Postprint: Monitoring and Analysis of Ecological Benefits of Water Conveyance in the Lower Tarim River over the Past Two Decades

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Abstract

Since the implementation in 2000 of the ecological water transfer project aimed at raising groundwater levels, rescuing the "green corridor" in the lower reaches of the Tarim River, and curbing continuous ecological deterioration, 21 ecological water transfers have been conducted to the lower Tarim River by 2020, with a cumulative water volume of 84.45$\times 10^8 m^{3}. Analysis of monitoring results over the past nearly 20 years shows: (1) At 100 m from the river channel, the groundwater
before water transfer to 498.54 km^2 in 2019, with the terminal lake—Taitema Lake—being "resurrected," reaching a surface water area of 455.27 km^2. (3) Following water transfer, the surface ecosystem responded sensitively; within 2000 m of the river channel, high vegetation coverage, Normalized Difference Vegetation Index (NDVI), Net Primary Production (NPP), and Gross Primary Productivity (GPP) in the lower Tarim River increased by 132 km^2, 0.07, 7.6 g C · m^{-2}, and 1221 g C · m^{-2} · season^{-1}, respectively. (4) The area of influence and improvement on surface vegetation in the lower Tarim River by water transfer reached 1423 km^2, with substantial increases in ecosystem service value and function; the carbon sink area grew from 1.54% of the study area in 2001 to 7.80% in 2020, with significant improvements in ecosystem health and ecological resilience, and enhanced soil carbon sink capacity. The nearly 20 years of ecological water transfer have substantially raised the groundwater level in the lower Tarim River, rescued and rejuvenated the desert riparian forest vegetation dominated by Populus euphratica along both banks, increased surface vegetation coverage, and essentially curbed the ecological degradation trend in the lower Tarim River.

Full Text

Monitoring and Analysis of Ecological Benefits of Water Conveyance in the Lower Reaches of the Tarim River in Recent 20 Years

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Abstract

Since the implementation of the ecological water conveyance project in 2000 aimed at raising groundwater levels, rescuing the "green corridor" in the lower reaches of the Tarim River, and curbing continuous ecological deterioration, a total of 84.45$×10^{8}$ m^3 of water has been delivered through multiple conveyance events by 2020. Monitoring results show that: (1) At monitoring sites 100 m from the river channel, groundwater depth in the upper, middle, and lower sections decreased from pre-conveyance levels of 7.76 m, 9.31 m, and 7.82 m to 3.70 m, 4.48 m, and 2.69 m respectively, with average rises of 4.06 m, 4.83 m, and 5.13 m. At 500 m from the channel, groundwater depth decreased from 8.21 m, 9.45 m, and 9.08 m to 6.61 m, 5.46 m, and 3.82 m respectively. At 1050 m from the channel, groundwater depth increased by 2.69 m, 1.38 m, and 1.59 m respectively. (2) The lateral influence range of ecological water conveyance on groundwater in all three sections exceeded 1000 m. The terminal lake—Taitma Lake—has "resurrected," with its surface water area reaching 455.27 km^2, while the total surface water area expanded from 49.00 km^2 to 498.54 km^2. (3) Surface ecological processes responded sensitively to water conveyance. Within 2000 m of the river channel, the area of high vegetation coverage, normalized difference vegetation index (NDVI), vegetation net primary productivity (NPP), and gross primary productivity (GPP) increased by 132 km^2, 0.07, 7.6 g $C \cdot m^{-2} \cdot season^{-1}$, and 1221 g $C \cdot m^{-2}$ respectively. (4) The water conveyance influenced and improved vegetation across 1423 km^2, substantially increasing ecosystem service value and function. The carbon sink area expanded from 1.54% of the study region in 2001 to 7.80% in 2020, with significantly improved ecosystem health, enhanced ecological resilience, and increased soil carbon sequestration capacity. In summary, nearly 20 years of ecological water conveyance has substantially raised groundwater levels in the lower Tarim River, rescued and revitalized desert riparian forests dominated by *Populus euphratica* along the riverbanks, increased surface vegetation coverage, and fundamentally curbed the trend of

ecological degradation.

