Postprint: Estimation of Groundwater Depth in River Cross-sections under Long-term Water Conveyance Conditions in the Lower Tarim River

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Abstract

Accurately estimating the dynamic variations of riparian groundwater depth under water conveyance conditions enables quantification of the response relationship between ecological water delivery volume and groundwater depth, thereby facilitating estimation of the required water delivery volume and duration for natural river channels. This holds significant scientific importance for sustainable water resources management in arid regions. Based on 20 years of ecological water delivery monitoring data from the lower Tarim River, a developed quasi-two-dimensional groundwater model incorporating both groundwater and soil water was employed to conduct a 20-year long-term simulation of groundwater depth variations at three cross-sections (Yingsu, Alagan, and Yiganbujima) located in the upper, middle, and lower segments of the lower Tarim River under water delivery conditions. Through comparison of simulated groundwater depth results with observational site data during the calibration period and the subsequent 11 years (2010–2020), strong consistency was observed, demonstrating the rationality and applicability of the model for long-term groundwater simulation at riparian cross-sections in the lower Tarim River. Subsequently, based on the 20-year simulation results from the three cross-sections, the long-term variations in groundwater depth and soil moisture under water delivery conditions and their response to ecological water delivery were analyzed. The results indicate that after 20 years of ecological water delivery, both groundwater level and soil moisture at the three cross-sections of Yingsu, Alagan, and Yiganbujima increased significantly, with groundwater depth rising from approximately 8 m before water delivery to about 4 m after delivery, and soil moisture increasing from an initial value of 0.20 to above 0.35. Particularly since 2009, increases in groundwater level and soil moisture have become notably pronounced with increasing annual water delivery volume. The interannual variation between ecological water delivery and groundwater exhibits a certain time lag, and due to the positive correlation between soil moisture and groundwater level, soil moisture also demonstrates a lagged response to water delivery volume. Compared with river discharge, the value of horizontal hydraulic conductivity plays a more critical role in governing cross-sectional groundwater depth variations. Furthermore, the interannual relationship between water delivery volume and groundwater suggests that to achieve sustained ecological benefits in the riparian zones of the lower Tarim River, intermittent ecological water delivery to the river channel is necessary.

Full Text

Estimation of Riparian Groundwater Table Depth in the Lower Reaches of Tarim River Under Long-Term Water Conveyance

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Abstract

Accurate estimation of groundwater table dynamics under water conveyance conditions is crucial for quantifying the response relationship between ecological water conveyance and groundwater depth, thereby determining the required water volume and duration for natural river channels. This is of significant scientific importance for sustainable water resources management in arid regions. Combining ecological water conveyance monitoring data from the lower reaches of Tarim River with a developed quasi-two-dimensional groundwater model that incorporates both groundwater and soil water dynamics, this study simulated groundwater depth variations at three sections (Yingsu, Alagan, and Yiganbujima) along the lower Tarim River from 2001 to 2020. Model calibration and validation results show good agreement with observed data, demonstrating the model' s rationality and applicability for long-term simulation of riparian groundwater at cross-sections in the lower Tarim River. Based on the 20-year simulation results, we analyzed the long-term changes in groundwater depth and soil moisture and their response to ecological water conveyance. The results indicate that after 20 years of water conveyance, both groundwater levels and soil moisture increased significantly at all three sections, with groundwater depth rising from approximately 8 m before conveyance to about 4 m. The increasing trend became more pronounced with higher annual water volumes, particularly since 2009. Inter-annual variations show a lagged response between groundwater and water conveyance volumes. Soil moisture exhibits a positive correlation with groundwater depth, resulting in similar lag characteristics. Compared with river discharge, the horizontal hydraulic conductivity parameter plays a more critical role in controlling groundwater depth variations at the cross-sections. Furthermore, the inter-annual relationship between water conveyance and groundwater suggests that intermittent ecological water conveyance is necessary to maintain sustained ecological benefits in the lower Tarim River.

Keywords: quasi-two-dimensional groundwater model; ecological water conveyance; long-term groundwater simulation; lower reaches of Tarim River

1 Study Area, Data, and Methods

1.1 Study Area Overview

The study area encompasses the river channel from Daxihaizi Reservoir to Taitema Lake in the lower reaches of Tarim River, spanning 321 km (Fig. 1). Located in the alluvial plain of the Tarim Basin, the region is bounded by the Kuruktag Desert to the east and the Taklamakan Desert to the west, with elevations ranging from 801.50 to 846.24 m. The area receives only 17.4–42.0 mm of annual precipitation but experiences potential evaporation of 2500–3000 mm, representing a typical continental arid climate with extremely fragile ecological conditions. Despite the harsh environment, extensive desert riparian forests thrive along the riverbanks, sustained by river water and groundwater, preventing the convergence of the two deserts and holding significant ecological and strategic importance.

