysis model. Results show that Ningxia is higher vulnerability under climate change scenarios. Improved set pair analysis model can fully take advantage of certain and uncertain knowledge, subjective and objective information compared with fuzzy assessment model and artificial neural network model. The improved set pair analysis is an extension to the vulnerability assessment model of water resources system.

Key words: *assessment, water resources vulnerability, climate change, Ningxia, improved set pair analysis*

Introduction

In the last decades, the average global surface temperature has increased by 0.74 °C. With global warming, climate change has greatly changed the regional hydrological cycles [1, 2]. Water resources vulnerability assessment has become a hot topic in the field of water resource management. In the background of climate change, the research on water resources vulnerability is relatively weak [3, 4]. As the response of regional water to climate change, water resources vulnerability will be an important basis for decision-making about regional water resources management. The influencing factors to water resource vulnerability are various. Assessment of water resource vulnerability is the process of multiple objective decision-makings, in which mathematics model needs to be established to provide scientific basis for the sustainable exploitation and utilization of water resources with multiple indices. General assessment methods included fuzzy set theory, artificial neural network model, analytic hierarchy process (AHP) and so on [5, 6]. Those assessment methods have some

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difficulties for assessing water resource vulnerability. The main reasons are given as: (1) It is very difficult to decide the index weights [6, 7]. (2) Although previous study had given similar classification index, they usually focused on one total index which cannot give the uncertain information.

Set pair analysis (SPA) theory was proposed by Keqin Zhao in 1989 [8]. The theory has advantage to deal with uncertainties [9]. Therefore, to solve the above problems, an improved set pair analysis (ISPA) model, is established, in which set pair analysis theory is introduced and the weights are determined by AHP method for water resource vulnerability assessment. Certain-uncertain information quantity of water resource vulnerability is calculated with ISPA model in Ningxia. Finally, ISPA model is used to assess water resource vulnerability in Ningxia under different climate scenarios.

Steps of ISPA model for assessing water resource vulnerability

SPA is a novel mathematical tool dealing with certain-uncertain information. The core of this theory is to consider certainties and uncertainties by the connection number index from the aspects of identity-discrepant-contrary [9]. ISPA model combines the AHP method and set pair analysis theory. The detail steps of ISPA model are given as follows.

Step 1. Determination of the weights for each index

The weights are determined by AHP model [8].

Step 2. Determination of the connection number

The n-member connection number μ_m of index layer I_m is given as:

$$\mu_m = r_{m1} + r_{m2}i_1 + r_{m3}i_2 + \cdots + r_{m(n-1)}i_{n-2} + r_{mn}j \tag{1}$$

where μ_m is determined by the formula in the related reference [9].

The n-member connection number of goal layer is:

$$\mu = r_1 + r_2 i_1 + r_3 i_2 + \cdots + r_{(n-1)}i_{n-2} + r_n j, \quad r_l = \sum_{m=1}^{M} w_m r_{ml} \quad (1 \le l \le n) \tag{2}$$

where r_1 is the component of I_m related to $C_l \sim C_{l+1}$ degree, w_m – the weight of I_m, μ – the n-member connection number of goal layer, r_1, $r_2 \cdots r_n$ – the correlative coefficients of each index layer, i_1, $i_2 \cdots i_{n-2}$ – the identical-discrepancy-contrary, and j – the contrary coefficient.

Step 3. Calculation of the certain information quantity and uncertain information quantity

The certain information quantity Q_i and uncertain information quantity Q_{ui} are expressed as:

$$Q_i = 1 - \frac{\sum_{k=2}^{n-1} r_k}{\sum_{k=1}^{n} r_k}, \quad Q_{ui} = \frac{\sum_{k=2}^{n-1} r_k}{\sum_{k=1}^{n} r_k} \tag{3}$$

Step 4. Calculation of the n-member connection number value of each layer

Supposing $\mu = r_1 + r_2 i_1 + r_3 i_2 + \ldots + r_{(n-1)} i_{n-2} + r_n j$ as n-member connection number, $\mu \in [-1, 1]$, we equally divide the interval [–1, 1] for determining the value of $i_{n-2}, i_{n-1}, \ldots, i_2, i_1$.