Keywords: ecological water conveyance; groundwater depth; surface ecological response; Tarim River

1 Study Area and Monitoring Setup

1.1 Study Area Overview

The Tarim River Basin is located in southern Xinjiang, China, bordered by the Tianshan Mountains to the north, the Kunlun Mountains to the south, and the Pamir Plateau to the west, covering an area of approximately 102$×10^{4}$ km^2. It serves as a core region of China' s Silk Road Economic Belt, characterized by both relatively abundant natural resources and extremely fragile ecological environments. The Tarim Basin is the most arid region in China, with multi-year average precipitation below 50 mm in most areas. Natural vegetation consists mainly of drought-resistant and salt-tolerant desert species that grow along river channels. Since the 1950s, intensive human economic and social activities centered on water and soil resource development have caused the lower 321 km of the Tarim River to dry up. After the river channel dried in [year], groundwater and soil moisture became the primary water sources for natural trees, shrubs, and herbaceous vegetation. With substantial groundwater level decline, desert riparian forest ecosystems dominated by *Populus euphratica* experienced accelerated degradation, manifested as reduced plant species, decreased species diversity indices, and simplified community structure from upstream to downstream and from near to far from the channel, with increasingly severe ecosystem degradation trends.

The lower reaches of the Tarim River form an alluvial fine-soil plain. Using the Qiala Hydrological Station as a node, this section is situated between the Taklamakan Desert and the Kuruktag Desert, terminating at Taitma Lake. The region experiences a continental warm-temperate desert arid climate with dry conditions and frequent sandstorms, average annual precipitation of 17.4–42.0 mm, and average annual evaporation of 2500–3000 mm, making it one of the most arid areas in the Tarim Basin (Fig. [Figure 17: see original paper]). The soil aquifer lithology is relatively uniform, primarily consisting of fluvio-lacustrine fine sand, silt, and aeolian sandy soil. The hydrogeological structure is simple, with aquifers exhibiting a multi-layered configuration that can be divided into phreatic and confined aquifers based on burial conditions, with the upper phreatic groundwater being closely connected to river water while having minimal hydraulic connection with the lower confined aquifer.

1.2 Monitoring Section Layout

To monitor and understand changes in groundwater level and surface vegetation along the Tarim River mainstem during water conveyance, a prototype long-term monitoring network for ecohydrological processes was established beginning in [year], covering 1321 km of the main river course within a 1520 km^2

area. The network includes [number] long-term monitoring sections, [number] groundwater monitoring wells, and [number] vegetation plots (100 m × 100 m each). Specifically, [number] monitoring sections and [number] groundwater wells were installed in the lower reaches of the Tarim River. Long-term fixed-position monitoring of groundwater level, water quality changes, and surface ecological responses during ecological water conveyance was conducted to analyze the relationship between groundwater level changes and desert riparian forest vegetation, reveal water use strategies of desert riparian forest vegetation at different scales and from physiological-ecological mechanisms, determine reasonable ecological water level thresholds, and provide scientific basis for determining ecological water requirements and restoring degraded ecosystems in the lower Tarim River.

1.3 Ecological Water Conveyance Volume

The ecological water conveyance project for the lower Tarim River was initiated in [year]. By [year], intermittent water conveyance had been implemented along the 321 km river channel [number] times, with a cumulative ecological water volume of 84.45$×10^{8}$ m^3. During the first [number] water conveyance events before [year], with a total duration of 227 days, water reached near the Ka' erdai section with a conveyance volume of approximately 1.0$×10^{8}$ m^3. After [number] conveyance events, water reached below the Alagan section with 2.3$×10^{8}$ m^3. Following subsequent conveyance events, except for [year], water consistently reached the river terminus at Taitma Lake in most years (Table).

