Fuzzy comprehensive model based on combination weighting in watershed application of ecological health assessment

Chao Sun¹ and Wen Chen

Hydrology and Water Resources Bureau of Gansu Province, Lanzhou 730000, China.

¹Email: 156973324@qq.com

Abstract. Watershed ecological environmental health assessment is an important basis for the rational development and utilization of water resources in the basin, economic and social sustainable development and ecological environment protection, and it is also a systematic diagnosis method for the ecological health status of the basin. On the basis of determining the ecological health evaluation index of the Shule River Basin, the weights of each index were determined by using the combination weighting method, and a comprehensive assessment of the ecosystem health of the river basin was made using the fuzzy comprehensive evaluation method. The degree of membership of the Shule River Basin is 0.316, which belongs to the sub-health (0.3 to 0.5) state.

1. Preface

River health is not a scientific concept in strict sense, but an assessment tool for river management. It dynamically monitors and evaluates the state of river ecosystem under the dual effects of natural forces and human activities to study its evolutionary trend and promote it through management. Toward a healthy development [1], river ecosystem health is a comprehensive reflection of the characteristics of river ecosystems. It is a complex social, economic, and natural ecosystem within a basin. Human activities and socioeconomic factors should be taken into account [2]. The system supports the socio-economic development in the basin and has a powerful service function. Because the river ecosystem is multivariate, its health standards should also be dynamic and multi-level [3]. Based on the combination weighting method, the fuzzy comprehensive evaluation model can fully analyze the data. By utilizing AHP and entropy method to carry out the comprehensive analysis of each indicator’s contribution in ecosystem, it can effectively reflect the weight of each indicator in the river health. Besides, by using each indicator’s weight and the vector of membership degree, a fuzzy evaluation matrix can be elicited to run fuzzy operation and normalization, determining the grade of each indicator and eventually reaching reasonable evaluation results. The fuzzy comprehensive evaluation model based on the combination weighting method comprehensively analyzes the contribution of each factor, which can effectively reflect the contribution of each factor to the ecological health status of the river basin and the decisive factors of the eco-environmental components, and make up for the lack of considering only one factor. Based on the quantitative evaluation of the Shule River Basin ecosystem, this paper analyzes its existing problems and proposes specific suggestions for the sustainable development of the basin.
2. Evaluation research status

The concept of ecosystem health was born in the early 1980s. In 1989, Rapport first discussed the connotation of ecosystem health, pointed out the criteria for ecosystem health, and put forward a preliminary method for the evaluation of ecosystem health [4,5]. In 2008, Pinto H studied the characteristics of benthic communities to evaluate the health of rivers in arid regions [6]. In 2013, Ivor Growns used an independent species distribution model to predict the number of fish in the natural state of some rivers in Australia, and then assess the health status of the river [7]. In 2016, Feng Guangchao analyzed the flow process variation and its influencing factors in the middle and lower reaches of the Hanjiang River. Through example calculations, the impact of flow process variation on river health in the middle and lower reaches of the Hanjiang River was quantitatively analyzed [8].

3. Basin overview

3.1. Location

The Shule River Basin is located in the west of the Hexi Corridor in Gansu Province. It borders on the Laiyang Nanshan and the Nuo River in the east of Jiayuguan, borders the Xinjiang Autonomous Region in the west, and is separated from Qinghai in the south by the Qilian Mountains, and borders with the People’s Republic of Mongolia and China’s Inner Mongolia Autonomous Region in the north. The geographic coordinates are between longitudes 92° 11’ to 99° 00’ east longitude and 38° 00’-42° 48’ north latitude.

3.2. River system

The Shule River originates from the Gangershiheili Ridge in Qilian Mountains. It consists of the Shule River system and the Sugan Lake system in the south. The drainage area is $4.13 \times 10^4$ km$^2$. The source of runoff recharge is mountainous precipitation and high mountain meltwater, and the average annual runoff $10.31 \times 10^8$ m$^3$, of which the glacier melting water accounts for 32.5% of the river runoff.

