Study on Groundwater Recharge from Ecological Water Conveyance in the Lower Tarim River (Postprint)

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Abstract

Groundwater is crucial for sustaining arid desert ecosystems. The recharge amount to groundwater and its influence range from ecological water conveyance are essential elements for evaluating conveyance effectiveness and are vital for accurately understanding groundwater circulation characteristics. Based on groundwater monitoring data during ecological water conveyance in the lower reaches of the Tarim River from 2000-2020, water level profile equations before and after conveyance were fitted, and spatiotemporal variations in groundwater depth, groundwater recharge amounts, and the maximum influence range of groundwater during the conveyance period over the past 20 a in the lower Tarim River were estimated and analyzed using the water balance principle. The results show that: (1) After implementing ecological water conveyance in the lower Tarim River, groundwater levels exhibited a significant rising trend with spatiotemporal differences, rising by 3.01 m, 2.87 m, and 5.75 m at the Yingsu, Ka' erdayi, and Alagan cross-sections, respectively; the effect of water conveyance on groundwater level rise in the first 10 a was significantly smaller than in the latter 10 a; (2) The total groundwater recharge from water conveyance over the past 20 a in the lower Tarim River was 30.6\$×10^{8}\$ m^3 (accounting for 36.2% of the total conveyance volume), vadose zone recharge was 40.1\$×10^{8}\$ m^3 (47.5%), and the volume entering Lake Taitema was 11.7\$×10^{8}\$ m^3 (13.8%); (3) The proportion of groundwater recharge from water conveyance in the first 10 a (61.6%) was greater than that in the latter 10 a (25.2%) in the lower Tarim River, mainly attributed to the increased conveyance volume and the decreased saturation deficit of soil water content resulting from reduced groundwater depth; (4) The maximum influence range of groundwater during the conveyance period in the lower Tarim River showed considerable fluctuation, positively correlated with pre-conveyance groundwater depth and conveyance volume; in the recent 10 a, the unilateral influence range of groundwater during the conveyance period at the Yingsu, Ka' erdayi, Alagan,

and Yiganbujima cross-sections reached up to 1075 m, 2326 m, 1623 m, and 856 m, respectively.

Full Text

Groundwater Recharge from Ecological Water Conveyance in the Lower Reaches of the Tarim River

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Abstract

Groundwater is crucial for maintaining desert ecosystems in arid regions. The amount of groundwater recharge from ecological water conveyance and its influence range are essential elements for evaluating conveyance effectiveness and are vital for accurately understanding groundwater cycle characteristics. Based on groundwater monitoring data collected during ecological water conveyance to the lower reaches of the Tarim River from 2000 to 2020, this study fitted groundwater level profile equations before and after conveyance and applied water balance principles to estimate and analyze spatiotemporal variations in groundwater depth, groundwater recharge volumes, and the maximum influence range of conveyance on groundwater over the past 21 years. Results indicate: (1) Following ecological water conveyance, groundwater levels exhibited a clear rising trend with spatiotemporal heterogeneity, increasing by 3.01 m, 2.87 m, and 5.75 m at the Yingsu, Kaerdayi, and Alagan sections, respectively. The effect of water conveyance on groundwater level rise during the first 10 years was significantly smaller than during the last 10 years. (2) The total groundwater recharge volume in the lower Tarim River over 21 years was 30.6$×10^{8}$ m^{3} (36.2% of total conveyance volume), while vadose zone recharge and inflow to Taitema Lake were 40.1$×10^{8}$ m^{3} (47.5%) and 11.7$×10^{8}$ m^{3} (13.8%), respectively. (3) Groundwater recharge during the first 10 years of conveyance (61.6% of total conveyance) substantially exceeded that during the last 10 years (25.2%), primarily due to increased conveyance volumes and reduced soil moisture saturation deficits. (4) The maximum influence range of groundwater during conveyance showed considerable fluctuation, positively correlating with pre-conveyance groundwater depth and conveyance volume. Over the last 10 years, the 单侧 influence ranges at Yingsu, Kaerdayi, Alagan, and Yiganbujima sections reached 1075 m, 2326 m, 1623 m, and 856 m, respectively.

