Simulation and Regulation of the Impact of Groundwater Depth on Soil Water and Salt Transport in Arid Regions: A Case Study of a Typical Field Plot in the Riparian Zone of the Lower Aksu River (Postprint)

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Abstract

Salinization in downstream irrigation districts of arid watersheds exacerbates soil degradation, crop yield reduction, and river water salinization, constraining the stability of agricultural production and ecological environments. Its formation is influenced by groundwater depth and improper irrigation and drainage management; scientifically formulating soil water-salt regulation measures is key to addressing these issues. This study conducted experiments in typical fields within the riparian zone of the lower Aksu River, developed an unsaturated model using HYDRUS-1D software based on dynamic observation and field survey data, simulated soil water and salt transport patterns during the cotton growth period, determined reasonable regulation schemes, and explored the relationship between stable groundwater evaporation depth and riparian zone soil structure. The results indicate that: the identification and validation accuracies for soil water content and TDS were 0.862 and 0.752, respectively, with root mean square errors of 0.033 and 0.008, respectively, demonstrating high model reliability; irrigation infiltration recharge accounted for 85% of total soil water recharge, introducing 127.164 mg · cm-2 of salt, soil water discharge to the phreatic zone constituted 59.67% of total discharge, removing 267.78 mg · cm-2 of salt, the water balance discrepancy was 9.2%, and the desalination rate was 33.89%; considering crop water requirement patterns and dynamic changes in soil salinity, adopting 70 cm as the optimal irrigation amount while controlling groundwater depth at approximately 220 cm can effectively reduce soil salinity in the root zone; in sand-interlayered-loam structures, the position of the loam layer has minimal influence on the critical evaporation depth of groundwater (150 cm), but primarily affects the stable evaporation depth of soil and actual evaporation amount; the closer the loam layer is to the surface, the shallower the stable evaporation depth and the smaller the actual evaporation amount. The research results can provide references for salinization prevention and control in arid regions and rational water resource allocation.

Full Text

Preamble

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Simulation and Regulation of Groundwater Depth Effects on Soil Water-Salt Transport in Arid Regions: A Case Study of Representative Farmland in the Riparian Zone of the Lower Aksu River

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Abstract: Salinization in downstream irrigation areas of arid watersheds exacerbates soil degradation, crop yield reduction, and river water salinization, constraining agricultural production and ecological stability. Its formation is influenced by groundwater depth and improper irrigation-drainage management, making scientifically formulated soil water-salt regulation measures essential for addressing these problems. This study conducted field experiments in a typical farmland plot in the riparian zone of the lower Aksu River. Based on dynamic observations and field survey data, an unsaturated model was established using HYDRUS-1D software to simulate soil water-salt transport patterns during the cotton growing season, determine reasonable regulation schemes, and explore the relationship between stable groundwater evaporation depth and riparian soil structure. Results showed that the identification and validation accuracies for soil moisture content and total dissolved solids (TDS) were 0.862 and 0.752, respectively, with root mean square errors of 0.033 and 0.008, indicating high model reliability. Irrigation infiltration recharge accounted for 85.66% of total soil water recharge, introducing 127.164 $\mathrm{mg \cdot cm^{-2}}$ of salt, while soil water discharge to groundwater accounted for 59.67% of total discharge, removing 267.78 $\mathrm{mg \cdot cm^{-2}}$ of salt. The water balance error was 9.2% and the desalination rate was 33.89%. Considering crop water requirements and dynamic soil salinity changes, setting the irrigation water depth at 70 cm while controlling groundwater depth at approximately 220 cm can effectively reduce root zone soil salinity. In sandy loam interlayer structures, the position of the loam layer has minimal influence on the critical groundwater evaporation depth (150 cm), but significantly affects the stable evaporation depth and actual evaporation rate. When the loam layer is closer to the surface, the stable evaporation depth becomes shallower and actual evaporation decreases. These findings provide a reference for salinization prevention and rational water resource allocation in arid regions.

