Postprint: Water Consumption Characteristics and Evolution of Water Conveyance Methods in the Lower Reaches of the Tarim River

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Abstract

Employing a combination of the water balance method, field investigation, and remote sensing imagery data, this study expounds upon the evolution of riverbed permeability performance and the water environment response characteristics under varying river channel water delivery methods following ecological water conveyance; it analyzes the water consumption rate and riverbed permeability patterns in the lower reaches of the Tarim River post-conveyance, as well as the MNDWI variation characteristics under near-natural overflow conditions behind ecological sluices. The results demonstrate that: (1) the surge irrigation effect in continuously watered river channels intensifies, reducing groundwater recharge; (2) the randomized water delivery behind ecological sluices, exemplified by Kumutage, lacks rational regulation, resulting in the formation of perennial flow reaches, which leads to excessively high groundwater levels in certain areas and increased phreatic evaporation; (3) the branch channel overflow under near-natural conditions, represented by Bozekule, plays a significant role in regulating groundwater levels and promoting vegetation restoration in the region; however, with the solidification of water conveyance branch channels and the formation of water accumulation surfaces, a landscape evolution from arid-region vegetation to wetland vegetation dominated by reeds has emerged, causing increased water surface evaporation; (4) both unregulated ecological sluices and near-natural water delivery methods have generated certain areas of water bodies and wetland vegetation. For the Tarim River Basin situated in an arid region, adhering to the principles of river ethics, regulated water delivery through artificial intervention should be implemented, employing a water delivery approach that combines rotational seepage of branch rivers with overflow. This approach not only enhances the utilization efficiency of released water volumes and further expands ecological restoration areas, but also enables the regulation of water dissipation across different restoration target zones, thereby maximizing vegetation restoration area.

Full Text

Study on Water Consumption Characteristics and Evolution of Water Delivery Methods in the Lower Reaches of the Tarim River

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Abstract

This study employs a combination of water balance methods, field investigations, and remote sensing imagery data to elucidate how changes in river channel water delivery patterns after ecological water transfer affect the evolution of riverbed permeability and water environment response characteristics under different delivery modes. We analyzed the water consumption rate and riverbed permeability patterns in the lower Tarim River following water transfer, and revealed Modified Normalized Difference Water Index (MNDWI) variation characteristics under near-natural overflow conditions behind ecological gates. The results indicate: (1) Continuous water delivery reduces the water consumption rate per unit river length and decreases groundwater recharge; (2) Randomized water delivery behind ecological gates, exemplified by the Kumtuge Gate, lacks proper regulation, creating perennial flow sections that cause excessively high groundwater levels and increased phreatic evaporation in some areas; (3) Ditch overflow under near-natural conditions, represented by the Bozkule area, plays a crucial role in raising groundwater levels and vegetation recovery, yet as delivery channels become consolidated and water surfaces form, vegetation transitions from arid-zone species to wetland species dominated by reeds, leading to increased water surface evaporation; (4) Both unregulated ecological gates and near-natural water delivery methods generate considerable areas of water bodies and wetland vegetation. For the arid Tarim River Basin, water delivery should follow river ethics principles through artificially intervened and regulated conveyance, adopting a combination of distributary rotation infiltration and overflow. This approach not only improves utilization efficiency of discharged water and expands ecological restoration areas, but also enables regulation of water dissipation in different restoration target zones to maximize vegetation recovery area.

Keywords: distributary water delivery; vegetation water consumption; ecological gate regulation; lower reaches of the Tarim River

Introduction

The Tarim River system provides irreplaceable ecological services, sustaining water resource security for both natural and artificial ecosystems throughout the Tarim Basin. Influenced by human activities, the lower Tarim River (hereinafter referred to as "the lower Tarim") experienced nearly 30 years of flow interruption by 2000, resulting in severe ecological degradation, massive die-off of poplar forests and shrublands, and intensified desertification. To salvage the downstream ecological environment, the State Council approved the "Tarim River Basin Comprehensive Management Project" in 2001, aiming to restore natural vegetation by raising groundwater levels through ecological water conveyance. By October 2020, 21 consecutive water deliveries had been implemented in the lower Tarim, with cumulative water discharge reaching 84.45×10^{8} m^3 and average annual discharge of 4.22×10^{8} m^3, exceeding the expected target of 3.50×10^{8} m^3. This has revitalized the terminal lake environment and generated significant environmental and social benefits.