Keywords: groundwater level; groundwater recharge; ecological water conveyance; lower reaches of the Tarim River

The lower reaches of the Tarim River are located in the arid region of northwest China and experience a typical continental arid climate with annual precipitation around 30–40 mm and potential evaporation exceeding 2500 mm, creating an extremely fragile ecological environment. Groundwater serves as a critical water source sustaining regional desert ecological processes. Since the 1970s, population growth and expanding irrigated agriculture led to overexploitation of water and land resources, drastically reducing downstream inflow. Particularly after the construction of Daxihaizi Reservoir in 1972, the lower Tarim River channel dried up and groundwater levels declined continuously, severely threatening the ecological security of the "green corridor." To rescue and restore the 濒临毁灭的 downstream ecosystem, 21 emergency ecological water conveyances have been implemented since May 2000, with water reaching Taitema Lake 13 times, effectively raising groundwater levels.

The effectiveness of long-term ecological water conveyance in the lower Tarim River has attracted widespread attention from domestic and international circles. Numerous scholars have studied post-conveyance groundwater level changes, lateral influence ranges, groundwater recovery volumes, ecological environmental responses, and water conveyance scheduling strategies from various perspectives. For instance, some studies indicated that groundwater level rise was significant within 250 m of both riverbanks after conveyance but 不明显 within 450–750 m. Yang Pengnian et al. derived a mathematical formula for net groundwater recovery after conveyance and calculated the net recovery volume after the fifth conveyance with high credibility. Wan Jianghui et al. fitted relationship curves between groundwater depth and distance from the riverbank using 21 ecological conveyance events, analyzing groundwater recharge and lateral influence ranges. Additionally, Yang Pengnian et al. simulated groundwater response processes at the Yingsu section during 12 conveyance events using Processing Modflow software. However, due to different time limitations, conclusions have been inconsistent, necessitating further research on groundwater recharge and influence ranges from ecological water conveyance. This study uses groundwater monitoring data from 2000–2020 in the lower Tarim River to fit groundwater level profile equations before and after conveyance, combining water balance principles to analyze spatiotemporal variations in groundwater depth, estimate groundwater recharge volumes, and determine the maximum influence range, providing scientific basis and data support for improved water conveyance implementation.

1.1 Data

This study utilizes surface water and groundwater depth monitoring data from the Tarim River Basin Authority. Evaporation data were obtained from measured values at the Tieganglik meteorological station in the lower Tarim River using an evaporation pan. Surface water data include measured discharge volumes, durations, and flow paths for each ecological conveyance event at the Daxihaizi and Taitema Lake sections. Groundwater depth data comprise monthly measured values from monitoring wells at six sections (Yingsu, Kaerdayi, Laoyingsu, Bozikule, Alagan, and Yiganbujima) from 2000-2020.

To monitor the effects of ecological water conveyance on groundwater depth along the lower Tarim River, 18 groundwater monitoring sections were established along the conveyance channel. Considering data completeness and long-term continuity, this study selected four sections with relatively complete records for statistical analysis: Yingsu, Kaerdayi, Alagan, and Yiganbujima, located 117.8 km, 204.5 km, 300.5 km, and 392.0 km from Daxihaizi Reservoir (the discharge point), respectively [Figure 1: see original paper]. Among these, the Yingsu section has five monitoring wells, while the others have six each. All monitoring wells in the lower Tarim River now feature automatic groundwater depth monitoring and data transmission.

Based on the river system characteristics [Figure 1: see original paper], the main channel splits into eastern and western branches from Daxihaizi Reservoir to Alagan: the western branch is the old Tarim River and the eastern branch is the Qiwenkuoer River, converging at Alagan. Ecological water conveyance includes single-channel and dual-channel modes. Single-channel conveyance occurs when discharge from Daxihaizi Reservoir flows only through the Qiwenkuoer River, with monitoring sections including Yingsu, Kaerdayi, Alagan, and Yiganbujima. Dual-channel conveyance involves flow through both the Qiwenkuoer and old Tarim Rivers. In the old Tarim River section, groundwater levels at Laoyingsu and Bozikule showed almost no change during single-channel conveyance, so these sections were excluded from analysis.

