Ecological Security Assessment and Ecological Restoration Strategies for the Dry-up Area of the Lower Tarim River (Postprint)

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Abstract

Restoring the ecological environment of dried-up river channels in the lower reaches of the Tarim River is of great significance for maintaining the overall ecological security of the lower reaches and consolidating the achievements of ecological water conveyance over the past two decades. Since 2000, ecological water conveyance has been implemented in the lower reaches of the Tarim River, achieving remarkable results; however, the ecological degradation situation in some local areas within the basin remains severe, and the channels of its tributaries—the Karanqi River and Nashen River—are still fragmented. Using remote sensing imagery of dried-up river channel areas and meteorological and hydrological data, combined with GIS technology and the Mann-Kendall non-parametric test method, this study analyzed the spatiotemporal variation patterns of ecological environmental elements, assessed the ecological security status, and proposed ecological restoration countermeasures. The results show that: (1) In terms of meteorological elements, dust storm days still increased despite the extremely significant decrease in days with strong wind from 1971 to 2019; temperature and precipitation showed an upward trend from 1957 to 2019, and the Temperature Vegetation Drought Index increased significantly from 2000 to 2018. (2) In terms of vegetation elements, vegetation coverage and productivity showed non-significant increasing trends from 2000 to 2018, but their levels were both very low; the ecological security of the dried-up river channel area is at warning and moderate warning levels.

Full Text

Ecological Security Assessment and Ecological Restoration Countermeasures in the Dry-up Area of the Lower Tarim River

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Abstract

Harnessing the ecological environment of the cutoff river channel in the lower reaches of the Tarim River is of great significance for maintaining the overall ecological security of the downstream area and consolidating the achievements of nearly two decades of ecological water conveyance. Since 2000, ecological water conveyance has been implemented in the lower Tarim River, yielding remarkable results. However, ecological degradation remains severe in localized areas within the basin, and its tributaries—the Karanqi River and Nashen River—remain fragmented. Using remote sensing imagery and meteorological-hydrological data from the river cutoff area, combined with GIS technology and the Mann-Kendall nonparametric test method, this study analyzes the spatiotemporal variation patterns of ecological environmental elements, evaluates the ecological security status, and proposes ecological restoration countermeasures. The results show that: (1) In terms of meteorological elements, the number of sandstorm days increased despite an extremely significant reduction in gale days from 1971 to 2019; both temperature and precipitation showed upward trends from 1957 to 2019; and the Temperature-Vegetation Drought Index (TVDI) increased significantly from 2000 to 2018. (2) In terms of vegetation factors, vegetation coverage and productivity showed non-significant increasing trends from 2000 to 2018, but their levels remained very low. (3) The ecological security of the river cutoff area is currently at the early warning and moderate warning levels.

Keywords: lower Tarim River; river cut-off area; ecological security; ecological restoration; water system connectivity

1. Study Area Overview

The lower reaches of the Tarim River are located within Yuli County and Ruoqiang County in Xinjiang, spanning the river section from Daxihaizi Reservoir to Taitema Lake with a total length of approximately 350 km. This river section runs southeastward through the narrow alluvial plain between the Taklamakan Desert and the Kuruk Desert. The terrain slopes from north to south, with a winding river channel severely deformed by wind erosion and aeolian deposition. After the Weiruo Diversion Gate, the lower Tarim River divides into two branches: the Qiwenkuoer River and the old Tarim River, which converge again at Alagan [Figure 1: see original paper].