Ecological water delivery in the lower Tarim has been characterized by substantial interannual variability in discharge volume due to fluctuations in upstream runoff and the implementation of water-saving agriculture and drip irrigation, creating distinct hydrological regimes and ecological responses. Previous studies have analyzed ecological effects and values of water delivery. Deng et al. examined vegetation responses to changing water delivery patterns. Wang et al. investigated land use/cover changes using time-series methods, finding major changes in flood overflow zones along riverbanks. Zou et al. analyzed increasing trends in permanent surface water bodies, showing that downstream discharge directly affects seasonal and permanent water areas. While many scholars have studied restoration effects, ecological risks, and water delivery strategies, research on delivery efficiency, overflow control, and ecological regulation under different water delivery modes requires further deepening. This study integrates downstream ecological water delivery data with Landsat imagery to analyze water body dynamics and overflow distribution using MNDWI, clarifying ecological environment changes and evolution patterns under ecological gate control versus near-natural overflow, providing a foundation for benefit evaluation and scientific management of future ecological water delivery.

Study Area Overview

The study area is located in the lower reaches of the Tarim River, with elevations ranging from 801.5 to 846.2 m, stretching from Daxihaizi Reservoir to Alagan. Below Daxihaizi, the river splits into two branches: the southern Old Tarim River (hereinafter "Old Tarim") and the northern Qiwenkuoer River (hereinafter "Qiwenkuoer"), which run roughly parallel and converge at Alagan, forming a connected network of channels and floodplains.

Situated between the Taklamakan and Kumtag deserts, the area receives scarce precipitation (17.0–42.0 mm annually) while experiencing extremely high evaporation (2500–3000 mm), representing a typical temperate continental warm temperate desert arid climate—the driest region in China. The lower Tarim lies on alluvial fine-soil plains composed primarily of fluvial-lacustrine fine sand, silt, and aeolian soils. The hydrogeological structure is simple, with aquifers that can be divided into phreatic and interlayer unconfined aquifers based on burial conditions. The upper phreatic groundwater is closely connected with the river, exhibiting mutual recharge relationships, while hydraulic connection with the lower interlayer water is weak due to underlying silt aquitards. The Qiwenkuoer riverbed consists mainly of fine particles brought by historical Kongque River flow, with strata dominated by silt interbedded with thin silt sand layers, forming a relatively stable channel. The Old Tarim, located southward along the Taklamakan Desert margin, has a bed composed of aeolian soils and alluvium that is easily eroded and prone to channel migration.

Data Sources

Hydrological and Groundwater Monitoring Data Hydrological cross-section flow data and groundwater depth data were provided by the Tarim River Basin Management Bureau (Table 1), including: (1) ecological water delivery volumes from 2000–2020; (2) monthly groundwater depth data from Daxihaizi, Yingsu, and Alagan (2000–2020); (3) surface water monitoring data at Yingsu, Ka' erdayi, Bozkule, and Yiganbujima cross-sections; and (4) Taitema Lake water level data.

Remote Sensing Imagery Landsat TM/ETM+/OLI imagery from 2000–2020 was obtained from the USGS Global Visualization Viewer (http://glovis.usgs.gov). A total of 78 scenes covering the study area were processed using ENVI 5.3 software, including radiometric calibration and atmospheric correction. Landsat 7 ETM+ imagery striping was removed using appropriate algorithms. The imagery was used to interpret water body spatial distribution under ecological gate delivery in the Qiwenkuoer River and natural overflow in the Old Tarim, providing theoretical foundations for ecosystem protection and management.

Methods

Water Consumption Rate and Flow Loss Rate Analysis River water loss occurs through evaporation and seepage that replenishes soil moisture and groundwater. Along-channel flow loss represents the river' s water consumption process, influenced by discharge, channel geometry, bed soil lithology, and riparian vegetation conditions. Based on monitoring data and water balance principles, we defined the unit river length water consumption rate indicator and analyzed water consumption characteristics and riverbed permeability evolution patterns under different delivery modes.

The water balance relationship is expressed as:

$$W_{up} - W_{down} = W_{con} + S_{in}$$

where W_{up} is inflow at the upper section, W_{down} is outflow at the lower section, W_{con} is water consumption between sections, and S_{in} is interval inflow.