1.2 Methods

1.2.1 Groundwater Recharge from Water Conveyance Assuming Q represents the recovered water volume per unit channel length on one side of the river channel and Q_0 represents the recovery volume directly beneath the riverbed, with symmetrical water level recovery curves on both sides [Figure 2: see original paper], the groundwater recharge volume per unit channel length (Q) is calculated as [11,18-19]:

$$Q \ = 2 \times Q + Q_0 = 1.36 \times (B + 2h) \times \quad \times \Delta h$$

where B is the average riverbed width (m), h is the average water depth during conveyance (m), is the soil water content saturation deficit, Δh is the difference between pre- and post-conveyance groundwater levels (m), and 1.36 is the soil dry bulk density ($g \cdot cm^{-3}$). The saturation deficit is calculated as the difference between soil saturated water content and average weight water content on both sides of the section before conveyance.

For a river reach between upstream and downstream sections with unit length recharge Q _{upper} and Q _{lower}, respectively, and channel distance L (km), the total groundwater recharge (W, 10^8 m^3) is [11]:

W = (Q _{upper} + Q _{lower})/2 × L

1.2.2 Maximum Unilateral Influence Range of Groundwater During Conveyance This study defines the maximum unilateral influence range (R, m) during conveyance as the x-coordinate where pre-conveyance and post-conveyance groundwater level curves intersect. The calculation formula is:

$R = \min\{x\ \ > 0 \mid f_1(x\ ) = f_2(x\ )\}$

where x is the positive root of equation (1), $f_1(x)$ is the pre-conveyance groundwater level profile on one side, and $f_2(x)$ is the post-conveyance profile.

1.2.3 River Surface Evaporation During Conveyance River surface evaporation during conveyance (E, 10^8 m^3) is calculated by:

$E = \ \ \times E_{20} \times B\_w \times L \times T$

where   is the water surface evaporation conversion coefficient (taken as 0.6), E_{20} is evaporation pan observations (mm), B_w is average river surface width (m), L is flow length (km), and T is total conveyance duration (months).

1.2.4 Vadose Zone Recharge Vadose zone recharge is calculated using water balance principles:

W_{vadose} = W_{total} - W_{groundwater} - W_{lake} - E

where W_{vadose} is vadose zone recharge (10^8 m^3), W_{total} is total inflow (10^8 m^3), W_{groundwater} is groundwater recharge (10^8 m^3), W_{lake} is inflow to Taitema Lake (10^8 m^3) from monitoring data, and E is river surface evaporation.

2 Results and Discussion

2.1 Spatiotemporal Variations of Groundwater Depth

2.1.1 Temporal Variations Groundwater depth near the riverbanks in the lower Tarim River showed significant spatiotemporal variation . Before 2000, the river channel dried up, and strong phreatic evaporation, scarce surface water, and water uptake by desert riparian forest roots caused groundwater depth to continuously increase within a certain range along the river. Since implementing ecological water conveyance in 2000, groundwater depth has shown a clear decreasing trend with spatiotemporal heterogeneity. From 2000-2020, groundwater depth decreased by 3.01 m, 2.87 m, and 5.75 m at Yingsu, Kaerdayi, and Alagan sections, respectively, while remaining below 10 m at Yiganbujima. By 2020, groundwater depth was less than 8 m at Yingsu and Alagan, and less than 10 m at Kaerdayi and Yiganbujima.

