Water Ecological Security Assessment and Driving Factors Analysis of the Lower Tarim River: Postprint

Authors: Li Mengyi, Deng Mingjiang, Ling Hongbo, Wang Guangyan, Xu Shengwu, Ling Hongbo

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Abstract

With the continuous strengthening of unified water resources management in the Tarim River Basin, ecological water conveyance to the lower reaches has increased, yielding phased achievements in ecological protection. However, scientific assessments are lacking regarding the water ecological security status and its evolution under strict water resources management in the lower Tarim River. To address this, the present study evaluates water ecological security status using principal component analysis and the comprehensive index method, based on data from 2000–2017 for the lower Tarim River, including water volume, groundwater depth at monitoring cross-sections, new biomass of Populus euphratica, vegetation coverage, drought index, and other indicators, thereby revealing the driving factors influencing water ecological security and their changing characteristics. Results indicate that from 2000 to 2017, the comprehensive water ecological security evaluation index for the lower Tarim River rose from 3.91 to 8.47, with ecological security levels continuously improving and transitioning from a moderate warning zone to a relatively safe zone. The primary factors influencing water ecological security assessment are hydrological and vegetation driving factors, among which discharge volume, groundwater depth, and vegetation diversity exert significant impacts on lower reach water ecological security. This research provides an important scientific basis for optimizing ecological water conveyance patterns in the lower Tarim River.

Evaluation of Ecological Water Security and Analysis of Driving Factors in the Lower Tarim River, China

LI Mengyi[1],[2], **DENG Mingjiang**[3], **LING Hongbo**[4], **WANG Guangyan**[5], **XU Shengwu**[5]

[1]State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300350, China
[2]School of Civil Engineering, Tianjin University, Tianjin 300350, China
[3]Xinjiang Irtysh River Basin Development and Construction Management Bureau, Urumqi 830000, Xinjiang, China
[4]Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China
[5]Management Bureau of the Main Stream of Xinjiang Tarim River Basin, Korla 841000, Xinjiang, China

Abstract

Due to the continuous strengthening of unified water resource management in the Tarim River Basin, ecological water conveyance to the lower reaches has increased, achieving periodic improvements in ecological protection. However, scientific assessments are lacking regarding the status and changing processes of water ecological security in the lower Tarim River under strict water resource management. This study utilized data from 2000 to 2017 on water volume, groundwater depth at monitoring sections, new *Populus euphratica* biomass, vegetation coverage, and drought indices in the lower Tarim River. Principal component analysis and the comprehensive index method were employed to evaluate water ecological security status and reveal the characteristics of driving factors. The results showed that from 2000 to 2017, the comprehensive water ecological security evaluation index increased from 39.1 to 84.7, with ecological security levels continuously improving and transitioning from a “moderate warning zone” to a “relatively safe zone.” The primary driving factors affecting water ecological security evaluation were hydrological and vegetation components, among which discharge volume, groundwater depth, and vegetation diversity had significant impacts on downstream water ecological security. These findings provide an important scientific basis for optimizing the ecological water conveyance model in the lower Tarim River.

Keywords: Tarim River; downstream ecological safety assessment; principal component analysis; driving factors

Introduction

The Tarim River is China’ s longest inland river, with a total length of 2,486 km when measured from its longest source, the Yarkant River. It represents one of the most ecologically fragile regions in China and globally. However, large-scale development of water and soil resources in the 1950s led to a sharp reduction in water flow in the main stream, declining groundwater levels, widespread vegetation degradation, and severe ecological damage. To maintain ecological security and save the endangered "green corridor" in the lower reaches, the Tarim River Basin Authority initiated ecological water conveyance downstream in 2000. To enhance comprehensive management effectiveness, unified water resource management was implemented across the Tarim River Basin in 2014, resulting in preliminary environmental improvements in the lower reaches by the end of 2017.

