Benefit Assessment of Ecological Water Transfer in the Lower Reaches of the Tarim River Based on Environmental Quality Index (Postprint)

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Abstract

The Environmental Quality Index (EQI) is a tool composed of environmental elements including climate/meteorology, water resources, soil, topography and landforms, and biodiversity, which enables rapid and comprehensive quantitative assessment of the overall quality of the natural environment. Based on multi-source data from remote sensing, field monitoring, literature, and other sources, EQI was calculated using methods such as the entropy method, principal component analysis, and analytic hierarchy process to conduct a comprehensive evaluation of natural environmental quality in the lower reaches of the Tarim River for the years 2000, 2010, and 2020. The results indicate that: (1) Under the influence of ecological water conveyance, the natural environmental quality in the lower reaches of the Tarim River improved significantly from 2000 to 2020, with areas of relatively high EQI values mainly distributed along both banks of the river channel and around lake basins. (2) Environmental quality improvement was more pronounced during 2000–2010 (improved area of 15,620 km^2) than during 2010–2020 (improved area of 13,831 km^2). (3) The most significant increases in EQI occurred in the categories of relatively poor and below ($EQI < 0.4$) and relatively good ($EQI \geq 0.8$), while increases in EQI for the categories of poor ($0.4 \leq EQI < 0.5$) and good ($0.6 \leq EQI < 0.8$) were not significant. The increase in ecological water conveyance volume significantly reduced the area of regions with low and medium EQI values and promoted an increase in the area of regions with high EQI values, indicating that ecological water conveyance has overall improved the environmental quality of the study area.

Full Text

Evaluation of Ecological Water Conveyance Benefits in the Lower Reaches of Tarim River Based on Environmental Quality Index

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Abstract: The environmental quality index (EQI) is a comprehensive tool for quantitatively assessing overall natural environmental quality, integrating environmental components such as climate and meteorology, water resources, soil, topography, and biodiversity. Based on multi-source data including remote sensing imagery, field monitoring, and literature, this study employs entropy method, principal component analysis, and hierarchical analysis to calculate EQI for comprehensive evaluation of environmental quality in the lower reaches of Tarim River. The results demonstrate: (1) Under the influence of ecological water conveyance, environmental quality has improved significantly. High EQI areas are predominantly distributed along riverbanks and around lake basins. (2) From 2000 to 2010, the area of environmental quality improvement was 15,620 km^2, while from 2010 to 2020, the improvement area was 13,831 km^2. (3) Areas with poor (EQI<0.4) and excellent (EQI$ 0.8)*environmentalqualityincreasedsignificantly*, *whereasareaswithmedium*(0.4 *EQI* < 0.5)*andgood*(0.6 $EQI<0.8) quality showed no significant change. The increase in water conveyance significantly reduced the area of low and medium EQI regions while promoting the expansion of high EQI areas, indicating that ecological water conveyance has overall improved environmental quality in the study area.

Keywords: environmental quality index; comprehensive assessment; multi-source data; lower reaches of Tarim River

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1.1 Study Area Overview

The Tarim River, China' s longest inland river, stretches 1,321 km in total length, with its lower reaches (from Qiala to Taitema Lake) extending 428 km. The lower Tarim River basin features an extremely arid continental climate, with an average annual temperature of 7.60 ℃, annual precipitation of 55 mm, evaporation of 2,870 mm, and total solar radiation of 498.7$×10^{3}$ MJ/m^2.

The region experiences frequent strong winds, representing one of China' s most arid areas. Soil types consist primarily of aeolian sandy soil, with small portions of Populus euphratica forest soil and marsh soil. A natural green barrier dominated by Populus euphratica forests has formed along both sides of the river channel, while the outer riparian zones consist mainly of fixed and semi-fixed mobile sand dunes. Key native plant species include Populus euphratica, Tamarix ramosissima, Haloxylon ammodendron, Phragmites australis, and Alhagi sparsifolia.

