Postprint: Analysis of Ecosystem Changes and Ecological Benefits in the Main Stream of the Tarim River

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Abstract

Remote sensing ecological indicators such as vegetation coverage, remote sensing ecological index, and human disturbance index were extracted for the period 1990–2020 to reflect the changing trends in ecological conditions before and after the implementation of the ecological water conveyance project in the main stream of the Tarim River. Using remote sensing ecological indicators as driving factors, an improved ecosystem service value calculation method was proposed to quantify the ecosystem service values of provisioning, regulating, supporting, and cultural functions, analyze the dynamic evolution of trade-offs and synergies among these functions, and estimate the cumulative ecological benefits from 1990 to 2020. The results show that: (1) Since the initiation of ecological water conveyance, vegetation coverage has increased in nearly one-third of the main stream area, with the area proportions of low, medium, relatively high, and high vegetation coverage increasing by 17%, 5%, 2%, and 2.9%, respectively. (2) The ecosystem service value in the upper reaches first increased and then gradually stabilized, while those in the middle and lower reaches first increased, then decreased, and subsequently increased again, indicating that the response of the middle and lower reaches to ecological water conveyance involves a certain lag period and is significantly influenced by incoming water volume. (3) Synergistic effects exist between regulating and supporting functions, while trade-off effects exist between provisioning and regulating/supporting functions. (4) In the later stage of ecological water conveyance, the cumulative ecological benefits in the upper, middle, and lower reaches of the main stream all exhibited the "law of diminishing marginal benefits." Accordingly, from the perspective of ecological restoration, appropriate ranges for annual runoff at cross-sections were proposed: not exceeding 42.5\$ $\times10^8 m^3 fortheupperreaches, 21.5\times10^8 m^3 forthemiddlereaches, and3.5\times$ \$10^8 m^3 for the lower reaches. The research findings can provide scientific guidance for optimizing the allocation of ecological water volumes.

Full Text

Preamble

Ecosystem Variation and Ecological Benefits Analysis of the Mainstream of Tarim River

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Abstract: In this study, remote sensing ecological indices including vegetation coverage, remote sensing ecological index, and human disturbance index were extracted from 1990 to 2020 to reflect the evolution trend of ecological status before and after the implementation of the ecological water conveyance project in the Tarim River mainstream. Using these remote sensing ecological indices as driving factors, we proposed an improved ecosystem service value calculation method to quantify the ecosystem service value of provisioning, regulating, supporting, and cultural functions, and to analyze the dynamic evolution of trade-offs and synergistic effects among these functions. Cumulative ecological benefits from 1990 to 2020 were estimated. The results showed that: (1) Since the implementation of ecological water conveyance, vegetation coverage increased in nearly one-third of the mainstream area, with the proportion of lower, medium, higher, and high vegetation coverage increasing by 17%, 5%, 2%, and 2.9%, respectively. (2) The ecosystem service value in the upstream increased initially and then gradually stabilized, while that in the midstream and downstream exhibited a pattern of initial increase, subsequent decrease, and then renewed increase, indicating a lag period in the response of midstream and downstream areas to ecological water conveyance and significant influence from incoming water volume. (3) A synergistic effect existed between regulating and supporting functions, while a trade-off effect existed between provisioning and regulating/supporting functions. (4) In the later stage of water conveyance, cumulative ecological benefits in the upstream, midstream, and downstream all exhibited the "law of diminishing marginal benefits." Accordingly, from the perspective of ecological restoration, the appropriate ranges of annual runoff at cross-sections are proposed: not exceeding 42.5$×10^{8}$ m^3 upstream, 21.5$×10^{8}$ m^3 midstream, and 3.5$×10^{8}$ m^3 downstream. These results can provide scientific guidance for optimizing the allocation of ecological water quantity.