The interval water consumption rate (k) and unit river length consumption rate (η) are calculated as:

$$k = \frac{W_{con}}{W_{up}} \times 100\%$$

$$\eta = \frac{W_{con}}{L}$$

where L is the river length between sections. Setting W as cross-section flow yields the unit river length flow loss rate (δ).

Surface Water Extraction For water body extraction from remote sensing imagery, we employed the Modified Normalized Difference Water Index (MNDWI), which leverages spectral differences between water and other features across bands to reduce classification errors:

$$\text{MNDWI} = \frac{\rho_{Green} - \rho_{SWIR}}{\rho_{Green} + \rho_{SWIR}}$$

where ρ_{Green} is the green band (0.52–0.60 m) and ρ_{SWIR} is the shortwave infrared band (1.55–1.75 m). Pixel values >0 indicate water bodies. Extracted water areas were statistically analyzed with water delivery data and groundwater depth data using Pearson correlation analysis.

Results and Analysis

Ecological Water Delivery History Downstream ecological water delivery can be divided into two phases based on upstream inflow conditions. The first phase (2000–2007) was emergency water delivery, utilizing abundant water from the Kaidu River and elevated Bosten Lake levels to implement ecological emergency conveyance through the Kongque River, unblocking both the Qiwenkuoer and Old Tarim channels, with flow eventually reaching Taitema Lake. The second phase (2008–2020) featured normalized water delivery. As the Kaidu River entered normal and dry years with declining Bosten Lake levels, water transfer decreased. From 2010 onward, abundant upstream flow increased downstream deliveries, establishing normalized conveyance primarily through the main channel.

The lower Tarim has evolved into a regularized delivery system combining dual-channel, distributary, and sheet flow methods. Ecological gates serve as water allocation pathways to deliver water to off-channel ecological zones, maintaining natural vegetation growth, expanding restoration range, and improving water use efficiency. Sheet flow occurs when discharge exceeds channel capacity, spreading water along banks, or through distributaries that convey water to low-lying areas, expanding influence zones.

Riverbed Permeability Evolution Analysis of interval water consumption rates (k) and unit river length consumption rates (η) for the first 20 deliveries reveals: (1) Along-channel distribution shows that k generally increases downstream, with decreasing flow frequency and magnitude, leading to greater water dissipation; (2) Across successive deliveries, η shows a decreasing trend in all reaches, indicating gradual recovery of riparian soil moisture and groundwater and stabilization of water loss rates; (3) Under linear flow conditions without diversion, groundwater quickly reaches a perched seepage state, causing rapid η decay. Continuous delivery reduces unit river length consumption rates and slows groundwater recharge. The combination of ecological gates and distributaries thus becomes a rational choice.

Under intermittent delivery, river infiltration resembles surge irrigation—a thin, dense silt layer forms on the bed surface that, despite being <1 cm thick, significantly reduces infiltration while increasing water front velocity. This explains why flow arrival time at Taitema Lake has gradually shortened. By 2020, the lower Tarim had undergone 21 ecological deliveries totaling 84.45$×10^{8}$ m^3, with the Tarim mainstream accounting for 84.2% and Bosten Lake for 15.8%.

Controlled Water Delivery Behind Ecological Gates The Qiwenkuoer River has seven ecological gates that form overflow zones to recharge groundwater. However, when reservoir discharge falls below 30 m^3/s, gates cannot operate. As water delivery duration increases, water body changes stabilize. The Kumtuge Gate exemplifies this semi-randomized delivery—its limited regulation capacity means diversion depends mainly on main channel water level, creating near-randomized patterns.

Analysis of monthly water area versus discharge in 2017 shows strong correlation ($R^2 = 0.82$), with water area changes closely following delivery processes: rapid expansion (2008-2010), slight increase (2011-2015), and stabilization (2016-present), with flow eventually pooling in low-lying areas. Remote sensing reveals spatial interchange between water bodies and vegetation behind the gate—water concentrates 10 km downstream, with some pooling near the gate and low-lying areas. This uncontrolled delivery, while important for riparian vegetation, has created permanent water bodies and shallow groundwater zones, increasing surface and phreatic evaporation and reducing water use efficiency—contrary to river ethics in this extremely arid region.