Previous studies have quantitatively analyzed various aspects of this restoration. Zhang et al. [?] examined spatiotemporal desertification trends before and after management interventions. Xu et al. [?] investigated groundwater dynamics and differential responses of natural vegetation to ecological water conveyance. Zhu et al. [?] and Huang et al. [?] explored vegetation recovery under ecological water conveyance using maximum and average vegetation coverage metrics. Jiang et al. [?] applied fuzzy comprehensive evaluation for quantitative remote sensing assessment of vegetation ecological risk. Deng et al. [?] systematically analyzed vegetation index changes and proposed methods for evaluating relative vegetation recovery. While these studies demonstrated environmental benefits from ecological, groundwater monitoring, and *Populus euphratica* growth perspectives, they primarily relied on single indicators. This research constructs a multi-indicator evaluation system for water ecological security in the lower Tarim River based on remote sensing data and observational records, clarifying recent changes and driving processes to objectively reflect ecological conditions. This provides a typical case study for investigating driving factors of ecological change in arid inland river basins and offers decision-making references for water resource management and allocation in the Tarim River Basin.

1.1 Study Area Overview

The lower Tarim River is located within Yuli and Ruoqiang counties in Xinjiang, extending from the Daxihaizi Reservoir to Lake Taitema with a total length of approximately 320 km. This river section is situated between the Taklamakan Desert and the Kumtag Desert, with geographical coordinates of 39°24 -41°40 N and 86°37 -88°30 E. The study area lies in the weak Robopo depression zone with stable tectonic conditions, featuring Quaternary deposits approximately 350 m thick composed primarily of clayey fluvial-lacustrine sediments. The terrain is flat, gently sloping eastward at approximately 17.4–42.0‰ gradient.

With annual precipitation of only 20–30 mm and evaporation reaching 2,500–3,000 mm, the region experiences a continental warm temperate extremely arid climate. The harsh environmental conditions result in extremely sensitive and fragile ecosystems [?]. Vegetation is distributed in bands along the river, transitioning from high-coverage *Populus euphratica* forests and *Tamarix* shrublands with halophytic grass belts upstream to medium-low coverage *Populus euphratica* forests and *Tamarix* shrublands, and further to low-coverage sparse *Tamarix* shrub belts downstream [?].

1.2 Data Sources

This study utilized the following datasets: (1) Annual discharge data from Daxihaizi Reservoir (19 instances) and groundwater depth data from four typical monitoring sections (Yingsu, Ka' erdayi, Alagan, and Yiganbujima) in the lower Tarim River, obtained from the Tarim River Main Stream Management Bureau. (2) Remote sensing data for Normalized Difference Vegetation Index (NDVI) and drought index (TVDI) from 2000 to 2017, sourced from MODIS MOD13Q1 and MOD11A2 products released by the United States. (3) Vegetation survey data from 2000 to 2017, collected from monitoring transects in the lower Tarim River. Each transect established a 25 m × 25 m quadrat near monitoring wells at distances of 150 m, 300 m, 500 m, 750 m, and 1,050 m from the river, recording vegetation species, individual counts, coverage, height, crown diameter, and frequency. (4) *Populus euphratica* growth data from 2000 to 2017, obtained from 100 m × 100 m quadrats at typical sections, including diameter at breast height, tree height, crown diameter, and growth vigor. (5) Meteorological data from 2000 to 2017 from the Tieganlike Meteorological Station.

1.3.1 Establishment of the Ecological Security Evaluation Index System

Establishing a reasonable ecological evaluation index system is crucial for assessing regional ecological security levels. Based on principles of scientific rigor, simplicity, and systematicity [?], and considering data availability and analytical operability, this study selected three categories of elements (hydrological, soil, and vegetation) comprising eight evaluation indicators to construct the water ecological security evaluation index system for the lower Tarim River [?].

[Figure 2: see original paper]

Ecological water conveyance is the fundamental approach to ensuring water ecological security in the lower reaches. Water supply includes recharge to groundwater and the vadose zone from discharged water, which raises groundwater levels and increases soil moisture content. Groundwater recovery after ecological water conveyance is critical for ecosystem restoration in the lower reaches. Soil moisture is the primary water source for vegetation growth, and the drought index, as an important parameter reflecting soil moisture content, serves as a key indicator for measuring vegetation habitat conditions. New *Populus euphratica* biomass, vegetation coverage, and vegetation diversity are important indicators for quantitatively measuring surface vegetation recovery status.

