Impact of Ecological Water Transfer Project on Vegetation Recovery in Dried-Up Kongque River, Northwest China

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Abstract: The ecological water transfer project (EWTP) plays a pivotal role in reinstating the flow of dried-up rivers in arid regions, promoting river connectivity and vegetation resurgence. An essential facet in ensuring the efficacious execution of the EWTP lies in determining the optimal duration of irrigation to facilitate vegetation recovery. Nevertheless, comprehensive reports concerning the EWTP process in arid river ecosystems are scarce. Here, we leverage remote sensing imagery to assess changes in surface water and vegetation dynamics before and after the implementation of the EWTP in a dried-up river. The results show that before the EWTP (1987–2016), riparian vegetation’s mean normalized difference vegetation index (NDVI) decreased from 0.181 to 0.066. After EWTP (2017–2022), the river’s flow was restored for a distance of 347 km. This restoration resulted in the formation of 81.47 km² of intermittent water bodies along the river. The mean NDVI increased from 0.065 to 0.093. As irrigation duration increased, the NDVI growth rate exhibited an initial rise followed by a subsequent decline, reaching its peak growth rate by irrigating for 18 days per year. The regions showing increased NDVI values exhibited a pronounced spatial correlation with the areas subjected to water transfer. These improvements in NDVI were predominantly concentrated on both sides of the river within a 550 m range. Interestingly, as moves farther away from the river, the growth rate of NDVI exhibited an initial increase followed by a subsequent decline. The pinnacle of NDVI growth rate materialized at a distance of 40–50 m from the river. These findings reveal the response characteristics of desert riparian vegetation to EWTP, providing valuable insights for selecting appropriate water transfer timing in future EWTP.

Keywords: remote sensing; vegetation index; surface water; water-stressed region; river restoration

1. Introduction

Global warming and increased anthropogenic utilization of water resources can lead to a reduction in river flow or complete interruption [1–3]. Regions where rivers have been interrupted face severe ecological challenges stemming from diminished water resources, including vegetation degradation and decline in biodiversity [4]. This phenomenon contributes to land desertification and causes ecological degradation. The effects of this process are particularly evident in drylands [5,6]. In arid zones, rivers serve as the primary water source for agriculture and desert vegetation due to the imbalance between evapotranspiration and precipitation [7,8]. These rivers act as the lifeblood of oasis agriculture, delivering essential water for crop cultivation and the sustenance of local communities [9,10]. Furthermore, rivers constitute vital components of riparian ecosystems. They furnish water and nutrients to support the survival of coastal vegetation and wildlife [11]. Additionally, these water bodies give rise to unique ecosystems such as wetlands and marshes, providing habitats for a diverse array of plant and animal species [12,13]. The interruption of river flow in arid regions can yield severe consequences, resulting in abrupt declines in vegetation productivity, soil fertility, and vegetation cover. These adverse
impacts can be catastrophic for a region’s ecological security and sustainable development, such as land desertification and reduction in biodiversity [14,15].

Environmental issues arising from river drying are pervasive globally. In the arid expanse of the Tarim River Basin in Northwestern China, the cultivated land area within the basin has doubled over the past three decades [16]. To meet the demands of agricultural irrigation, over ten large and medium-sized reservoirs have been constructed in the upper-middle reaches. This has led to the overutilization of water resources [17]. Since the 1970s, the downstream stretch of the river spanning 320 km has dried up, resulting in deteriorating ecological environment and severe desertification [18,19]. Similarly, the Aral Sea in Central Asia has experienced significant shrinkage due to excessive water usage for irrigation and dam construction [20]. Restoration efforts are underway to reestablish the flow of rivers feeding the Aral Sea, encompassing initiatives such as water transfers, wetland and floodplain restoration, and enhanced water management practices. The Rio Grande, traversing the southwestern United States and northern Mexico, has faced adverse impacts arising from water diversions and climate change, resulting in reduced downstream flow [21]. Even in regions characterized by humid climates, reduced or interrupted flow can occur due to human activities such as the construction of dams on rivers. This phenomenon is observed in various rivers, including the Mekong River [22], the Danube River [23], and the Mississippi River [24].

