Vulnerability Assessment of Regional Water Resources

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Abstract. This paper established the regional water resources vulnerability impact factor system by selecting the impact factors and screening out the key factors based on principal component analysis and DPSIR model. Then combing with multipolar fuzzy pattern recognition model and improved fuzzy clustering iterative model, the regional water resource vulnerability assessment model was proposed. Taking Jinan city as an example, the results of water resource vulnerability assessment from 2000 to 2016 show that the water resource status of Jinan city has gone from bad to good, then to worse, and finally slowly getting better.

1. Introduction
With the development of human beings, the world is faced with three major challenges: the rapid growth of population, the extreme shortage of resources and the deteriorating environment, which aggravates the pressure and vulnerability of water resources. In order to alleviate the pressure of water resources system, it is necessary to assess the regional water resources vulnerability [1-2]. The concept of water resource vulnerability was first proposed in the late 1960s. In 2000, Chinese researchers gave the definition of water resource vulnerability [3]. The index system method has been more widespread applied to water resource vulnerability assessment than the single index method, which can be established by DPSIR model [4]. The quantitative analysis of vulnerability is mostly based on objective weighting and fuzzy mathematics, such as entropy method and set pair analysis [5-7]. Qualitative analysis mostly adopts subjective weighting method, such as analytic hierarchy process [8].

At present, there is no unified standard of water resources vulnerability impact factors system in China. Key impact factors in different regions vary due to differences in environment and human activities, and the results obtained by different vulnerability assessment models also vary to some extent. Therefore, it is necessary to screen key impact factors in different regions, establish key impact factors system and select the vulnerability assessment model to clearly reflect the characteristics of regional water resources.

2. Selection of impact factor
Based on the frequency statistical method, five water resource vulnerability indexes with the highest utilization rate were screened out including water resources status, climate status, underlying surface status, human activities and water quality status. Different impact factors have been determined according to the connotation of the five selected indexes, but the repeated meanings of factors often occur. After fully considering the availability of factors and physical concepts, 19 impact factors (see Table 1) related to five types of indexes are proposed.
Table 1. Water resources vulnerability impact factors.

| Index | Number | Impact Factor                                   | Index | Number | Impact Factor                        | Index | Number | Impact Factor                      |
|-------|--------|-----------------------------------------------|-------|--------|--------------------------------------|-------|--------|------------------------------------|
| I₁    | Water resources status | Water resources per capita                         | I₈    | Population density                      |
| I₂    | Water resources per mu                                     | I₉    | GDP per capita                                           |
| I₃    | Annual precipitation                                  | I₁₀   | Water consumption per 10^4 yuan of GDP                    |
| I₄    | Drought index                                         Human Activities | I₁₁   | Water consumption per 10^4 yuan of industrial added value |
| I₅    | Shallow groundwater table                               |
| I₆    | Area ratio of hardened ground                           | I₁₂   | Water consumption of urban residents                     |
| I₇    | Artificial afforestation area                           | I₁₃   | Water consumption of ecology                             |
| I₈    | Population density                                     |
| I₉    | GDP per capita                                          |
| I₁₀   | Water consumption per 10^4 yuan of GDP                   |
| I₁₁   | Water consumption per 10^4 yuan of industrial added value |
| I₁₂   | Water consumption of urban residents                    |
| I₁₃   | Water consumption of ecology                             |
| I₁₄   | Irrigation water use efficiency                         |

3. Determination of water resources vulnerability assessment model

3.1. Screening of key impact factors
In order to facilitate practical application, principal component analysis (PCA) was used to identify and rank the relative importance of the 19 impact factors mentioned above, and key impact factors were determined when needed to simplify the vulnerability assessment process. PCA synthesizes the original factors into a few principal components. When the cumulative variance contribution rate of the current component is more than 85%, it means the unexplainable variance is less than 15%, which will not cause too much information loss. It improves the efficiency of analysis and processing.[9]

After selecting key impact factors, based on DPSIR model and the local environment and human activities of the study area, the key impact factors system of study area is established.