3.3. Topography

The Shule River Basin is located on the transitional belt between the Qinghai-Tibet Plateau and the Alxa Plateau. The terrain can be divided into the southern Qilian Mountains and the fold belt. The area has more precipitation and is the area where water resources are generated. The north Maji Mountain Block consists of several series of low mountains. Residual mounds are composed of 1400-2400m above sea level, with severe wind erosion and bare rocks in the foothills. The Hexi Corridor depression belt in the central part consists of alluvial alluvial fan-shaped, downstream alluvial plains, Beishan, and the Gobi alluvial fan plain on the south side of Maji Mountain.

3.4. Climate precipitation

Shule River Basin is located in the hinterland of Eurasia, with less precipitation, large evaporation, and long sunshine. It is one of the extremely arid regions in China. In the southern Qilian Mountains, the terrain is high and cold, and it belongs to a high-cold and semi-arid climate zone. The precipitation is about 200mm, and the annual average temperature is lower than 2°C. The central mountain corridor plain area and the northern low-lying mountain area of Majushan are temperate or warm temperate arid areas, and the precipitation 36 ~ 63.4mm, annual average temperature of 7 ~ 9 °C, evaporation of 1500 ~ 2500mm.

3.5. Economic society

In 2015, the total population of the entire river basin was 524,200, of which the agricultural population was 227,400. An area of 204.05 million mu of arable land, and an area of 1.947 million mu of farmland. The gross regional product is 37.66 billion yuan, of which, the total output value of a total output is 3.67 billion yuan, the total output value of the secondary output is 20.90 billion yuan, and the total output value of the tertiary industry is 13.10 billion yuan.
3.6. Water resources and development and utilization
The total water resources of the Shule River mainstream is 11.34×10⁸ m³, of which the river runoff is 10.82×10⁸ m³, and the groundwater resources that do not overlap with the river runoff are 0.52×10⁸ m³. The distribution of runoff during the year is extremely uneven, with runoff from June to October accounting for 74% of the annual total. In 2013, the total water consumption in the entire river basin was 18.14×10⁸ m³, of which, the agricultural water consumption was 15.78×10⁸ m³, the industrial water consumption was 0.84×10⁸ m³, and the domestic water consumption was 0.12×10⁸ m³.

4. Fuzzy comprehensive evaluation model
On the basis of evaluating indicators, evaluation indicator grading system and threshold values, fuzzy comprehensive evaluation models determine the evaluation indicator grading system after multi-level compound operation. By using fuzzy set transformation, it describes the fuzzy limits of each indicator by the degree of membership, constructing a fuzzy comprehensive evaluation matrix.

4.1. Establish factor sets and evaluation sets
The core factors affecting the health of the river basin are the scale and quality of the river's natural attributes, economic and social functions, and social service capabilities. According to the principle of reliability and adequacy of evaluation indicators, considering the characteristics of water resources in the Shule River Basin, establish a set of factors = {degree of utilization of water resources (The number represents the scarcity of water resources. The larger the number is, the scarcer water resources are. Exceeding a certain point, the river health will be negatively influenced), availability of per capita water resources (Water resources carrying capacity. The smaller the number is, the higher the pressure on the river health is), water-saving irrigation rate (It reflects water conservation in agricultural engineering. The higher the number is, the higher the agricultural water use efficiency is), water consumption per million yuan of GDP (It reflects the level of economic development and water use efficiency. The higher the number is, the higher the pressure on the river health is), and agriculture Ratio of water use, discharge of sewage per capita in cities and towns (It reflects the environmental pressure on the river health), precipitation, flow variation (It reflects the variation of annual runoff), and vertical connectivity (It reflects the continuity of water flow and the connection of water system) }. The meanings of the indicators are as follows: Level of water resources development and utilization: gross water consumption/total water resources, per capita water resources availability: water resources availability/total population, water-saving irrigation rate: water-saving irrigation area/farmland effective irrigation Area, million yuan GDP water consumption: total water consumption/GDP, agricultural water ratio: agricultural water consumption/total water consumption; urban per capita wastewater discharge: total waste water discharge / urban population, runoff depth; annual average runoff/area, Longitudinal connectivity: Number of river dams/length of river. Divide the river's health status into 5 grades, then the evaluation set = {health (0.7 ~ 1.0): watershed environment is not stressful, strong recovery ability, can meet the good socio-economic development; basic health (0.5 ~ 0.8): basin water environment Light pressure, strong recovery ability, good natural condition; sub-health (0.3-0.5): certain pressure in the watershed environment, general recovery capacity, to meet a certain degree of socio-economic development; morbid (0.2-0.3): pressure on the basin's environmental conditions Poor recovery capacity; collapse in the (0 ~ 0.2): the pressure on the environment of the basin is very large, poor recovery ability, it is difficult to meet the social and economic sustainable development}[9].