1.3.2 Calculation of the Evaluation Index System

Drought Index (TVDI): The Temperature Vegetation Drought Index reflects vegetation distribution characteristics under different drought conditions. The calculation method is shown in Equation (1):

$$TVDI = \frac{T_s - T_{s_{min}}}{T_{s_{max}} - T_{s_{min}}}$$

where T_s represents land surface temperature, $T_{s_{min}}$ represents the minimum land surface temperature, and $T_{s_{max}}$ represents the maximum land surface temperature. TVDI values range from 0 to 1, where values closer to 0 indicate soil moisture approaching field capacity, and values closer to 1 indicate soil moisture approaching the wilting point.

Vegetation Diversity: The Shannon-Wiener index was used to characterize vegetation diversity, as shown in Equation (2):

$$D = -\sum_{i=1}^{S} P_i \ln P_i$$

where D is the diversity index, S represents the number of species in the quadrat, and P_i represents the frequency of the i-th species, calculated as $P_i = N_i/N$, where N is the total number of individuals of all species in the quadrat and N_i is the number of individuals of the i-th species.

Vegetation Coverage (V_c): There is an extremely significant linear correlation between vegetation coverage and NDVI. Vegetation coverage can be calculated using NDVI as shown in Equation (3):

$$V_c = \frac{NDVI - NDVI_s}{NDVI_v - NDVI_s}$$

where V_c is vegetation coverage, $NDVI_v$ represents pure vegetation pixels, and $NDVI_s$ represents bare land in the study area.

1.3.3 Remote Sensing Image Data Processing

MODIS datasets from 2000 to 2017 were processed using ENVI 5.0 software, including extraction, radiometric correction, geometric correction, and projection transformation to obtain NDVI data for the lower Tarim River. The MODIS NDVI dataset underwent format and projection conversion, clipping, and Savitzky-Golay synthesis processing to obtain annual average NDVI data for the lower Tarim River from 2000 to 2017.

1.3.4 Determination of Evaluation Index Classification Standards and Assessment Calculation

Referencing ecological security evaluation systems for typical arid region rivers such as the Tarim and Heihe Rivers [**?**, **?**], and considering the environmental conditions of the lower reaches, classification criteria were determined as follows: (1) Discharge volume and water supply were classified based on groundwater level rise and vegetation recovery. (2) Groundwater depth classification was based on suitable groundwater depths for various vegetation types in the lower reaches. (3) Vegetation coverage and diversity were classified according to vegetation growth status. (4) The drought index classification was determined based on actual conditions and expert opinions.

The water ecological security level in the lower Tarim River was divided into five grades (Table 1) with corresponding scores: severe warning zone (20–40 points), moderate warning zone (40–60 points), warning zone (60–70 points), relatively safe zone (70–85 points), and safe zone (85–100 points).

The comprehensive water ecological security evaluation index K was calculated using the comprehensive index method [**?**], as shown in Equation (4):

$$K = \sum_{j=1}^{n} r_j \times C_j$$

where r_j and C_j represent the weight and assigned score of the j-th indicator, respectively. Based on the discrimination standards for ecological security levels, K values were categorized into the five zones mentioned above.

2.1 Determination of Evaluation Index Weights

Principal component analysis was conducted on the selected water ecological security evaluation indicators (X_1-X_8) for the lower Tarim River. The results showed that the first three principal components accounted for 91.39% of the cumulative variance contribution rate (Table 2), indicating that the selected evaluation indicators were comprehensive and reasonable.

The principal component loading matrix (Table 3) revealed that the first principal component had strong positive correlations with X_1, X_2, X_3, X_6, and X_7, indicating that hydrological and vegetation factors are key elements affecting water ecological security in the lower reaches. The second and third principal components showed positive correlations with X_4 and X_5, demonstrating that meteorological factors also influence regional water ecological security.

