Study on early warning mechanism of ecological water safety in typical watershed of arid areas

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Abstract. In order to improve the comprehensive management level of water resources in the Tarim river basin, a regional water ecological security early warning indicator system were established. Combining the Analytic Hierarchy Process (AHP) and the Fuzzy Comprehensive Evaluation (FCE), the complex adaptive mechanism of the water security system was integrated. The watershed overall water security belongs to safer status. Regional water security status showed a certain difference, and overall decreased gradually from west to east. Secondary indicators also different in time and space scale, and showed the geographical consistency. While Aksu and Bazhou were in a slight warning status, and regional water resources development level was moderate. Therefore, the regional economic development and water use efficiency should be enhanced to ensure water safety of the basin.

1. Introduction
With the global warming and the increasing demand for water resources, the water shortages and water security problem in the inland river are becoming more and more serious. The per capita occupancy of water resources in China is small and the spatial and temporal distribution of water resources varies greatly, especially in the arid and semi-arid areas in the northwest, where the ecological environment is relatively fragile [1]. Further study the ecological water security early warning mechanism and indicator system are significant for protecting the river ecological environment [2].

The Tarim River is a typical inland river in the arid region of China. With the growth of population and the development of social economy, the consumption of water resources increased rapidly and the competition for ecological water intensified [3]. In the past, the evaluation of water resources in Tarim River Basin (TRB) mainly considered ecological environmental factors and water resources utilize level. However, these studies lacked comprehensive evaluation of ecological water security [4].

Watershed ecological water safety early warning is a timely alarm for the degeneration of regional environmental quality and ecosystem [5]. Ling et al. [1] assessed the water resources security of Manas river basin. Shi et al. [6] based on improved variable fuzzy method to assess the regional water resources carrying capacity. Analytic hierarchy process (AHP) can determine weights according to expert scores, and fuzzy comprehensive evaluation (FCE) can make a comprehensive overall evaluation of the regional security situation on the basis of comprehensive evaluation matrix [6-7]. The paper based on the improved evaluation framework, combined AHP and FCE methods to analyze
regional water security level. The research can provide decision-making basis for the ecological management and water resources sustainable utilization of TRB in the future.

2. Research methods

2.1. Establish evaluation framework
Currently the Pressure-State-Response (PSR) framework is the most widely used indicator system [3]. The framework was proposed by the Organization for Economic Cooperation and Development (OECD) and the United Nations Environment Program (UNEP). The pressure layer characterizes the stress of human activities on the environment, and the status layer reflect environmental status in a specific period, the response layer indicates the measures provided by human to protect the ecology [7]. Considering the actual development conditions of the watershed, the stability evaluation factors were added, and the Pressure-State-Response-Sustainability (PSRS) evaluation framework was constructed. Finally, 24 evaluation indicators were selected to establish the evaluation index system.

2.2. Analytic hierarchy process

2.2.1. Standardization of evaluation index factors. Analytic hierarchy process (AHP) is based on the membership function between the criterion layer and the index layer. Reference to expert scoring and mathematical calculation, it can give the reasonable relative weight of each index layer [2]. Considering the difference of indicators, the original data was standardized by extreme value transformation method.

2.2.2. Determination of indicator weights. First, construct a judgment matrix X. Take A as the target, B_i, B_j (i, j = 1, 2, ..., n) represents the factor, and B_{ij} represents relative importance of B_i to B_j [1-2]. Then use Matlab7.0 edit formulas and loops in the command window to calculate the eigenvector x (i, 1) with the maximum eigenvalue lambda_{max}, and the index weight value W (i). Finally, consistency test is executed to judge whether weight distribution obtained is reasonable [8]. The test formula is:

\[
CR = CI / RI
\]

\[
CI = (\lambda_{max} - n) / (n-1)
\]

Where CR is the random consistency ratio of the judgment matrix. The weight distribution is reasonable when CR<0.1. CI refers to the consistency of the judgment matrix standard; RI is the average random consistency index. RI values of the judgment matrix of order 1 to 9 are 0, 0, 0.58, 0.90, 1.12, 1.24, 1.32, 1.41 and 1.45 respectively.

2.3. Fuzzy comprehensive evaluation
The fuzzy comprehensive evaluation can calculate the membership degree of each evaluation factor to different rating levels. Set two finite universe \(U = \{u_1, u_2, ..., u_m\}\) and \(V = \{v_1, v_2, ..., v_n\}\), where \(U\) represents total collection of evaluation factors, \(V\) is a collection of all reviews [9]. The single evaluation factor \(u_i\) determines the membership degree \(r_{ij}\) of the rating level \(v_j\), then the fuzzy evaluation matrix \(R\) was established [6].