Index threshold value is a vital parameter to judge whether the river is in good condition or not by referring to the index value. It can directly affects the authenticify of the diagnostic results. Index threshold values can be determined based on the following information: national, industrial or regional standards and regulations; the established results in river-basin planning; opinions from experienced experts in this field; results and relevant data from the existing assessment of river health [10-12];
Based on the above mentioned information, the evaluating indicator grading system of the Shule River can be proposed. The evaluation indicators and standards are shown in Table 1.

Table 1. Evaluation factors index and standard.

| Evaluation standard                                      | Healthy | Basic healthy | Sub-healthy | Pathological | About to collapse | Shule river |
|----------------------------------------------------------|---------|---------------|-------------|--------------|-------------------|-------------|
| Water resources development and utilization/%           | 20      | 40            | 60          | 75           | 85                | 75          |
| Water use per capita/m³                                  | 1000    | 700           | 500         | 350          | 150               | 2636        |
| Water-saving irrigation rate/%                          | 80      | 70            | 60          | 40           | 20                | 63          |
| Million yuan of GDP water consumption/m³                | 60      | 200           | 400         | 600          | 800               | 482         |
| Agricultural water ratio/%                              | 20      | 40            | 60          | 75           | 90                | 87          |
| Urban sewage discharge per capita/m³                    | 50      | 130           | 200         | 300          | 600               | 49          |
| Precipitation/mm                                         | 500     | 300           | 100         | 50           | 25                | 95          |
| Flow variation                                          | 0.05    | 0.1           | 0.3         | 1.5          | 3.5               | 0.23        |
| Vertical connectivity/.(100km)⁻¹                         | 0.3     | 0.5           | 0.8         | 1.0          | 1.2               | 1.5         |

4.2. Establish a fuzzy relation matrix \( R \)

After constructing the factor set, quantify each factor on the evaluated object one by one, and then obtain the fuzzy relation matrix \( R \);

\[
R = \left[ \begin{array}{c|c|c|c|c|c|c|c}
& U_1 & & & & & \\
R & & U_2 & & & & \\
& & & \vdots & & & \\
& & & & & U_6 & & \\
\end{array} \right] = \left[ \begin{array}{cccc}
\text{ } & r_{11} & r_{12} & \cdots & r_{15} \\
\text{ } & r_{21} & r_{22} & \cdots & r_{25} \\
\text{ } & \vdots & \vdots & \ddots & \vdots \\
\text{ } & r_{61} & r_{62} & \cdots & r_{66} \\
\end{array} \right]
\]

The elements in the row and column of the matrix \( R \) represent the degree of membership of the rated fuzzy subset for a certain evaluated object from factor [13]. In this paper, by consulting the literature and combining expert opinions, the formula for determining the membership function of evaluation factors is determined as [14] ( \( i \) represents the \( j \) level health standard for the \( i \) indicators):

(1) The indicator value is positively related to the health of the river (the higher the indicator value, the higher the health):

When the \( i \) th term \( u_i \) is greater than its Grade I health condition (healthy), its membership degree of “healthy” is \( 1 \), 0 otherwise. Namely:

\[
u_i > h_{i,1}, r_{i1} = 1, r_{i2} = r_{i3} = r_{i4} = r_{i5} = 0
\]

When the \( i \) th term \( u_i \) is between the standard values \( h_{i,j} \) and \( h_{i,j+1} \) defined in Grade \( j \) and Grade \( j+1 \) health condition respectively, its membership degrees to “Grade \( j \) healthy” and “Grade \( j+1 \) healthy” are:

\[
h_{i,j} < u_i < h_{i,j+1}, r_{i,j} = \frac{u_i - h_{i,j+1}}{h_{i,j} - h_{i,j+1}}, r_{i,j+1} = \frac{h_{i,j} - u_i}{h_{i,j} - h_{i,j+1}}
\]
When the $i$th term $u_i$ is less than its Grade V health condition (on the brink of collapse), its membership degree of “on the brink of collapse” is 1, 0 otherwise. Namely:

$$ u_i < h_{i,j}, r_{r_1} = 1, \quad r_{r_2} = r_{r_3} = r_{r_4} = 0 $$

(2) The indicator value is negatively correlated with the health of the river (the larger the indicator, the lower the health):