Keywords: water-salt regulation; cotton; arid regions; riparian zone; groundwater depth; stable evaporation depth

Introduction

Northwest China' s arid inland basins predominantly feature alluvial-proluvial landforms, with water resources derived from alpine snowmelt that infiltrates and evaporates in desert oases. As groundwater flows through aquifers rich in soluble minerals, it undergoes rock dissolution, gradually increasing soluble salt content during downstream discharge. In oasis agricultural areas, irrigation represents another major pathway affecting field salt distribution, particularly in regions with well-developed water systems and shallow groundwater depths. Under intense evaporation, water carries salts upward to the surface as capillary water, causing soil salinization.

The Aksu region, located at the southern foothills of the central Tianshan Mountains and the northwestern edge of the Tarim Basin, is primarily fed by the Aksu River and serves as Xinjiang' s largest long-staple cotton production base. Since the 1990s, market-oriented policies have enhanced farmers' enthusiasm for land reclamation, converting abandoned saline-alkali lands downstream of the Aksu River into cultivated farmland. To avoid salt stress on crop growth in these newly reclaimed lands, farmers often apply excessive irrigation water for "salt leaching." While this temporarily suppresses salinization development, it also raises groundwater levels and alters the water-salt cycle in the vadose zone vegetation, triggering environmental problems such as farmland "salt return" and Aksu River salinization. Clearly, rational irrigation systems and orderly groundwater regulation are critical for effective water resource utilization and solving soil salinization problems in the study area.

Previous studies have used HYDRUS models to simulate groundwater level effects on soil water-salt distribution and proposed improved irrigation management and groundwater regulation strategies. However, these simulations lacked crop yield as a constraint condition for water level regulation, limiting their practical applicability. Although some research explored water-salt regulation effects on soil salt distribution and crop yield through modified irrigation volumes and groundwater depths, these measures primarily focused on irrigation methods and strategies. Only a few scholars have investigated soil salinity and crop yield changes under different groundwater depths and irrigation strategies, revealing the critical role of groundwater regulation in salinization prevention and water resource management. Furthermore, for the variable soil structures in riparian zones, clarifying the role of soil texture in water-salt regulation models—

particularly its influence on critical and stable groundwater evaporation depths—remains a key issue. Soil physical properties such as pore structure and hydraulic conductivity significantly affect vertical water migration, capillary rise, and dynamic water-salt distribution, thereby determining the critical and stable depths of groundwater evaporation. Therefore, incorporating dynamic changes in soil texture can deepen understanding of water-salt migration mechanisms in riparian zones, improve model adaptability under changing conditions, and provide more refined support for salinization prevention and water resource optimization.

Against this background, this study constructed an unsaturated model using HYDRUS-1D based on local cultivation management calendars, soil salinity surveys, and cotton yield investigations. The research objectives were: (1) to simulate soil water-salt transport during the cotton growing season and propose field water-salt regulation schemes that balance water-saving irrigation and salinization prevention; (2) to quantify groundwater critical evaporation depth and stable evaporation depth under different groundwater depths using the calibrated model; and (3) to conduct sensitivity analysis on how layered soil structures affect these evaporation depths. While the results are primarily relevant to the experimental area, certain methodological aspects—particularly the multi-angle consideration of physical processes—may have reference value for other regions.

1 Study Area Overview and Research Methods

1.1 Study Area Overview

This study selected the riparian zone of the lower Aksu River for field investigation and experiments, where groundwater is shallow and soil salinization is severe. The experimental area is located in Xinkailing Town, Regiment 13, Aral City, on the alluvial plain downstream of the Aksu River, with geographic coordinates of 80°47 43.90 E, 40°31 06.60 N. The region has a typical warm temperate continental arid climate, with an average annual temperature of 11.2-12.2°C, frost-free period of 193-310 days, annual precipitation of 60.5-98.2 mm, and sunshine duration of 2761-2827.7 hours. The experimental plot area is 4.5×10^3 m^2.