The Kongque River originates from Bosten Lake, flows westward from the lake, passes through Korla City and Yuli County, and eventually empties into Lop Nur, with a total length of 841 km. Due to agricultural development, it seasonally dries up after passing Daxihaizi Reservoir. The Karanqi River is an ancient branch of the Kongque River, with a total length of 106 km. Before the 1960s, water from the Kongque River flowed through the Karanqi and Nashen Rivers and converged with the Tarim River. However, due to large-scale water and soil development, the middle and lower reaches of the Kongque River subsequently dried up. The Nashen River originates from Qiala Reservoir and empties into the Qiwenkuoer River at the Maimaituohuti Ecological Gate, with a total length of 244 km, serving as the third water conveyance channel in the lower Tarim River besides the old Tarim River and Qiwenkuoer River. After the 1970s, as upstream water volume in the Tarim River decreased, the Nashen River gradually dried up, and riparian vegetation approached death.

The study area' s landforms consist of three types: alluvial plains, hills, and deserts. The climate is influenced by the Taklamakan and Kuruk Deserts, characterized by drought with little rain and snow, strong evaporation, frequent winds in spring and autumn, annual precipitation between 17.4–42.0 mm, and evaporation as high as 2500–3000 mm. This represents a typical north temperate continental arid desert climate, with an extremely sensitive and fragile ecological environment.

2. Data Sources and Methods

2.1 Data Sources and Preprocessing Remote sensing data includes time series data for Normalized Difference Vegetation Index (NDVI), land surface temperature (LST), and evapotranspiration (ET). NDVI and LST time series data were obtained from NASA' s EOS MODIS MOD13Q1 and MOD11A2 datasets, with temporal resolutions of 16 days and 8 days, and spatial resolutions of 250 m and 1000 m, respectively. ET time series data were obtained from the GLASS ET_{MODIS} dataset released by the National Earth System Science Data Sharing Service Platform, with a temporal resolution of 8 days and spatial resolution of 1000 m. To ensure spatial consistency, the 1000 m resolution data were resampled to 250 m. Additionally, annual time series data were processed using maximum value composition (MVC).

Meteorological element data includes monthly total solar radiation from 98 stations, monthly temperature and precipitation from 756 stations, and annual gale and sandstorm days from the Tikanlik Meteorological Station from 2000 to 2018. These data were obtained from the National Meteorological Information Center. Monthly solar radiation spatial distribution data were interpolated using ArcGIS software for 98 national stations. Monthly temperature and precipitation data were interpolated using Anusplin software. To ensure spatial matching with remote sensing data, the pixel size was set to 250 m during interpolation.

2.2 Methods

2.2.1 Index Calculation To analyze the ecological environment changes in the study area, vegetation coverage, Temperature-Vegetation Drought Index (TVDI), vegetation productivity (NPP), Standardized Precipitation Evapotranspiration Index (SPEI), and evapotranspiration (ET) were calculated. Vegetation coverage data were calculated based on NDVI data using the pixel dichotomy model. NPP data were calculated using the GLASS light use efficiency model based on total solar radiation, temperature, and precipitation data. TVDI was calculated using the LST-NDVI feature space method based on MOD11A2 and MOD13Q1 data. SPEI was calculated based on monthly temperature and precipitation data using the Thornthwaite method. ET data were obtained directly from the GLASS ET_{MODIS} product dataset.

2.2.2 Comprehensive Ecological Security Evaluation Method The key to assessing regional ecological security levels is establishing a reasonable ecological security evaluation index system. Based on data availability, representativeness, and relative independence, and considering the ecological characteristics of scarce precipitation and no runoff in the river cutoff area, this study selected six evaluation indicators: vegetation coverage, vegetation productivity, evapotranspiration, TVDI, gale days, and sandstorm days.

The survival and recovery of vegetation in the lower Tarim River are important indicators of regional ecological security development. Vegetation coverage and productivity are crucial measures of surface vegetation conditions. Evapotranspiration is closely related to plant species, growth status, soil moisture, and meteorological conditions, serving as an important indicator of regional ecological environment changes. The SPEI index includes comprehensive changes in temperature and precipitation, reflecting meteorological drought conditions. TVDI is closely related to soil moisture, representing the relative drought degree of the entire region and serving as an important indicator of plant habitat conditions. Wind-sand hazards are key factors endangering ecological security in the Tarim River Basin, and changes in the frequency and intensity of gale and sandstorm weather directly reflect the development trend of the green corridor' s ecological functions.