When the $i$th term $u_i$ is smaller than its Grade I health condition (healthy), its membership degree of “healthy” is 1, 0 otherwise. Namely:

$$ u_i < h_{1,i}, r_{r_1} = 1, \quad r_{r_2} = r_{r_3} = r_{r_4} = 0 $$

When the $i$th term $u_i$ is between the standard values $h_{i,j}$ and $h_{i,j+1}$ defined in Grade $j$ and Grade $j+1$ health condition respectively, its membership degrees to “Grade $j$ healthy” and “Grade $j+1$ healthy” are:

$$ h_{i,j} < u_i < h_{i,j+1}, \quad r_{r_1} = h_{i,j+1} - u_i, \quad r_{r_2} = u_i - h_{i,j} $$

When the $i$th term $u_i$ is greater than its Grade V health condition (on the brink of collapse), its membership degree of “on the brink of collapse” is 1, 0 otherwise. Namely:

$$ u_i > h_{i,5}, r_{r_1} = 1, \quad r_{r_2} = r_{r_3} = r_{r_4} = 0 $$

According to the calculation formula, the membership rating matrix for the health of the Shule River Basin is:

$$ R = \begin{bmatrix}
0.00 & 0.00 & 0.00 & 0.97 & 0.03 \\
1.00 & 0.00 & 0.00 & 0.00 & 0.00 \\
0.00 & 0.28 & 0.72 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.59 & 0.41 & 0.00 \\
0.00 & 0.00 & 0.00 & 0.20 & 0.80 \\
1.00 & 0.00 & 0.00 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.90 & 0.10 & 0.00 \\
0.00 & 0.35 & 0.65 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.00 & 0.00 & 1.00 
\end{bmatrix}$$

5. Combination weighting determines index weights

5.1. Analytic hierarchy process model determines the subjective weight vector

| A   | C₁ | C₂ | C₃   |
|-----|----|----|------|
| C₁  | 1  | 2  | 1/2  |
| C₂  | 1/2| 1  | 1/3  |
| C₃  | 2  | 3  | 1    |

5.1.1. Construction judgment matrix The ecosystem health assessment is divided into three levels. The first level is the target level (A), which is the health level of the Shule River Basin ecosystem; the second level is the criteria level (C), including the economic development function (C₁), social service function (C₂), natural attributes (C₃), etc.; the third layer is the program layer (u), which is the set of factors. According to expert opinion, use the pairwise comparison method and 1 to 9 comparison scales to construct the judgment matrix until the lowest level [15].
This article only lists the judgment matrix with the criterion layer and the target layer as examples. The judgment matrix is shown in Table 2.

5.1.2. Determination of weight vector and consistency check

The determination of the weight vector is based on the judgment matrix of an element at the upper level, using the summation method or the root method to calculate the weight of the relative importance of a certain level factor to the upper level factor. This article uses the root method to calculate the weight vector of each indicator. The basic steps are: normalize each column of the judgment matrix; normalize the column vector and add the lines to the power; open the square root vector, determine Indicators weight vector. The weight vector calculation results are shown in Table 3.

Due to the complexity of ecological health assessment and people's ambiguity in their understanding, the consistency of the judgment matrix needs to be tested. The formula is: 

\[ CR = \frac{CI}{RI} \]

\[ CI = \frac{\lambda_{max} - n}{n - 1} \]

When \( CR < 0.1 \), it is considered that the inverse symmetric matrix of the pairwise comparison is acceptable. When the test fails, the existing matrix needs to be corrected. The consistency test is shown in Table 4.