The experimental area features layered soil structures dominated by sandy and loamy soils. Soil types include crusted solonchak, salinized meadow soil, and meadow solonchak. The main crop is cotton, which has long relied on shallow groundwater for agricultural irrigation. Due to siltation and aging of the canal system, combined with the backwater effect of the Aksu River, groundwater depth during the crop growing season remains around 104-156 cm, with groundwater mineralization ranging from 2.35-2.57 $g \cdot L^{-1}$. Root zone (0-60 cm) soil salinity maintains approximately 0.68%, classified as moderately salinized according to Xinjiang soil salinization classification standards, with obvious surface salt accumulation.

1.2 Experimental Design

The cotton variety planted was "Tuonong 1," arranged in "wide-narrow row" planting with 6 rows, wide row spacing of 50 cm and narrow row spacing of 30 cm. Water level and quality monitoring wells were installed in both wide and narrow rows. To reduce calculation errors from water outflow during irrigation, field ridges were covered with plastic film (ridge width 25 cm), while the cotton planting area remained uncovered. The experiment ran from sowing on April 15, 2022, to harvest on October 31, 2022. Field management followed local agricultural practices, with irrigation periods set for May 15, June 15, July 15, and August 15, each with 30 cm water depth. Irrigation water was sourced from local groundwater (dissolved solids 1.048 $g \cdot L^{-1}$). Irrigation methods included flood irrigation and spring irrigation (pre-sowing irrigation).

1.3 Observation Content and Methods

1.3.1 Meteorological and Three-Parameter Data Meteorological data were obtained from an automatic weather station (HOBO H21-001, Onset), including maximum temperature, minimum temperature, relative humidity, wind speed, solar radiation, air pressure, precipitation, and sunshine duration. Daily reference evapotranspiration (ET_0) was calculated using the Penman-Monteith formula. Soil moisture content, electrical conductivity, and temperature were monitored in real-time using sensors (WET-2, Delta T Devices) buried at 15 cm, 40 cm, 70 cm, 110 cm, and 150 cm depths in narrow rows, with a collection frequency of every 5 minutes. Annual rainfall and ET_0 in the experimental area are shown in [Figure 3: see original paper], with rainfall concentrated in May-August and daily average temperature showing a clear decreasing trend during this period. Groundwater depth and quality variations are shown in [Figure 4: see original paper], with depth ranging 104-156 cm and mineralization 2.35-2.57 $g \cdot L^{-1}$. Smaller groundwater depth corresponds to higher mineralization.

1.3.2 Soil Physical Parameters Before the experiment, soil texture distribution and layering were determined through drilling. Soil samples were collected at depths of 0-0.35 m, 0.35-0.8 m, and 0.8-1.8 m. Soil bulk density and saturated hydraulic conductivity were measured using the ring knife method, particle size distribution was determined using a laser particle size analyzer (Microtrac Inc., USA), and van Genuchten parameters were predicted using the Rosetta function. The soil profile consists of three layers: silty sand (0-0.35 m), loam (0.35-0.8 m), and fine sand (0.8-1.8 m and below), representative of riparian zones. Sand, silt, and clay percentages are 74.65%, 23.63%, and 1.72% in the 0-0.35 m layer; 65.82%, 30.26%, and 3.92% in the 0.35-0.8 m layer; and 88.58%, 10.96%, and 0.46% in the 0.8-1.8 m layer. Basic physical properties and VG parameters are shown in .

1.4 Soil Water-Salt Dynamic Model

The HYDRUS-1D model features a user-friendly interface, detailed modular functions, and is suitable for secondary development and integration with Intel Visual Fortran programs. It is widely applied in agriculture, hydrogeology, water conservancy, and environmental fields. Referencing actual conditions, the simulation considered crop root growth and water uptake, used the Galerkin finite element method for equation solving, and employed the Marquardt-Levenberg parameter optimization algorithm in the inversion module to solve soil hydraulic and solute transport parameters. Heat transport was not considered. The simulation process is shown in [Figure 5: see original paper], with the inversion flow including initial parameter selection, model running, error function calculation, parameter updating, and convergence checking.

