Study on vulnerability assessment of Xiaoxiang water source in Qujing

J J Zeng¹, K M Li¹³, Y Q Cui², L F Kang¹ and S Z Cao¹
¹College of Geography and Environmental Engineering, Lanzhou City University, Lanzhou 730000, China
²College of Geography and Environmental Science, Northwest Normal University, Lanzhou 730000, China
E-mail: lkm_wd@126.com

Abstract. Most of the urban water sources in Yunnan Plateau Basin, which are mainly reservoir type, are located in Karst mountainous area, with low eco-environmental capacity, high sensitivity and strong vulnerability. However, the vulnerability assessment of water source area is the basis of scientific protection and ecological restoration measures of urban water source area in plateau basin. Based on the study of vulnerability, started from the point of view of the vulnerability of urban water sources in Yunnan plateau basin, and combined with the concept and connotation of urban water source vulnerability in plateau basin, this paper constructs an evaluation index system that reflects the vulnerability of urban water sources in the plateau basin. In this paper, the fuzzy comprehensive evaluation model of urban water source vulnerability in plateau basin is constructed by using the method of fuzzy mathematics, and an example is given to evaluate the vulnerability of Xiaoxiang urban water source in Qujing. The evaluation results show, then combined with the principle of maximum membership degree, it is concluded that the vulnerability comprehensive evaluation vector of Xiaoxiang water source area is (0.125, 0.087, 0.414, 0.359, 0.019), the Xiaoxiang water source area in Qujing is moderately fragile. Among them, hydrometeorological factors and eco-environmental factors are in a state of moderate vulnerability, water pollution factors are in a high vulnerability state, and surface disturbance factors are in a state of non-vulnerability.

1. Introduction
Water resources are the basis and source power of regional social survival and economic development [1]. Water resources play a very important role in maintaining a good ecological environment and ensuring the healthy and sustainable development of the regional economy. Climate change and human activities are changing or affecting the temporal and spatial changes of water resources. Human development has been faced with a series of problems, such as shortage of water resources, deterioration of water ecological environment, frequent occurrence of extreme weather events and so on [2,3].

Urban water source is the strategic basic resource of urban development and the key element of the virtuous cycle of urban ecosystem [4-9]. Most of the plateau basin cities are distributed in the fault basins with relatively closed topography, there are no major rivers around the city, and the water source reservoir has become the most important water source of the city [10,11]. Therefore, the water source reservoir is the lifeblood of urban water security and even urban economic and social development for the plateau basin city [6-9]. With the aggravation of human activities in water sources
and the uneven temporal and spatial distribution of rainfall, there are some problems in some urban water sources [12-15], such as water pollution, shortage of water, decline of water level, serious shortage of water storage in reservoirs and so on. As a result, the urban water source in the plateau basin suffers severely tested. The vulnerability assessment of urban water sources can reflect the changes of ecological environment, water conservation function and recovery ability comprehensively. The vulnerability assessment of urban water sources is an effective method to judge the health status of water sources and its main control factors, and also the basis to reveal the formation mechanism of vulnerability of urban water sources. The vulnerability assessment of water sources is the basis for the formulation of scientific protection and ecological restoration measures for urban water sources in the plateau basin. At present, the connotation and evaluation index of water source vulnerability have been preliminarily discussed in related study, but its vulnerability has not been systematically evaluated. In order to describe the vulnerability of urban water sources in the plateau basin, find out the dominant factors of urban water sources vulnerability in the plateau basin, and provide necessary auxiliary decision-making for the comprehensive improvement of the administrative departments in the process of water source protection and ecological restoration, Using fuzzy mathematics to evaluate urban water source vulnerability in plateau basin and evaluating the vulnerability of Xiaoxiang urban water source in Qujing. In water source protection and ecological restoration, particular attention should be paid to factors with high degree of vulnerability.

2. General situation of the study area

![Distribution map of land types in Xiaoxiang water source area.](image)

Xiaoxiang Reservoir is located in the upper reaches of Xiaoxiang River in Qianguanchang Village, the southwest of Qilin District, Qujing City, which is a tributary of Nanpanjiang River in the Xijiang River system of the Pearl River Basin (figure 1). It is 7 km away from the center of Qujing, and the watershed area is 380 km², and the total storage capacity is 44.37 million m³. The water source area
belongs to the subtropical plateau monsoon climate, the annual average precipitation is 838.7 mm, the annual average temperature is 14.5°C, the annual average runoff is 152 million m$^3$, and the annual average water supply is 30.05 million m$^3$.