[Figure 1: see original paper]

1.2 Data Sources

According to the United Nations Environment Programme (UNEP), the natural environment comprises elements including climate and meteorology, hydrology and water resources, soil, topography, and biodiversity. Based on this framework and local conditions, this study established an EQI evaluation index system consisting of 16 indicators (Table 1). Due to the scarcity of meteorological stations in the study area, obtaining gridded temperature data from station observations is challenging. Therefore, this study utilized MODIS land surface temperature data as a temperature proxy. A 3 km$×$3 km moving window was applied to calculate standard deviations of day-night land surface temperature differences across spring, summer, autumn, and winter seasons, followed by principal component analysis (PCA) to compute a comprehensive land surface temperature index.

Soil data were obtained from the National Earth System Science Data Center (https://essd.copernicus.org) and Soil Geodata platform (http://soil.geodata.cn). Soil total nitrogen, total phosphorus, organic carbon, pH, and moisture content data were used to calculate a surface wetness index. Landsat 7/8 OLI data were employed to compute the soil moisture content index. Subsequently, based on soil moisture content index, normalized difference vegetation index (NDVI), and soil moisture data products (https://engine.piesat.cn/dataset), a general linear model was used to downscale the soil moisture data product to 1 km$×$1 km resolution. Maximum-minimum normalization was applied to standardize soil data, and the entropy method was used to calculate the soil fertility index for the study area from 2000 to 2020.

To assess desertification and salinization changes during the ecological water conveyance period, this study first calculated land desertification index, standardized difference soil index, soil-adjusted vegetation index, and soil salinization index based on Landsat 7/8 OLI data. Bare soil density data calculated through a 3 km$×$3 km moving window were then combined to derive a comprehensive desertification index. For salinization assessment, a comprehensive salinization index was calculated.

Vegetation and biodiversity data: Since natural vegetation plays a crucial role in maintaining regional biodiversity, this study selected vegetation cover and plant diversity-related indicators to represent biodiversity. Landsat 7/8 OLI data were used to compute NDVI, enhanced vegetation index (EVI), and soil-adjusted vegetation index (SAVI), while MODIS leaf area index (LAI) products reflected vegetation growth conditions. A 3 km$×$3 km moving window was then applied to calculate standard deviations of these vegetation indices, and PCA was used to derive a comprehensive vegetation index.

Water resources: Due to the lack of surface and groundwater monitoring data in the study area, water body index was calculated based on Landsat OLI data to determine water area. A 3 km$×*3kmmovingwindowwassubsequentlyusedtosumpixelswithineach2km*^{2}$ range, generating gridded surface water data. Based on water area data, a sliding window method calculated distance from river channels.

Species diversity and groundwater depth data: To obtain plant species diversity and groundwater data, literature searches were conducted in Google Scholar and Web of Science using Chinese and English keywords including "lower Tarim River," "groundwater," "diversity," "ecological water conveyance," and "species richness," yielding 156 search results. After screening for relevance, 156 articles were compiled into a literature database. Plot Digitizer software was used to extract data on groundwater level (or depth), distance from river channels, Shannon-Wiener diversity index, Simpson diversity index, species richness, latitude/longitude, and place names from these articles. This process yielded 156 groundwater depth data points and 156 plant species diversity data points.

1.3 Research Methods

Determining indicator weights is essential for environmental quality assessment. Common weighting methods include hierarchical analysis, entropy method, and principal component analysis, each with distinct advantages and limitations. To calculate weights scientifically and effectively, this study first computed contribution weights for each environmental component using the above three methods, then determined final weights (Wj) through geometric averaging. The environmental quality index was subsequently calculated using weighted averaging:

$$EQI = \sum_i w_j V_j$$

where w_a, w_e, and w_p represent weights calculated through hierarchical analysis, entropy method, and principal component analysis for the j-th variable, respectively; V_j is the value of the j-th variable; and w_j is the final weight obtained through geometric mean.