The ecological water transfer project (EWTP) has emerged as a viable solution for reinstating ecological equilibrium in regions afflicted by river desiccation [25–27]. The primary objective of the EWTP lies in providing a source of water to revive the flow of dried-up rivers. In arid and semiarid regions, rivers often constitute the sole water source, and the consequences of river desiccation are particularly dire. The EWTP typically involves the transfer of water from other rivers or reservoirs to meet the environmental water needs for the rehabilitation of impaired river ecosystems [28–30].

Illustrating the global challenges posed by river desiccation, we now turn our attention to the EWTP initiated in the Kongque River in Northwestern China, a region grappling with severe ecological consequences due to prolonged river interruption. The Kongque River holds a pivotal position within the “Four Sources and One Stem” water system of the Tarim River. It plays a multifaceted role as a vital water source for the Korla-Yuli Oasis. The Kongque River fulfills essential functions such as agricultural irrigation, residential water supply, ecological and environmental water provision, and water transfer to the lower reaches of the Tarim River [31,32]. The natural vegetation present along the lower reaches of the Kongque River and the Tarim River collectively forms a “green corridor”, effectively thwarting the convergence of the Kuruk Desert and the Taklamakan Desert [33]. Regrettably, over the past five decades, the lower reaches of the Kongque River have experienced desiccation, primarily due to excessive water resource utilization in the upper-middle reaches, resulting in the deterioration of the Populus euphratica forest on both banks [34,35].

In 2000, the Chinese government launched the EWTP in the lower Tarim River, with an investment of USD1.5 billion. Up to 2022, a cumulative total of 23 water transfer operations have been executed, releasing a cumulative volume of $9.12 \times 10^8$ m$^3$ of water [36,37]. Following the implementation of the EWTP, the Taitema Lake area in the tail lake of the Tarim River expanded from being dried up to encompassing 511 km$^2$ [38], the groundwater level experienced a rise [33,39], and both vegetation area and coverage increased [17]. Since 2016, the EWTP further expanded to encompass the entire basin, with the Kongque River as a key water transport area. By 2022, the Kongque River had been undergoing water transfer operations for seven years [40].

As the scale of the EWTP continues to expand and more resources are allocated, it becomes imperative to engage in dynamic monitoring of surface water areas. Additionally, conducting quantitative assessments of ecological restoration following EWTP implementation is crucial. This evaluation serves as a vital mechanism for making necessary adjustments and optimizations within the project. Numerous studies have employed field
investigations and observation stations to gather essential measurement data, encompassing vegetation coverage, species diversity, population structure, and groundwater dynamics. These datasets play a pivotal role in assessing the effectiveness of the EWTP [4,41,42]. Nevertheless, due to the challenging climatic conditions prevalent in the lower Kongque River area, there exists a paucity of available field observations. Furthermore, the extensive expanse covered by the EWTP poses formidable challenges regarding executing comprehensive and dynamic surveys and assessments solely through field studies [40,43]. To address this gap, it is necessary to employ new methods for comprehensive monitoring and evaluation of EWTP’s effects. This is essential to provide decision-makers with information for the restoration of the ecological environment in dried-up rivers.

Remote sensing offers substantial macroscopic and dynamic advantages across the domains of earth science, environmental science, resource science, and global change research [44,45]. Particularly within expansive areas and environmentally harsh regions, remote sensing has emerged as an unparalleled and indispensable method for conducting long-term observations [46,47]. Research consistently underscores that in studies pertaining to water monitoring and vegetation assessment, remote sensing stands out as a cost-effective and time-efficient approach capable of delivering precise and dependable results [48,49]. In this study, a method is proposed to comprehensively monitor the EWTP using remote sensing imagery obtained from Sentinel-2 and Landsat satellites, providing a dynamic assessment of the impacts of EWTP on surface water and vegetation recovery in the lower Kongque River. This interdisciplinary research provides additional insights into the ecological restoration of dried-up rivers. The innovation of this paper lies in the comprehensive assessment of vegetation recovery under different water transfer and inundation conditions, contributing to a more thorough understanding of the multifaceted impacts of EWTP on vegetation recovery and proposing rational water transfer strategies. This study aims to (1) monitor and evaluate changes in surface water area and vegetation in the lower Kongque River over nearly three decades after its desiccation; (2) assess the restoration of river flow and the spatiotemporal distribution of surface water following EWTP implementation, comprehensively evaluating vegetation recovery; and (3) propose optimal irrigation timing for vegetation to ensure optimal growth and health.