Step 5. Determination of the degree of water resource vulnerability assessment

Equally dividing interval [–1, 1], every interval corresponds to degree of $C_1, C_2, \ldots, C_n, C_{n+1}$. Comparing with the value of evaluation degree and connection number, we can obtain the degree of water resource vulnerability.

Assessment of water resource vulnerability in Ningxia

Ningxia is located in the west northern part of China. Aiming at Ningxia, the degree of water resource vulnerability can be divided into 5 grades (or levels) with twelve indices: lowest (1 or I), lower (2 or II), middle high (3 or III), higher (4 or IV), highest (5 or V). We use the four scenarios on climate change. Scenario I stands for the rainfall which is increased by 10%; Scenario II stands for the rainfall which is decreased by 10%; Scenario III stands for the rainfall which is increased by 20%; Scenario IV stands for the rainfall decreased by 20%.

Assessment standard

According to the principle of scientificalness, representative, completeness and operability, the index systems and criteria of water resources vulnerability assessment in terms of water cycle, socio-economy, and ecological environment are established based on the analysis of sensibility and adaptability in this study. The 12 indices which can reflect sensitive to climate change and water resources are selected as final assessment indices. Table 1 shows the assessment indices and standard on water resource vulnerability.

Table 1. Assessment indices and standard on water resource vulnerability

Assessment indices	Split point of each grade				
	I	II	III	IV	V
No. 1. Annual precipitation, [mm]	>800	600	400	250	<250
No. 2. Flood and drought area ratio, [%]	<0.05	0.30	0.45	1.0	>1.0
No. 3. Per capita water resources, [m^3 per capita]	>3000	1500	800	300	<300
No. 4. Per area water resources, [ten thousand $m^3 km^{-2}$]	>1500	600	300	100	<100
No. 5. The vegetation coverage ratio, [%]	>34.0	25.0	10.0	4.5	<4.5
No. 6. Per capita water use, [m^3 per capita]	<180	240	300	750	>750
No. 7. Population density, [people per km^2]	<50	220	550	1000	>1000
No. 8. Per capita GDP, [ten thousand yuan per capita]	>6.0	4.5	2.5	1.6	<1.6
No. 9. Cultivated land area ratio, [%]	<1.0	2.8	4.0	5.5	>5.5
No. 10. Reservoir's regulation capacity	>0.1	0.048	0.025	0.011	<0.011
No. 11. Daily treatment capacity of wastewater, [ten thousand m^3]	>90	85	75	65	<65
No. 12. Compliance percent of water function area, [%]	>80.0	50.5	28.2	7.1	<7.1

Results and analysis

Application of ISPA in water resource vulnerability assessment, the indices of water resource vulnerability assessment are seen as set A, and the evaluation grades of water resource vulnerability assessment are seen as set B, then the two sets constitute a set pair H = (A, B). Based on ISPA model, the optimal weight vector w is obtained as:

$$w = (0.18\ 0.12\ 0.15\ 0.06\ 0.06\ 0.006\ 0.048\ 0.064\ 0.048\ 0.096\ 0.072\ 0.096) \tag{4}$$

Then the four-member connection degree of each index can be obtained according to tab. 1. The weight of each index and the four-member connection degree of I_m in Ningxia at present are given as tab. 2.

Table 2. The connection degree of Ningxia at present

Index number	Weight of each index	Connection degree
No. 1	0.180	$\mu_1 = 0.3410i_2 + 0.6590j$
No. 2	0.120	$\mu_2 = 1.0000j$
No. 3	0.150	$\mu_3 = 1.0000j$
No. 4	0.060	$\mu_4 = 1.0000j$
No. 5	0.060	$\mu_5 = 0.9709i_2 + 0.0291j$
No. 6	0.006	$\mu_6 = 1.0000j$
No. 7	0.048	$\mu_7 = 0.5775 + 0.4225i_1$
No. 8	0.064	$\mu_8 = 0.0850i_1 + 0.9150i_2$
No. 9	0.048	$\mu_9 = 1.0000$
No. 10	0.096	$\mu_{10} = 0.4286i_2 + 0.5714j$
No. 11	0.072	$\mu_{11} = 0.3000i_1 + 0.7000i_2$
No. 12	0.096	$\mu_{12} = 0.2287i_1 + 0.7713i_2$

