Comprehensive Assessment of Water Resources Vulnerability Based on ISPA Model under Climate Change in Haihe River Basin

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Comprehensive Assessment of Water Resources Vulnerability Based on ISPA Model under Climate Change in Haihe River Basin

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Abstract: Water resource system is a complex uncertain system under climate change. To assess the water resources vulnerability rationally, an improved set pair analysis (ISPA) model is established, in which set pair analysis theory is introduced and the weights are determined by use of the maximum entropy principle and the improved analytic hierarchy process method. And the index systems and criteria of water resources vulnerability assessment are established in this study. Uncertainties are analyzed in the assessment of water resource vulnerability by use of the ISPA model. ISPA model is used to assess water resource vulnerability of seven administrative divisions in the Haihe River Basin under four kinds of future climate scenarios. Certain and uncertain information quantity of water resource vulnerability is calculated by connection numbers in the ISPA model. Results show that ISPA model can fully take advantage of certain and uncertain knowledge, subjective and objective information compared with fuzzy assessment model and artificial neural network model. Finally, we make some suggestions for water resources management in Haihe River Basin.

Keywords: water resources vulnerability; assessment; climate change; Haihe River Basin; improved set pair analysis.

1. INTRODUCTION

Water resources vulnerability assessment has become a hot topic in the field of water resource management (Fowler et al., 2003; Lilian et al., 2008; Zhang, 2013). The increasing impacts of human activities and climate change have imposed great challenges on water resource vulnerability in the world. In the background of climate change, water resources vulnerability research is relatively weak (Xia, 2003). The third report of IPCC (2001) defines vulnerability as the scope or degree of natural and social system, which is easy to suffer from the climate change. As the response of regional water to climate change, water resources vulnerability will be an important basis for decision-making for regional water resources management.

The influencing factors to water resource vulnerability are various. These factors influence each other and constitute a system which has the features of hierarchy, uncertainty and complexity. So, the 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 and so on (Cohon et al., 1975; Chu et al., 1979; Maier et al., 1996; Iliadis et al., 2007; Saaty 2007). Those assessment methods have some difficulties for assessing water resource vulnerability rationally. The main reasons are given as follows: (1) It is very difficult to decide the index weights (Yang et al., 2004). (2) Although previous study had given similar classification index, they usually focused on one total index which could represent the assessment result that can not give the uncertain information and can not find which factor plays an important role in the assessment system.
Set pair analysis (SPA) theory was proposed by Keqin Zhao in 1989 (Zhao, 2000). The theory has advantage to deal with uncertainties (Yang et al., 2011). 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 use of maximum entropy principle and AHP method for water resource vulnerability assessment. Certain- uncertain information quantity of water resource vulnerability is calculated with ISPA model in Haihe River Basin. Finally, ISPA model is used to assess water resource vulnerability of seven administrative divisions in the Haihe River Basin under different climate scenarios.

2. MODELING APPROACH

In this study, the set pair analysis (SPA), maximum entropy, improved analytic hierarchy process (IAHP) method are employed to assess water resource vulnerability. For more details of SPA and IAHP, please see the references (Guo et al., 2011; Yang et al., 2011; Mei et al., 2013). The improved set pair analysis (ISPA) model is established by combining set pair analysis (SPA) theory, maximum entropy principle and AHP method for water resource vulnerability assessment. The overall ISPA processes of the modeling framework are as follows:

**Step 1.** Determine the weights for each index by use of the maximum entropy principle and the improved analytic hierarchy process (IAHP) model (Mei et al., 2013).

**Step 2.** Determine the connection number. The $n$-member connection number $\mu_m$ of index layer is given as follows:

$$\mu_m = r_{m1} + r_{m2} + \cdots + r_{m(n-1)} + r_{mn}$$ (1)

The $n$-member connection number $\mu$ of goal layer is:

$$\mu = r_1 + r_2 + \cdots + r_{(n-1)} + r_n = \sum_{m=1}^{M} w_m r_{mg} \quad (1 \leq l \leq n)$$ (2)

$\mu_m, \mu$ are determined using the formula in the references (Guo et al., 2011; Yang et al., 2011; Mei et al., 2013). $w_m$ is the weight of index layer. $r_i$ is the component of $I_m$ related to $C_i \sim C_{i-1}$ degree. $i_1, i_2, \cdots, i_{n-2}$ represent identical-discrepancy-contrary, and $j$ represents contrary coefficient.

**Step 3.** Calculate the certain information quantity and uncertain information quantity. The certain information quantity and uncertain information quantity are calculated as the reference (Yang et al., 2011).

**Step 4.** Determine the assessment degree by above connection numbers. Equally dividing interval $[-1,1]$, every interval corresponds to assessment degree of $C_1, C_2, \cdots, C_n, C_{n+1}$. Through comparing with the value of evaluation degree and connection number, we can obtain the assessment degree of water resource vulnerability.