2. Materials and Methods
2.1. Study Area

The Kongque River originates from Bosten Lake and traverses through Korla City and Yuli County, ultimately disappearing into Lop Nur, which already dried up, prior to 1972 [50]. When measured from Bosten Lake to Lop Nur, the Kongque River spans a length of 942 km (Figure 1). Situated in an arid zone, the Kongque River experiences a multiyear average precipitation of approximately 57 mm and an annual potential evaporation rate of approximately 2775 mm, characterizing it as a typical warm temperate continental arid climate [51]. The upper and middle reaches of the Kongque River encompass a total of 2700 km² of farmland. In contrast, the lower reaches feature fewer agricultural lands and instead nurture an extensive expanse of desert riparian forests, predominantly comprising Populus euphratica and Tamarix chinensis [52]. These forests coexist with the Populus euphratica forests in the lower reaches of the Tarim River, serving as an important ecological security barrier and effectively preventing the expansion of the desert.

The water source for the water transfer to the Kongque River encompasses diversions from Bosten Lake and the mainstream of the Tarim River. Since 2016, the implementation of the EWTP has been underway in the middle–lower reaches of the Kongque River, involving a total volume of 23.93 × 10⁸ m³ (including 3.32 × 10⁸ m³ of water transfer from the Tarim River). This study specifically focuses on the lower reaches of the river, which is the ecological water transfer section without the influence of cultivated land.
2.2. Data and Data Processing

The remote sensing imagery utilized in this study encompasses data from Landsat 5, 7, and 8, as well as Sentinel-2A/B. Landsat 5, 7, and 8 satellites, with a revisit period of 16 days and a resolution of 30 m, have accumulated nearly 40 years of long time-series images. The combination of Sentinel-2 A and B satellites, with a revisit period of 5 days and a resolution of 10 m, is suitable for monitoring the health of surface water and vegetation in a dense time series. Landsat Level-2 science products were sourced from the United States Geological Survey Earth Resources Observation and Science Archive—Landsat archive (https://earthexplorer.usgs.gov/, accessed on 24 October 2023). A total of 225 Level-2 Landsat images were acquired for the period spanning 1987–2016. Sentinel-2A/B Level-2A products were procured from the Copernicus Open Access Hub of the European Space Agency (ESA) (https://scihub.copernicus.eu/, accessed on 6 October 2023). It is worth noting that not all images were provided by the ESA as Level-2A products. For the images lacking Level-2A products, the Sen2Cor tool provided by ESA was employed to process and generate Level-2A products. A total of 444 Sentinel-2A/B images were acquired for the period of 2017–2022.

2.3. Consistency Analysis of Landsat NDVI

Normalized difference vegetation index (NDVI) is an indicator that reflects the greenness or health of vegetation [53]. Landsat 5, 7, and 8 images were employed to examine changes in the NDVI before the implementation of the EWTP. Due to the inconsistency in bandwidth designation among the three Landsat sensors, direct comparisons between images captured by different sensors may not be entirely equivalent [54,55]. In this context, maintaining consistency in NDVI measurements from Landsat 5, 7, and 8 satellites is important to ensure the continuity of high data quality. Given the nearly identical bandwidth ranges for the red and near-infrared bands in Landsat 5 TM and Landsat 7 ETM+ imagery, it is reasonable to conclude that the mean differences between the NDVIs of Landsat 5 and 7 were close to zero [56]. Since Landsat 5 was retired in 2013, inconsistencies in NDVI values between Landsat 5, 7 and Landsat 8 were eliminated by analyzing NDVI differences between Landsat 7 and Landsat 8.
imagery (Figure A1). In the study area, the coefficient of determination ($R^2$) for the regression fit between the two NDVI datasets was determined to be 0.95. On average, Landsat 8 NDVI values were observed to be 0.0321 higher than Landsat 7 NDVI values. Furthermore, the differences in NDVI values between the two satellite platforms were found to follow a normal distribution. Based on the results above, the NDVI of Landsat 8 was harmonised with the NDVI of Landsat 5 and 7 to reduce the potential differences in NDVI values between them. This process ensured the consistency of NDVI measurements from different Landsat sensors.