Based on principal component analysis, comprehensive scores and weights for the water ecological security evaluation indicators were calculated (Table 4). The importance ranking of indicators was: discharge volume (X_1) > groundwater depth (X_3) > water supply (X_2) > vegetation diversity (X_7) > vegetation coverage (X_6) > drought index (X_4) > new *Populus euphratica* biomass (X_5). The combined weight of hydrological indicators (X_1, X_2, X_3) was 0.524, while that of vegetation indicators (X_5, X_6, X_7) was 0.349, confirming that hydrological and vegetation elements are the main driving factors of water ecological security in the lower Tarim River.

2.2 Evaluation Results of Water Ecological Security in the Lower Tarim River

Based on the weights and scores of water ecological security evaluation indicators, the water ecological security status of the lower Tarim River from 2000 to 2017 was assessed. The results show that the comprehensive water ecological security evaluation index exhibited a fluctuating upward trend, with security levels transitioning from "moderate warning zone" to "relatively safe zone."

From 2000 to 2002, the evaluation index increased annually from 39.1 to 52.8, with the security level upgrading from moderate warning zone to warning zone, indicating significant improvement in water ecological security after ecological water conveyance. From 2003 to 2005, the comprehensive evaluation index showed a declining trend, with the security level dropping back to moderate warning zone. From 2006 to 2017, the evaluation index increased significantly and showed a basically year-by-year growth pattern, rising from 55.4 (2006) to 84.7 (2017). During this period, water ecological security levels transitioned from "moderate warning zone → warning zone" (2006–2011) and "warning zone → relatively safe zone" (2012–2017), demonstrating that unified basin water resource management significantly improved downstream water ecological security.

[Figure 3: see original paper]

2.3 Analysis of Driving Factors for Water Ecological Security Changes in the Lower Tarim River

Water is the most critical factor for the existence and development of oasis and desert systems in the lower Tarim River, maintaining the structural integrity and dynamic balance of fragile ecosystems. Figure 4 illustrates that water ecological security evaluation results changed synchronously with discharge volume. Discharge volume increased annually from 2000 to 2002, reaching 6.20×10^8 m^3. In 2003, discharge volume decreased significantly to only 83.03% of the 2002 maximum, causing water ecological security levels to decline. From 2004 to 2017, discharge volume showed a fluctuating upward trend, with water ecological security levels first decreasing then increasing.

[Figure 4: see original paper]

Water supply changes followed the same pattern as discharge volume. Since the implementation of ecological water conveyance, groundwater depth in the lower Tarim River has generally shown a rising trend, increasing from 7.40 m (2000) to 3.74 m (2017), a change amplitude of 36.75%. However, groundwater depth changes exhibited volatility and instability: from 2000 to 2004, groundwater levels showed a significant declining trend, reaching the lowest value of 5.79 m in 2004 due to insufficient timely water supply. From 2005 onward, the rate of groundwater depth increase became more significant. The cumulative total water conveyance to the lower Tarim River reached 17.65×10^8 m^3, with an average annual groundwater level rise from 5.23 m to 2.06 m, basically meeting the 2-6 m requirement for recovery of major constructive vegetation.

Desert riparian vegetation is crucial for maintaining ecosystem stability and preventing desertification in arid regions. New *Populus euphratica* biomass increased overall from 16.6 $\text{kg} \cdot \text{hm}^{-2}$ (2000) to 54.3 $\text{kg} \cdot \text{hm}^{-2}$ (2017). Except for a slight decrease in 2003 due to insufficient ecological water supply, biomass increased steadily in other years, with a growth of 37.7 $\text{kg} \cdot \text{hm}^{-2}$ in 2017—2.3 times higher than in 2000. Vegetation coverage increased year by year from 2000, reaching its lowest point in 2004 before rapidly recovering to 35.8% in 2017. Plant diversity showed a continuous growth trend, increasing rapidly during 2000-2005 and growing at a slower rate in other years.