The comprehensive ecological security evaluation was calculated using the comprehensive evaluation index (K) method:

$$K = \sum_{j=1}^{6} r_j \times C_j$$

where r_j is the weight of the jth indicator and C_j is the evaluation value of the jth indicator.

To determine indicator weights, this study introduced the Analytic Hierarchy Process (AHP) to obtain weight coefficients by solving the eigenvector of the judgment matrix. Based on the characteristics of the study area' s ecosystem and referencing existing research, the ecological risk evaluation classification standard was proposed . According to the ecological security scale value criteria, the comprehensive ecological security evaluation index was divided into five intervals from high to low: when $K < 0.2$, it is a severe warning zone; when $0.2 \leq K < 0.4$, it is a moderate warning zone; when $0.4 \leq K < 0.6$, it is an early warning zone; when $0.6 \leq K < 0.8$, it is a relatively safe zone; and when $K \geq 0.8$, it is a safe zone.

3. Results

3.1.1 Trends in Wind-sand, Temperature, and Precipitation Changes

The Mann-Kendall nonparametric test was used to analyze trends in wind-sand, temperature, and precipitation changes. From 1971 to 2019, the average number of sandstorm days in the lower Tarim River showed a non-significant upward trend, with an average annual increase of 0.05 days. The number of gale days showed an extremely significant decreasing trend ($P < 0.01$), with an average annual decrease of -0.24 days $\cdot$ a^{-1}. According to [Figure 2: see original paper], the number of gale days in the lower Tarim River experienced a significant turning point around 1986. In terms of interannual fluctuations, the number of sandstorm days showed obvious differences in different periods. The mean values for three periods were 5.43 days (1971–1985), 7.08 days (1986–2002), and 12.29 days (2003–2019), with sandstorm days increasing significantly in the latter period.

Comparing gale days with sandstorm days reveals that while gale days decreased extremely significantly, sandstorm days increased. Gale is the key dynamic factor causing sandstorms, while vegetation cover is the crucial factor inhibiting sandstorm occurrence. This indirectly indicates that under conditions of river cutoff and lack of water supply, the vegetation cover level around the Kongque River that inhibits sandstorm occurrence is gradually decreasing, and vegetation degradation is becoming increasingly severe.

For temperature and precipitation changes, [Figure 2: see original paper] shows that temperature in the lower Tarim River continued to rise from 1957 to 2019, with a Mann-Kendall trend test value of $Z_c = 6.34$, reaching an extremely significant level ($P < 0.01$), with an average annual warming of 0.03°C and a mean temperature of 11.15°C. Precipitation showed an increasing trend, with a Z_c value of 1.96, reaching a significant level, with an average annual increase of 0.28 mm and a mean precipitation of 36.8 mm.

3.1.2 Spatiotemporal Variation Characteristics of TVDI Using TVDI data from 2000 to 2018, the study analyzed drought conditions in the research area. TVDI was divided into four drought levels: 0–0.5 (light drought), 0.5–0.6 (moderate drought), 0.6–0.75 (severe drought), and > 0.75 (extreme drought). The results show that the overall drought level in the study area remained high, with the proportion of extreme drought areas reaching 65.1%, mainly distributed throughout the Karanqi River and from Weimake to Maimaituohuti Ecological Gate on the Nashen River. Severe drought areas accounted for 24.1%, mainly distributed in the upper reaches of the Karanqi River. Moderate drought areas accounted for 8.3%, mainly distributed near the starting point of the Karanqi River close to the Kongque River, from the artificial oasis outlet to the Weimake section, and at the tail of the Nashen River. Light drought areas had the lowest proportion at only 2.5%, mainly distributed in the No. 2 Forest, Yantian area, and river sections within the regiment.