2 Monitoring Results

During the ecological water conveyance period in the lower Tarim River, groundwater depth and surface ecological processes underwent substantial changes. Groundwater depth showed more pronounced changes in the early stage, closely related to both pre-conveyance depth and conveyance volume, while surface ecological responses exhibited a certain time-lag characteristic following groundwater level rise.

2.1 Groundwater Level and Quality Changes

The water source for ecological conveyance in the lower Tarim River primarily comes from Bosten Lake, China' s largest inland freshwater lake. Water is transferred from Bosten Lake along the Konqi River through a diversion sluice into the Tarim River, then released naturally along the Qiwenkuoer River, a major tributary of the lower Tarim River, from the Daxihaizi Reservoir. Since the Tarim River downstream climate is extremely arid with negligible precipitation, shallow groundwater depth directly relates to the composition, distribution, and growth of desert riparian forest vegetation dominated by *Populus euphratica*. River channel drying caused substantial groundwater decline and soil moisture reduction, becoming the dominant factor causing natural vegetation degradation and reduced species diversity in desert riparian forests. Consequently, groundwater changes during conveyance have been a focal issue.

2.1.1 Groundwater Depth Changes Along the river course from the upper section (Yingsu) through the middle section (Ka' erdai) to the lower section (Yiganbujima), monitoring within 100 m of the river channel shows groundwater depth decreased from pre-conveyance levels of 7.76 m, 9.31 m, and 7.82 m to 3.70 m, 4.48 m, and 2.69 m respectively, with rises of 4.06 m, 4.83 m, and 5.13 m. At 300 m from the channel, groundwater depth decreased from 8.09 m, 9.15 m, and 8.25 m to 3.29 m, 3.56 m, and 4.53 m respectively, with rises of 4.80 m, 5.59 m, and 3.72 m. At 500 m from the channel, groundwater depth decreased from 8.21 m, 9.45 m, and 9.08 m to 6.61 m, 5.46 m, and 3.82 m respectively, with rises of 1.60 m, 3.99 m, and 5.26 m. In the direction perpendicular to the river channel, the influence range of ecological water conveyance on groundwater in all three sections exceeded 1000 m. Groundwater monitoring well data at 1050 m from the channel show groundwater depth in the upper, middle, and lower sections increased by 2.69 m, 1.38 m, and 1.59 m respectively. Analysis of groundwater level rise patterns in the upper, middle, and lower sections of the lower Tarim River shows that the rise amplitude is related to pre-conveyance depth, conveyance volume, duration, and water head reach area. Groundwater level rise in the upper and middle sections showed greater changes in the early stage (2000–2005), with the rate slowing after 2005 as water levels approached equilibrium, though the lateral influence range continued expanding.

2.1.2 Groundwater Quality Changes Accompanying ecological water conveyance, groundwater mineralization in the lower Tarim River decreased significantly, expanding the scope of freshwater zones along both banks. The shallow groundwater usable by ecosystems primarily consists of oasis agricultural drainage and Tarim River seepage. After river channel drying in [year], groundwater lost surface water recharge, and mineralization continuously increased with declining groundwater levels. Pre-conveyance groundwater mineralization along both banks generally exceeded 3 $g \cdot L^{-1}$, with some sections surpassing 10 $g \cdot L^{-1}$, exacerbating osmotic stress and overall vegetation degradation. Ecological water conveyance substantially reduced groundwater mineralization, decreasing average levels from 4–11 $g \cdot L^{-1}$ pre-conveyance to 1–5 $g \cdot L^{-1}$ within the lateral range along both banks, with freshwater influence extending up to 1000 m from the channel. Monitoring revealed that groundwater mineralization is significantly correlated with conveyance volume; during periods with less conveyance water, mineralization showed a clear upward trend.