2.4. Surface Water Mapping and Accuracy Assessment

The extraction of surface water was conducted in three sequential steps. In the first step, a spatial analysis buffer tool was employed to expand buffers on both sides of a river, defining the target extraction area for surface water. In the second step, the normalized difference water index (NDWI), as proposed by McFeeters [57], was constructed, and a threshold segmentation method was applied to extract initial water bodies. During the third step, it was observed that certain salt-affected soil pixels exhibited NDWI values lower than those of water but had NIR band reflectance greater than 0.3. In contrast, water typically exhibits a reflectance of less than 0.2 in both Landsat and Sentinel-2 satellites [58,59]. Consequently, by setting NIR < 0.2, the error introduced by mistaking salinity-affected soils for water bodies can be eliminated. Additionally, a few sand dune shadows were misclassified as water bodies. Despite the challenge of mitigating their influence using terrain information, they were removed through manual interpretation on a computer screen.

To establish the threshold for surface water segmentation in Landsat and Sentinel-2 imagery and validate the results, we downloaded Level 3A surface reflectance images (PlanetScope Ortho Tile Product, from planet Company of USA) from Planet Labs with a pixel size of 3.125 m [46]. PlanetScope images for three dates, 9 June 2022, 15 June 2019, and 23 October 2018, were selected based on the availability of the corresponding Landsat or Sentinel-2 images captured on or around the target date. To discriminate between water and non-water pixels, we applied an NDWI threshold of $-0.075$, determined through an independent sample of visually classified water and non-water pixels. The water bodies extracted from PlanetScope images were utilized as ground truth to compare the extraction results at various NDWI thresholds (with an interval of 0.01) for both Landsat and Sentinel-2 data. The best result of surface water segmentation on Landsat and Sentinel-2 images is selected as the best NDWI threshold. Finally, to validate the extracted surface water from Landsat and Sentinel-2, we utilized the results extracted from the PlanetScope images as the ground truth and evaluated the accuracy of extraction results by calculating the overall accuracy (OA), producer’s accuracy (PA), and user’s accuracy (UA) for both water and non-water. The formulae are as follows:

$$OA = \frac{\sum_{i=1}^{n} x_{ii}}{N}$$  \hspace{1cm} (1)

where $\sum_{i=1}^{n} x_{ii}$ represents the number of pixels of all samples correctly classified, and $N$ represents the total number of samples.

$$PA = \frac{C_c}{C_t}$$  \hspace{1cm} (2)

where $C_c$ represents the correctly classified samples of a specific class, and $C_t$ is the total number of pixels in the category.

$$UA = \frac{C_c}{C_r}$$  \hspace{1cm} (3)

where $C_r$ represents the total number of pixels classified into this category.

2.5. Methods for Evaluating Vegetation Response to EWTP

The NDVI serves as a time-series signal of vegetation response to EWTP. In arid regions, only pixels with NDVI > 0.05 are usually analyzed to reduce the effect of sparsely vegetated
A batch-processing NDVI calculation program was developed using the ENVI 5.6 + IDL 8.8 platform to automate the calculation of NDVI for multiple periods of remote sensing images and generate a time series. To assess the improvement in vegetation following the implementation of the EWTP, the Theil–Sen estimator was employed to analyze the trends in NDVI time series changes, and the Mann–Kendall test was to determine their significance. These calculations were executed pixel by pixel using Python 3.9. To obtain information regarding the restoration status of vegetation at different distances around the EWTP, we utilized ArcGIS multiple-ring buffer analysis. Additionally, Pearson correlation analysis was used to investigate the relationship between vegetation change trends and the frequency of irrigation carried out by the EWTP.