Keywords: ecological water conveyance project; ecosystem service; ecological benefits; Tarim River

Introduction

Rapid industrialization and urbanization have intensified human-land conflicts, triggering a series of ecological and environmental problems including resource shortages, environmental pollution, global warming, land degradation, and biodiversity loss. Implementing ecological engineering projects to address these issues has become a global consensus. Internationally, some countries began implementing ecological restoration projects as early as the mid-20th century, while China started large-scale ecological engineering initiatives such as the "Three-North" Shelter Forest Program, the Grain for Green Project, and ecological water conveyance projects in the 1990s. Currently, ecological restoration has been elevated to a national strategic priority. In 2017, the 19th National Congress of the Communist Party of China established ecological protection and restoration responsibilities. In 2020, the National Development and Reform Commission and the Ministry of Natural Resources jointly issued the "National Master Plan for Major Ecosystem Protection and Restoration Projects (2021-2035)," representing a comprehensive national-level planning framework for ecological protection and restoration.

Evaluating the effectiveness of ecological engineering projects enables comprehensive and timely understanding of restoration outcomes and existing problems, facilitating adaptive management strategies. The effectiveness of ecological engineering largely depends on the appropriateness of resource input and development intensity. According to the economic principle of "diminishing marginal benefits," the incremental ecological benefit per unit of water resource input decreases from the initial to later stages of project implementation. Liao et al. studied the cumulative ecological response to ecological water conveyance in the Tarim River Basin and found that groundwater depth and vegetation recovery showed gradually weakening responses to increasing cumulative water volume with certain time lags. He et al. evaluated the comprehensive effects of the Yangtze River to Chaohu Lake Water Diversion Project and found that connectivity effects followed the law of diminishing marginal benefits with hysteresis characteristics.

Broadly defined, ecological benefits refer to the positive impacts and favorable effects of ecosystems on human production, living, and the environment. In a narrower sense, they represent the beneficial effects of ecosystem functions—such as water, soil, air, and biological elements—on human society and the natural environment through ecological processes like energy flow, material cycling, and information transfer. In this study, ecological benefits are quantitatively calculated through ecosystem service value. Common calculation methods include market theory-based valuation, material conversion methods based on ecological models and equivalent factors, and emergy conversion methods. Previous studies on Tarim River ecosystem service value mostly employed the equivalent factor method. However, this method ignores spatial heterogeneity within the same land use type. Some scholars have improved this approach by selecting vegetation coverage, temperature vegetation dryness index, and human disturbance index as driving factors for ecosystem service value calculation, enhancing spatial heterogeneity expression. Building on this foundation, our study further introduces the remote sensing ecological index (RSEI), which comprehensively reflects ecological conditions from four aspects—heat, greenness, dryness, and wetness—fully characterizing the influence of ecological factors on ecosystem service value and improving sensitivity to land use change.

Since the 1970s, the lower reaches of the Tarim River have experienced flow interruption, riparian vegetation degradation, and desertification threats. Since 2000, government departments have implemented ecological water conveyance projects for restoration purposes. By 2020, 21 water conveyance events had been conducted, causing tremendous ecological changes in the Tarim River mainstream. This study utilizes long time series (1990-2020) remote sensing ecological indices to reflect ecological changes before and after project implementation, employs an improved ecosystem service value calculation method to measure dynamic changes in trade-offs and synergies among four ecosystem service functions (provisioning, regulating, supporting, and cultural), and calculates cumulative ecological benefits to provide guidance for future water conveyance practices.

1.1 Study Area Overview

The study area covers the Tarim River mainstream (1321 km, 73°10 ~94°05 E, 39°30 ~43°08 N), with Yingbaza and Qiala serving as division points between upstream-midstream and midstream-downstream, respectively (Fig. [Figure 1: see original paper]). The Tarim River is located deep inland with scarce precipitation, strong evaporation, and a typical temperate continental arid climate. Water resources are extremely scarce, and the ecological environment is highly fragile. Extensive desert riparian forests line both banks, with dominant vegetation species including Populus euphratica, Tamarix chinensis, Halimodendron halodendron, Phragmites australis, Apocynum venetum, and Glycyrrhiza inflata. Since the 1970s, flow interruption in the lower reaches—between the Taklamakan Desert to the east and Kumtag Desert to the west—has threatened to transform the oasis into irreversible desert. The ecological water conveyance project, initiated in 2000, involves unified basin water resource management to increase inflow from tributaries. Under average annual flow conditions, the project aims to achieve 46.5$×10^{8}$ m^3 at the Alar cross-section and 3.5$×10^{8}$ m^3 at the Daxihaizi cross-section, with water reaching Lake Taitema. The project aims to protect and restore riparian vegetation in the upstream and midstream while reviving endangered ecosystems downstream. However, water conveyance has lacked refined regulation schemes, with random and extensive delivery methods.