Near-Natural Overflow Water Delivery The Old Tarim bed, composed of aeolian soils and alluvium, is easily eroded, so no ecological gates were constructed. Water consumption occurs through natural distributary overflow. The Old Tarim delivered water 18 times, with consumption via bank-side distributaries and flood overflow constrained by main channel discharge and water level, forming near-natural delivery patterns.

The Bozkule area serves as a typical study site. In 2000, water distribution concentrated near the channel; by 2005, overflow expanded to 60.03 km^2 maximum extent, later stabilizing. Correlation analysis shows water area increases correlate with delivery volume ($R^2 = 0.71$) and duration ($R^2 = 0.88$). Groundwater monitoring shows similar consolidation and permanent water surface formation as in the Qiwenkuoer River, with water area negatively correlating with groundwater depth ($R^2 = 0.85$). Long-term delivery has gradually stabilized overflow areas, but reduced groundwater recharge rates and created water pooling, increasing ineffective evaporation.

Discussion

Imbalanced water resource allocation due to human activity was the primary cause of severe ecological degradation in the lower Tarim. Using 20 years of delivery data, we analyzed spatial distribution characteristics of water consumption and evolving delivery patterns. Hydrological monitoring and remote sensing interpretation demonstrate how changing delivery methods expand groundwater level and vegetation recovery ranges, while revealing phased evolution of water dissipation patterns.

Intermittent delivery creates a "surge irrigation effect" that reduces riverbed permeability. The Qiwenkuoer River' s high fine-particle content easily forms siltation layers. Even natural distributaries behind ecological gates exhibit this effect after long-term intermittent delivery, shown by increased water depth in inundated areas. The Old Tarim' s silty sand bed shows weaker surge effects, maintaining better water-groundwater exchange. However, long-term delivery reduces riparian groundwater storage capacity, accelerates water table rise, and increases phreatic evaporation. Field surveys in 2020 revealed widespread ice formation in overflow zones, indicating substantial groundwater recovery.

Current practices show that over time, continuous delivery gradually reduces riverbed-to-groundwater conversion rates. The shift from single-channel to dual-channel, then to ecological gate, and finally to distributary delivery appears as active human adjustment but actually reflects the intrinsic interplay between groundwater recovery and riverbed permeability evolution.

Conclusions

By the end of 2020, 21 ecological deliveries in the lower Tarim had occurred, with delivery methods evolving from single-channel → dual-channel → single/dual-channel with ecological gates → dual-channel with gates and distributaries. Long-term delivery has caused riverbed siltation, gradually reducing groundwater recharge rates and increasing ineffective evaporation. Future research should strengthen monitoring of post-overflow wetlands, vegetation responses, and biodiversity, studying water dissipation patterns from a river ethics perspective to better regulate ecological water delivery and vegetation recovery.

Key findings include: (1) The Qiwenkuoer River primarily uses ecological gate regulation, where post-gate influence correlates closely with main channel inflow processes. The Kumtuge Gate underwent rapid expansion-reduction-slight increase-significant increase-stabilization, forming fixed channels where prolonged delivery increases water depth rather than area. Randomized gate delivery causes excessive groundwater levels and reduced efficiency, necessitating water dissipation regulation. (2) The Old Tarim uses near-natural distributary and overflow delivery due to its larger bed slope and silty composition. The Bozkule overflow area has consolidated into reed-dominated vegetation, representing natural river attributes but creating excessive water surfaces that increase ineffective evaporation. (3) The "surge irrigation effect" and groundwater backwater action reduce groundwater recharge and increase ineffective evaporation under intermittent delivery. Timely, artificially intervened regulated delivery using dual-channel, rotational distributary infiltration, and periodic overflow can expand wetted areas, maintain optimal groundwater depths, improve water use efficiency, and maximize vegetation recovery area, thereby better interpreting river ethics in arid regions.