3. Results
3.1. Accuracy Verification of Water Extraction

The accuracy assessment results for surface water extraction were derived from a random sample of 2000 points (Table 1). The overall classification accuracy of Landsat was determined to be 86.2%. More specifically, for the water class, the user’s accuracy was 90.0%, and the producer's accuracy was 81.4%. In comparison, Sentinel-2 exhibited a higher overall classification accuracy of 92.4%. For the water class, the user’s accuracy reached 95.4%, and the producer’s accuracy was 89.0%. The accuracy achieved meets the criteria for satisfactory levels of precision and can be effectively utilized for subsequent analyses.

<table>
<thead>
<tr>
<th>Samples (N = 2000)</th>
<th>Landsat Image Classification</th>
<th>Sentinel-2 Image Classification</th>
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<td>User’s accuracy</td>
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3.2. Pre-EWTP Surface Water Area and NDVI Time Series

The surface water area decreased from 5.03 km² in 1987 to 0.26 km² in 2016 (Figure 2). Notably, there were anomalous increases in the surface water area in 2001 and 2003, with the peak occurring in 2003 at 35.58 km². This anomalous increase is associated with extreme increases in precipitation. Prior to the implementation of the EWTP, there was a decline in the NDVI value, plummeting from 0.181 to 0.066. Prior to implementing the EWTP, the river had almost dried up, and the vegetation on both sides of the river had severely degraded.

Figure 2. Surface water area and NDVI time series before the ecological water transfer project.
3.3. Changes in Water Area after the Implementation of the EWTP

3.3.1. Spatial Distribution of Water Frequency

Ecological water primarily follows the natural flow paths of river channels, leading to the distribution of surface water along these channels (Figure 3). The water surface produced by ecological water transport is mainly distributed in the range of 500 m of the river. There are two channels in the upper section of the river, and only one channel in the middle and lower sections. During periods of significant water inflow, excess water tends to naturally overflow at shallower sections of the river channel. This overflow results in sporadic water surfaces appearing outside the main riverbed, as illustrated at Locations 1, 2, and 5 in Figure 3. The termination point of water transport is situated at Position 6, where a maximum water surface area of 17.66 km$^2$ is formed. Over the period from 2017 to 2022, the total inundation area amounts to 81.48 km$^2$. Statistical analysis of water frequency from 2017 to 2022 reveals that the areas with a frequency of 1–30 times (Low-frequency intermittent water bodies) cover 64.98 km$^2$, areas with a frequency of 31–60 times (High-frequency intermittent water bodies) span 11.33 km$^2$, and areas with a frequency exceeding 60 times (permanent water body) encompass 5.17 km$^2$. Based on water frequency calculations, areas submerged in water for less than 75 days per year constitute 80% of the total submerged area.

![Figure 3. Surface water coverage frequency after ecological water transfer project (top row) and six regions (Rows 2–3) to show the details.](image)

3.3.2. Surface Water Time Series

The surface water area within the study area exhibits periodic fluctuations in response to the initiation and cessation of the EWTP (Figure 4). The initial introduction of ecological water downstream of the Kongque River occurred between October and November 2017, resulting in an expansion of the water area. More specifically, the total water area increased from 1.26 km$^2$ on 3 October to 27.08 km$^2$ on 22 November. In 2018, two water transfers took place during different periods. The first water transfer occurred from
May to June, resulting in a peak water area of 18.39 km². The second water transfer occurred in October, reaching a maximum water area of 20.95 km². Similarly, in 2019, two water transfers were conducted. The first water transfer occurred from May to June, resulting in a maximum water area of 25.10 km². The second water transfer spanned from October to December and led to a peak water area of 27.62 km². In 2020, the arrival of water extended from March to June, representing the longest duration and the largest water area in the 2017–2022 period. The peak water area during this period reached 47.38 km². The intensity of ecological water transfer decreased significantly after 2020, and the surface water area gradually decreased.

