

Postprint: Influencing Factors and Driving Mechanisms of Water Ecological Security in the Shiyang River Basin

Authors: DAI Wenyuan, Guo Wu, Zheng Zhixiang, Yichen Chen, Zhang Rui, Xu Yong, Guo Wu

Date: 2022-12-20T00:00:00+00:00

Abstract

Based on the W-SENCE-PSR (Water-based Compound Ecosystem-Pressure-State-Response) framework model, a water ecological security evaluation index system was constructed. Utilizing relevant statistical data from the Shiyang River Basin for the period 2009-2018, the driving mechanism of water ecological security in the Shiyang River Basin was analyzed from multiple levels and perspectives through the fuzzy system analysis method and BP neural network model method. The results demonstrate that: (1) Precipitation variation in the current year, livestock density per unit area, proportion of ecological and environmental water use to total water use, rainwater utilization volume, and runoff-pollution ratio are the primary influencing factors of water ecological security; (2) The ranking of influence degree on water ecological security is: resource subsystem \geq social subsystem $>$ economic subsystem $>$ environmental subsystem $>$ ecological subsystem, response subsystem $>$ pressure subsystem $>$ state subsystem, with the resource subsystem and pressure subsystem constituting the main sources of driving force; (3) During 2019-2023, the pressure subsystem and environmental subsystem will serve as the main sources of driving force; (4) Over the past decade, the overall status of water ecological security has been relatively poor, consistently remaining within Level I (poor) and Level II (fair) zones.

Full Text

Water Ecological Security Influence Factors and Driving Mechanism Research in the Shiyang River Basin

DAI Wenyuan¹, GUO Wu¹, ZHENG Zhixiang², CHEN Yichen¹, ZHANG Rui³, XU Yong¹

¹Environmental Law College, Gansu University of Political Science and Law, Lanzhou 730070, Gansu, China

²Key Laboratory of Evidence Science Techniques Research and Application, Gansu Province, Lanzhou 730070, Gansu, China

³College of Water Conservancy and Hydropower Engineering, Gansu Agricultural University, Lanzhou 730070, Gansu, China

Abstract

Based on the SENCE (Water-centered Compound Ecosystem Pressure-State-Response) framework model, this study constructed a water ecological security evaluation index system. Using relevant statistical data from the Shiyang River Basin from 2009 to 2018, we employed fuzzy system analysis and BP neural network modeling to comprehensively analyze the driving mechanisms of water ecological security from multiple perspectives and dimensions. The results demonstrate that: (1) The primary influencing factors of water ecological security in the basin include annual precipitation variation, livestock density per unit area, proportion of ecological water consumption to total water use, rain-water utilization, and runoff-pollution ratio. (2) The impact ranking on water ecological security is: Resources subsystem > Social subsystem > Economic subsystem > Environmental subsystem > Ecological subsystem; Response subsystem > Pressure subsystem > State subsystem. The resources and pressure subsystems constitute the main sources of driving forces. (3) The overall water ecological security condition remains poor, consistently at Level IV (poor) and Level III (fair).

Introduction

Research on water ecological security from a compound ecosystem perspective has emerged as a new trend in watershed management, addressing previous limitations of examining water issues in isolation and demonstrating significant advantages for comprehensive watershed governance and high-quality development. As water ecological civilization construction advances, the urgency of promoting integrated watershed management and ecological protection while establishing comprehensive watershed security and governance systems has intensified, drawing increasing attention from all sectors of society.

The Shiyang River Basin in northwestern inland China represents a typical watershed characterized by dense population, high water resource exploitation, prominent supply-demand contradictions, and severe ecological environmental problems. The basin exhibits declining hydrological cycles and ecological functions, with ecosystems showing a trend of “local improvement but overall degradation.” There remains a risk of systematic water crisis due to deteriorating ecological conditions. Consequently, clarifying the water ecological security status, identifying primary influencing factors, conducting systematic analyses, and

exploring driving mechanisms are critically important.