The water ecological security level upgraded to warning zone during 2000-2002 mainly due to continuous ecological water conveyance that restored groundwater levels and vegetation. In 2003, despite good vegetation recovery, discharge volume and water supply decreased by nearly 50% compared to the previous year, causing the water ecological security level to drop to moderate warning zone. The lowest water ecological security level occurred in 2004 due to suspended ecological water conveyance, resulting in decreased vegetation coverage and *Populus euphratica* biomass. A slight decline in 2013 occurred because discharge volume decreased sharply, though changes in groundwater depth and vegetation factors mitigated the impact of reduced discharge on water ecological security.

3.1 Rationality of the Evaluation Method

Current research on water ecological security evaluation for the lower Tarim River ecosystem is relatively limited, though regional ecological security evaluation studies are more common [?, ?, ?]. For typical arid regions like the lower Tarim River, where ecosystems are fragile, water supply originates from source streams, and vegetation survival depends primarily on groundwater, establishing an appropriate evaluation index system is critical. Existing evaluation systems for arid regions include ecological risk assessment based on ecological health, pressure-state-response indicator systems, and systems based on ecological security connotations [?, ?]. Based on a comprehensive understanding of the lower Tarim River' s ecological environment and referencing relevant achievements in arid region ecological security evaluation, this study' s index system covers major ecological elements and can characterize water ecological security status [?]. Required data can be obtained through field investigations and remote sensing, ensuring operability.

Various methods exist for quantitative regional ecological security evaluation and index weight determination, including grey correlation analysis, landscape ecology methods, analytic hierarchy process, fuzzy evaluation, and comprehensive index methods [?, ?]. The lower Tarim River ecosystem has experienced severe degradation, with interconnected and multi-coupled factors affecting water ecological security. Principal component analysis employs a "dimensionality reduction" approach to transform multiple original variables into several uncorrelated principal components. This method offers strong objectivity and reflects most information from original variables [?], making it an increasingly recognized approach.

3.2 Limitations of the Evaluation System

From a systemic perspective, the lower Tarim River ecosystem continuously changes under multiple factors including natural environment and human interference. Therefore, water ecological security evaluation can only represent the basic state at a specific moment. This evaluation system lacks dynamic assessment of water ecological security and explanation of its evolution mechanisms. Methodologically, the evaluation results depend on the selected method and index system construction. This study' s lack of social element indicators for the lower Tarim River represents a certain limitation. Although the population in the lower Tarim River area accounts for only 2.25% of the entire basin with relatively minor human interference, social factors still influence evaluation results and require enhanced data collection.

From a result validation perspective, water ecological security is a complex issue encompassing multiple factors with inconsistent interpretations across different regions and scales, making verification difficult. Comparative analysis with existing research results [?, ?] demonstrates that the water ecological security evaluation results for the lower Tarim River remain highly reliable and practically significant, offering valuable references for basin management in the Tarim River and other arid/semi-arid regions.

4 Conclusions

1) The water ecological security evaluation index for the lower Tarim River increased significantly from 2000 to 2017, indicating that implementation of basin water resource management systems is key to ensuring downstream ecological water security. Discharge volume, groundwater depth, and biodiversity are the main factors affecting downstream water ecological security.

2) Sustained ecological water conveyance not only improves downstream water ecological security levels but also maintains groundwater depth within a relatively stable range of 4-6 m. Nevertheless, groundwater depth has not yet reached the optimal 2-4 m range suitable for *Populus euphratica* and *Tamarix*, leaving downstream vegetation under severe drought stress. To ensure water ecological security, continuous water conveyance should be combined with multiple water delivery methods. Linear water conveyance during March–April (the germination period for most herbaceous plants) can dredge river channels, while branch and sheet water conveyance during May–June (the sprouting period for constructive veg-

etation) can expand vegetation water-receiving areas [?] and increase vadose zone recharge.

3) An annual discharge volume of 3.5×10^8 m^3 is the basic requirement for improving water ecological security levels in the lower Tarim River. From 2000 to 2011, discharge basically met requirements, but since 2012, discharge has decreased sharply, with annual volumes below 3.5×10^8 m^3 (only 0.1×10^8 m^3 in 2013). Consequently, water ecological security in the lower Tarim River remains unstable. From 2014 to 2017, water ecological security levels continued to improve, with discharge basically meeting requirements except in 2015.

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