After obtaining EQI raster data, the natural breaks classification method was used to categorize environmental quality into six grades: very poor (EQI<0.3), poor (0.3≤EQI<0.4), fair (0.4≤EQI<0.5), good (0.5≤EQI<0.6), very good (0.6≤EQI<0.8), and excellent (EQI$ 0.8).*Priortoanalysis*, *K* −

*nearestneighborandgenerallinearmodelmethodswereappliedtounifythespatialresolutionofalldatato*1*km*×$1 km.

For biodiversity data, dimensionality reduction orthogonal processing was performed using PCA to obtain comprehensive plant diversity index data. For groundwater depth data, classification standards of 0-1 m (soil salt accumulation threshold), 1-1.5 m (plant wilting threshold), 1.5-2 m, 2-3 m, 3-3.5 m, 3.5-4 m, and 4.0-4.5 m were applied to classify groundwater depth raster data. Expert scoring, hierarchical analysis, and weighted averaging were then used to obtain a comprehensive groundwater environment index. Finally, combined with water area data, water environment comprehensive index was calculated. Transfer matrix analysis, ANOVA multiple comparisons, and regression analysis were employed to explore relationships between environmental quality and ecological water conveyance volume.

All data preprocessing, analysis, and mapping were completed using ArcMap 10.3 software (Figure 2).

[Figure 2: see original paper]

2.1 Spatial-Temporal Patterns of Natural Environmental Quality

From 2000 to 2020, environmental quality in the lower Tarim River improved significantly. In 2000, areas with poor environmental quality (0.4≤EQI<0.5) and fair quality (0.3≤EQI<0.4) accounted for 24.53% and 16.60% of the study area, respectively, while good quality areas (0.6≤EQI<0.8) comprised only 7.26%. By 2020, the area of poor and below-quality regions decreased from 5,092.92 km^2 to 495.69 km^2, while fair quality areas decreased from 4,816.5 km^2 to 2,283.54 km^2. Concurrently, good and above-quality areas expanded from 1,301.92 km^2 to 4,816.5 km^2, with the average EQI increasing from 0.44 to 0.56. Although fluctuations occurred during the study period, the overall trend remained stable (Figure 3).

Spatially, regions with relatively high environmental quality were concentrated along riverbanks and around lake basins, with particularly notable improvements around Taitema Lake. Regression analysis revealed that the area of good and above-quality regions (EQI$ 0.6)*waspositivelycorrelatedwithwaterconveyancevolume*(*r* = 0.56), *whileareaswithpoorandbelow*−*quality*(*EQI* < 0.5)*andfairquality*(0.5 $EQI<0.6) showed negative correlations (r=-0.75 and r=-0.44, respectively), indicating that ecological water conveyance suppressed low and medium-quality areas while promoting high-quality regions (Figure 4).

[Figure 3: see original paper] [Figure 4: see original paper]

2.2 Relationship Between Environmental Quality Change and Water Conveyance

During 2000-2020, different EQI grades in the lower Tarim River basin showed overall increasing trends. Specifically, very poor ($EQI<0.3$) and good ($0.5 \leq EQI<0.6$) grades increased annually, while poor ($0.3 \leq EQI<0.4$) and fair ($0.4 \leq EQI<0.5$) grades remained relatively stable before undergoing significant changes after 2010. The area of very good quality ($0.6 \leq EQI<0.8$) increased most prominently, while excellent quality (EQI$ $0.8) areas also expanded substantially.

Environmental quality improvement was spatially correlated with distance from river channels. Improved areas were concentrated near river channels, particularly where vegetation cover increased after water conveyance, leading to higher EQI values. Poor ($0.4 \leq EQI<0.5$) and good ($0.6 \leq EQI<0.8$) quality areas were concentrated in sparsely vegetated regions far from river channels and the Daxihaizi Reservoir. Due to insufficient groundwater recharge, the effects of ecological water conveyance in these areas may be limited. Additionally, soil seed bank density is low in sparsely vegetated areas, and improved soil moisture alone may not activate seed germination. In some cases, excessive groundwater elevation has caused soil salinization, reducing the area of drought-resistant herbaceous plants. Consequently, significant EQI changes did not occur in these poor and good quality regions.