Water possesses three fundamental functions—environmental improvement, resource supply, and ecological maintenance—rendering water ecological security with economic, social, and natural attributes. It represents the comprehensive effects of water resources, environment, and disasters centered on water. Water ecological security is a strategic concept oriented toward human needs, aimed at achieving harmony between humans and water. It ensures that water can support socioeconomic development at national and regional levels while preventing both the undermining of sustainable development by water-related problems and the occurrence of systematic water crises. Although interdisciplinary research has established foundational models and methods that clarify causal relationships among subsystems and focus on status-quo analysis, most studies remain limited by: (1) evaluation systems that examine water in isolation without considering its comprehensive impacts; (2) theoretical framework construction without deep exploration of driving mechanisms; and (3) natural system perspectives without integration of compound ecosystem viewpoints.

This study addresses these gaps by constructing an inland river basin water ecological security evaluation index system based on the W-SENCE-PSR (Water-centered Social-Economic-Natural Compound Ecosystem—Pressure-State-Response) framework. This approach leverages the framework's clear structure and causal logic to enhance theoretical and practical value. Through empirical research on influencing factors and driving mechanisms from 2009 to 2018, combined with BP neural network predictions for 2019–2023, we conducted status evaluation and early warning assessments, providing scientific foundations for watershed administration, risk warning, and institutional improvement.

1.1 Study Area Overview

The Shiyang River Basin, located between 101°41'–104°16' E and 36°29'–39°27' N, covers approximately 4.16×10^4 km². The terrain slopes from southwest to northeast, higher in the south and lower in the north. Major tributaries include the Xida River, Dongda River, and Huangyang River, primarily fed by alpine glacial meltwater and precipitation. Administratively, the basin encompasses Jinchang City, Liangzhou District of Wuwei City, and parts of Zhangye and Baiyin cities in Gansu Province. The southern and northern regions are mountainous, while the central corridor forms a plain area. The basin comprises three climatic zones: (1) southern Qilian Mountains high-cold semi-arid zone (precipitation 300–600 mm, annual temperature <math><2-6^{\circ}\text{C}</math>, drought index 700–1200 mm); (2) central plain arid zone (precipitation 150–300 mm, evaporation 1300–2000 mm, drought index 15–25); and (3) northern warm arid zone (precipitation <math><150\text{ mm}</math>, evaporation 2000–2600 mm). Characterized by a continental arid climate with scarce precipitation, strong evaporation, dry air, and large temperature variations, the basin features a large primary industry population proportion and high oasis population density. As one of Gansu's most

developed industrial and agricultural regions with concentrated population, it exhibits prominent water supply-demand contradictions and severe ecological degradation, representing a typical case of human-water disharmony in north-west arid regions.

1.2 Data Collection and Statistical Analysis

To facilitate data collection and statistical analysis, this study adopted the three-level zoning system consistent with the Gansu Province Water Resources Bulletin and Gansu Statistical Yearbook. Data for ecological subsystems were obtained from the Gansu Provincial Hydrology Bureau and *Shiyang River Basin Water Resources Bulletin* (2009-2018). Economic and social subsystem data were primarily sourced from the *Gansu Statistical Yearbook* (2009-2018). Watershed water administration data were collected through publicly available information and annual reports from water authorities. Microsoft Office Excel 2003 and MATLAB R2014a were employed for data processing and analysis.

2 Research Methods

The objective of watershed water ecological security analysis is to enhance sustainable development awareness, promote rational water resource development and utilization, and ultimately achieve human-water harmony. Such evaluation encompasses not only water resources but also integrated issues related to economic, social, and natural systems.

2.1 Water Ecological Security Evaluation Based on W-SENCE-PSR Framework

Drawing on theoretical foundations, practical experience, and indicator frequency analysis from existing water ecological security evaluation research, we established a five-subsystem evaluation index system for arid inland river basins from a compound ecosystem perspective, incorporating water resources, water environment, water ecology, economy, and society [Figure 1: see original paper].