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Figures

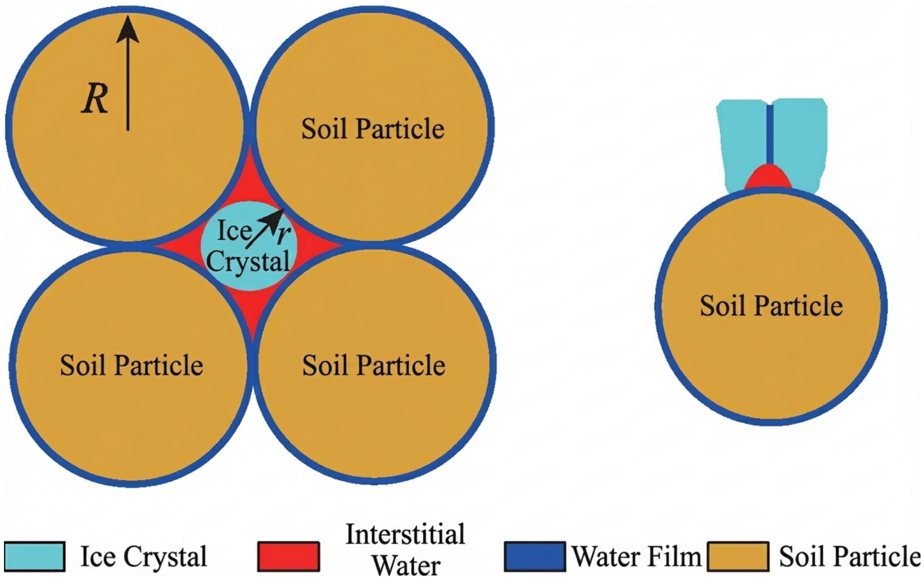

Figure 1: Figure 1

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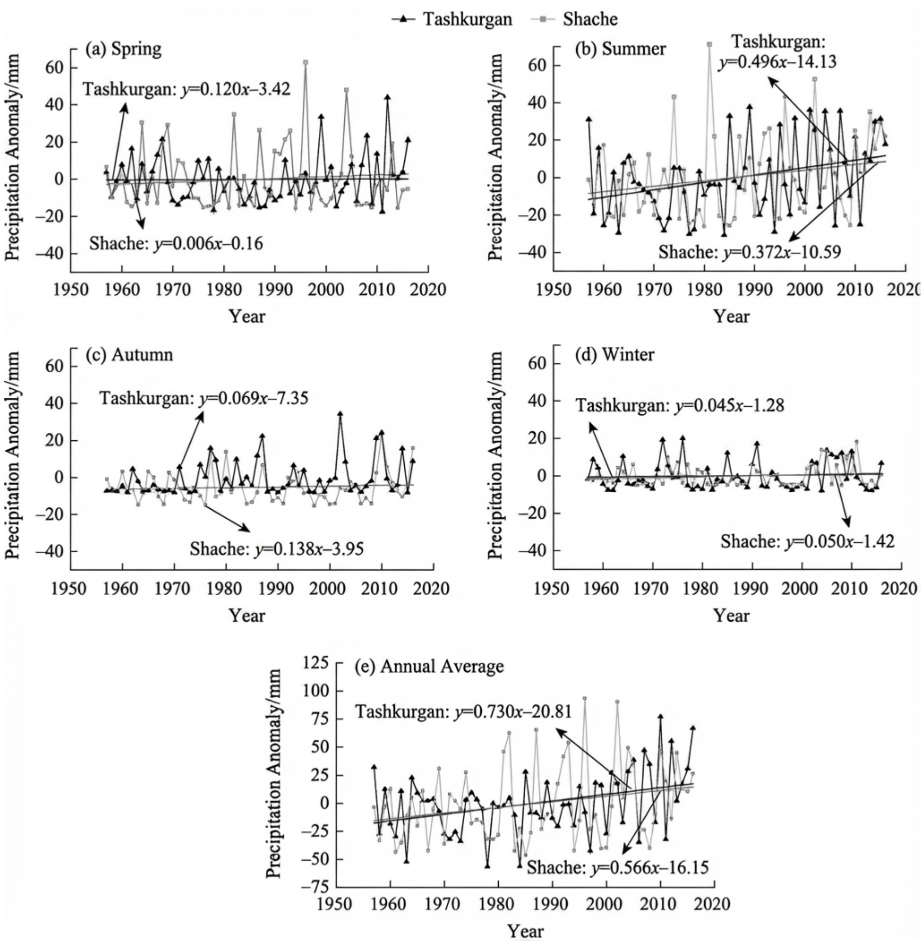