3. Research methods

Fuzzy comprehensive evaluation, based on fuzzy mathematics, can quantify some evaluation indexes whose boundaries are unclear and difficult to quantify, that is, to determine the degree of membership. It changes from a low-level, small system to a high-level, large-scale system, to achieve the final evaluation results through the gradual synthesis [16-18]. Due to this method shows unique advantages in dealing with a variety of complex system problems which are difficult to be described by accurate mathematical methods, it has been more and more widely used in various disciplines. In geography, fuzzy comprehensive evaluation method is often used in resource and environmental condition evaluation, ecological evaluation, regional sustainable development evaluation and so on [19,20].

The general steps of fuzzy comprehensive evaluation are as follows:

- Establish the factor domain of the evaluation object (evaluation index) $U = \{U_1, U_2, \ldots, U_n\}$, there are $n$ factors (evaluation index).
- Establish the evaluation domain (evaluation grade) $V = \{V_1, V_2, \ldots, V_m\}$, there are $m$ factors (evaluation grade).
- Determine the weight vector set of evaluation index $W = [W_1, W_2, \ldots, W_n]$ (the weight of evaluation index is determined by analytic hierarchy process).

4. Study on vulnerability assessment of Xiaoxiang water source area

4.1. Establishment of index system

On the basis of combing the research progress of vulnerability [21-26], combined with the geographical environment characteristics of Yunnan-Guizhou Plateau, this paper analyzes the connotation of water source vulnerability from three aspects: the natural attribute of water source, the manifestation of vulnerability and the external driving force of vulnerability. At the same time, the index system should reflect the influence degree of each evaluation index on the vulnerability of water source. Therefore, the evaluation index system of urban water source vulnerability in plateau basin includes the following 14 indexes, that is, 2 vulnerabilities of urban water source in plateau basin, ( primary vulnerability and stress vulnerability), 4 influencing factors (hydrometeorological factors, eco-environmental factors, water pollution factors, surface disturbance factors), 8 evaluation objects (precipitation conditions, temperature change rate, geological environment, soil and water loss, water conservation function, water quality status, water pollution stress degree, surface disturbance stress degree [6,9,13,15]).

In the aspect of hydrometeorology, four indexes are selected: annual average rainfall ($D_1$), interannual variation coefficient of precipitation ($D_2$), annual distribution uniformity of precipitation ($D_3$) and temperature change rate ($D_4$). In the aspect of eco-environmental factors, six indexes were selected: hydrogeology ($D_5$), soil erosion modulus ($D_6$), forest coverage ($D_7$), soil saturated water content ($D_8$), water quality category ($D_9$) and comprehensive nutritional status index ($D_{10}$). Water source pollution factors mainly select waste sewage discharge per unit area ($D_{11}$) and solid pollutant load per unit area ($D_{12}$). The main surface disturbance factors are construction land area ratio ($D_{13}$) and cultivated land area ratio ($D_{14}$).

The values of each evaluation index in this paper are obtained directly or indirectly through statistical yearbook, hydrometeorological observation data, remote sensing interpretation, field investigation, sampling analysis and so on.

4.2. Division of evaluation grade and determination of evaluation index standard

The evaluation criteria are divided into five levels: level $V_1$ (not fragile), level $V_2$ (slightly vulnerable), level $V_3$ (moderately vulnerable), level $V_4$ (highly vulnerable) and level $V_5$ (extremely vulnerable). In
this paper, the evaluation standards are established, which is based on the physical meaning of the evaluation index of urban water source in plateau basin and its effect on the natural, social, resource and environmental sustainability of water source, in accordance with the research results of the critical pressure of urban water sources in plateau basin and the evaluation criteria of similar water sources. It conforms to the standards issued by the local government and the objectives of the planning area, and meets the requirements for the protection of drinking water sources throughout the country. In addition, the evaluation standard adopts the maximum and minimum values of each index of urban water source in Yunnan Plateau Basin [6,9,13,15]. The specific operation is as follows: each index is classified by the method of equal spacing difference, that is, the maximum and minimum values of the index are determined first, and then 5 equal divisions are carried out to determine each grade interval. The criteria for the evaluation of indicators are shown in Table 1.