Temporally, TVDI showed an increasing trend, with an average annual increase of $0.008 \cdot a^{-1}$, but the trend was not significant. Spatially, 83.8% of the area showed an increasing trend, consistent with the overall intensification of drought in the region.

3.2.1 Spatiotemporal Variation Characteristics of Vegetation Coverage Based on the vegetation distribution characteristics of the study area, vegetation coverage was divided into four levels: 0–5%, 5–10%, 10–15%, and $> 15\%$. [Figure 4: see original paper] shows that vegetation coverage in the study area is relatively low, with 76.5% of the area having coverage below 5%, and the average vegetation coverage of the entire area is only 4.41%. Areas with coverage above 15% account for only 4.1%, mainly distributed in the tail area of the regiment and the Nashen River within the regiment, where agricultural vegetation is intensively planted and irrigated with large water volumes. Additionally, at the Maimaituohuti Ecological Gate where the Nashen River joins the Qiwenkuoer River, vegetation coverage is relatively high due to its proximity to the ecological water conveyance area of the lower Tarim River.

Temporally, vegetation coverage showed an increasing trend from 2000 to 2018, with 64.8% of the area showing a non-significant increase, mainly distributed in the Karanqi River area. Areas with decreasing vegetation coverage were mainly distributed in the Nashen River section from the regiment outlet to the Sanba section, with significantly decreasing areas mainly distributed from Weimake to Sanba, accounting for 6.34% of the area.

3.2.2 Spatiotemporal Variation Characteristics of Vegetation Productivity Using NPP spatial distribution as the baseline, vegetation productivity was divided into four levels: 0–25 g $C \cdot m^{-2}$, 25–50 g $C \cdot m^{-2}$, 50–75 g $C \cdot m^{-2}$, and > 75 g $C \cdot m^{-2}$. The results show that the current average vegetation productivity in the study area is 32.01 g $C \cdot m^{-2}$, indicating very low productivity levels. Spatially, areas with 0–25 g $C \cdot m^{-2}$ account for the highest proportion at 45.88%, mainly distributed in the Karanqi River and the Nashen River section from the regiment outlet to Sanba. Areas with > 75 g $C \cdot m^{-2}$ are the smallest, accounting for only 6.34%, and are mainly distributed within artificial oases.

Temporally, vegetation productivity showed an increasing trend from 2000 to 2018, but the change was not significant, with an average annual increase of only 0.009 g $C \cdot m^{-2}$. The Mann-Kendall test Z_c value was only 0.223. Spatially, 57.9% of the area showed an increasing trend, while 32.01% showed a decreasing trend, mainly distributed in the Weimake to Sanba section of the Nashen River.

3.3 Comprehensive Ecological Security Assessment of the Cutoff River Channel in the Lower Tarim River Based on the comprehensive evaluation index method, the annual ecological security evaluation index values for the cutoff river channel were calculated [Figure 6: see original paper]. From 2000 to 2018, the ecological security comprehensive evaluation index was consistently located in the early warning and moderate warning zones, showing an overall declining trend. In the indicator system, vegetation coverage and TVDI had relatively large weights of 0.327 and 0.279, respectively, while gale and sandstorm days had weights of 0.163 and 0.131, respectively. NPP and ET had the smallest weights at 0.063 and 0.037 .

The ecological security status of the study area remains poor and continues to deteriorate. River cutoff and water shortage have significantly impacted regional ecological security, and the impact continues to deepen.

Comparing with the ecological water conveyance area, the overall TVDI in the water conveyance area shows a decreasing trend, opposite to the significant increasing trend in the cutoff area. The mean TVDI in the water conveyance area is 19.8% lower than in the cutoff area. Vegetation coverage in the water conveyance area increased at an extremely significant rate, while the cutoff area showed a non-significant increasing trend. The mean vegetation coverage in the water conveyance area is 50.6% higher than in the cutoff area. Vegetation productivity in the water conveyance area increased significantly, with a mean value 95.5% higher than in the cutoff area.