The improvement magnitude was greater during 2000-2010 than during 2010-2020. Early-stage water conveyance (2000-2010) alleviated drought stress, promoted soil seed germination, and increased vegetation coverage. However, in later stages (2010-2020), areas far from river channels remained water-deficient, and riparian vegetation may have reached a saturation state regarding water availability. Therefore, despite increased total water conveyance in 2020 compared to 2010, environmental quality did not improve significantly. With increasing water conveyance, the area of fair and below-quality regions decreased while good and above-quality areas increased (Figure 5). Ecological water conveyance improved soil moisture and nutrient conditions, facilitated seed dispersal and germination, enhanced vegetation coverage, reduced land surface temperature, and increased species diversity and vegetation productivity. These changes improved the natural environment in the lower Tarim River, gradually reducing low-quality areas while expanding high-quality regions.

[Figure 5: see original paper]

3.1 Spatial-Temporal Patterns of Natural Environmental Quality

This study demonstrates that environmental quality in the lower Tarim River has improved significantly since 2000, consistent with previous research findings. Poor and below-quality areas decreased to 4,352.93 km^2, while good and above-quality areas expanded to 15,620 km^2. Spatially, higher environmental quality areas were concentrated near river channels and lake basins, with increasing connectivity of high EQI regions, particularly around Taitema Lake (Figure 6). The improvement area reached 15,620 km^2 from 2000-2010, though the improvement area slightly decreased to 13,831 km^2 during 2010-2020. Negative changes primarily occurred in areas with fair and above-quality (EQI$ $0.5), but overall environmental quality remained at a relatively high level.

Environmental quality improvement was spatially correlated with distance from river channels. High EQI areas were mainly distributed in near-river zones (Figure 6), where vegetation cover increased after water conveyance, leading to EQI increases. Poor (EQI<0.4) and good (0.6≤EQI<0.8) quality areas were concentrated in sparsely vegetated regions far from river channels and the Daxihaizi Reservoir. Due to insufficient groundwater recharge, ecological water conveyance effects may be limited in these areas. Additionally, low soil seed bank density in sparsely vegetated regions means that improved soil moisture alone is insufficient to activate seed germination. In some areas, excessive groundwater elevation has caused soil salinization, reducing the area of drought-resistant herbaceous plants and leading to decreased species diversity in vegetation-sparse zones around Taitema Lake and riverbanks. Consequently, significant EQI changes did not occur in these poor and good quality regions.

Although environmental quality has improved, soil quality, particularly organic carbon storage, has not increased significantly and may have even decreased. This may be related to land cover type changes. While ecological water conveyance increased herbaceous vegetation coverage such as reeds, the area of large woody plants like Populus euphratica and Tamarix ramosissima did not change substantially. Farmland expansion reduced plant litter input to soils, and in low vegetation cover areas of the lower reaches, excessive evaporation and groundwater elevation may cause soil salinization and death of drought-resistant plants, leading to declines in soil carbon storage.

[Figure 6: see original paper]

3.2 Effects of Ecological Water Conveyance on Natural Environmental Quality

This study reveals that ecological water conveyance significantly reduced the area of poor and below-quality regions (EQI<0.4) while increasing excellent quality areas (0.8≤EQI<0.9). However, changes in poor and good quality areas were not significant. This may be because vegetation in poor-quality areas is too sparse to respond effectively to water conveyance, while good-quality areas may have reached an ecological saturation state, limiting further improvement. The relationship between vegetation and environmental factors follows a dose-response pattern. Early-stage water conveyance (2000-2010) alleviated drought stress and promoted soil seed germination, increasing vegetation coverage. In later stages (2010-2020), areas far from river channels remained water-deficient, and riparian vegetation may have reached a water saturation state. Therefore, despite increased total water conveyance in 2020, environmental quality did not improve significantly.