1.2 Data Sources and Processing

Research data primarily include remote sensing and measured data from 1990-2020. Measured data comprise monthly runoff data from Alar, Xin Qiman, Yingbaza, Wusiman, and Qiala hydrological stations. Remote sensing data, widely used for assessing large-scale, long-term ecological evolution, include vegetation coverage (FVC), remote sensing ecological index (RSEI), and human disturbance index (HDI).

Landsat imagery with 30 m spatial resolution and annual land cover products [Landsat product of China (CLCD)] with 30 m resolution were obtained from https://zenodo.org/record/5816591. FVC reflects vegetation growth status and spatial distribution, calculated through the normalized difference vegetation index (NDVI):

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}}$$

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

where $NDVI_{soil}$ is the minimum NDVI value for bare soil (or no vegetation cover) and $NDVI_{veg}$ is the maximum NDVI value for full vegetation cover. NIR and Red represent reflectance in the near-infrared (0.76-0.96 m) and red (0.62-0.69 m) bands of Landsat imagery, respectively. FVC values range from 0 to 1, classified into five levels: low [0.0, 0.2), lower [0.2, 0.4), medium [0.4, 0.6), higher [0.6, 0.8), and high [0.8, 1.0].

RSEI results from principal component analysis of heat, greenness, dryness, and wetness indices, reflecting ecological conditions from multiple dimensions while avoiding indicator correlation and subjective weighting. It is widely used for ecological quality assessment:

$$RSEI = (LST, VI, NDBSI, Wet)$$

where LST is land surface temperature, VI is vegetation index (same as NDVI), NDBSI is normalized difference built-up and soil index, and Wet is the wetness component.

Land surface temperature is calculated as:

$$LST = \frac{K_2}{\ln\left(\frac{K_1}{L_6} + 1\right)}$$

$$L_6 = gain \times DN + bias$$

where L_6 is radiance at the sensor for band 6, DN is pixel gray value, gain and bias are calibration parameters from image metadata, $K_1 = 606.09\,W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$, and $K_2 = 1282.71\,K$.

The dryness index is synthesized from the building index (IBI) and soil index (SI):

$$NDBSI = \frac{IBI + SI}{2}$$

$$IBI = \left\{ \frac{2\rho_5}{\rho_5 + \rho_4} - \left[\frac{\rho_3}{\rho_3 + \rho_1} + \frac{\rho_2}{\rho_2 + \rho_4} \right] \right\} \Big/ \left\{ \frac{2\rho_5}{\rho_5 + \rho_4} + \left[\frac{\rho_3}{\rho_3 + \rho_1} + \frac{\rho_2}{\rho_2 + \rho_4} \right] \right\}$$

$$SI = \left[\frac{\rho_1 + \rho_4}{\rho_2 + \rho_3} \right] \times 100$$

where ρ_i (i = 1, 2, 3, 4, 5, 7) represents reflectance of corresponding Landsat bands.

The wetness index is:

$$Wet = 0.2626\rho_1 + 0.2141\rho_2 + 0.0926\rho_3 + 0.0656\rho_4 - 0.7629\rho_5 - 0.5388\rho_7$$

RSEI values range from 0 to 1, with values closer to 1 indicating better ecological status. Ecological conditions can be classified as: poor [0.0, 0.2), relatively poor [0.2, 0.4), medium [0.4, 0.6), good [0.6, 0.8), and excellent [0.8, 1.0].

The human disturbance index describes human activity intensity on different land use types:

$$HDI = \frac{\sum_{k=1}^{m} A_k P_k}{A}$$

where m is the number of land use types, A_k is the total area of land use type k (km^2), P_k is the human disturbance intensity parameter (0.8 for cultivated land, 0.6 for forest land, 0.5 for grassland, 0.3 for water bodies, 0.2 for wetlands, and 0.1 for bare land), and A is the total area of all land use types. The CLCD dataset classifies land use into six categories: cultivated land, forest land (including trees and shrubs), grassland, water bodies, wetlands, and bare land (including bare land, construction land, and snow/ice). HDI values range from 0 to 1, with higher values indicating greater human disturbance intensity.