3.2. Improvement of fuzzy clustering iterative model
This paper proposed an improved fuzzy clustering iterative model based on the result of multipolar fuzzy pattern recognition model.[10] Input value of the original fuzzy clustering iterative model is only a random matrix that satisfies the relevant constraints, and the iteration only starts from a fixed end. In this paper, the relative membership degree matrix of the samples obtained by the fuzzy pattern recognition model, and the eigenvalue matrix of c levels obtained by the positive and negative directions of impact factors, are regarded as initial fuzzy clustering matrix and the initial fuzzy clustering centre matrix respectively. By putting them into the fuzzy clustering iterative model at the same time, the uncertainty caused by the random matrix is reduced and the accuracy of the calculated results is increased. The steps are as follow:

- Suppose there are n samples in the study area, and each sample is represented by m impact factors. Establish the relative membership degree matrix of the impact factors of n samples:

  \[ R_{\text{row}} = (R_{\text{1}}, R_{\text{2}}, \ldots, R_{\text{n}})^T \]  

  \[ R_i = [r_i(1), r_i(2), \ldots, r_i(m)], \quad i = 1, 2, \ldots, n \]  

- Establish the eigenvalue matrix of c levels, and process it into dimensionless pattern to obtain the first impact factors eigenvalue matrix of c levels:

  \[ S_{\text{row}} = (S_1, S_2, \ldots, S_c)^T \]  

  \[ S_j = [s_j(1), s_j(2), \ldots, s_j(m)], \quad 0 < s_j(j) < 1, \quad j = 1, 2, \ldots, m \]  

According to the positive and negative directions of impact factors, establish a random impact factors eigenvalue matrix that satisfies equation (4):
The weight of each impact factor is calculated by entropy method:

\[ \omega_j = (\omega_1, \omega_2, ..., \omega_m), \sum_{j=1}^{m} \omega_j = 1 \]  \hspace{1cm} (6)

Put equation (1), (3) and (6) into multipolar fuzzy pattern recognition model, the relative membership degree matrix of \( n \) samples for each vulnerability level is obtained:

\[ U_{n \times c} = (U_1, U_2, ..., U_c)^T \]  \hspace{1cm} (7)

\[ U_h = [u_h(1), u_h(2), ..., u_h(m)], \hspace{0.5cm} 0 \leq u_h(i) \leq 1, \sum_{h=1}^{c} u_h(i) = 1 \]  \hspace{1cm} (8)

The weighted generalized Euclidean distance is used to represent the difference between the \( i \) sample and the \( h \) level, construct the relative Lagrange function, then take the partial derivatives of \( u_h(i) \) and \( s_j(j) \), get the fuzzy clustering iterative model as shown below:

\[ s_j(j) = \frac{\sum_{i=1}^{n} u_h(i)^2 \omega_j^2 r_j(j)}{\sum_{i=1}^{n} u_h(i)^2 \omega_j^2} \]  \hspace{1cm} (9)

\[ u_h(i) = \frac{1}{\sum_{i=1}^{n} \left( \sum_{j=1}^{m} (\omega_j (r_j(j) - s_j(j)))\right)^2} \]  \hspace{1cm} (10)

The \( U_{n \times c} \) get from the fuzzy pattern recognition model was used as the initial clustering matrix, put it into equation (9) for first group iterative calculation; \( S_{n \times m} \) is given as the initial clustering center matrix, put it into equation (10) for second group iterative calculation. Through MATLAB, \( n \) iterations were performed until the difference between the results of \( n \) and \( n-1 \) was less than \( 10^{-6} \), and the mean value of the results of the two groups was the optimal fuzzy clustering matrix.

4. Determination of key impact factors system in study area

In this paper, key impact factors identification and water resource vulnerability assessment were conducted in Jinan city as an example.

Jinan city is located in the central and western part of Shandong Province, the average annual precipitation is 645mm. The Water Resources Per Capita in Jinan is 264.6 m³, which is only 1/8 of the national per capita water resources. In recent years, the contradiction between supply and demand of water resources has become an important factor restricting the economic development of Jinan city.

4.1. Screening of key impact factors in Jinan city

The dataset of 19 impact factors of Jinan city from 2000 to 2016 is obtained by "Jinan Water Resources Bulletin" and "Jinan Statistical Yearbook". The eigenvalues of principal component are obtained through the specific operation of SPSS as shown in figure 1, and the variance contribution rate and variance cumulative contribution rate of the selected principal components are shown in Table 2.
Figure 1. The eigenvalues of principal component.