During inter-conveyance periods, groundwater depth near the riverbanks decreased significantly, with notable spatiotemporal differences. As shown in [Figure 3: see original paper], during 2000-2010 when total conveyance volume was approximately 26.3$×10^{8}$ m³, groundwater depth reductions during inter-conveyance periods were 3.11 m, 1.18 m, 2.00 m, and 2.72 m at Yingsu, Kaerdayi, Alagan, and Yiganbujima, respectively. During 2010–2020 with conveyance volume of about 61.7$×10^{8}$ m^3, the reductions were 2.00 m, 1.44 m, 1.11 m, and 1.69 m, respectively. This indicates that as conveyance continued, the response amplitude of groundwater depth gradually decreased, with a relatively larger proportion of conveyance water recharging the vadose zone and ultimately dissipating through soil evaporation and vegetation transpiration [16,21].

2.1.2 Spatial Variations [Figure 4: see original paper] shows groundwater depth changes at different distances from the river. Overall, the reduction in groundwater depth was significantly smaller at greater distances from the river, indicating that groundwater depth is closely related to conveyance volume and duration. Generally, areas closer to the river showed greater groundwater depth reduction. At Yingsu, the five monitoring wells showed small differences before conveyance but obvious differences afterward. Similar patterns occurred at Kaerdayi and Yiganbujima. At Alagan, however, the six monitoring wells showed minimal differences both before and after conveyance, likely due to local topography and hydrogeological conditions. All four sections exhibited clear spatial heterogeneity in groundwater depth reduction.

2.2 Groundwater Recharge

2.2.1 Groundwater Table Profile Equations Based on monitoring data before and after each conveyance event, we fitted relationship curves between groundwater level and distance from the river for each section in 2020 [Figure 5: see original paper]. Results show that post-conveyance groundwater level profiles follow quadratic polynomials with R^2 values exceeding 0.9, indicating good fit quality. For post-conveyance profiles, areas closer to the river have higher groundwater levels and steeper hydraulic gradients, while levels and gradients decrease with distance until the profiles intersect with pre-conveyance curves. Coefficients of the post-conveyance equations varied among sections and conveyance events, indicating that hydraulic gradients are closely related to conveyance volume, pre-conveyance water levels, and soil properties. The large groundwater depth in the lower Tarim River creates steep hydraulic gradients during conveyance, causing groundwater to flow laterally and downstream, resulting in faster and greater water level rise near the river and slower, smaller rises farther away. During inter-conveyance periods, lateral hydraulic gradients gradually decrease to zero, allowing continued groundwater flow and water level rise in certain areas.

2.2.2 Groundwater Recharge Volumes Using the fitted groundwater profile equations and formula (1), we estimated groundwater recharge for each river reach during each conveyance event from 2000–2020, then summed these to obtain total groundwater recharge for the entire lower Tarim River [Figure 6: see original paper]. Comparing our results with those of Deng Mingjiang et al. [13] shows good consistency, confirming the reliability of our estimates. Over 21 conveyance events, total groundwater recharge was 30.6\$×10^{8}\$ m^3, accounting for 36.2% of total conveyance volume. Groundwater recharge showed significant spatial variation [Figure 7: see original paper]. During the first 10 conveyances, the Qiwenkuoer River reach, old Tarim River reach, and Alagan-Taitema Lake section accounted for 52.8%, 12.0%, and 35.2% of total recharge, respectively. During the last 11 conveyances, these percentages were 71.3%, 11.6%, and 17.2%, respectively. Generally, the Qiwenkuoer River reach showed much higher recharge percentages than the old Tarim River reach, with percentages decreasing with distance from Daxihaizi Reservoir, primarily because ecological conveyance preferentially uses the Qiwenkuoer River, which is straighter and wider, while water consumption along the channel reduces infiltration [25].