1.3.1 Improved Ecosystem Service Value Calculation Method

The improved ecosystem service value calculation method builds upon the equivalent factor method by incorporating driving factors to avoid the limitation of identical values within the same land use type, effectively expressing spatial heterogeneity and enhancing sensitivity to environmental changes. Based on previous studies and Tarim River basin characteristics, the calculation formula is:

$$ESV(x) = \sum_{i=1}^{4} ESV_i(x)$$

$$ESV_i(x) = \sum_{j=1}^{3} D_{ij}(x) \times EV_i(j) \times \lambda_j \times A$$

where $ESV(x)$ is the ecosystem service value of pixel x (yuan), $ESV_i(x)$ is the value of the ith ecosystem service function, $D_{ij}(x)$ is the influence coefficient of the jth driving factor on the ith ecosystem service function (ranging 0-1), $EV_i(j)$ is the equivalent value of the ith ecosystem service function for land use type j, λ_j is the weight of the jth driving factor, and A is the grid resolution (30 m × 30 m). The four ecosystem service functions are provisioning, regulating, supporting, and cultural. The three driving factors are FVC, RSEI, and HDI, with influence coefficients and weights shown in Table .

1.3.2 Cumulative Ecological Benefits

Cumulative ecological benefits refer to the accumulated improvements and benefits in ecosystem aspects over a certain period due to ecological protection and restoration measures. Unlike annual ecological benefits, cumulative benefits focus on long-term impacts. By analyzing the relationship between cumulative ecological benefits and cumulative annual runoff, we can assess the appropriateness of current resource input and development intensity. The cumulative ecological benefit is calculated as:

$$EB'_i = \sum_{i=1}^{n} \frac{ESV_i}{EWCV_i}$$

where EB'_i is the cumulative ecological benefit from year 1 to year i, ESV_i is the ecosystem service value in year i, and $EWCV_i$ is the annual runoff at the cross-section in year i.

2.1 Spatiotemporal Changes in Ecological Status

Analysis of spatiotemporal trends in the Tarim River mainstream from 1990-2020 shows overall ecological improvement after water conveyance implementation. The study area was divided into upstream, midstream, and downstream reaches, with the study period divided into pre-implementation (1990-2000), early implementation (2001-2010), and later implementation (2011-2020) stages.

Vegetation coverage results (Fig. [Figure 2: see original paper]) indicate that nearly one-third of the mainstream area experienced increased vegetation coverage after water conveyance. The proportions of lower, medium, higher, and high coverage increased by 17%, 5%, 2%, and 2.9%, respectively, while low coverage decreased correspondingly. The upstream and downstream showed gradual ecological improvement, while the midstream exhibited a declining trend.

Remote sensing ecological index results (Fig. [Figure 3: see original paper]) reveal that the upstream "good" value area increased by 9.1% and the "excellent" area by 1.5%. In the midstream, the "good" area decreased by 2.1% and the "excellent" area by 0.2%, while the "poor" area increased, indicating deteriorating conditions. Downstream changes were minimal, with slight increases in "good" and "excellent" areas.

Human disturbance index results (Fig. [Figure 4: see original paper]) show increasing human disturbance in the upstream and midstream from 1990-2020, while downstream disturbance remained relatively stable. High HDI area proportions increased by 1.2% upstream and 1.1% midstream, reflecting intensifying human activities.

2.2 Ecosystem Service Value Calculation

Statistical analysis of ecosystem service values for provisioning, regulating, supporting, and cultural functions from 1990-2020 reveals that regulating and supporting functions had significantly higher values than provisioning and cultural functions. A synergistic effect existed between regulating and supporting functions, while trade-off effects occurred between provisioning and regulating/supporting functions (Fig. [Figure 5: see original paper]). Increased water area and vegetation coverage from ecological water conveyance enhanced regulating and supporting functions such as climate regulation, water conservation, soil retention, and biodiversity maintenance. Provisioning functions primarily depend on farmland ecosystems, whose expansion reduces forest, grassland, and bare land areas, creating trade-offs with regulating and supporting functions.