2.2 Normalized Difference Vegetation Index (NDVI) Changes

Normalized Difference Vegetation Index (NDVI) is an important indicator reflecting vegetation growth conditions. Based on remote sensing data (MOD13Q1, MCD12Q1), analysis of NDVI changes during ecological water conveyance in the lower Tarim River shows that vegetation coverage increased by approximately [value], with the influence range on natural vegetation expanding from 492 km^2 to 1423 km^2, representing an increase of 188.0%. The areas of low, medium, and high vegetation coverage increased by 33.3% (277 km^2), 20.8% (537 km^2), and 448.0% (132 km^2) respectively compared to pre-conveyance levels. Spatially, vegetation area and coverage increases in the middle section (Yingsu–Alagan) were higher than in the upper section (Daxihaizi Reservoir–Yingsu) and lower section (Alagan–Taitma Lake). Analysis shows that groundwater level rise amplitude is related to pre-conveyance depth, conveyance volume, duration, and water head reach area. Groundwater level rises in the upper and middle sections were more pronounced in the early conveyance period (2000–2005), slowing after 2005 as levels approached equilibrium, though the lateral influence range continued expanding. Vegetation coverage showed higher values within 500 m of the river channel, with greater increases during water conveyance, while values and increase rates gradually decreased at distances of 1000–2000 m from the channel.

2.3 Surface Water Area Changes

Changes in water body area in arid regions are directly related to terrestrial ecology. Based on Landsat imagery data and ecological water conveyance data, this study employed the Google Earth Engine (GEE) platform and multivariate statistical analysis methods to monitor surface water area changes during the ecological water conveyance period. Results show that total surface water area, seasonal water body area, and permanent water body area in the lower Tarim River region exhibited fluctuating upward trends. In the upper section (Yingsu region), surface water and permanent water body areas showed fluctuating changes, while seasonal water body area increased significantly. In the middle section (Yingsu–Alagan), surface water, seasonal water body, and permanent water body areas increased at rates of 1.75 $km^2 \cdot a^{-1}$, 1.58 $km^2 \cdot a^{-1}$, and 0.16 $km^2 \cdot a^{-1}$ respectively. In the lower section (below Alagan), these areas increased at rates of 5.23 $km^2 \cdot a^{-1}$, 13.48 $km^2 \cdot a^{-1}$, and 8.24 $km^2 \cdot a^{-1}$ respectively. After years of ecological water conveyance, the permanent and seasonal water body areas in the Taitma Lake region reached 267.27 km^2 and 188.00 km^2 respectively, with total water body area of approximately 455.27 km^2. Surface water area changes, particularly permanent water body area, are closely correlated with water conveyance volume in the lower Tarim River. During 2000–2005, less water was delivered to the lower reaches, resulting in significant decreases in surface water, seasonal water body, and permanent water body areas. Surface water area shows a strong negative correlation with groundwater depth (Cor = -0.81). Herbaceous and shrub vegetation show stronger correlations with groundwater depth (Cor = -0.76) than *Populus euphratica* (Cor = -0.46). Peak vegetation occurs at groundwater depths of 4–6 m, with vegetation declining when groundwater levels fall below this range.

2.4 Natural Vegetation Net Primary Productivity (NPP) Changes

Vegetation Net Primary Productivity (NPP) is a key parameter of terrestrial ecosystem carbon cycling and energy flow, reflecting not only ecosystem productivity but also ecosystem quality, playing an important role in global change and carbon balance. Based on remote sensing data (NASA LP DAAC MOD17A2H) and the Google Earth Engine platform, this study analyzed changes in terrestrial ecosystem growth during ecological water conveyance using the Carnegie-Ames-Stanford Approach (CASA) model. Results show that ecological water conveyance significantly improved the overall ecological environment of the Tarim River mainstem area. During conveyance, NPP in the lower Tarim River showed a significant increasing trend, rising from 3675.51 g $C \cdot m^{-2} \cdot season^{-1}$ to 4896.61 g $C \cdot m^{-2} \cdot season^{-1}$, an increase of 1221 g $C \cdot m^{-2}$ per growing season. Spatially, natural vegetation NPP in the lower Tarim River is directly related to groundwater depth, decreasing with distance from the river channel. Longitudinally, distinct spatial distribution patterns exist across different sections. The upper section shows a unimodal trend of first increasing then decreasing, while the lower section exhibits a bimodal pattern. During water conveyance, areas with increased and significantly increased NPP accounted for 11.49% and 38.10% respectively, with an increase rate of 0.40 g $C \cdot m^{-2} \cdot a^{-1}$. Seasonal contribution analysis reveals that summer contributes most to growing season NPP in the upper section (31.93%), followed by spring (31.42%), with autumn slightly smaller. In the lower section, autumn contributes most (31.00%), followed by summer. Among vegetation types, shrub communities show the largest NPP increase during water conveyance, with NPP values ranking as *Tamarix* > herbaceous > *Populus euphratica* communities.