Figure 2: Figure 3

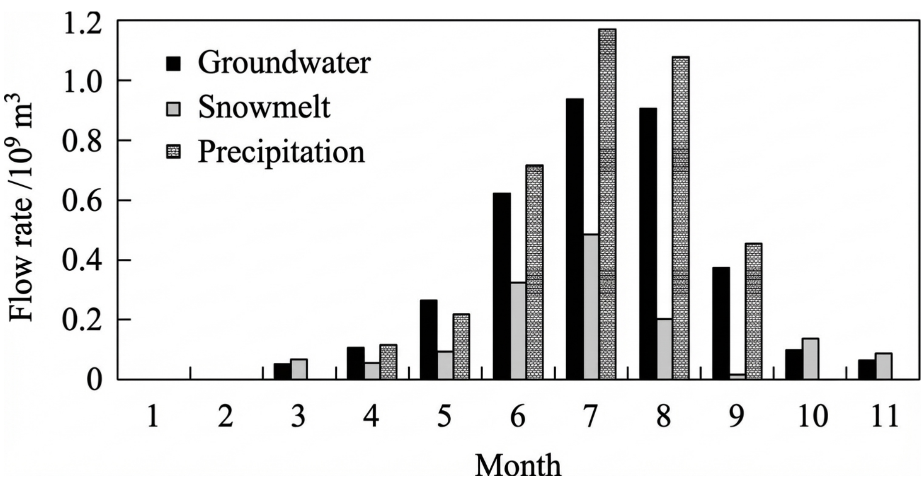

Figure 3: Figure 7

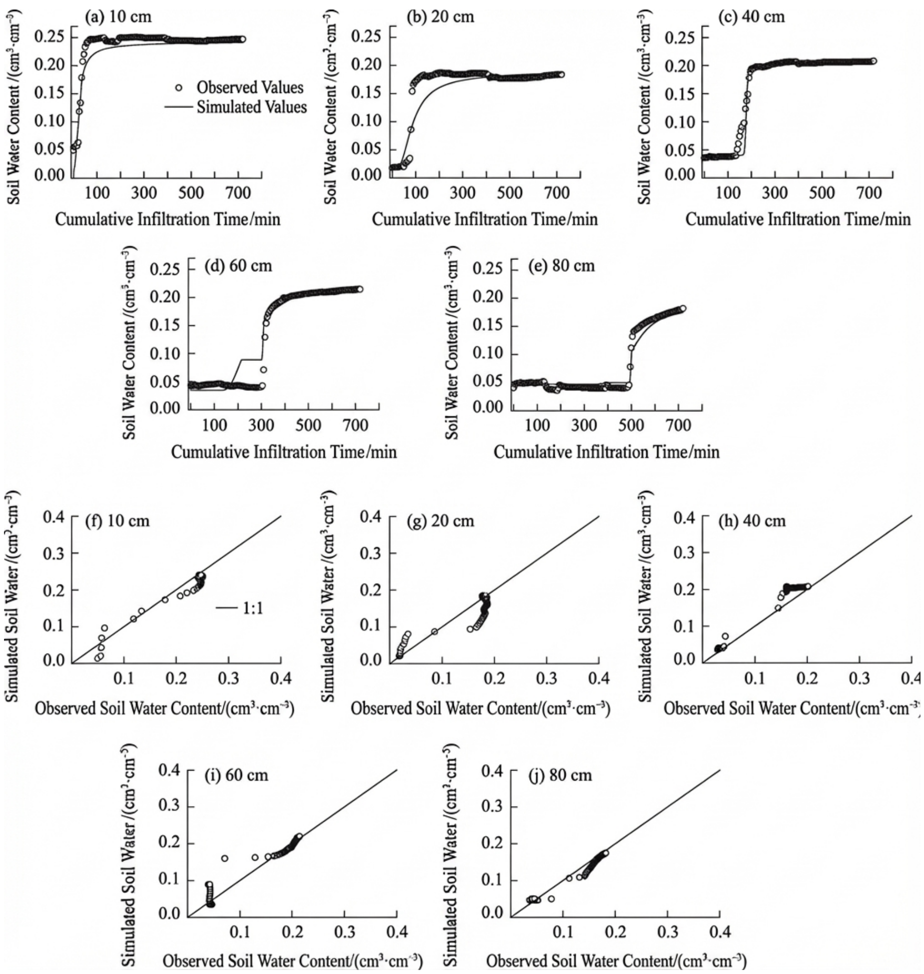

Figure 4: Figure 8