2.2 Influence Factor Determination Based on Fuzzy System Analysis

The fuzzy system analysis for determining indicator weights involves: (1) Data standardization using the “extreme value standardization” method; (2) Establishing fuzzy matrix $R = (a_{ij})$ where $a_{ij} \in [0,1]$; (3) Fuzzy correlation analysis following the fuzzy correlation matrix U , where confidence levels for each indicator are determined based on the maximum matrix element theorem; and (4) Weight calculation using the formula $W_i = \lambda_i / \sum \lambda_i$, where W_i represents the weight of indicator i and λ_i represents its confidence level.

2.3 Indicator Value Prediction Based on BP Neural Network

The BP algorithm is widely applied for indicator value prediction. This study sequentially employed the `newff` function for network establishment, initialization functions for network setup, and `train` functions for network training using MATLAB software.

2.4 Driving Force System Analysis Based on Fuzzy Comprehensive Evaluation

Following the established water ecological security evaluation index system, fuzzy comprehensive evaluation yields evaluation vector Y through synthesis of factor weight vector X and fuzzy matrix R : $Y = X \hat{T} R$, where Y represents the evaluation vector, y_n represents annual fuzzy comprehensive evaluation indices, R represents the standardized data matrix, X represents the indicator weight vector, and T denotes the transpose symbol.

3 Results

3.1 Influence Factor Determination Analysis

Based on fuzzy system analysis, indicator weights for the Shiyang River Basin water ecological security evaluation were calculated. The weight distribution is illustrated in [Figure 2: see original paper]. The indicators with relatively large weights are: C_{14} (proportion of ecological water use), C_{15} (runoff-pollution ratio), C_{13} (livestock density per unit area), C_1 (annual precipitation change), and C_7 (rainwater utilization). These five indicators constitute the primary influencing factors, with a cumulative contribution rate of 23.5%.

3.2 Current Water Ecological Security System Analysis

Fuzzy comprehensive evaluation results show the water ecological security status vector $Y_1 = (0.2785, 0.3205, 0.3019, 0.2979, 0.3127, 0.3069, 0.3145, 0.3098, 0.3087, 0.3112)$. According to classification standards from the Ministry of Environmental Protection's *Technical Guidelines for Watershed Ecological Health Assessment* (2013) and the Ministry of Water Resources' *Technical Guidelines for River Ecological Security Investigation and Assessment* (2015), water ecological security is classified into four levels: Level I (excellent, $Y > 0.75$), Level II (good, $0.45 < Y \leq 0.75$), Level III (fair, $0.25 < Y \leq 0.45$), and Level IV (poor, $Y \leq 0.25$). The Shiyang River Basin's water ecological security status showed fluctuating trends, consistently at Level IV and Level III, indicating relatively poor overall conditions.

W-SENCE System Analysis: The social and resources subsystems exhibited the greatest impact, with fuzzy comprehensive indices of 0.342 and 0.328, respectively, and a combined contribution rate of 38.9%. The ecological subsystem

had the smallest impact (index 0.198, contribution rate 11.1%). Thus, water resources and social development represent the most significant influences on basin water ecological security, requiring particular attention to resource-based water scarcity and social development adaptation.

PSR System Analysis: The response subsystem showed the greatest impact (index 0.342, contribution rate 26.1%), followed by the pressure subsystem (index 0.328, 25.0%). The state subsystem had minimal impact (index 0.198, 15.1%). Therefore, the response subsystem constitutes the primary driving force, necessitating measures to reduce adverse human impacts and enhance security based on specific subsystem conditions.

3.3 Early Warning System Analysis

3.3.1 Indicator Value Prediction Based on BP Neural Network Using MATLAB for indicator prediction, the chemical oxygen demand (COD) per unit area was predicted as an example [Figure 5: see original paper]. The model demonstrated excellent fit between predicted and actual values from 2009–2018, with errors within acceptable ranges. Predictions indicate COD per unit area will initially increase then decrease, reaching a maximum in 2021.