2.5 Plant Water Use Efficiency (WUE) Changes

Water Use Efficiency (WUE) is an important indicator for studying plant survival, productivity, fitness, and the coupling of carbon and water cycles, as well as a key parameter for understanding terrestrial ecosystem metabolism. In the lower Tarim River, natural vegetation WUE decreases from the river channel toward both sides and from upstream to downstream. Studies on the spatiotemporal changes of WUE and its dynamic response to ecological water conveyance show that WUE is positively correlated with both conveyance volume and duration.

2.6 Vegetation Gross Primary Productivity (GPP) Changes

Vegetation Gross Primary Productivity (GPP) is a key component of terrestrial ecosystem carbon cycling, crucial for maintaining global carbon balance. Based on remote sensing data and the Google Earth Engine platform, this study analyzed GPP changes during ecological water conveyance. Results show that GPP in the lower Tarim River exhibited a significant increasing trend during the conveyance period.

2.7 Vegetation Carbon Sink Area Changes

Ecological water conveyance in the lower Tarim River has improved the ecological environment, with increased vegetation coverage enhancing regional carbon sequestration capacity through photosynthesis. Based on a modified CASA model and soil microbial respiration model, Net Ecosystem Productivity (NEP) was estimated and vegetation carbon source/sink spatial changes were analyzed. Results show that the desert sparse vegetation ecosystem in the lower Tarim River is characterized by low carbon sequestration. Since 2000, ecological water conveyance has restored degraded ecosystems to some extent, with vegetation net primary productivity (NPP) increasing at a rate of 0.541 g $C \cdot m^{-2} \cdot a^{-1}$, and summer increase rate of 0.406 g $C \cdot m^{-2} \cdot a^{-1}$. The carbon sink area gradually expanded from 1.54% of the study region in 2001 to 7.80% in 2020. Spatially, increases were more pronounced in the northwest and south of Yingsu and the northeast of Taitma Lake. Seasonally, changes were most obvious in summer, with no significant carbon sink area appearing in winter. Cumulative ecological water conveyance shows good linear relationship with carbon sink area, with approximately a [value]-year lag effect.

3 Discussion and Conclusion

Since the implementation of ecological water conveyance to the lower Tarim River in 2000, a total ecological water volume of 84.45$×10^{8}$ m^3 has been released from the Daxihaizi Reservoir over [duration]. Of this, approximately 30.6$×10^{8}$ m^3 recharged groundwater through riverbed seepage, and 11.7$×10^{8}$ m^3 reached the terminal lake Taitma Lake, accounting for 13.80% of the total conveyance volume. Water conveyance has raised groundwater levels by 3–5 m along both banks of the lower Tarim River, with groundwater influence exceeding 1000 m laterally. The influence range on natural vegetation expanded from 492 km^2 pre-conveyance to 1423 km^2. The trend of continuous ecological deterioration along the riverbanks has been curbed, degraded desert riparian forest ecosystems dominated by *Populus euphratica* have been partially restored, the "green corridor" has been rescued and protected, and Taitma Lake has "resurrected," forming a water area of 455.27 km^2 (including inflow from the Kunlun Mountain-origin Qarqan River).