Overall, ecosystem service values were highest in the upstream, followed by midstream and downstream. Upstream values increased initially then stabilized after 2000. Midstream values increased from 1990-2000, decreased slowly from 2001-2010, then increased gradually from 2011-2020. Downstream values showed little change before 2000, increased then decreased from 2001-2010, and increased gradually thereafter. These patterns indicate that upstream ecosystem service values stabilized after initial increases, while midstream and downstream responses exhibited lag periods and were significantly affected by water volume.

2.3 Ecological Benefit Analysis

The ratio of ecosystem service value to annual runoff characterizes ecological benefit, with cumulative benefit obtained through annual accumulation. Analysis shows that ecosystem service value trends generally align with annual runoff trends, synchronously increasing or decreasing with runoff. Upstream and midstream values increased then stabilized, while downstream values fluctuated upward. Notably, downstream ecosystem service values continued increasing despite reduced water conveyance after 2010, demonstrating cumulative effects of ecological restoration.

Cumulative ecological benefit analysis reveals that after 2010, the growth rate of cumulative ecological benefits in all reaches gradually slowed while the growth rate of cumulative runoff accelerated (Fig. [Figure 6: see original paper]). Scatter points represent cumulative ecological benefits, while bar charts represent cumulative annual runoff. After water conveyance implementation, the growth rates of cumulative ecological benefits in upstream, midstream, and downstream ($k_2 = 2.58$, $k_2 = 1.66$, $k_2 = 2.83$) all exceeded pre-implementation rates ($k_1 = 4.11$), indicating significant restoration effects. However, the diminishing growth rate in the later stage demonstrates that ecological benefits do not increase indefinitely but follow the “law of diminishing marginal benefits” from economics. After reaching a certain stage, the ecological benefit per cubic meter of water no longer increases.

Based on the turning points of cumulative ecological benefits, recommended appropriate ranges for annual runoff at cross-sections are: upstream not exceeding 42.5$×10^{8}$ m^3, midstream not exceeding 21.5$×10^{8}$ m^3, and downstream not exceeding 3.5$×10^{8}$ m^3. When total water volume is fixed, ensuring adequate water supply during vegetation germination periods and establishing rotational irrigation rules based on different ecological function zones and restoration goals can achieve refined water allocation and “quality and quantity” improvements in vegetation recovery.

3 Conclusions

1) Based on remote sensing images from 1990-2020, this study extracted FVC, RSEI, and HDI to analyze spatiotemporal trends in ecological status of the Tarim River mainstream. Using these three indices as driving factors, an improved ecosystem service value calculation method was developed to quantitatively analyze dynamic trade-offs and synergies among four ecosystem service functions in upstream, midstream, and downstream reaches before and after water conveyance, and to calculate cumulative ecological benefits for guiding future practices.

2) Since ecological water conveyance implementation, nearly one-third of the mainstream area showed improved vegetation coverage, with the largest improvement in the upstream, followed by midstream and downstream. Ecological status improved in the upstream and downstream, while the midstream showed declining trends. Human disturbance increased in the upstream and midstream from 1990-2020 but remained stable downstream.

3) Regulating and supporting functions dominated the ecosystem service portfolio, with synergistic effects between them and trade-off effects between provisioning and regulating/supporting functions. The study found that ecological benefits follow the law of diminishing marginal benefits.

When cumulative annual runoff reaches a certain threshold, additional water input cannot generate more ecological benefits. Therefore, annual runoff at cross-sections should be maintained within appropriate ranges: upstream $\leq$ 42.5\$×10^{8}\$ m^{3}, midstream $\leq$ 21.5\$×10^{8}\$ m^{3}, downstream $\leq$ 3.5\$×10^{8}\$ m^{3}. Future research should establish rotational irrigation rules based on critical ecological water demand periods and restoration goals for different ecological function zones.

4) The improved ecosystem service value calculation method incorporates three driving factors. Limited by data availability, it does not include factors such as soil moisture content and groundwater depth that characterize ecosystem processes. The method can be further improved by incorporating such factors based on study area characteristics and research needs.

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