Geologically, the area lies within the weak Rob Depression with stable tectonics. Frequent channel migrations during geological history deposited a Quaternary loose sediment layer approximately 350 m thick, dominated by clayey fluvial-lacustrine deposits. The terrain is flat, gently sloping eastward at about 1‰. Soils along the riverbanks are primarily coarse silt, very fine sand, and fine sand due to wind-blown sand influences, creating strong interactions between groundwater and soil water. Vegetation is distributed in bands along the river, transitioning from high-coverage Populus euphratica forests and Tamarix shrublands with halophytic grass belts in the upper reaches to medium- and low-coverage forests and sparse shrublands downstream.

Since the 1970s, unsustainable water resource utilization for agriculture and artificial oases has caused severe water allocation imbalances between tributaries and the main stream, leading to channel drying downstream of Daxihaizi Reservoir, declining groundwater tables, large-scale vegetation die-off, accelerated soil desertification, and serious ecological degradation. To restore the ecological environment, the Ministry of Water Resources, the Xinjiang Uygur Autonomous Region People' s Government, and the Xinjiang Production and Construction

Corps initiated intermittent ecological water conveyance to the lower reaches starting in 2000. By 2020, 20 water conveyance events had delivered a cumulative volume of 84.4$×10^{8}$ m^3, effectively restoring regional ecological vegetation.

1.2 Data Sources and Preprocessing

River discharge data for the lower Tarim River were obtained from the Tarim River Basin Administration. Cross-section river flow and groundwater depth data were provided by the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. Due to data availability limitations, we collected partial channel flow and groundwater data for the first 13 years (2001-2013) of water conveyance, including data from 2 monitoring wells at Yingsu section, 4 wells at Alagan section, and 4 wells at Yiganbujima section.

Ground surface elevation data were interpolated from monitoring well elevations to calculate the vertical distance from the surface to the groundwater table for vertical soil water transport boundary equations. Soil parameters were determined through literature review and reference tables. Geological surveys indicate that soils in the lower Tarim River are primarily sandy loam and sand, with saturated water content of 0.45-0.50 m^3/m^3. Based on the study area' s coordinates, we consulted a global soil classification table identifying the soil type as sandy loam with: saturated soil water content ( ) = 0.48 m^3/m^3, saturated matric potential ( ) = -0.20 m, vertical saturated hydraulic conductivity (K) = 0.54432 m/d, and soil texture parameter (b) = 4.32. These parameters are consistent with literature values and were applied uniformly across all sections.

1.3 Methods

1.3.1 Quasi-Two-Dimensional Groundwater Model This study employs the quasi-two-dimensional groundwater model developed by Di et al. [11], which simplifies the fully two-dimensional soil water-groundwater interaction problem into a coupled system of horizontally-dominated groundwater flow and vertically-dominated soil water flow equations. The model comprises:

Groundwater flow equation:

$$t = \frac{\partial}{\partial x}\left(K_{sh}\frac{\partial h}{\partial x}\right) + q_z$$

Soil water flow equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial q_z}{\partial z}$$

where: - n_e is specific yield - K_{sh} is horizontal hydraulic conductivity of groundwater - $h(x, t)$ is groundwater elevation at distance x from the riverbank at time t - q_z is vertical exchange flux between groundwater and overlying soil water at the phreatic surface - θ is soil water content - q_z is calculated using the

Richards equation with unsaturated hydraulic conductivity and diffusivity following the Clapp-Hornberger relationship based on saturated soil water content (θ_s), saturated matric potential (ψ_s), and soil texture parameter (b)

The model uses an implicit difference scheme with numerical solution via the 追赶法 (Thomas algorithm). Specific details are provided in Di et al. [11]. This physics-based model requires only initial groundwater depth and daily river flow as boundary conditions to conduct long-term simulations.

