Postprint: Assessment of Water Ecological Security in the Hexi Inland River Basin

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Abstract

Research on water security evaluation has produced numerous achievements, yet the vast majority adopts the P-S-R (Pressure-State-Response) model and its extensions, with optimization and calibration of evaluation index systems rarely mentioned. This paper introduces the W-SENCE (Water-related Social-Economic-Natural Compound Ecosystem) model into the field of water ecological security evaluation, constructing a water ecological security evaluation index system from the perspectives of natural attributes and socio-economic attributes of water ecological security. The index system is analyzed and optimized by combining fuzzy system analysis with improved niche theory, and the optimized index system is employed to conduct a fuzzy comprehensive evaluation of water ecological security status in the Hexi Inland River Basin from 2014 to 2017. The results demonstrate that indicators B3 (industrial added value), B13 (river base flow), B17 (water yield coefficient), and B20 (water diversion volume) exhibit relatively maximum improved niche width values and minimal relative impact on the index system, and are therefore eliminated when establishing the optimized index system. In the optimized index system, indicators C11 (multi-year average precipitation), C16 (water storage capacity), C17 (surface water supply), C18 (groundwater resources supply), C24 (ecological and environmental water consumption), and C29 (water-saving irrigation area) possess the greatest weights, representing the primary influencing factors of basin water ecological security. This indicates that increasing investment in water conservancy infrastructure, developing water-saving irrigation agriculture, and protecting the ecological environment constitute the most effective measures for improving water ecological security status in inland river basins. From 2014 to 2017, the water ecological security status of the Heihe River Basin continuously improved, while that of the Shiyang River and Shule River Basins exhibited a continuous deteriorating trend, which should be designated as key governance areas. The trend of "overall improvement with local deterioration" in water ecological security status of inland river basins continues. The results can provide theoretical support for water administration, ecological environment management, and ecological risk decision-making in the Hexi Inland River Basin.

Full Text

Evaluation of Water Ecological Security in Hexi Inland River Basins

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Abstract

Water security evaluation research has produced numerous outcomes, yet most studies adopt the traditional Pressure-State-Response (P-S-R) model, with optimization and calibration of evaluation index systems rarely addressed. This paper introduces the Water-related Society-Economic-Nature Composite Ecosystem (W-SENCE) model into water ecological security evaluation. A water ecological security evaluation index system was constructed from both natural and socio-economic attributes of water security, which was then analyzed and optimized using fuzzy system analysis and improved niche theory. The optimized index system was applied to conduct a fuzzy comprehensive evaluation of water ecological security in the Hexi inland river basins from 2014 to 2017. Results indicate that indicators B3 (industrial added value), B13 (river base flow), B17 (water yield coefficient), and B20 (water diversion) exhibited the largest improved niche width values, exerting minimal influence on the index system and were consequently eliminated during optimization. In the optimized index system, indicators C11 (perennial average precipitation), C16 (water storage), C17 (surface water supply), C18 (groundwater supply), C24 (ecological environment water consumption), and C29 (water-saving irrigation area) demonstrated the greatest weights, representing the primary influencing factors of basin water ecological security. This suggests that increasing investment in water conservancy infrastructure, developing water-saving irrigation agriculture, and protecting the ecological environment constitute the most effective measures for improving water ecological security in inland river basins. From 2014 to 2017, water ecological security in the Heihe River Basin continuously improved, while conditions in the Shiyang and Shule River Basins exhibited persistent deterioration trends, designating them as priority governance areas. The pattern of "overall improvement with localized deterioration" in inland river basin water ecological security continues. These findings provide theoretical support for water administration, ecological environment management, and ecological risk decision-making in the Hexi inland river basins.

Keywords: improved niche theory; fuzzy system analysis; water ecological security; Hexi inland river

1. Study Area Overview

Gansu' s Hexi Corridor contains three major inland rivers from east to west: the Shiyang River, Heihe River, and Shule River. Throughout history, the Hexi Corridor has served critical functions in western China' s politics, economy, military affairs, and culture. Presently, these inland river basins face severe ecological crises, with prominent environmental problems. According to Gansu Provincial Meteorological Bureau data, all three inland river basins exhibit serious ecological degradation, primarily manifested through reduced vegetation coverage and intensified ecological issues in certain regions.