1.4.1 Soil Water Movement Equation Assuming isotropic and rigid soil matrix, the Richards equation with source-sink terms was used:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S$$

where θ is volumetric water content ($\mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$), t is time (d), h is pressure head (cm, positive for saturated, negative for unsaturated), z is vertical coordinate (positive upward), $K(h)$ is unsaturated hydraulic conductivity ($\mathrm{cm} \cdot \mathrm{d}^{-1}$), and S is the source-sink term representing root water uptake.

The soil water characteristic curve and unsaturated hydraulic conductivity function $K(h)$ were described using the van Genuchten-Mualem model:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m}$$

$$K(h) = K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2$$

where K_s is saturated hydraulic conductivity ($\mathrm{cm} \cdot \mathrm{d}^{-1}$), θ_s is saturated water content ($\mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$), θ_r is residual water content ($\mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$), S_e is effective saturation, α, m, n are empirical shape parameters, and l is a pore connectivity parameter (generally 0.5).

Root Water Uptake Model: The source-sink term S at depth x is calculated as:

$$S(x) = b(x) \cdot \alpha(h) \cdot T_p$$

where $b(x)$ is the normalized water uptake distribution function, $\alpha(h)$ is the water stress response function, and T_p is potential transpiration.

The normalized water uptake distribution $b(x)$ follows the non-linear distribution proposed by Hoffman and van Genuchten, dependent on root depth L_R:

$$b(x) = \frac{1.667}{L_R} - \frac{2.0833}{L_R^2}x$$

Root depth L_R varies daily during growth, modeled using a Logistic function in the absence of field observations:

$$L_R(t) = \frac{L_m}{1 + e^{r(t-t_{50})}}$$

where L_m is maximum root depth (60 cm), r is growth rate, and t_{50} is time when root depth reaches half of maximum.

1.4.2 Soil Solute Transport Equation Based on mass conservation, the convection-dispersion equation considering soil adsorption but excluding root absorption was used:

$$\frac{\partial(\theta c_l + \rho_b c_s)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D_e \frac{\partial c_l}{\partial z} - q_w c_l\right) + \phi$$

where c_s is adsorbed solute concentration ($\mathrm{mg} \cdot \mathrm{g}^{-1}$), ρ_b is soil bulk density ($\mathrm{g} \cdot \mathrm{cm}^{-3}$), D_e is hydrodynamic dispersion coefficient ($\mathrm{cm}^2 \cdot \mathrm{d}^{-1}$), c_l is solute concentration in water ($\mathrm{mg} \cdot \mathrm{mL}^{-1}$), q_w is water flux ($\mathrm{cm} \cdot \mathrm{d}^{-1}$), and ϕ represents source-sink terms.

1.4.3 Canopy Transpiration and Soil Evaporation Calculation Reference crop evapotranspiration ET_0 was calculated using the Penman-Monteith formula. Potential soil evaporation E_p and crop transpiration T_p were partitioned using leaf area index and extinction coefficient:

$$E_p = ET_c(1 - e^{-\lambda \cdot LAI})$$

$$T_p = ET_c \cdot e^{-\lambda \cdot LAI}$$

where ET_c is actual crop evapotranspiration under no water stress (mm), LAI is leaf area index, K_c is crop coefficient, and λ is canopy extinction coefficient (0.6 for cotton).

1.4.4 Soil Water-Salt Balance Calculation

Water Balance Equation: Within a control volume, water input, output, and storage change satisfy:

$$P + I + U - ET - D - R = \Delta S_w$$

where P, I, U, ET, D, R, and ΔS_w represent precipitation, irrigation, groundwater recharge, evapotranspiration, deep percolation, runoff, and soil water storage change (all in mm). No runoff occurred during irrigation, so $R = 0$.

Salt Balance Equation: Neglecting rainfall effects, soil salt sources and sinks include:

$$I_s + U_s - L_s - S_s = \Delta S_s$$

where I_s, U_s, L_s, S_s, and ΔS_s represent salt input from irrigation, salt from groundwater recharge, salt discharged by deep percolation, and soil salt storage change (all in $\mathrm{mg \cdot cm^{-2}}$). When $S_s > 0$, soil salt accumulates, potentially causing secondary salinization.