With increasing water conveyance volume, the area of fair and below-quality regions decreased while good and above-quality areas increased (Figure 7). Ecological water conveyance improved soil moisture and nutrient conditions, promoted seed dispersal and germination, enhanced vegetation coverage, reduced land surface temperature, and increased species diversity and vegetation productivity. These changes improved the natural environment in the lower Tarim River, gradually reducing low-quality areas while expanding high-quality regions. The transfer matrix analysis shows that most areas remained within their original quality grades, with some improvement from poor to fair quality and from fair to good quality (Table 2).

[Figure 7: see original paper]

4.1 Conclusions

1. (1) Under the positive influence of ecological water conveyance, the natural environmental quality in the lower reaches of Tarim River has improved significantly. From 2000 to 2020, the average EQI increased from 0.44 to 0.56. The area of poor and below-quality regions (EQI<0.5) decreased from 5,092.92 km^2 to 495.69 km^2, while good and above-quality areas (EQI$ 0.6)*increasedsubstantiallyfrom*1, 301.92*km*^{2}$ to 4,816.5 km^2. Regions with relatively high environmental quality are mainly concentrated along riverbanks and around lake basins.
2. (2) From 2000 to 2010, the environmental quality improvement area reached 15,620 km^2, while from 2010 to 2020, the improvement area was 13,831 km^2. Although environmental quality degradation occurred primarily in areas with fair and above-quality (EQI$ $0.5), the overall environmental quality remained at a high level. The area of poor and excellent quality grades increased significantly, while fair-quality areas showed no significant increase.
3. (3) Ecological water conveyance volume had inhibitory effects on areas with fair, poor, and below-quality grades, while promoting expansion of good and above-quality areas. These positive changes demonstrate that ecological water conveyance measures have effectively improved the natural environment in the lower Tarim River.

4.2 Challenges and Recommendations

Since 2000, the lower Tarim River has received ecological water conveyance totaling 8.45$×10^{9}$ m^3. Although environmental conditions have improved, there remains potential for further enhancement. Specifically:

(1) The spatial distribution of water conveyance effects is uneven, with significant improvement near river channels but persistent challenges in oasis margin areas where vegetation recovery remains ineffective.

(2) Long-term anthropogenic intervention may trigger plant community succession. Increased soil moisture and salinity are unfavorable for Populus euphratica seedlings but have less impact on Tamarix ramosissima. In areas with low Populus euphratica coverage, rising groundwater levels and salinity may cause community succession from Populus euphratica to Tamarix ramosissima, reducing carbon storage. Therefore, regular monitoring of soil moisture, salinity, and riparian ecosystem community composition is necessary during water conveyance to avoid negative impacts from anthropogenic water delivery.

(3) Scientific water conveyance planning is essential. Climate change may affect the hydrothermal pattern in the Tarim River Basin, influencing evaporation, snowmelt, and plant phenology, dispersal, growth, and reproduction. Therefore, water release timing and volume should be scientifically selected to maximize ecological benefits and reduce ineffective water consumption.

(4) The role of the Qarqan River should be emphasized. Recent studies show that the Qarqan River significantly influences water area changes in the Taitema-Kanglak Lakes, with less water consumption per unit distance than the Tarim River due to its shorter distance to Taitema Lake and greater elevation drop. Therefore, the Qarqan River should be given greater attention in future ecological restoration efforts in the lower Tarim River.

(5) Water use efficiency should be improved to avoid damaging natural vegetation and enhance environmental quality. Although environmental quality has improved, the ecosystem remains fragile. Compared with the 1980s-1990s, the coverage area of keystone species such as Populus euphratica remains low. In agriculture, water-saving irrigation and planting drought- and salt-tolerant plants such as Apocynum venetum can significantly reduce irrigation water consumption. Meanwhile, improving irrigation efficiency in the upper Tarim River is crucial for downstream ecological restoration. Currently, irrigation water consumption per unit area in the upper reaches approaches twice the Xinjiang average, leading to extensive saline-alkali land development. Reducing upper-reach irrigation to the provincial average could not only decrease salinization and increase crop yields but also provide nearly double the current water volume for downstream ecological restoration.

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