The Shule River system lies at the western end of the corridor, bordered by the eastern Altun Mountains and western Qilian Mountains with high elevations, and fronted by an east-west trending series of denuded rocky low mountains. The northern boundary is the Mazong Mountains. The central corridor comprises the middle reaches of the Shule River oasis and the Dunhuang oasis at the lower Dang River reaches, while the lower Shule River consists of saline-alkali flats. Outside the oasis lies extensive gobi desert interspersed with sand dunes.

The Heihe River system extends between the Dahuang Mountains and Jiayuguan, with most areas comprising gravel desert and sandy gravel desert, featuring extensive sand dunes along the northern margin. Large oases formed between Zhangye, Linze, Gaotai, and the Jiuquan area constitute important agricultural regions in Hexi.

The Shiyang River system occupies the eastern corridor section, with loess ridge and hill landforms and piedmont alluvial-proluvial fans in the southern Qilian Mountains' foothill region, and primarily gravel desert in the north with denuded rocky mountains and residual hills. The southern edge borders the Tengger Desert, while the central area is the Wuwei Basin.

The Hexi Corridor is situated in the middle of China' s geographic landscape, in the depression between the Tibetan Plateau and Inner Mongolia Plateau, where the Siberian High passes unimpeded. The ecological condition of the Hexi Corridor' s inland river basins directly affects China' s overall ecological status, making water security evaluation in this region critically important.

2. Research Methods

Water ecological security evaluation represents an interdisciplinary research field with complex index system construction, where scholars hold diverse perspectives. Previous research has seldom addressed analysis and optimization of evaluation index systems. Since water ecological security evaluation constitutes a fuzzy, comprehensive multi-indicator systematic assessment process, this study leverages the theoretical and practical advantages of fuzzy mathematics. Fuzzy system analysis was employed to determine indicator weights, while improved niche theory was utilized to identify priority regulation indicators, thereby optimizing the evaluation index system. The optimized system was then applied for fuzzy comprehensive evaluation of inland river basin water ecological security.

2.1 Construction of Water Ecological Security Evaluation Index System Based on W-SENCE

Following principles of scientific validity, dynamism, systematicity, openness, hierarchy, and regionality in constructing water ecological security evaluation index systems, indicators were selected through theoretical optimization, practical experience, and frequency analysis. Based on actual water ecological security problems in Gansu' s three major inland river basins—including overgrazing, low water use efficiency, serious waste, and backward water conservancy facilities—corresponding evaluation indicators were selected (e.g., livestock numbers, water storage, water diversion). Grounded in the W-SENCE model and guided by the concept of water ecological civilization and systematic governance of mountains-waters-forests-farmlands-lakes-grasslands as a life community, a preliminary water ecological security evaluation index system was constructed from both socio-economic and natural attributes (resource, environmental, ecological, and disaster attributes) of water ecological security (Table 1).

2.2 Fuzzy System Analysis

2.2.1 Establishment of Fuzzy Matrix R Standardized data x_{ik} and x_{jk} were substituted into equation (1):

$$\gamma_{ij} = x_{ik} \times x_{jk}, \quad (i \neq j)$$

where x_{ik} represents the dimensionless parameter of the kth indicator (water ecological security evaluation indicator) for the ith basin; x_{jk} represents the dimensionless parameter of the kth indicator for the jth basin; m is the total number of samples (basins). The constructed $n \times n$ matrix is called the fuzzy matrix.

For diagonal elements:

$$\gamma_{ij} = 1, \quad (i = j)$$

2.2.2 Establishment of Fuzzy Correlation Matrix U The fuzzy correlation matrix U is constructed as:

$$U = \begin{pmatrix} a_{11} & a_{12} & \cdots \\ a_{21} & a_{22} & \cdots \\ \vdots & \vdots & \ddots \\ a_{n1} & a_{n2} & \cdots \end{pmatrix}$$

where a_{ij} are matrix elements, $i = 1, 2, \dots, n$.