1.3.2 SCE-UA Parameter Calibration Method The SCE-UA (Shuffled Complex Evolution-University of Arizona) algorithm [28] is a global parameter optimization method combining genetic algorithms and the simplex method. It requires no direct derivative calculation and efficiently finds global optimal solutions, making it widely used in hydrological model calibration. Following Di et al. [11], we optimized the horizontal hydraulic conductivity (K_{sh}) parameter while assuming constant vertical saturated hydraulic conductivity (K_v) consistent with tabulated values.

1.3.3 Simulation Experiment Setup The left boundary of the groundwater equation is the river channel with time-varying river water levels. The right boundary is set as a zero-flux constant-head boundary representing an equipotential seepage surface. The upper boundary of the soil water equation is the land surface with multi-year average surface flux (precipitation minus evaporation minus runoff) set at -178.5 mm/a. The lower boundary uses fixed saturated soil water content (0.48 m^3/m^3).

The initial groundwater depth for simulation day 1 used observed values, with subsequent depths simulated by the model. Initial soil water values were unavailable, so we assumed uniform soil water content from the phreatic surface to the land surface. Simulation periods varied by section: Yingsu (April 1, 2001-December 31, 2020), Alagan (April 1, 2002-December 31, 2020), and Yiganbujima (April 1, 2003-December 31, 2020). The first water conveyance event with monitoring data served as the calibration period for each section (Yingsu: 2001-2005, Alagan: 2002-2006, Yiganbujima: 2003-2007), with subsequent years as unconstrained simulation periods. The last 10 years (2011-2020) served as validation periods. Simulations covered a 1000 m transect perpendicular to the riverbank at each section with 20 m spatial resolution and 0.5 h time steps.

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2 Results

2.1 Parameter Calibration of the Quasi-Two-Dimensional Groundwater Model

Using SCE-UA optimization with observed groundwater depth data, we calibrated the K_{sh} parameter for each section. Figure 2 compares simulated and observed groundwater elevations during calibration periods for 2 wells at Yingsu (G1-G2), 4 wells at Alagan (G3-G6), and 4 wells at Yiganbujima (H2-H5). After calibration, simulated groundwater elevations closely match observations, with mean absolute errors (MAE) of 0.194 m, 0.214 m, and 0.189 m for Yingsu, Alagan, and Yiganbujima, respectively. Simulated groundwater levels decrease with distance from the riverbank, consistent with observations. These results demonstrate that the quasi-two-dimensional groundwater model reasonably simulates riparian groundwater variation under ecological water conveyance in the lower Tarim River, providing a suitable platform for long-term simulation.

2.2 Long-Term Simulation of Cross-Section Groundwater Depth

Using the optimal K_{sh} parameters and 20-year water conveyance data from Daxihaizi Reservoir, we conducted long-term simulations of groundwater depth at the three sections. Figure 3 compares simulated and observed mean annual groundwater depths within 1000 m of the riverbank from 2011 to 2020. Simulated values represent annual averages across the entire 1000 m transect, while observations are from monitoring wells at 150 m, 300 m, 500 m, 750 m, and 1050 m. The mean simulation errors are 0.484 m for Yingsu, 0.575 m for Alagan, and 0.595 m for Yiganbujima. Although these errors appear relatively high, they are acceptable given that daily river flows were interpolated from annual totals. Correlation coefficients between simulated and observed values are high: 0.85 for Yingsu, 0.83 for Alagan, and 0.81 for Yiganbujima, confirming the model' s reliability.

Figure 4 shows the simulated mean annual groundwater depth variations over the 20-year period. Groundwater depth decreased (water table rose) consistently across all sections, demonstrating the positive impact of ecological water conveyance. Specifically, average groundwater depth increased from approximately 8 m before conveyance to about 4 m after 20 years of water delivery. The rising trend accelerated significantly after 2009 with increased annual water volumes. Notably, while Alagan (middle section) received higher flows than Yiganbujima (lower section), Yiganbujima' s groundwater table is higher due to its greater horizontal hydraulic conductivity (0.171 m/d vs. 0.079 m/d), which enhances lateral infiltration and accelerates groundwater rise.

The relationship between water conveyance volume and groundwater depth exhibits clear lag effects (Figure 5). Years with maximum groundwater depth decline (e.g., 2005, 2010, 2015) occurred 1-2 years after minimum water conveyance years, while minimum groundwater depths followed peak conveyance years by 1-2 years. This lagged response, confirmed by previous monitoring studies [5, 7, 8], indicates that groundwater recharge requires time to propagate through the aquifer.