4. Discussion

4.1 Changes in Ecological Environment Indicators of the Cutoff River Channel In summary, the cutoff area experienced rising temperatures and increasing precipitation, with vegetation coverage and productivity also showing increasing trends. This is consistent with previous research on climate warming and humidification and vegetation improvement in northwestern arid regions of China. Improved precipitation conditions provide favorable conditions for vegetation growth in the cutoff area. However, the increase in vegetation at the upstream regiment area of the Nashen River and its confluence with the Qiwenkuoer River mainly benefits from irrigation water and ecological water conveyance from the Qiwenkuoer River.

Although vegetation coverage and productivity in the cutoff area show increasing trends, the degree of aridification remains severe and continues to intensify. The intensification of aridification despite increased precipitation is likely due to rising temperatures accelerating evaporation, causing increased evaporation to exceed increased precipitation. This is consistent with the situation in northwestern China where increased precipitation is accompanied by intensified drought. Furthermore, analysis of wind-sand changes shows that while gale days decreased significantly, sandstorm days increased significantly, exacerbating sand hazards. This indicates that the environmental conditions and ecological functions of the ecological corridor in the cutoff area have not improved with vegetation increases but continue to deteriorate with prolonged cutoff duration.

4.2 Comparison of Ecological Security Status Between Cutoff and Water Conveyance River Channels Since 2000, both vegetation coverage and productivity in the cutoff river area (Nashen River and Karanqi River sections) have remained at low levels, with ecological security issues becoming increasingly severe. The ecological water conveyance methods from the water conveyance area (Daxihaizi Reservoir to Taitema Lake section) should be used as a reference for ecological management to improve ecological security in the cutoff area.

Comparing the two areas, TVDI in the water conveyance area shows a decreasing trend, with the decreasing trend becoming more significant after unified management. In contrast, TVDI in the cutoff area consistently shows an increasing trend. Before unified management, the mean TVDI in the water conveyance area was 11.8% lower than in the cutoff area; after unified management, it was 19.8% lower. Vegetation coverage in the water conveyance area increased at an extremely significant rate, while the cutoff area showed a non-significant increasing trend. The mean vegetation coverage in the water conveyance area was 50.6% higher than in the cutoff area before unified management and 15.3% higher after unified management. Vegetation productivity in the water conveyance area increased significantly, with mean values 52.3% and 15.7% higher than in the cutoff area before and after unified management, respectively.

5. Countermeasures and Suggestions for Ecological Restoration

1) **Accelerate the implementation of water system connectivity projects in the lower Tarim River**. Historically, the Kongque River was naturally connected with the Tarim River and could supply water to

each other, possessing natural conditions for river-to-river connectivity. Since 2000, due to abundant water inflow from mountainous areas in the Kaidu River Basin, water inflow to Bosten Lake has increased and water levels have gradually risen. Concurrently, water inflow to the Tarim River has been higher than in previous years. We should fully utilize this favorable trend of abundant water years in the Tarim River Basin, give full play to the ecological regulation function of Daxihaizi Reservoir, open up the ecological water conveyance channel from the Kongque River to the main stream of the Tarim River, and expand the ecological water-receiving area and ecological restoration range. Using the Karanqi River, a tributary of the Kongque River, a new artificial channel should be constructed to convey ecological water from the Kongque River into the Nashen River. Additionally, using the main canal of Daxihaizi Reservoir and newly constructed connecting channels, ecological water from Daxihaizi Reservoir should be conveyed into the Nashen River. The ecological water resources will ultimately flow into the Qiwenkuoer River at the Maimaituohuti Ecological Gate and then into Taitema Lake. During implementation, existing water conveyance culverts and traffic bridges with severe sedimentation and blockages should be reconstructed, and the river channels of the Karanqi River and Nashen River should be dredged.