According to the subfactor set \(\{U_i\}\) correspond to weight \(W_i\), the evaluation result \(E\) is the fuzzy subset of \(V\), then the comprehensive evaluation of the \(i\)-th factor is as follows:

\[
E = A \ast R = (b_1, b_2, \cdots, b_m)
\]

Where * is a generalized fuzzy synthesis operation; \(b_{ij}\) is the membership degree of the \(i\)-th factor to the \(j\)-th rating level. The weighting coefficients of the evaluation factors was \(A = \{a_1, a_2, ..., a_m\}\) [7]. The weighted average operator \(M(\ast, \oplus)\) was used to determine the result of comprehensive evaluation, the evaluation score \(a\) calculation formula is:
\[ a = \frac{\sum^n_{i=1} b_i^k a_j}{\sum^n_{i=1} b_i^k} \]  

(4)

Where \( a \) value is the comprehensive evaluation score based on evaluation matrix \( B \). The higher of \( a \) value, the safer of water safety situation.

3. Evaluation criteria and ratings

3.1. Evaluation criteria

By referring to HJ 192–2015 Technical Specifications for Assessment of Ecological Environment, and related research, the ecological water safety status was divided into five levels [9–10]. The evaluation criteria of ecological water safety level as shown in Table 1.

| Evaluation scores | Judging level | Warning status               |
|-------------------|---------------|------------------------------|
| [0-0.2]           | V             | Severe warning (Bad condition) |
| (0.2-0.4]         | IV            | Moderate warning (Poor condition) |
| (0.4–0.6]         | III           | Slight warning (General status) |
| (0.6–0.8]         | II            | Safer (Good condition)        |
| (0.8–1.0]         | I             | Safety (Ideal state)          |

3.2. Evaluation level

The standard values of the evaluation mainly refer to the following four aspects: national, industry and local standards; ecological background values of the study area; the native ecological factors under similar habitat conditions as an analogy standard; related scientific research results and expert experience values [10–11]. Considering the natural geography, ecological environment and economic conditions, 24 evaluation factors were selected to analyze ecological water safety comprehensively.

4. Comprehensive evaluation of ecological water safety

4.1. Weight calculation

In general, the watershed ecological water safety assessment index system was summarized into three hierarchical structures, namely target layer (A), criterion layer (B) and index layer (C). The target layer was the ecological water security status, and the criterion layer include four aspects: pressure, state, response and sustainability [12]. Based on the characteristics of watershed, 24 indexes were selected to form the evaluation index system of water security (Table 2).

The weight determination of fuzzy comprehensive evaluation was important. Corresponding weight of each index can be obtained by using formula (1)–(2), as shown in Table 2. The evaluation factors of criterion layer and indicator layer should satisfy the consistency test \((CR<0.1)\). The judgment matrix \( CR \) of pressure, state, response and stability was 0.0036, 0.0044, 0.0027 and 0.0053, respectively. Correspondingly, the weight distribution was reasonable. Weight vector of the criterion layer was \( B = (0.304, 0.276, 0.152, 0.268) \). Based on the expert scores, the five evaluation levels were determined, then evaluation row vector was set as \( X = (0.95, 0.75, 0.55, 0.35, 0.15) \).
Table 2. Integrated indicator system of water resources security index and the weights.

| Criterion layer B | Index layer C                                                                 | Weights | Level definition standard |
|-------------------|-------------------------------------------------------------------------------|---------|--------------------------|
| Pressure          | Per capita GDP/(10⁴ yuan/person)                                              | 0.039   | <2.5                     |
|                   | Per capita water resources (10³ m³/person)                                    | 0.044   | ≥4                       |
|                   | unit GDP water loss/(10⁸ m³/yuan)                                            | 0.039   | ≤0.5                     |
|                   | Domestic water quota/(L/person·d)                                            | 0.044   | <160                     |
|                   | Irrigation water quota/(m³/mu)                                               | 0.069   | <250                     |
|                   | Groundwater exploit modulus/(10⁷ m³/km²)                                      | 0.069   | ≤0.5                     |
| State             | Surface water modulus/(10⁴ m³/km²)                                           | 0.042   | >8                       |
|                   | Groundwater modulus/(10³ m³/km²)                                             | 0.042   | >5                       |
|                   | Surface average precipitation/(10³ m³/km²)                                    | 0.032   | >40                      |
|                   | Water production modulus/(10⁷ m³/km²)                                         | 0.042   | >10                      |
|                   | Water resources utilization%                                                  | 0.059   | ≤10                      |
| Response          | Ecological water ratio%                                                       | 0.026   | ≥40                      |
|                   | Tertiary industry ratio%                                                      | 0.018   | ≥70                      |
|                   | Sewage treatment rate%                                                        | 0.026   | ≥95                      |
|                   | Environmental investment ratio%                                              | 0.026   | ≥40                      |
|                   | Water quality compliance rate%                                               | 0.028   | ≥95                      |
|                   | Water resource recycle%                                                       | 0.028   | ≥80                      |
| Sustainability    | Water supply & demand ratio%                                                 | 0.052   | ≥1.2                     |
|                   | Water supply modulus/(10³ m³/km²)                                            | 0.052   | <10                      |
|                   | Water supply per capita/(m³/person)                                          | 0.058   | >800                     |
|                   | Groundwater supply ratio%                                                    | 0.058   | ≤10                      |
|                   | Coefficient of irrigation water%                                             | 0.024   | ≥70                      |
|                   | Urbanization level%                                                           | 0.024   | ≥60                      |