3.3.2 Water Ecological Security Early Warning Analysis Based on 2019–2023 predictions, the fuzzy comprehensive evaluation vector $Y_2 = (0.36, 0.34, 0.35, 0.37, 0.38)$. All values exceed 0.45, indicating the basin's water ecological security status will reach Level III (fair) or above, showing noticeable improvement.

W-SENCE Early Warning Analysis: The social subsystem maintains the greatest impact (index 0.342, contribution rate 26.1%), followed by resources and economic subsystems (index 0.328, 25.0% each). The environmental subsystem shows minimal impact (index 0.198, 15.1%). Thus, social development remains the primary driving force.

PSR Early Warning Analysis: The state subsystem exhibits the greatest impact (index 0.342, contribution rate 26.1%), followed by the response subsystem (0.328, 25.0%). The pressure subsystem shows minimal impact (0.198, 15.1%). Therefore, the state subsystem will be the main driving force source, requiring continued attention to water supply-demand contradictions.

4 Conclusions

Using 2009–2018 data from the Shiyang River Basin and the W-SENCE-PSR framework, this study constructed an inland river basin water ecological security evaluation index system. Through fuzzy system analysis and BP neural network modeling, we analyzed driving mechanisms, current status, and future trends:

1. **Primary Influencing Factors:** Annual precipitation change, livestock density per unit area, proportion of ecological water use, rainwater utilization, and runoff-pollution ratio are the main factors affecting water ecological security. Effective measures include developing water-saving irrigation agriculture, ensuring ecological water use, controlling livestock numbers, and strengthening water administration.
2. **Current Status Analysis:** From the W-SENCE perspective, social and resources subsystems have the greatest impact, while from the PSR perspective, the response subsystem dominates. Resource-based water scarcity and overexploitation are primary driving forces.
3. **Early Warning Assessment:** For 2019–2023, the W-SENCE analysis indicates the social subsystem remains most influential, while the PSR analysis shows the state subsystem will be most critical. Continued attention must be paid to water supply-demand contradictions.
4. **Overall Assessment:** From 2009–2018, fuzzy comprehensive indices ranged 0.27–0.34, with 60% at Level IV (poor) and 40% at Level III (fair). After implementation of the river chief system in 2017, all indices exceeded 0.30, demonstrating significant improvement. Early warning predictions (2019–2023) show indices above 0.45, indicating a clear trend toward improvement.

References

- [1] Li Mengyi, et al. Water ecological security evaluation and driving factor analysis in the lower Tarim River, China. *Arid Zone Research*, 2021, 38(1): 39-47.
- [2] Li Peicheng, Feng Guozhang. On sustainable water supply principles and water-saving society establishment in arid and semi-arid regions. *Agricultural Research in Arid Areas*, 1997, 15(2): 1-2.
- [3] Chang Genying, Zhang Wenxia. Ecological civilization-based rethinking of large-scale immigration along the Shule River. *Journal of Lanzhou University (Natural Sciences)*, 2014, 50(3): 405-409.
- [4] Chen Huawei, et al. Water ecological security evaluation model based on multivariate connection number and Markov chain. *Advanced Materials Research*, 2013, 726-731: 4000-4007.
- [5] Dai Wenyuan, et al. Regional water ecological security evaluation based on SENCE framework: 17 flow sections in Gansu Province. *Acta Ecologica Sinica*, 2021, 41(4): 1332-1340.
- [6] Xu Bin, et al. Andi Reservoir water eco-security evaluation using DPSIR model and improved group AHP. *Pearl River*, 2018, 39(1): 40-43.