![Figure 4](image)

**Figure 4.** Time series of surface water area after the ecological water transfer project.

### 3.4. Changes in Vegetation after the EWTP

The NDVI of vegetation along the river exhibits an increasing trend. For instance, Locations 1, 2, 6, and 7 in Figure 5 demonstrate a consistent rise in vegetation dynamics, characterized by an average annual increase rate ranging from 0.01 to 0.02 year⁻¹. In regions outside the water transfer areas, the majority of these regions remain unaltered or exhibit a substantial decline, as indicated by Locations 3, 4, 5, and 8. The prolonged water scarcity in areas far from the water transfer zone is a primary cause of vegetation degradation. From 2017 to 2022, the NDVI increased from 0.065 to 0.093, and compared to 2017, the area with NDVI > 0.1 increased by 54.20 km² in 2022, representing a growth of 120.19%.

The NDVI change trend was categorized into five classes: significant increase for slope > 0 and p-value < 0.05, slight increase for slope > 0 and p-value < 0.1, essentially stable for p-value > 0.1, slight degradation for slope < 0 and p-value < 0.1, and significant degradation for slope < 0 and p-value < 0.05. The areas experiencing an increase in NDVI are closely associated with the spatial distribution of ecological water transfer areas (Figure A2). The area of significant increase is 24.05 km², while the area of slight increase is 53.21 km². The slight degradation area is 2.85 km², and the significant degradation area is 1.39 km².
Based on the spatial distribution characteristics of surface water over the past 30 years, the river can be divided into three segments: upper, middle, and lower (Figure 3). The statistical results of vegetation changes in each river section reveal that the upper section stands out as having the most significant vegetation recovery, accounting for 70% of the total recovery area. Meanwhile, the middle section has the smallest area, accounting for only 11% (Figure 6). In the lower section, a large water area forms at the endpoint of the water transfer, resulting in a relatively large area of vegetation recovery.

Figure 5. Spatial distribution of the NDVI trend after the ecological water transfer project (top row) and eight plots NDVI time series (Rows 2–5).
Vegetation changes at different distances from the Kongque River channel were analyzed in intervals of 10 m using a multi-ring buffer analysis (Figure 7). The results indicate that in the range of 0–50 m from the river, the area of vegetation recovery gradually increased with an increase in distance from the river, reaching its maximum at 40–50 m. Beyond 50 m, the area of recovery gradually decreased with greater distance from the river. When the distance exceeded 550 m, the curve representing the vegetation increase area started to flatten out and remained relatively stable (rate of change = 0). This suggests that there was limited or no significant recovery of vegetation at distances greater than 550 m from the river.

3.5. Response of the NDVI Trend to Irrigation Frequency

To assess the impact of inundation time on vegetation recovery, the correlation between irrigation frequency and trends in vegetation NDVI was analyzed (Figure 8). The rate of vegetation recovery experiences a rapid increase as the frequency of irrigation rises within the range of 1–6 times. Within this range, the recovery rate can reach up to five times the growth rate of vegetation in non-inundated areas. However, when the frequency exceeds six times, the growth rate decreases with the increasing frequency of irrigation. As the irrigation frequency reaches 60–65 times, the growth rate of vegetation decreases to a level similar to that in non-irrigated areas. When the irrigation frequency reaches 70
times, the growth rate of NDVI fluctuates between negative values and zero. Converting the frequency of irrigation to the number of days per year, the optimal duration of vegetation irrigation, in terms of achieving the highest rate of recovery, was found to be 18 days per year.

![Graph showing the relation between water irrigation frequency and NDVI change rate.](image)

**Figure 8.** Relation between water irrigation frequency and NDVI change rate.

### 4. Discussion

Between 1987 and 2016, there were only two years with water in the lower reaches of the Kongque River, 2001 and 2003. The restoration of water flow during these years was primarily attributed to a significant increase in water volume from Bosten Lake, the source of the Kongque River [61]. This increased water volume led to higher discharges into the Kongque River during those years. In the remaining years, the river experienced extended periods of interrupted water flow. The main reason is that the Kongque River basin is situated in an arid region, and water from Bosten Lake is extensively utilized for agricultural irrigation and urban water supply in the upper reaches of the Kongque River, leading to water scarcity downstream [34,35]. This scarcity was the primary driver behind the observed trend of vegetation degradation from 1987 to 2016. As precipitation is scarce in arid regions, rivers are an important source of water for sustaining vegetation. In previous studies, it has also been found that river disruption significantly contributes to vegetation degradation [19,20].