During 2000–2020, ecological water conveyance in the lower Tarim River primarily followed natural river channels. This approach effectively raised groundwater levels on both sides and significantly promoted growth and revitalization of existing natural vegetation near the river. However, recent monitoring of groundwater level changes indicates that the rate of groundwater rise has slowed in recent years, with some sections approaching equilibrium. Moreover, the current natural channel-based conveyance only affects vegetation near riverbanks, limiting the restoration range. It also fails to achieve seed dispersal and regeneration for regional ecological sustainability. Furthermore, channel-based conveyance makes large-scale restoration of herbaceous plants on both banks difficult, limiting increases in surface coverage. Therefore, we recommend that based on current "linear" channel conveyance and maintenance of ecological flow, engineering-assisted, planned, top-down implementation of zonal surface flooding be adopted. Through "areal water supply," this would activate soil seeds while promoting seed dispersal and regeneration, expanding the receiving area and ecological effects of water conveyance in the lower Tarim River.

Under global warming, climate conditions in the Tarim River Basin are changing, affecting mountain water storage and ice-snow melt. Research indicates that intensified extreme climatic and hydrological events caused by global warming may alter mountain runoff, increasing water resource uncertainty. Meanwhile, intra-annual distribution shows a trend of peak flow shifting earlier in the Kaidu River Basin, while summer flows in the Yarkant and Hotan rivers have increased. This is crucial for selecting time windows and developing strategies for ecological water conveyance. Future water conveyance scheduling must fully consider increasing frequency of extreme flood and drought events and the occurrence of consecutive extreme low-flow years. Water resource management and allocation should take precautionary measures to reduce risks to sustainable ecological water conveyance in the lower Tarim River.

References

[1] Chen Yaning, Zhang Xiaolei, Zhu Xiangmin, et al. The ecosystem effect analysis of water input in Tarim River[J]. Science in China Ser. D Earth Sciences, 2004, 34(5): 475-482.

[2] Chen Yaning. Study on eco-hydrological problems in Tarim River Basin in Xinjiang[M]. Beijing: Science Press, 2010: 517-571.

[3] Chen Yaning, Li Weihong, Xu Hailiang, et al. The influence of groundwater on vegetation in the lower reaches of Tarim River, China[J]. Acta Geographica Sinica, 2003, 58(4): 542-549.

[4] Pang Z H, Huang T M, Chen Y N. Diminished groundwater recharge and circulation relative to degrading riparian vegetation in the middle Tarim River[J]. Hydrological Processes, 2010, 24: 147-158.

[5] Wang W R, Chen Y N, Wang W H, et al. Evolution characteristics of groundwater and its response to climate and land cover changes in the oasis of dried up river in Tarim Basin[J]. Journal of Hydrology, 2020, 125644, doi: 10.1016/j.jhydrol.2020.125644.

[6] Fu A H, Chen Y N, Li W H. Analysis on water potential of *Populus euphratica* Oliv and its meaning in the lower reaches of Tarim River, Xinjiang[J]. Chinese Science Bulletin, 2006, 51(S1): 221-228.

[7] Hao X M, LI W H. Impact of ecological water conveyance on groundwater dynamics and vegetation recovery in the lower reaches of the Tarim River in northwest China[J]. Environmental Monitoring and Assessment, 2014, 186: 7605-7616.

[8] Myneni R B, Keeling C D, Tucker C J, et al. Increased plant growth in the northern high latitudes from 1981 to 1991[J]. Nature, 1997, 386(6626): 698-702.

[9] Field C B, Behrenfeld M J, Randerson J T, et al. Primary production of the biosphere: Integrating terrestrial and oceanic components[J]. Science, 1998, 5374(281): 237-240.

[10] Beer C, Reichstein M, Tomelleri E, et al. Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate[J]. Science, 2010, 329(5993): 834-838.

[11] Chen Yaning. Study on water resources in arid areas of northwest China[M]. Beijing: Science Press, 2014.

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