Table 1. Classification standard of vulnerability index system of urban water source in Plateau Basin.

| Classification        | $V_1$ | $V_2$ | $V_3$ | $V_4$ | $V_5$ |
|-----------------------|-------|-------|-------|-------|-------|
| not fragile           | >1000 | 850-1000 | 700-850 | 550-700 | <550  |
| slightly vulnerable   | <3    | 0.3-0.43 | 0.43-0.56 | 0.56-0.7 | >0.7  |
| moderately vulnerable | >0.8  | 0.63-0.8 | 0.47-0.63 | 0.3-0.47 | <0.3  |
| highly vulnerable     | <0    | 0.2-0.4  | 0.2-0.4  | 0.4-0.6  | >0.6  |
| extremely vulnerable  | <10   | 10-40   | 40-70   | 70-100   | >100  |
|                      | <500  | 500-2000 | 2000-3500 | 3500-5000 | >5000 |
|                      | >80   | 80-60   | 60-40   | 40-20    | <20   |
|                      | >25   | 25-37   | 37-49   | 49-60    | <60   |
|                      | I     | II     | III     | IV     | V     |
|                      | <40   | 40-50   | 50-60   | 60-70    | >70   |
|                      | <6    | 0.6-2.04 | 2.04-4.02 | 4.02-6  | >6    |
|                      | <5    | 5-20    | 20-35   | 35-50    | >50   |
|                      | <0.03 | 0.03-0.12 | 0.12-0.21 | 0.21-0.3 | >0.3  |
|                      | <0.67 | 0.67-2.68 | 2.68-4.69 | 4.69-6.7 | >6.7  |

4.3. Study on vulnerability assessment of Xiaoxiang water source area

4.3.1. Determination of the weight of evaluation index. The weight of evaluation index is determined by analytic hierarchy process (AHP) [6,9,27,28] (see table 2):

Table 2. Weight of each evaluation index.

| $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ | $D_6$ | $D_7$ | $D_8$ | $D_9$ | $D_{10}$ | $D_{11}$ | $D_{12}$ | $D_{13}$ | $D_{14}$ |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|----------|----------|----------|----------|----------|
| 0.11  | 0.03  | 0.03  | 0.02  | 0.08  | 0.05  | 0.09  | 0.05  | 0.15  | 0.15     | 0.10     | 0.03     | 0.08     | 0.04     |

4.3.2. Calculate the membership function and establish the R matrix. Membership function is used to describe fuzzy sets and is the application basis of fuzzy comprehensive evaluation method. The construction of correct membership function is the key to fuzzy comprehensive evaluation, which directly affects the quality of the evaluation results. In order to ensure the smooth transition of the membership function of the quantitative evaluation index at all levels, it should eliminate the fuzzy phenomenon of the near evaluation grade due to the small difference of some evaluation index values. Therefore, in this study, the evaluation set is divided into five evaluation levels $V=\{V_1, V_2, V_3, V_4, V_5\}$, corresponding to four critical values ($k_1, k_3, k_5, k_7$) and the midpoint values of three critical values ($k_2, k_4, k_6$). According to the principle of relative membership function, combined with the corresponding relationship between actual value and $k_i$ and $k_{i+1}$ ($k_i$ is the critical value of each grade, and $k_{i+1}$ is the midpoint value of each adjacent critical value), this paper constructs the following membership degree calculation formulas (1)-(5) for the five evaluation grades to realize the above fuzzification.
requirements.

\[
U_1 = \begin{cases} 
0.5(1 + \frac{K_1 - U_i}{K_2 - K_i}), & U_i < K_1 \\
0.5(1 - \frac{U_i - K_2}{K_2 - K_1}), & K_1 \leq U_i < K_2 \\
0, & U_i \geq K_2 
\end{cases}
\]  

(1)

\[
U_2 = \begin{cases} 
0.5(1 - \frac{K_1 - U_i}{K_2 - U_i}), & U_i < K_1 \\
0.5(1 + \frac{K_1 - U_i}{K_1 - K_2}), & K_1 \leq U_i < K_2 \\
0.5(1 + \frac{K_3 - U_i}{K_3 - K_2}), & K_2 \leq U_i < K_3 \\
0.5(1 - \frac{K_3 - U_i}{K_3 - K_4}), & K_3 \leq U_i < K_4 \\
0, & U_i \geq K_4 
\end{cases}
\]  

(2)

\[
U_3 = \begin{cases} 
0, & U_i \leq K_2 \\
0.5(1 - \frac{K_3 - U_i}{K_3 - K_2}), & K_2 \leq U_i < K_3 \\
0.5(1 + \frac{K_3 - U_i}{K_3 - K_4}), & K_3 \leq U_i < K_4 \\
0.5(1 + \frac{K_5 - U_i}{K_5 - K_4}), & K_4 \leq U_i < K_5 \\
0.5(1 - \frac{K_5 - U_i}{K_5 - K_6}), & K_5 \leq U_i < K_6 \\
0, & U_i \geq K_6 
\end{cases}
\]  

(3)

\[
U_4 = \begin{cases} 
0, & U_i \leq K_4 \\
0.5(1 - \frac{K_5 - U_i}{K_5 - K_4}), & K_4 \leq U_i < K_5 \\
0.5(1 + \frac{K_5 - U_i}{K_5 - K_6}), & K_5 \leq U_i < K_6 \\
0.5(1 + \frac{K_7 - U_i}{K_7 - K_6}), & K_6 \leq U_i < K_7 \\
0.5(1 - \frac{K_7 - U_i}{K_6 - U_i}), & U_i \geq K_7 
\end{cases}
\]  