Analysis of individual monitoring wells (Figure 6) reveals that wells closer to the river (e.g., at 150 m) consistently show shallower groundwater depths and greater rise amplitudes than distant wells (e.g., at 1050 m). Water level differences between wells decreased over the conveyance period, indicating that sustained ecological water delivery has raised groundwater levels across the entire riparian zone.

2.3 Long-Term Simulation of Cross-Section Soil Moisture

Ecological water conveyance aims not only to raise groundwater tables but also to increase unsaturated soil moisture to support riparian vegetation and ameliorate soil salinization. For consistency, we analyzed simulated mean soil moisture within 2 m depth across the 1000 m transect (Figure 7). Soil moisture increased progressively over the 20-year period, rising from initial values of approximately 0.20 to over 0.35. Yingsu (upper section) and Yiganbujima (lower section) show the highest soil moisture (mean 0.36), followed by Alagan (middle section, mean 0.33). Yingsu exhibits the greatest temporal variability, while the other two sections show steadier increases.

Soil moisture correlates strongly with groundwater depth (Figure 8), with correlation coefficients of 0.88 for Yingsu, 0.85 for Alagan, and 0.87 for Yiganbujima over the 20-year period. Since vertical saturated hydraulic conductivity is uniform across sections, soil moisture variation is primarily driven by groundwater table rise. Similar to groundwater, soil moisture shows lagged responses to water conveyance: soil moisture continued increasing for 2–3 years after the peak conveyance year (2017) and reached local minima 1–2 years after minimum conveyance years (2006, 2012, 2016).

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3 Conclusions

This study applied a quasi-two-dimensional groundwater model incorporating soil water-groundwater interaction to simulate 20 years (2001–2020) of groundwater depth and soil moisture variation at three sections (Yingsu, Alagan, and Yiganbujima) in the lower Tarim River under ecological water conveyance conditions. The main conclusions are:

1) **Model Calibration and Applicability**: Using observed groundwater data, we calibrated the horizontal hydraulic conductivity parameter for each section. Calibration periods were selected based on data availability: the first five water conveyance events for Yingsu and Alagan, and the first four events for Yiganbujima. Mean absolute errors were 0.194 m, 0.214 m, and 0.189 m, respectively. Simulated groundwater levels decreased with distance from the river, confirming the model’ s ability to capture spatial patterns. Validation against 2011–2020 data yielded mean errors of approximately 0.5 m, which is acceptable given uncertainties in daily river flow data. High correlation coefficients (0.81–0.85) demonstrate the model’ s suitability for long-term simulation in this region.

2) **Groundwater Response to Water Conveyance**: The 20-year simulation reveals significant groundwater table rise across all sections, from approximately 8 m depth before conveyance to about 4 m. The rising trend intensified after 2009 with increased water volumes. Horizontal hydraulic conductivity is more influential than river discharge in controlling groundwater variation: Yiganbujima’ s conductivity (0.171 m/d) is more than double Alagan’ s (0.079 m/d), resulting in higher groundwater levels despite lower river flows. Groundwater response lags 1-2 years behind water conveyance volumes, and wells nearer the river show greater rise amplitudes than distant wells. These findings confirm the model’ s ability to simulate both temporal dynamics and spatial patterns.

3) **Soil Moisture Response**: Soil moisture within 2 m depth increased from approximately 0.20 to over 0.35 across all sections, with Yingsu and Yiganbujima showing the greatest increases (about 0.16). Soil moisture correlates strongly with groundwater depth ($r > 0.85$) and exhibits similar lag effects relative to water conveyance. Since vertical hydraulic conductivity is uniform, soil moisture increases are primarily driven by groundwater table rise, which is crucial for vegetation restoration.

4) **Management Implications**: The positive correlation and lagged response between water conveyance and groundwater/soil moisture indicate that intermittent ecological water conveyance is essential for sustained ecological benefits in the lower Tarim River. Continuous water delivery is not necessary; strategic timing of conveyance events can maintain groundwater levels and soil moisture for vegetation health while optimizing water use efficiency.

Future research should incorporate additional physical processes such as vegetation photosynthesis, soil freeze-thaw cycles, and dynamic vegetation changes to improve model accuracy. Integrating multiple data sources—including measured river levels, precipitation, actual evapotranspiration, additional monitoring wells, and soil moisture measurements—will enable more robust calibration and validation. Ultimately, scenario-based water conveyance strategies can be designed to meet ecological water requirements with minimal water use, providing critical guidance for ecological water resources management in arid regions.

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