2.2.3 Fuzzy Correlation Degree Analysis Based on the established fuzzy correlation matrix, the maximum matrix element was taken as the confidence level λ to obtain each indicator's confidence level. According to the fuzzy matrix maximum element theorem, indicator weights were derived using formula (4):

$$W_i = \frac{\lambda_i}{\sum_{i=1}^{n} \lambda_i}$$

where W_i is the weight of the ith indicator; λ_i is the confidence level of the ith indicator; $i = 1, 2, \dots, n$.

2.3 Optimization of Water Ecological Security Evaluation Index System

Hutchinson conceptualized niche as an n-dimensional hypervolume, with its n coordinate axes comprising key physical environmental factors determining species survival status. Niche calculation is simple and highly operational, forming the basis of numerous theoretical and field studies, widely applied in habitat selection, species spatiotemporal distribution dynamics, conservation, and community succession. This study employs the most widely used Levins niche width model. Larger niche width of a resource axis (water ecological security evaluation indicator) for a basin indicates smaller impact on basin water ecological security, making it a non-controlling indicator. Conversely, priority regulation should be considered. The membership degree concept from fuzzy mathematics was introduced into niche calculation. Before calculating niche width, each resource axis was divided into different gradients to compute the probability of each typical basin belonging to different gradient levels on each resource axis. The Levins niche width model was improved to formula (5) for calculating niche width:

$$B_i = \frac{1}{\sum_{j=1}^{R} (P_{ij}\gamma_{ij})^2}$$

where B_i is the niche width of the basin; P_{ij} is the proportion (%) of basin i' s quantity at gradient j to the total quantity of both; R is the total number of gradient levels; γ_{ij} is the membership degree of basin i at gradient j, with a value range of [0,1].

2.4 Fuzzy Comprehensive Evaluation

Using the optimized water ecological security evaluation index system, fuzzy comprehensive evaluation was conducted. The resulting evaluation vector represents the synthesis of the factor weight vector and fuzzy matrix:

$$Y = R \times X = (y_1, y_2, \dots, y_n)^T$$

where Y is the evaluation vector ($y_1, y_2, \ldots, y_n$ are annual comprehensive evaluation indices); R is the standardized evaluation indicator matrix (composed of standardized data); X is the evaluation weight vector (composed of evaluation indicator weights); T is the vector transpose symbol.

3. Data Sources and Processing

3.1 Data Sources

Water resources and water environment data were primarily obtained from the Gansu Provincial Hydrology Bureau' s statistical materials and *Gansu Provincial Water Resources Bulletin* (2014–2017). Socio-economic data related to water were sourced from *Gansu Statistical Yearbook*, *China Water and Soil Conservation Bulletin*, *China Environmental Statistics Yearbook*, and *China Forestry Statistics Yearbook* (2014–2017). Some water management data were obtained from publicly available information and annual reports from Gansu Provincial Water Conservancy departments.

3.2 Data Standardization

Following establishment of the preliminary water ecological security evaluation index system, indicator data required standardization to adjust according to uniform "standards" and eliminate impacts from different units. Using 2017 data as an example, indicator data were standardized as follows:

For larger-is-safer indicators:

$$y_{ij} = \frac{x_{ij} - \min x_i}{\max x_i - \min x_i}$$

For smaller-is-safer indicators:

$$y_{ij} = \frac{\max x_i - x_{ij}}{\max x_i - \min x_i}$$

where y_{ij} is the standardized data in row i, column j; $\max x_i$ is the maximum value in row i; $\min x_i$ is the minimum value in row i.

3.3 Optimization Based on Improved Niche Theory

Applying the membership degree concept from fuzzy mathematics and improved niche theory, 33 evaluation indicators served as resource axes to calculate their membership degrees and niche widths across different gradients. Using the membership function, the membership degrees of each basin' s water ecological security evaluation indicators were calculated. Based on formula (5), niche widths of the three major inland river basins in the Hexi Corridor across 33 resource axes were computed (Table 3). Using 2017 data as an example, the average niche width of water ecological security evaluation indicators shows that indicators B3 (industrial added value), B13 (river base flow), B17 (water yield coefficient), and B20 (water diversion) had relatively largest niche width values, exerting minimal influence on the index system. These four indicators were eliminated to obtain the optimized evaluation index system comprising 29 indicators (Table 4).