(4)
For the qualitative index, it is first described by natural language, that is, quantitative assignment, and then evaluated by the membership function of rectangular distribution.

\[ U(x) = \begin{cases} 
1 & k_i < U \leq k_{i+1} \\
0 & U \leq k_i, U > k_{i+1}
\end{cases} \]  

(6)

The fuzzy relation matrix R of vulnerability evaluation index of Xiaoxiang water source area is established.

\[
R = \begin{bmatrix}
0.000 & 0.000 & 0.776 & 0.224 & 0.000 \\
0.000 & 0.000 & 0.810 & 0.190 & 0.000 \\
0.000 & 0.000 & 0.673 & 0.367 & 0.000 \\
0.000 & 0.000 & 0.000 & 0.500 & 0.500 \\
0.000 & 0.777 & 0.223 & 0.000 & 0.000 \\
0.000 & 0.000 & 0.000 & 0.742 & 0.258 \\
0.000 & 0.477 & 0.523 & 0.000 & 0.000 \\
0.000 & 0.000 & 1.000 & 0.000 & 0.000 \\
0.000 & 0.000 & 0.266 & 0.734 & 0.000 \\
0.000 & 0.000 & 0.313 & 0.687 & 0.000 \\
0.000 & 0.000 & 0.156 & 0.844 & 0.000 \\
1.000 & 0.000 & 0.000 & 0.000 & 0.000 \\
1.000 & 0.000 & 0.000 & 0.000 & 0.000 
\end{bmatrix}
\]

Finally, the evaluation set of each criterion layer and target layer are calculated by the method of weighted average, which based on the determined weight distribution set A and the fuzzy relation matrix R obtained from the membership function, by using the fuzzy comprehensive evaluation model \( B = A \cdot R \).

\[
B_1 = A_1 \cdot R_1 = (0.594, 0.160, 0.160, 0.086) \cdot \\
\begin{bmatrix}
0.000 & 0.000 & 0.776 & 0.224 & 0.000 \\
0.000 & 0.000 & 0.810 & 0.190 & 0.000 \\
0.000 & 0.000 & 0.673 & 0.367 & 0.000 \\
0.000 & 0.000 & 0.500 & 0.500 & 0.000 \\
0.000 & 0.698 & 0.265 & 0.043 \\
\end{bmatrix}
\]

6
Then combined with the principle of maximum membership degree, it is concluded that the vulnerability comprehensive evaluation vector of Xiaoxiang water source area is (0.125, 0.087, 0.414, 0.359, 0.019), corresponding to $V_3$ grade, so Xiaoxiang water source area is moderately fragile.

5. Conclusion and discussion

Based on the study of vulnerability, started from the point of view of the vulnerability of urban water sources in Yunnan plateau basin, and combined with the concept and connotation of urban water source vulnerability in plateau basin, this paper constructs an evaluation index system that reflects the vulnerability of urban water sources in the plateau basin. In this paper, the fuzzy comprehensive evaluation model of urban water source vulnerability in plateau basin is constructed by using the method of fuzzy mathematics, and an example is given to evaluate the vulnerability of Xiaoxiang urban water source in Qujing. The evaluation results show, Then combined with the principle of maximum membership degree, it is concluded that the vulnerability comprehensive evaluation vector of Xiaoxiang water source area is (0.125, 0.087, 0.414, 0.359, 0.019), the Xiaoxiang water source area in Qujing is moderately fragile. Among them, hydrometeorological factors and eco-environmental factors are in a state of moderate vulnerability, water pollution factors are in a high vulnerability state, and surface disturbance factors are in a state of non-vulnerability.

As a kind of macro-evaluation, water source vulnerability state assessment can only outline the general situation of water source vulnerability. Compared with the evaluation results of single index correlation degree of Xiaoxiang water source area, it can be found that the vulnerability grade of single index correlation degree of many water source areas exceeds the vulnerability grade of comprehensive correlation degree, such as the water pollution factor is in a highly fragile state. Therefore, in the process of water source protection and ecological restoration, measures should be
taken according to the factors with high degree of vulnerability to further strengthen the protection of water source. Therefore, in the process of water source protection and ecological restoration, measures should be taken to address the factors with high vulnerability to achieve twice the result with half the effort. At the same time, the dominant influencing factors were found through the vulnerability assessment of urban water sources in Plateau basin, which laid a foundation for further revealing the formation mechanism of urban water sources vulnerability.

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