Table 2. The variance contribution rate of principal component.

| Principal Component | Component Eigenvalue | Variance Contribution Rate | Variance Cumulative Contribution Rate |
|---------------------|----------------------|-----------------------------|---------------------------------------|
| 1                   | 9.781                | 51.481                      | 51.481                                |
| 2                   | 3.854                | 20.283                      | 71.764                                |
| 3                   | 1.793                | 9.435                       | 81.199                                |
| 4                   | 1.217                | 6.404                       | 87.604                                |

As can be seen from table 2, the cumulative contribution rate of the variance of the first four principal components is 87.604%, extract the first four components as the principal components. The variance maximization rotation was performed on the impact factors load matrix of the four principal components, and the result of rotation factor load value is shown in table 3.

Table 3. Rotation factor load value of principal component.

| Impact Factor | Principal Component 1 | Principal Component 2 | Principal Component 3 | Principal Component 4 |
|---------------|-----------------------|-----------------------|-----------------------|-----------------------|
| $I_1$         | -.170                 | .957                  | .091                  | -.007                 |
| $I_2$         | -.268                 | .939                  | .040                  | -.055                 |
| $I_3$         | .077                  | .971                  | -.013                 | .067                  |
| $I_4$         | -.258                 | -.874                 | .225                  | -.180                 |
| $I_5$         | -.585                 | .159                  | .593                  | -.147                 |
| $I_6$         | .959                  | -.023                 | -.245                 | -.036                 |
| $I_7$         | -.060                 | .204                  | -.095                 | .854                  |
| $I_8$         | -.581                 | .415                  | .363                  | -.274                 |
| $I_9$         | .963                  | -.133                 | .008                  | .143                  |
| $I_{10}$      | -.931                 | -.075                 | .318                  | -.050                 |

As can be seen from table 3, the absolute value of $I_6, I_9, I_{10}, I_{19}$ in principal component 1 are all greater than 0.85; The absolute value of $I_1, I_2, I_3$ in principal component 2 are all greater than 0.9; The absolute value of $I_{14}$ in principal component 3 are all greater than 0.85; The absolute value of $I_7$ in principal component 4 are greater than 0.85.

4.2. Determination of key impact factors system in Jinan city

Based on the comprehensive consideration of the natural factors and social factors, the key impact factors obtained from principal component analysis were adjusted based on DPSIR model as shown in table 4. For positive type factor, the greater value, the greater vulnerability level is. At the same time, each impact factors are divided into five vulnerability levels correspond to very poor, poor, medium, good and pretty good of water resources status respectively, as shown in Table 5.
Table 4. Impact factors system in Jinan city.

| Index                  | DPSIR Index                | Impact Factor                          | Unit            | Factor Type |
|------------------------|----------------------------|----------------------------------------|-----------------|-------------|
| Water Resources Status | State Index                | Water resources per capita             | m³/person       | +           |
|                        |                            | Water resources per mu                 | m³/μ            | +           |
| Climate Status         |                            | Annual precipitation                    | mm              | +           |
| Underlying Surface     | Driving Force Index        | Shallow groundwater table              | m               | +           |
| Status                 |                            | Area ratio of hardened ground          | %               | +           |
| Human Activities       | Pressure Index             | GDP per capita                         | 10⁴ yuan /person | -           |
|                        |                            | Water consumption per 104 yuan of GDP  | m³/10⁴ yuan     | -           |
|                        |                            | Water consumption per 104 yuan of industrial added value | m³/10⁴ yuan | -           |
|                        |                            | Water consumption of urban residents   | L/person·d      | -           |
| Water Quality Status   | Impact Response Index      | Irrigation water use efficiency        | %               | +           |
|                        |                            | Water qualification rate in water functional area | % | +           |

Table 5. Classification of water resources vulnerability assessment.

| Vulnerability Level | 1   | 2   | 3   | 4   | 5   |
|---------------------|-----|-----|-----|-----|-----|
| Water Resources Status | Very poor | Poor | Medium | Good | Pretty good |

As can be seen in table 4, the driving force index are the potential causes of water resources changes in the natural environment caused by human society; The pressure index reflect the pressure caused by human activities on the water resources reserve in the surrounding environment; The state index represent the natural environment of the study area under the above pressure; The impact response index indicate the impact of the changing environment on water resources and the protection of water resources in the process of sustainable development.