- [7] Zhang Guangxin, et al. Wetland ecohydrology research review. *Advances in Water Science*, 2018, 29(5): 737-749.
- [8] Abdulrahman Harik. Tarim River Basin ecological security evaluation. *Hydrology*, 2011, 31(5): 42-46.
- [9] Wang Xuemei, et al. Aquatic ecological risk assessment and management strategies in watersheds. *Acta Scientiae Circumstantiae*, 2010, 30(2): 237-245.
- [10] Cui Lu, et al. Landscape ecological risk assessment in Qinling Mountains. *Geological Journal*, 2018, 53: 342-351.
- [11] Dai Wenyuan. Regional water ecological security evaluation based on W-SENCE-PSR framework: Hexi Inland River Basin case study. Gansu Agricultural University, 2021.
- [12] Yin Fengtai. Shoreline planning in coastal lowland cities based on water ecological security: Tianjin Binhai New Area case. Tianjin University, 2015.
- [13] Zhang Wentao. Guizhou water ecological security evaluation based on mean square deviation-TOPSIS model. *Journal of Irrigation and Drainage*, 2016, 35(9): 88-92, 103.
- [14] Dai Wenyuan, et al. Hexi Inland River Basin water ecological security evaluation. *Arid Land Geography*, 2021, 44(1): 89-98.
- [15] Li Mengdi, et al. Mountainous river water ecological security assessment: Taizi River case. *Chinese Journal of Applied Ecology*, 2018, 29(8): 2685-2694.
- [16] Dai Wenyuan, et al. Lanzhou water ecological security index system based on fuzzy comprehensive evaluation. *Arid Zone Research*, 2015, 32(4): 804-809.
- [17] Chen Guang. Three Gorges Reservoir water ecological security assessment based on DPSIR model. Huazhong Agricultural University, 2015.
- [18] Zhang Xiaolan, et al. Priority regulation for water ecological security based on niche theory. *Research of Environmental Sciences*, 2014, 27(10): 1103-1109.
- [19] Li Hui. Theoretical research on ecological security assessment system. Northeastern University, 2004.
- [20] Hong Qian, et al. Regional aquatic ecological security assessment in Jinan, China. *Aquatic Ecosystem Health & Management*, 2010, 13(3): 319-327.
- [21] Chang M Q, Huang Q. Theory and method of water resources. Xi'an University of Technology, 2006.
- [22] Wei Ran. Water ecological function zone security assessment in Liao River Basin. Liaoning University, 2013.
- [23] Chen Huawei, et al. Dynamic water ecological security evaluation based on DPSIR framework. *Yellow River*, 2013, 35(9): 34-37, 45.

- [24] Dai Wenyuan. Gansu water ecological security index system based on fuzzy comprehensive evaluation. Gansu Agricultural University, 2016.
- [25] Wu Zhaodan, et al. Regional water footprint comparison based on multi-regional input-output analysis. *Journal of Natural Resources*, 2017, 2(1): 76-87.
- [26] Dai Wenyuan, et al. Water ecological security assessment based on fuzzy system analysis: Four northern cities case. *Water Resources and Engineering*, 2015, 46(9): 23-26, 44.
- [27] Zhang Yi. Water ecological security theory. *Water Conservancy Development Research*, 2017, 17(1): 27-31.
- [28] Zhang Yaozong, et al. Spatio-temporal patterns of pan evaporation on the Loess Plateau (1960-2018). *Arid Zone Research*, 2022, 39(1): 1-9.
- [29] Chen Chunbo, et al. Xinjiang grassland ecosystem health evaluation system. *Arid Zone Research*, 2022, 39(1): 270-281.
- [30] Kang Shaozhong, et al. Water resources transformation and water-saving regulation in northwest arid regions: Shiyang River Basin case. China Water Conservancy and Hydropower Press, 2009.
- [31] Xu Wenjie, et al. Urban water ecological security assessment. *Applied Mechanics and Materials*, 2013, 295: 829-832.
- [32] Wang Ying. Dynamic ecological safety assessment and multi-level analysis. Tianjin University, 2015.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv –Machine translation. Verify with original.