3.4 Fuzzy System Analysis

Based on formula (1), standardized data for water ecological security evaluation indicators in the three major inland river basins of the Hexi Corridor were processed (Table 2). According to the established fuzzy correlation matrix, the maximum matrix element served as the confidence level to obtain each indicator' s confidence level. Using formula (4), indicator weights were calculated, yielding weights for the 29 indicators in the optimized water ecological security evaluation index system (Table 5).

3.5 Fuzzy Comprehensive Evaluation

Using the optimized water ecological security evaluation index system, fuzzy comprehensive evaluation was conducted on water ecological security conditions in the three major inland river basins of the Hexi Corridor (Shule River, Heihe River, Shiyang River) from 2014 to 2017. Based on Table 2 (standardized data) and Table 5 (indicator weights), formula (6) yielded continuous water ecological security evaluation vectors:

$$Y_{2014} = (0.268, 0.480, 0.534)^T$$

$$Y_{2015} = (0.294, 0.475, 0.487)^T$$

$$Y_{2016} = (0.132, 0.401, 0.629)^T$$

$$Y_{2017} = (0.223, 0.294, 0.658)^T$$

4. Results

4.1 Optimization of Evaluation Index System Using Improved Niche Theory

Based on the average niche width of each resource axis (water ecological security evaluation indicator) in the water ecological security evaluation index system, indicators B3 (industrial added value), B13 (river base flow), B17 (water yield coefficient), and B20 (water diversion) exhibited relatively largest niche width values, indicating minimal impact on current water ecological security evaluation and small influence on water ecological security conditions in the three major inland river basins of the Hexi Corridor. These represent secondary influencing factors and were consequently eliminated from the final optimized evaluation index system. The average niche width values for Shule River, Heihe River, and Shiyang River basins were 0.312, 0.308, and 0.311, respectively. The similar niche width values across the three basins indicate comparable adaptability under the current index system, necessitating targeted regulation based on actual evaluation indicator conditions.

4.2 Determination of Main Influencing Factors Using Fuzzy System Analysis

Fuzzy system analysis (Figure 1) revealed that indicators C11 (perennial average precipitation), C16 (water storage), C17 (surface water supply), C18 (groundwater supply), C24 (ecological environment water consumption), and C29 (water-saving irrigation area) had the largest relative weights, with a cumulative weight of 36.18%, representing the most significant influencing factors affecting water ecological security conditions in the three major inland river basins of the Hexi Corridor. Indicators C12 (farmland actual irrigation area), C13 (farmland irrigation water volume), C14 (forest, fishery, and livestock water consumption), and C23 (socio-economic water consumption) had small weights with a cumulative weight of 0.46%, representing secondary influencing factors.

4.3 Analysis of Water Ecological Security Status in Gansu Inland River Basins

Referencing previous research findings and the *Technical Guidelines for River Ecological Security Investigation and Assessment* jointly issued by ministries and commissions in 2015, as well as the *Technical Guidelines for Watershed Ecological Health Assessment* issued by the Ministry of Environmental Protection in 2013, evaluation results were classified into three levels: $y \geq 0.45$ as Level I (safe zone), $0.3 \leq y < 0.45$ as Level II (moderately safe zone), and $y < 0.3$ as Level III (unsafe zone).