2.2.3 Water Balance of Ecological Water Conveyance Based on conveyance data, the water balance for the lower Tarim River over 21 events shows that during the first 10 conveyances, water mainly dissipated through vadose zone and groundwater recharge (46-78% and 17-46%, respectively), with river surface evaporation and lake inflow accounting for small proportions (<5%). Conversely, during the last 11 conveyances, water mainly dissipated through vadose zone recharge (36-76%), with groundwater recharge percentages decreasing to 20-40%. Over 21 years, total conveyance was 84.45\$×10^{8}\$ m^3, with vadose zone recharge of 40.1\$×10^{8}\$ m^3 (47.5%), groundwater recharge of 30.6\$×10^{8}\$ m^3 (36.2%), river surface evaporation of 2.1\$×10^{8}\$ m^3 (2.5%), and Taitema Lake inflow of 11.7\$×10^{8}\$ m^3 (13.8%). In the thick vadose zone of the lower Tarim River with low soil moisture, recharged water mainly dissipates through soil evaporation and deep-rooted desert riparian forest transpiration. Recharged groundwater primarily raises water levels near the riverbank, with groundwater at Yingsu rising 5.75 m 300 m from the river. However, as conveyance continues, rising groundwater levels reduce soil moisture saturation deficits, decreasing groundwater recharge proportions and slowing water level rise rates [16,21].

2.3 Maximum Unilateral Influence Range of Groundwater During Conveyance

Using the fitted groundwater profile equations and formula (1), we calculated the maximum unilateral influence range for each section during each conveyance from 2010-2020 [Figure 8: see original paper]. Results show significant spatiotemporal variation in influence range, which initially increased substantially then stabilized dynamically with continued conveyance. The influence range is closely related to conveyance volume—smaller or zero conveyance volumes correspond to smaller influence ranges, while subsequent periods show noticeable increases. Specifically, from 2010-2020, the maximum influence ranges at Yingsu, Kaerdayi, Alagan, and Yiganbujima were approximately 460-856 m, 207-2326 m, 392-1623 m, and 500-1075 m, respectively, peaking in 2017. The influence range results from multiple factors including conveyance volume and duration, timing, cumulative volume, groundwater depth, topography, soil texture and moisture, and evaporation intensity. Pre-conveyance groundwater depth and conveyance volume are the dominant factors, both positively correlated with maximum influence range. Generally, smaller pre-conveyance depths and conveyance volumes produce smaller influence ranges, likely due to groundwater table confinement, hydraulic gradient magnitude, and phreatic evaporation conditions [16,19].

3 Conclusions

Using groundwater monitoring data from 2000-2020 in the lower Tarim River, this study fitted groundwater level profile equations before and after conveyance, combined with water balance principles to estimate and analyze spatiotemporal variations in groundwater depth, groundwater recharge, and maximum influence range following ecological water conveyance. Main conclusions are:

(1) Groundwater depth decreased significantly after ecological water conveyance with spatiotemporal heterogeneity. From 2000-2020, groundwater depth decreased by 3.01 m, 2.87 m, and 5.75 m at Yingsu, Kaerdayi, and Alagan sections, respectively. The effect on groundwater level rise was smaller in the first 10 years than the last 10 years due to increased conveyance intensity.

(2) Groundwater recharge from 21 conveyance events totaled 30.6×10^{8} m^3 (36.2% of total conveyance), with vadose zone recharge of 40.1×10^{8} m^3 (47.5%) and Taitema Lake inflow of 11.7×10^{8} m^3 (13.8%). Groundwater recharge during the first 10 years (61.6% of conveyance) exceeded that during the last 10 years (25.2%), primarily because increased conveyance reduced soil moisture saturation deficits.

(3) Fitted groundwater profile equations for each section before and after conveyance showed R^2 values exceeding 0.9, confirming high reliability. The maximum unilateral influence range during conveyance fluctuated considerably, positively correlating with pre-conveyance groundwater depth and conveyance volume. Over the last 10 years, maximum influence ranges at Yingsu, Kaerdayi, Alagan, and Yiganbujima reached 1075 m, 2326 m, 1623 m, and 856 m, respectively.

These results demonstrate that after multiple consecutive conveyances, the incremental increases in groundwater level rise, recharge volume, and influence range gradually decrease, suggesting that ecological effects of later conveyances may have substantial room for improvement. Therefore, future ecological water scheduling should, while ensuring ecological baseflow during conveyance periods, determine conveyance volume based on hydrological effects from previous events to optimize water use efficiency.

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