5. Result of water resources vulnerability assessment in Jinan

According to the key impact factors system determined above, the impact factors relative membership degree matrix $R_{17 \times 11}$ and the impact factors eigenvalue matrix $S_{5 \times 11}$ of the 11 key impact factors of water resource vulnerability in Jinan city from 2000 to 2016 were obtained as shown in figure 2:

Based on the entropy method, the weight vectors of the key influencing factors in Jinan city were determined as (0.094, 0.094, 0.092, 0.093, 0.088, 0.097, 0.088, 0.089, 0.090, 0.087, 0.088), the result of water resources vulnerability assessment in Jinan city are shown in table 6 and table 7, and the comparison of two models is shown in figure 3.
Figure 2. Matrix of eigenvalues: (a) the impact factors relative membership degree matrix; (b) the impact factors eigenvalue matrix.

Table 6. The vulnerability assessment results of multipolar fuzzy pattern recognition model.

| Year | Membership | Level | Year | Membership | Level | Year | Membership | Level |
|------|------------|------|------|------------|------|------|------------|------|
| 2000 | 2.42       | 2    | 2006 | 2.46       | 2    | 2012 | 2.84       | 3    |
| 2001 | 1.98       | 2    | 2007 | 2.33       | 2    | 2013 | 2.80       | 3    |
| 2002 | 2.85       | 3    | 2008 | 2.30       | 2    | 2014 | 2.88       | 3    |
| 2003 | 3.12       | 3    | 2009 | 2.08       | 2    | 2015 | 2.93       | 3    |
| 2004 | 3.51       | 4    | 2010 | 2.43       | 2    | 2016 | 3.09       | 3    |
| 2005 | 2.99       | 3    | 2011 | 2.75       | 3    |

Table 7. The vulnerability assessment results of fuzzy clustering iterative model.

| Year | Membership | Level | Year | Membership | Level | Year | Membership | Level |
|------|------------|------|------|------------|------|------|------------|------|
| 2000 | 1.41       | 1    | 2006 | 3.11       | 3    | 2012 | 2.75       | 3    |
| 2001 | 1.02       | 1    | 2007 | 2.98       | 3    | 2013 | 2.67       | 3    |
| 2002 | 1.62       | 2    | 2008 | 2.51       | 3    | 2014 | 2.94       | 3    |
| 2003 | 3.74       | 4    | 2009 | 2.13       | 2    | 2015 | 2.99       | 3    |
| 2004 | 4.99       | 5    | 2010 | 2.20       | 2    | 2016 | 3.02       | 3    |
| 2005 | 4.00       | 4    | 2011 | 2.64       | 3    |

As can be seen from table 6, table 7, and figure 4:

- The water resources vulnerability assessment results of the multipolar fuzzy pattern recognition model and the fuzzy clustering iterative model are consistent in the variation trend, which show that the water resource status of Jinan city has gone from bad to good, then to worse, and finally slowly getting better;

- The result of multipolar fuzzy pattern recognition model has less fluctuation, which cannot clearly reflect the characteristics of the vulnerability of water resources in Jinan city. The result of fuzzy clustering iteration model is consistent with the actual situation of Jinan city and has good stability and accuracy, using this model as the final vulnerability assessment model.

6. Conclusion

- Combining with the principal component analysis and the improved fuzzy clustering iterative model, the key impact factors are screened out according to the characteristic of water resources in different region, and the results of vulnerability assessment are clearly identified.
According to the current situation of water resources in Jinan city, the key impact factors combining scientific nature and operability, comprehensiveness and representativeness are selected to establish the key impact factors system.

The result of water resources vulnerability assessment reflects the actual situation of Jinan city from 2000 to 2016, and provides scientific basis for rational development, scientific utilization and effective protection of water resources in Jinan city;

Due to the limitation of dataset, 11 key impact factors of water resource vulnerability are selected in this paper. With the increase of data sequence, the impact factors can be further refined to establish a more reasonable factor system.

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