**Table 3. Results of normalized weighting.**

| A                          | C   | U_i | Normalized weights W_j |
|---------------------------|-----|-----|------------------------|
| Shule river basin         | 0.3 | 0.36| 0.1071                 |
| health evaluation         | 0.3 | 0.51| 0.1522                 |
|                           | 0.13| 0.13| 0.0380                 |
|                           | 0.3 | 0.3 | 0.0487                 |

**Table 4. The weight coefficient calculation and consistency check results.**

| Judgment matrix | W_1 | W_2 | W_3 | CI   | RI   | CR   | Consistency test |
|-----------------|-----|-----|-----|------|------|------|------------------|
| A-C             | 0.3 | 0.16| 0.54| 0.0046| 0.0079| Satisfied       |
| C_1-U           | 0.36| 0.51| 0.13| 0.0543| 0.0937| Satisfied       |
| C_2-U           | 0.3 | 0.54| 0.16| 0.0046| 0.0079| Satisfied       |
| C_3-U           | 0.54| 0.3 | 0.16| 0.0051| 0.0088| Satisfied       |

5.2. Entropy method determines the objective weight of indicators

Raw data matrix \( x_{ij} \), which represents the original value of the \( j \) indicator of the \( i \) scenario.

(1) Normalize the data and normalize \( x_{ij} \);

(2) Calculate the entropy of the index \( \varepsilon_j = -k \sum_{i=1}^{m} p_{ij} \ln p_{ij}; k = 1/ \ln m, i = 1, 2, ..., m; j = 1, 2, ..., n \)
(3) Calculate the weight of the $j$th indicator $g_j = \frac{1}{e_j}, j = 1, 2, ..., n$ and normalize it so that 

$$\sum h_j = 1 ,$$

the weight of the $j$th indicator is $h_j = \frac{g_j}{\sum g_j}$. The index entropy and weight calculation results are shown in Table 5.

| Index entropy $e_j$ | $e_1$ | $e_2$ | $e_3$ | $e_4$ | $e_5$ | $e_6$ | $e_7$ | $e_8$ | $e_9$ |
|---------------------|------|------|------|------|------|------|------|------|------|
|                     | 0.9988 | 0.9883 | 0.9999 | 0.9987 | 1.0000 | 0.9983 | 0.9962 | 0.9931 | 0.9656 |

| Index weight $g_j$ | $g_1$ | $g_2$ | $g_3$ | $g_4$ | $g_5$ | $g_6$ | $g_7$ | $g_8$ | $g_9$ |
|-------------------|------|------|------|------|------|------|------|------|------|
|                   | 1.0012 | 1.0119 | 1.0001 | 1.0013 | 1.0000 | 1.0017 | 1.0038 | 1.0070 | 1.0356 |

| Normalized indicator weights $h_j$ | $h_1$ | $h_2$ | $h_3$ | $h_4$ | $h_5$ | $h_6$ | $h_7$ | $h_8$ | $h_9$ |
|-----------------------------------|------|------|------|------|------|------|------|------|------|
|                                   | 0.1105 | 0.1117 | 0.1104 | 0.1105 | 0.1103 | 0.1105 | 0.1108 | 0.1111 | 0.1143 |

5.3. Subjective and objective combination of empowerment

Calculate the geometric mean of the subjective weights ($w_j$) and the objective weights ($h_j$) of the entropy method. The formula is:

$$W_j = \sqrt[\sum g_j]{w_j h_j} , j = 1, 2, ..., n ,$$

$$W_j = [0.1193, 0.1430, 0.0710, 0.1080, 0.1453, 0.0801, 0.1447, 0.1076, 0.0810] .$$

5.4. Comprehensive evaluation result

Based on the above $R$ matrix and the normalized weight vector $w_j$, the fuzzy-transformation $B = w_j[R]$ can be used to obtain the ecological health value of Shule River Basin. The calculation results are shown in Table 6. The grading system of river health adoped in this paper: healthy (0.7 to 1.0), mostly healthy (0.5 to 0.8), sub-healthy (0.3 to 0.5), morbid (0.2 to 0.3), on the brink of collapse (0 to 0.2).