Following the implementation of the EWTP, remote sensing monitoring results demonstrated that the 347 km lower section of the river, previously experiencing dry conditions, now contains water. Water transfer successfully facilitated hydrological recovery in the lower Kongque River, enhancing connectivity between its upstream and downstream segments. This restoration of the natural flow regime is vital for maintaining the ecological integrity of the river system. Surface water created through water transfer is mainly distributed along the river channel, with occasional overflow. Given that vegetation primarily grows along the river channel, this is advantageous for the restoration of endangered riparian forests.

The surface water formed by the EWTP typically disappears within 1–2 months after the conclusion of the water transfer. Desert vegetation is generally unsuitable for prolonged irrigation. Desert plants have evolved to thrive in arid environments, with specialized features in their roots and leaves to withstand drought. Relevant studies showed that the soil in the Tarim Basin has a high salinity content, and an excess of water transfer accelerates the accumulation of sodium and chloride ions in the soil in the plant roots, resulting in the impaired function of the *Populus euphratica* root system and hindering its
growth [62,63]. Excessive and prolonged inundation can lead to oxygen deprivation and root rot, ultimately resulting in plant mortality. Moderate irrigation can provide plants with water and promote their growth. The findings of this study also indicate that when irrigation frequency exceeds 18 days per year, vegetation recovery levels do not increase but, in fact, decrease. In future implementation of the EWTP, water managers should develop a rational ecological water transfer plan based on the objectives of ecological restoration and the characteristics of the plant community’s response to irrigation. Ensuring the transfer of the minimum amount of ecological water needed to sustain vegetation growth is critical to the sustainability of vegetation restoration.

The areas experiencing vegetation recovery are concentrated within a 550 m range on both sides of the river channel, whereas regions farther from the river channel largely remain unchanged or show signs of degradation. This illustrates that plants in arid regions must adapt to the distribution of water resources for survival and reproduction [64]. To expand the scope of vegetation restoration in the lower reaches of the Kongque River, a potential strategy could involve excavating water channels on both sides of the riverbed to further increase the overflow area. In the middle reaches of the Tarim River, water is directed to vegetation areas further from the river channel through ecological canals. Consequently, substantial vegetation recovery has been observed within a 30 km buffer zone [65]. However, it is important to note that this approach necessitates a larger water supply to meet increased irrigation demands. Augmented water resources can stimulate the growth and expansion of riparian vegetation, creating crucial habitats for various aquatic and terrestrial species, and thereby enhancing the ecological environment [33].

In this paper, the remote sensing monitoring and assessment of ecological restoration of interrupted river flow primarily encompass two aspects: surface water monitoring and the derivation of ecological proxy factors. In arid regions, the occurrence of water is sporadic and challenging to predict, and detailed monitoring of spatiotemporal changes in surface water through remote sensing requires the use of temporally dense imagery with high spatial resolution [46]. In this study, Sentinel-2A/B imagery, with a temporal interval of 5 d and a spatial resolution of 10 m, is employed to monitor changes in surface water following the implementation of the EWTP. Given the predominantly sunny weather in drylands, it is feasible to achieve good monitoring results. With the launch of Landsat-9, combining Landsat-8, 9, and Sentinel-2A/B imagery can further enhance temporal resolution and provide a more detailed depiction of surface water changes [66]. However, addressing the challenge of scale transformation resulting from different spatial resolutions is necessary. NASA has already developed the Harmonized Landsat–Sentinel-2 product, which harmonizes resolution and spectral characteristics, facilitating future surface water monitoring using more densely time-series remote sensing imagery [67].