4.2. Regional fuzzy comprehensive evaluation

The formula (3)-(4) in the previous section can be used for matrix calculation. Considering the river distribution and the administrative division, the study area was divided into five sections: Bazhou, Aksu, Kezhou, Kashgar and Hotan [5]. Take Bazhou as an example: \( E = (0.1203, 0.2238, 0.3420, 0.1829, 0.1310) \cdot C = 0.5539 \). The assessment results showed that the water security in Bazhou was in a slight warning status, and the membership degree reaches 0.342. According to the fuzzy comprehensive evaluation procedure, the assessment results were shown in Table 3.

It can be seen that Kezhou, Kashgar and Hotan were in a higher membership degree of safer level, which were 0.4513, 0.3419 and 0.3111 respectively. With the principle of maximum membership degree, water safety status of the three regions were in comparison. The water safety area accounts for 76.7%, and Bazhou and Aksu both with a higher subordination degree to slight security level [12]. The ecological water security status of each object was analyzed as follows:

Table 3. Fuzzy comprehensive evaluation results of ecological water security in TRB.

| Evaluation object | Security Level | Score |
|-------------------|----------------|-------|
| Bazhou            | 0.1203         | 0.0539|
| Aksu              | 0.2190         | 0.5907|
| Kezhou            | 0.3789         | 0.7765|
| Kashgar           | 0.2766         | 0.6904|
| Hotan             | 0.2379         | 0.6378|
From the source area to the main stream region, the ecological vulnerability was gradually increasing. The forest coverage rate of the whole basin was low, which was not conducive to regional ecological regulation and ecosystem stability [3]. Bazhu was located in the edge of Taklamakan desert, with little rainfall and runoff. In recent years, with overgrazing and illegal exploitation, a lot of drought-resistant shrubs have decreased [4]. The overall evaluation score was 0.5539, which was relative insecurity (Table 3). However, the regional per capita of water resources was abundant and groundwater exploitation level was low. With the implementation of treatment project, the water security situation was gradually improved.

The per capita water consumption in Aksu was large, reaching 4253.2 m$^3$/person. The ecological environment and the water quality compliance rate was low, the membership degree was higher in slight warning level, which reaching 0.2344. Regional evaluation score was 0.5907 (Table 3). In terms of large population and development of agriculture, water supply contradiction was also prominent [12].

Surface water of Kezhou was abundant, and groundwater recharge was in a large scale. What’s more, regional water production modulus was high, and population density was small. The level of urbanization and water resources utilization was low. Therefore, the state of water security was relatively safer. The evaluation score was 0.7765, which means that regional water resources have good development potential [13].

Kashgar and Hotan scored 0.6904 and 0.6378 respectively. The Kashgar surface water resources modulus was high and the water production condition was good. The urbanization rate was 22.2%, and the population density was 41.64 person/km$^2$, so the regional overall situation was a safer status. Hotan has a high natural population growth rate and the regional per capita GDP was little. The industrial and agricultural production was mainly based on surface water [12-14]. Domestic sewage treatment rate was low, and the environmental investment need to be strengthened.

5. Conclusion

Through the combination of analytic hierarchy process (AHP) and fuzzy comprehensive evaluation (FCE), the comprehensive score of water security in the Tarim River Basin (TRB) was 0.6581. The early-warning status of Bazhou and Aksu were in slight alarm level, with comprehensive score 0.5539 and 0.5907. The ecological water of these regions was in a low level. Agricultural water consumption was in a large scale and water resource dissipation was serious. Due to the low technical conditions and productivity level, the ecological response level was not high.

The comprehensive application of AHP and FCE can evaluate the security situation of water resources more accurately, with strong adaptability and feasibility. AHP can determine the weight of index through expert scores and mathematical calculations. FCE can deduce multi-factor comprehensive evaluation of regional safety status, and achieved the unity of subjective and objective evaluation.

Due to the high weight of irrigation quota, water supply quota and the water yield modulus, the regional water safety situation was not optimistic. Therefore, water-saving technology and precision agriculture should be vigorously developed. The management of water resources need to be strengthened, and regional population should be controlled to improve the water security in the watershed. The evaluation results can provide decision-making basis for regional future ecological recovery and social and economic sustainable development.

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