2) **Reference the successful experience of ecological water conveyance in the lower Tarim River for cutoff river channel water conveyance**. Since the implementation of ecological water conveyance to the lower Tarim River in 2000, the growth and rejuvenation of existing natural vegetation near the river channel have been obvious. However, the restoration task for the Karanqi River and Nashen River remains arduous. With strong support from the national river-reservoir connectivity policy and the stable water source system guarantee of unified management of the four source streams, scientific and reasonable ecological water conveyance to the Karanqi River and Nashen River, referencing the restoration models and successful experiences of the lower Tarim River, is a wise choice for consolidating the comprehensive management achievements and forming a water conveyance pattern from linear to planar, from single-channel to dual-channel to multi-channel water conveyance. Early water conveyance in the lower Tarim River was intermittent—when the river had water, it recharged groundwater; when water conveyance stopped, groundwater levels declined. This directly led to unstable groundwater levels. Therefore, only through long-term water conveyance to the Karanqi River and Nashen River can groundwater levels be maintained to meet the needs of natural vegetation growth and ecological restoration. In terms of water conveyance methods, engineering measures such as ecological gates should be implemented gradually and in sections through "planar water supply" methods like flooding or overflow, combined with ecological restoration techniques such as root sprouting

and activation of soil seed banks to achieve seed renewal of plants, thereby increasing surface coverage and accelerating natural vegetation restoration. Regarding water conveyance timing, considering the consistency between plant seed maturity and ecological water conveyance timing, seed dispersal should coincide with water conveyance timing so that seeds can receive adequate moisture after falling, facilitating germination and ultimately expanding the ecological effects of water conveyance to the lower Tarim River and achieving ecosystem sustainability.

3) **Strengthen the construction of an ecological monitoring system for cutoff river channels in the lower Tarim River**. During the research process, it was found that monitoring data on groundwater level and plant diversity in the Karanqi River and Nashen River are scarce, and ecological environment monitoring has not formed a systematic scientific system, limiting the comprehensive assessment of the study area' s ecological security status. Therefore, long-term monitoring of the study area should be strengthened, mainly including surface water, groundwater, and soil water monitoring, vegetation change monitoring, and biodiversity surveys, to more comprehensively evaluate the effects of ecological water conveyance in real-time and continuously improve water conveyance schemes.

6. Conclusions

1) From 1971 to 2019, gale days in the lower Tarim River decreased significantly, but sandstorm days still showed an increasing trend, indicating declining protective functions of the riparian ecosystems. From 1957 to 2019, both temperature and precipitation showed upward trends, but the increase in precipitation was not significant. The current annual TVDI in the river cutoff area has reached severe drought levels, with only the regiment area experiencing light drought. Temporally, TVDI shows an increasing trend; spatially, 83.8% of the area shows an increasing trend, with drought conditions intensifying.

2) The current average vegetation coverage in the lower Tarim River cutoff area is only 4.41%, with 76.5% of the area having coverage below 5%. Vegetation coverage is relatively high only near the regiment area. Temporally, vegetation coverage showed an increasing trend from 2000 to 2018, with 64.8% of the area increasing. Spatially, vegetation coverage increased in areas near the downstream ecological water conveyance zone, with a significant increasing trend in the Nashen River.

3) The current average vegetation net primary productivity in the study area is 32.01 g $C \cdot m^{-2}$. Temporally, 87.80% of the area showed an increasing trend from 2000 to 2018, but the overall change was not significant. Spatially, 57.9% of the area showed an increasing trend, while 32.01% showed a decreasing trend, mainly in the Weimake to Sanba section of the Nashen

River.

4) From 2000 to 2018, the ecological security comprehensive evaluation index was consistently in the early warning and moderate warning zones, showing an overall declining trend. Based on the deteriorating ecological security status of the cutoff area, countermeasures and suggestions for ecological protection and restoration of the cutoff river channel area in the lower Tarim River have been proposed.

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