3. ASSESSMENT OF WATER RESOURCE VULNERABILITY IN THE HAIHE RIVER BASIN

Haihe River Basin is located in the northern part of China. The average annual precipitation is 534.8 mm. In this study, Haihe River Basin is divided into seven administrative divisions. Aiming at Haihe River Basin, the degree of water resource vulnerability can be divided into the following five grades (or levels, degrees) with twelve indices. We use the four scenarios on climate change according to the reference (Zhang, 2013). 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 which is decreased by 20%.
3.1 Assessment index and standard

According to the principle of scientificality, representativeness, completeness and operability, the index systems and standard of water resources vulnerability assessment in terms of water cycle, socio-economy, and ecological environment are established based on the analysis of sensitivity and adaptability in this study. The following twelve indices which can reflect sensitive to climate change and water resources are selected as final assessment indexes. The twelve indices are as follows: (a) Sensitive index to climate change: No.1, Annual precipitation (mm); No.2, Flood and drought area ratio (%); (b) Sensitive index to water resources: No.3, Per capita water resources (m³/Per capita); No.4, Per area water resources (Trend thousand m³/km²); No.5, The vegetation coverage ratio (%); No.6, Per capita water use (m³/Per capita); (c) Condition of social and economy: No.7, Population density (Person/km²); No.8, Per capita GDP (Trend thousand yuan/Per capita); No.9, Cultivated land area ratio (%); (d) Support ability of water resources: No.10, Reservoir’s regulation capacity; No.11, Daily treatment capacity of wastewater (Trend thousand m³); No.12, Compliance percent of water function area (%).

In this study, assessment degree of water resource vulnerability is divided into five grades. The meaning of each grade of water resource vulnerability is showed as follows: (a) Highest degree (5 or V) indicates water resource system is the highest vulnerability; (b) Higher degree (4 or IV) indicates water resource system is very high vulnerability; (c) Middle high degree (3 or III) indicates water resource system is the middle vulnerability; (d) Lower degree (2 or II) indicates water resource system is the low vulnerability; (e) Lowest degree (1 or I) indicates water resource system is not vulnerability. Split points of the grade standard of each index are given in the relative reference (Zhang, 2013).

3.2 Results and analysis

Based on ISPA model method, the optimal weight vector w is obtained as follows: \( w = (0.18, 0.12, 0.15, 0.06, 0.06, 0.006, 0.048, 0.064, 0.048, 0.096, 0.072, 0.096) \). Then, based on above weight vector w, we calculate the four-member connection number of each province when summarizing the connection degree of twelve indices. For example, the certain-information quantity, uncertain-information quantity of seven administrative divisions in the Haihe River Basin at present situation is in Table 1. CIQ stands for certain-information quantity, and UIQ stands for uncertain-information quantity.

<table>
<thead>
<tr>
<th>Province</th>
<th>Four-member connection degree</th>
<th>CIQ</th>
<th>UIQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shanxi</td>
<td>( \mu_i = 0.0060 + 0.3384i_1 + 0.2296i_2 + 0.4260j )</td>
<td>0.4320</td>
<td>0.5680</td>
</tr>
<tr>
<td>Shandong</td>
<td>( \mu_2 = 0.1571 + 0.2217i_1 + 0.2367i_2 + 0.3845j )</td>
<td>0.5416</td>
<td>0.4584</td>
</tr>
<tr>
<td>Henan</td>
<td>( \mu_3 = 0.1756 + 0.2125i_1 + 0.3230i_2 + 0.2888j )</td>
<td>0.4644</td>
<td>0.5356</td>
</tr>
<tr>
<td>Tianjin</td>
<td>( \mu_4 = 0.1223 + 0.2844i_1 + 0.1109i_2 + 0.4824j )</td>
<td>0.6047</td>
<td>0.3953</td>
</tr>
<tr>
<td>Inner Mongolia</td>
<td>( \mu_5 = 0.0666 + 0.3334i_1 + 0.1622i_2 + 0.4377j )</td>
<td>0.5044</td>
<td>0.4956</td>
</tr>
<tr>
<td>Hebei</td>
<td>( \mu_6 = 0.0720 + 0.2803i_1 + 0.2179i_2 + 0.4298j )</td>
<td>0.5018</td>
<td>0.4982</td>
</tr>
<tr>
<td>Beijing</td>
<td>( \mu_7 = 0.2738 + 0.3389i_1 + 0.0693i_2 + 0.3180j )</td>
<td>0.5918</td>
<td>0.4082</td>
</tr>
</tbody>
</table>
Figure 1. Uncertain-information quantity of water resources vulnerability assessment in the Haihe River Basin based on ISPA model under different scenarios.

From Figure 1, we can see that there is much uncertain-information quantity of water resources vulnerability assessment in the Haihe River Basin under the above different scenarios.

Take Shanxi province as an example, according Table 1 and ISPA’s formulas, let $i_1 = 1/3, i_2 = -1/3, j = -1$, and then the four-member connection number can be obtained, and the value is 0.3838. The 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 grade of water resource vulnerability respectively. Also taking Shanxi as an example, the four-member connection number is 0.3838, which corresponds the interval (-0.6, -0.2], so the evaluation grade of water resource vulnerability of Shanxi is higher (4 or IV).