Based on above weight vector w, we calculate the four-member connection number by summarizing the connection degree of 12 indices. For example, the certain-information quantity and uncertain-information quantity in Ningxia under different scenarios are in tab. 3. CIQ stands for certain-information quantity, and UIQ stands for uncertain-information quantity.

From tab. 3, we can see that there is much uncertain-information quantity of water resources vulnerability assessment in the Ningxia under the above different scenarios. Here we let $i_1 = 1/3, i_2 = -1/3,$ and $j = -1,$ the total connection number (TCN) can be obtained, and the TCN value is –0.5270 at present. The connection number of water resource vulnerability in the Ningxia is given in tab. 4 under different climate change scenarios.

Table 3. Uncertain-information quantity of water resource vulnerability in Ningxia under different scenarios

Scenario	Connection degree	CIQ	UIQ
Present	$\mu_1 = 0.0757 + 0.0693i_1 + 0.3438i_2 + 0.5112j$	0.5869	0 .4131
Scenario I	$\mu_2 = 0.0757 + 0.0693i_1 + 0.3799i_2 + 0.4751j$	0.5508	0 .4492
Scenario II	$\mu_3 = 0.0757 + 0.0693i_1 + 0.3076i_2 + 0.5474j$	0.6231	0.3769
Scenario III	$\mu_4 = 0.0757 + 0.0693i_1 + 0.4161i_2 + 0.4390j$	0.5147	0.4853
Scenario IV	$\mu_5 = 0.0757 + 0.0693i_1 + 0.2824i_2 + 0.5726j$	0.6483	0.3517

Interval [–1, 1] is divided into 5 parts: (0.6, 1], (0.2, 0.6], (–0.2, 0.2], (–0.6, –0.2], [–1, –0.6]. These intervals correspond to the lowest (1 or I), lower (2 or II), middle high (3 or III), higher (4 or IV), highest (5 or V) evaluation grades of water resource vulnerability, respectively. Taking present as an example, the four-member connection number is –0.5270, which corresponds the interval (–0.6, –0.2], so the evaluation grade of water resource vulnerability of Ningxia is higher (4 or IV).

Comprehensive assessment results of water resources vulnerability in Ningxia based on ISPA model under different climate change scenarios are given in tab. 4. Here FAM stands for fuzzy assessment model, and ANN stands for artificial neural network model.

From tab. 4, it can be concluded that: as to water resource vulnerability, Ningxia is higher (4 or IV) under above different climate change scenarios. Especially, compared with present situation, it will become better under scenario I and III, and will become worse under scenario II and IV.

Table 4. The assessment result of water resource vulnerability in Ningxia under different scenarios

Index /models	Assessment result				
	Present	Scenario I	Scenario II	Scenario III	Scenario IV
TCN	–0.5270	–0.5029	–0.5511	–0.4788	–0.5679
ISPA	4	4	4	4	4
FAM	4	4	4	4	4
ANN	4	4	4	4	4

Conclusions

In order to assess the water resource vulnerability scientifically, an ISPA model is established, which combines the AHP and set pair analysis. The above model is used to assess the water resource vulnerability in Ningxia. The main conclusions are:

- ISPA can not only determine the weight, but also calculate the certain and uncertain information quantity of water resource vulnerability in Ningxia. ISPA is a new way to assess water resource vulnerability.
- Compared with the FAM and ANN models, ISPA can fully take advantage of subjective and objective information, which makes the assessment result more reasonable.
- As to water resource vulnerability in Ningxia with ISPA model, we can see that, Ningxia are higher vulnerability (4 or IV) under above different climate change scenarios. Especially, compared with present situation, water resource vulnerability in Ningxia will become better under scenario I and III, and will become worse under scenario II and IV.

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