The fuzzy comprehensive evaluation results for water ecological security status in the three major inland river basins of the Hexi Corridor (Figure 2) show that the Heihe River Basin' s water ecological security status remained in Level I (safe zone) from 2014 to 2017, with the fuzzy comprehensive evaluation index consistently above 0.45, showing a linear prediction trend of annual increase and continuous improvement in water ecological security conditions—the best among the three basins. The Shiyang River Basin' s fuzzy comprehensive evaluation index decreased from 0.5 to below 0.3, transitioning from safe to unsafe zones with a continuously declining linear prediction trend. The Shule River Basin' s fuzzy comprehensive evaluation index hovered around 0.2, remaining in Level III (unsafe zone) with a slowly declining linear prediction trend, representing the worst water ecological security status. Therefore, future efforts must focus on intensifying water ecological security governance in the Shiyang and Shule River basins to prevent further deterioration, with the Shule River Basin designated as the priority governance area in inland river basins. These findings align with current ecological degradation events and environmental damage realities in the three major basins, yielding relatively objective evaluation results through fuzzy comprehensive evaluation.

5. Conclusions

1) Through fuzzy system analysis, indicators including perennial average precipitation, water storage, surface water supply, groundwater supply, ecological environment water consumption, and water-saving irrigation area exhibited the largest relative weights, with a cumulative weight of 36.18%, representing the most significant factors influencing basin water ecological security conditions. This demonstrates that increasing water supply through storage measures, augmenting ecological environment water use, and improving agricultural water-saving practices play crucial roles in enhancing water ecological security. Therefore, increasing investment in basic water conservancy facilities, developing water-saving irrigation agriculture, and protecting the ecological environment constitute the most effective current measures for improving water ecological security in the Hexi inland river basins, highlighting that inland river basin socio-economic development is heavily constrained by water resources and that developing water-saving irrigation agriculture aligns completely with practical needs.
2) The improved niche theory was applied to optimize the preliminary water ecological security evaluation index system. Four indicators—industrial added value, river base flow, water yield coefficient, and water diversion —exhibited relatively largest niche width values and minimal impact on water ecological security conditions in the Hexi Corridor' s three major inland river basins, and were consequently eliminated, yielding an optimized index system comprising 29 indicators (Table 4). This suggests that water diversion, base flow, and industrial added value have limited impact on inland river basin water ecological security, likely because these indicators show little variation across basins and are not limiting factors.
3) Fuzzy comprehensive evaluation of water ecological security conditions in the three major inland river basins from 2014 to 2017 revealed that the Heihe River Basin' s water ecological security continuously improved, while the Shiyang and Shule River basins experienced persistent deterioration, designating them as key governance areas. The pattern of "overall improvement with localized deterioration" in inland river basin water ecological security continues, with evaluation results largely reflecting current basin conditions and validating the scientific feasibility of this evaluation methodology.

6. Discussion

This study constructed a basin water ecological security structural model based on the interaction relationships within the water-related economic, social, and natural composite ecosystem (W-SENCE), departing from fundamental water attributes. Compared with previous research [16-20,27], this approach overcomes conventional DPSIR model limitations in effectively grasping system structure and decision-making processes, more comprehensively covering main influencing factors of basin water ecological security conditions. The improved niche theory was employed to optimize the evaluation index system by eliminating four secondary influencing factors, yielding an optimized system. Fuzzy system analysis was used to determine evaluation index system weights, overcoming the substantial subjectivity of previous studies relying on analytic hierarchy processes and expert scoring methods.

Fuzzy system analysis results demonstrate that increasing basic water conservancy infrastructure investment, developing water-saving irrigation agriculture, and protecting the ecological environment are the most effective measures for improving water ecological security in Hexi inland river basins. These findings provide references for basin water administration and water resources planning, offering new ideas for high-quality development of river basins in Gansu Province and beyond. Fuzzy comprehensive evaluation produced water ecological security status results for the three major inland river basins from 2014 to 2017. Interannual trend analysis reveals deteriorating conditions in the Shiyang and Shule River basins, identifying them as priority governance areas. The trend of "overall improvement with localized deterioration" in the Hexi inland river basins remains fundamentally unchanged. Evaluation results align well with current basin realities, validating the methodology's scientific feasibility.

Basin water ecological security evaluation constitutes an important component of ecological security research and an intrinsic requirement of water ecological civilization construction. Enhancing basin water ecological security and improving water ecological risk prevention and control require further exploration in water ecological security early warning systems.

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