According to the grading system of river health mentioned above, the Shule River’s membership degrees of “healthy”, “sub-healthy” and “on the brink of collapse” are 0.225, 0.316 and 0.202 respectively. Based on the rule of maximum membership, it can be seen that the ecosystem of the Shule river basin is sub-healthy.

| Table 6. Results of ecological evaluation of Shule River Basin |
|---------------------------------------------------------------|
| Health level                  | Healthy | Basic healthy | Sub healthy | Pathological | About to collapse |
| Degree of membership          | 0.225   | 0.046         | 0.316       | 0.211        | 0.202             |

6. Conclusions and suggestions

The ecological environment of the Shule River Basin is relatively fragile. The evaluation value of the degree of membership of the health degree is 0.316, which belongs to the sub-health state. Analysis of its main ecological and environmental issues: low rainfall, large evaporation, relatively scarce water resources; high degree of water resources development and utilization, uncoordinated development of
water and land resources, resulting in reduced grassland, wetland area, desertification, biodiversity destruction and reduction of water conservation capacity. The structure of water within the river basin is irrational, water use efficiency is low, and the proportion of water used for agriculture is high. The application of chemical fertilizers and pesticides causes eutrophication of water bodies. In response to the above problems, the following suggestions are made for the use and protection of water resources:

1. Strengthen the control and management of the total water use in the river basin and water use efficiency.

2. Determine the industrial layout and scale of land use with water as the center to increase the carrying capacity of the ecological environment. For the non-major cotton producing areas in the Shule River basin, water conservation can be realized by encouraging farmers to change their agricultural planting structure. Reducing the planting area of crops that consume water intensively, such as vegetables and cottons and encouraging farmers to work in forestry and animal farming.

3. In 2014, the water-saving irrigation rate in the Shule River Basin was 63%, which corresponds to the evaluation criteria for the state of health (water-saving irrigation rate of 80%), and there is still much room for improvement. Watersheds should vigorously develop efficient water-saving irrigation, and different crops should adopt different water-saving irrigation techniques, promote green agriculture, reduce pesticide, fertilizer and other dosage.

4. Water right transactions should be implemented comprehensively; establish a policy guarantee and price compensation mechanism for ecological water use; use agriculture to float water prices during the season; guide agricultural irrigation to avoid water peaks and ensure ecological water use.

5. Give watershed management agencies the right to enforce the law, and on the basis of reasonable planning, timely and appropriate scientific water transfer, strengthen supervision and inspection of water use, identify problems, and deal with them in a timely manner to ensure the sustainable development of the river basin.

6. Strengthen the protection and restoration of water conservation areas in Qilian Mountain, the source of the Shule River; prohibit the use of pressure and reclamation wetlands, woodlands, lakes, etc., and provide ecological water restoration and restoration measures for damaged protected areas.

References
[1] Zheren Dong 2005 J. China Water Resources 4 15
[2] Xiaoping Zhang, Keqin Yang 1998 J.Bulletin of Soil and Water Conservation 18 57
[3] Xiong W, Siping Huang J. The People of The Yangtze River 41 8
[4] Rapport D j, Gaudet C L, Calow P 1993 Evaluating and monitoring the health of large scale ecosystems Global Environment Change Proceedings of the NATO Advanced Research Workshop 1993
[5] Rapport D J 1989 What constitutes ecosystem health of perspectiv es in biology and medicine 33
[6] Pinto H, Maheshwari B A 2014 Framework for assessing river health in peri-urban landscapes Ecohydrology & Hydrobiology
[7] Vor growsn Meaghan Rourke, Dean Gilligan 2013 J. Ecological Indicators
[8] Guangchao Feng, Wenjie Li 2016 J. Journal of China Hydrology 36 46
[9] Zuoliang Hu, Shenghong Zhang 2010 Study on the ecological protection and restoration model of plain rivers in Haihe River Basin 31
[10] Xiaorong Huang, Yunling Li 2013 Study on the Evaluation Index system and method of Water Resources allocation rationality in the Yellow River Basin 190
[11] Aihong Fu, Yaning Chen 2009 J. Acta Ecologica Sinica 29
[12] Zhihong Zheng 2014 Study on the theory and application of River Health Assessment and Ecological Environment Water demand 29
[13] Zheng L 2013 Mathematical Models 190
[14] Qiaoling Guo 2012 The ecological water system health evaluation and the heihe river basin 131
[15] Qiyuan Jiang, Jinxing Xie 2010 Mathematical Models 249