Comprehensive assessment results of water resources vulnerability of seven administrative divisions in the Haihe River Basin based on ISPA model under different climate change scenarios are given in Table 2 and Figure 2. Here FAM stands for fuzzy assessment model, and ANN stands for artificial neural network model (Zhang, 2013).

Table 2. The result comparisons of water resource vulnerability of the administrative divisions of the Haihe River Basin under climate change scenarios.

<table>
<thead>
<tr>
<th>Province</th>
<th>Present ISPA/FAM/ANN</th>
<th>Scenario I ISPA/FAM/ANN</th>
<th>Scenario II ISPA/FAM/ANN</th>
<th>Scenario III ISPA/FAM/ANN</th>
<th>Scenario IV ISPA/FAM/ANN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shanxi</td>
<td>4 4 4</td>
<td>4 4 4</td>
<td>4 4 4</td>
<td>4 4 4</td>
<td>4 4 4</td>
</tr>
<tr>
<td>Shandong</td>
<td>4 3 4</td>
<td>3 3 3</td>
<td>4 4 4</td>
<td>3 3 3</td>
<td>4 4 4</td>
</tr>
<tr>
<td>Henan</td>
<td>3 3 4</td>
<td>3 3 4</td>
<td>4 3 5</td>
<td>3 3 4</td>
<td>4 4 5</td>
</tr>
<tr>
<td>Tianjing</td>
<td>4 4 4</td>
<td>4 3 4</td>
<td>4 4 4</td>
<td>4 3 4</td>
<td>4 4 4</td>
</tr>
<tr>
<td>Inner Mongolia</td>
<td>3 3 4</td>
<td>3 3 3</td>
<td>4 4 3</td>
<td>3 3 3</td>
<td>4 4 3</td>
</tr>
<tr>
<td>Hebei</td>
<td>4 4 4</td>
<td>4 4 4</td>
<td>4 4 4</td>
<td>4 3 4</td>
<td>4 4 4</td>
</tr>
<tr>
<td>Beijing</td>
<td>3 3 4</td>
<td>3 2 3</td>
<td>3 3 4</td>
<td>3 2 3</td>
<td>3 3 4</td>
</tr>
</tbody>
</table>

* 1. 2. 3. 4. 5 stand for the evaluation degree of I. II. III. IV. V.

From the Table 2, we can see that the assessment result of water resource vulnerability in the administrative divisions are between FAM and ANN model for the Haihe River basin with ISPA model under different climate change scenarios.
Figure 2. Comprehensive assessment results of water resources vulnerability in the Haihe River Basin based on ISPA model under different scenarios: (a) At present; (b) Scenario I,III; (c) Scenario II, IV.

From the Table 2 and Figure 2, it can be concluded that: as to water resource vulnerability, for present situation, Shanxi, Shandong, Tianjing, Inner Mongolia, Hebei are higher, Henan and Beijing are the middle vulnerability; for Scenario I and III, Shanxi, Tianjing, Inner Mongolia, Hebei are higher, Henan, Shandong and Beijing are the middle vulnerability; for Scenario II and IV, Shanxi, Shandong, Tianjing, Inner Mongolia, Hebei, Henan are higher, and Beijing are the middle vulnerability. So it can be seen that most of the water resource vulnerability in Haihe River Basin are higher under above different climate change scenarios. Especially, compared with present situation, Shandong will become better under Scenario I and III, and Henan will become worse under Scenario II and IV.

4. SUMMARY AND DISCUSSION

In order to assess the water resource vulnerability scientifically, the ISPA model is established, which takes the maximum entropy principle, improved analytic hierarchy process and set pair analysis as a basis. The above model is used to assess the water resource vulnerability for seven administrative divisions of the Haihe River Basin. The following observations were made:

(a) The advantage of ISPA is that it can not only provide more rational method to determine the weight, but also calculate the certain and uncertain information quantity of water resource vulnerability in the Haihe River Basin. ISPA is a new way to assess water resource vulnerability.

(b) Compared with the FAM and ANN models. ISPA can fully take advantage of subjective and objective information, which makes the assessment result more reasonable.

(c) As to water resource vulnerability of seven administrative divisions in the Haihe River Basin with ISPA model, we can see that, for present situation, Shanxi, Shandong, Tianjing, Inner Mongolia, Hebei are higher, Henan and Beijing are the middle vulnerability.

Compared with present situation, Henan will become worse under scenario II and IV. And the nature environment of these regions is not so optimistic. The assessment results suggest that we can focus on not only the natural aspect of water resource vulnerability but also society environment if we want to reduce water resource vulnerability in the Haihe River Basin, for example, we should draft fitting water-saving planning, groundwater-protecting planning or other programming.

5. ACKNOWLEDGMENTS

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6. REFERENCES