The inversion of ecological proxy factors plays a pivotal role in the ecological restoration of dried-up rivers. Ecological proxy factors serve as indicators that offer insights into the functional status of an ecosystem, encompassing aspects such as vegetation coverage and soil moisture content. These factors aid in assessing the overall health and functioning of the ecosystem and provide guidance for restoration efforts, ensuring effective ecological recovery [68,69]. In the context of the ecological restoration of dried-up rivers, the inversion of ecological proxy factors serves to evaluate the effectiveness of ecological restoration and inform subsequent restoration work [70]. In this study, the NDVI inverted from optical satellite data was mainly used to obtain the greenness and health status of vegetation. While compared to optical satellites, LiDAR data such as Global Ecosystem Dynamics Investigation (GEDI) and Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) offer the capability to measure the three-dimensional structure of vegetation, forests, and terrain on the Earth surface [71,72], providing information on tree height and biomass. The availability of such data can greatly enhance the precision of assessments of ecological recovery following EWTP implementation in dried-up river ecosystems. Therefore, in subsequent research, it is recommended to utilize multi-modal remote sensing imagery to
capture additional vegetation information and conduct a more comprehensive assessment of vegetation changes following EWTP.

5. Conclusions

The remote sensing monitoring of surface water and vegetation in the downstream area of the Kongque River, spanning from 1987 to 2022, highlighted the hazards of river drying. It also unveiled the vegetation’s response to the implementation of the EWTP. Our study’s findings underscore the critical role of rivers as virtually the sole water source for vegetation growth and reproduction in arid and semiarid regions. Furthermore, the allocation of water resources plays a pivotal role in shaping the spatial distribution of vegetation. Interruptions in river flow give rise to severe ecological challenges, including water scarcity, land degradation, and diminished vegetation coverage. The implementation of the EWTP proved to be an effective strategy for reinstating river flow, thereby making contributions to the rejuvenation of riparian vegetation and the enhancement of the overall ecological environment. Given the backdrop of global warming and population expansion, it is imperative for governments to fortify water resource management efforts. This requires a balance between local economic development and environmental protection to achieve sustainable development. This entails exploring the avenues for promoting equitable sharing of water resources between upstream and downstream regions. Additionally, remote sensing, as an effective means for long-term, large-scale environmental monitoring, can provide real-time and continuous monitoring and assessment of river ecosystems through multi-source satellite images, thereby enhancing the management and utilization of water resources in arid rivers. These findings provide a valuable reference for the future monitoring and restoration of river ecosystems and the management of water resources.

Author Contributions: Conceptualization, Z.W. (Zhen Wang) and L.F.; methodology, Z.W. (Zhen Wang) and J.S.; validation, Z.W. (Zhen Wang), J.S. and Z.W (Zhijun Wang); formal analysis, Z.W. (Zhen Wang) and J.S.; investigation, Z.W. (Zhen Wang), L.F. and Z.W (Zhijun Wang); resources, L.F.; data curation, Z.W. (Zhen Wang) and L.F.; writing—original draft preparation, Z.W. (Zhen Wang), L.F.; writing—review and editing, Z.W. (Zhen Wang), L.F. and J.S.; visualization, Z.W. (Zheng Wang) and Z.W (Zhijun Wang); supervision, L.F.; project administration, Z.W. (Zhen Wang); funding acquisition, L.F. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by State Scholarships for Doctoral Studies and Henan Polytechnic University Key Discipline Construction Project.

Data Availability Statement: The data presented in this study are available from the corresponding author upon reasonable request. The Landsat and Sentinel-2 data used in this paper can be obtained from the United States Geological Survey Earth Resources Observation and Science Archive—Landsat archive (https://earthexplorer.usgs.gov/, accessed on 24 October 2023), Copernicus Open Access Hub of the European Space Agency (ESA) (https://scihub.copernicus.eu/, accessed on 6 October 2023).

Acknowledgments: We thank the “United States Geological Survey, and European Space Agency” for providing data support. Technical support from the PlanetScope team is gratefully acknowledged.

Conflicts of Interest: The authors declare no conflicts of interest.
Appendix A

Figure A1. NDVI differences between Landsat 7 and Landsat 8, (a) histogram of the differences between Landsat 8 and Landsat 7 NDVI, (b) correlation between Landsat 8 and Landsat 7 NDVI.

Figure A2. Classification of NDVI trends after the implementation of the ecological water transfer project.
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