Salt input from irrigation, groundwater recharge, and deep percolation discharge were calculated as:

$$I_s = \sum W_{ij} \times C_{ij} \times 10$$

$$U_s = \sum W_{dj} \times C_{dj} \times 10$$

$$L_s = \sum W_{gj} \times C_{gj} \times 10$$

where W_{ij}, W_{dj}, W_{gj} are water input, groundwater recharge, and deep drainage at time j (mm), and C_{ij}, C_{dj}, C_{gj} are corresponding salt concentrations ($\mathrm{mg \cdot mL^{-1}}$).

1.5 Model Setup

1.5.1 Boundary Conditions

Initial Conditions:

$$\theta(z, 0) = \theta_0(z)$$

$$h(z, 0) = h_0(z)$$

Boundary Conditions: - Upper boundary: Atmospheric boundary with daily precipitation and evapotranspiration input - Lower boundary: Variable head boundary with pressure head determined by daily groundwater depth

Solute Transport: - Initial condition: $c(z, 0) = c_0(z)$ - Upper boundary: Concentration flux boundary $q_s c_s(t)$ - Lower boundary: Concentration boundary $c = C_b$

For subsequent simulations exploring stable and critical evaporation depths, the upper boundary used atmospheric data from the crop growing season, while the lower boundary was set as constant head. Precipitation and irrigation were excluded to isolate groundwater' s contribution to evaporation.

1.5.2 Spatial and Temporal Discretization

Spatial Discretization: Based on field conditions, simulation depth was set to 180 cm, divided into 3 layers according to measured soil texture (Table 1) with 70 nodes at 15 cm spacing. Observation points were set at 15 cm, 40 cm, 70 cm, 110 cm, and 150 cm.

Temporal Discretization: Simulation covered the cotton growing season (April 15–October 31, 201 days) with daily time steps, minimum step of 0.01 d, and maximum step of 1 d.

1.5.3 Soil Parameter Acquisition

Initial soil parameters (θ_s, θ_r, K_s, α, n, l) were predicted using the Rosetta function based on sand, silt, and clay contents (Table 1). Feddes model water potential thresholds for root water uptake (h_1, h_2, h_3, h_4) used software default values and literature data for cotton: $h_1 = -10$ cm, $h_2 = -25$ cm, $h_3^H = -200$ cm, $h_3^L = -600$ cm, $h_4 = -14000$ cm, with maximum root depth of 60 cm.

1.5.4 Model Calibration and Validation

The trial-and-error method was first used for coarse parameter adjustment, followed by inverse modeling for fine-tuning. Since soil water-salt changes were minimal during non-irrigation periods, irrigation period data were used for model identification and validation. Model accuracy was evaluated using R^2 and RMSE—smaller values indicate higher precision.

Fitting results for measured vs. simulated soil moisture and TDS at different depths are shown in [Figure 8: see original paper]. Most data points fell near the 1:1 line, with only a few outliers due to surface soil structure being susceptible to climate and human activities, introducing complexity and uncertainty. Table 2 shows accuracy verification results: R^2 for moisture ranged 0.351-0.682, and for TDS ranged 0.322-0.752. Lower R^2 values in deeper soils primarily resulted from small baseline variations—when observation data fluctuated little from baseline, even accurate predictions showed large relative errors. Overall, model accuracy was high and parameters met requirements. Calibrated parameters are shown in Table 3.

2 Results

2.1 Soil Water Balance Analysis

Using the calibrated model to analyze water balance during the cotton growing season (Table 4), total irrigation was 1269.40 mm, accounting for 85.66% of soil water recharge. Groundwater recharge contributed 14.34% (212.42 mm). Soil water discharge occurred mainly through bottom boundary recharge to groundwater (59.67%, 802.94 mm), while actual evapotranspiration accounted for 40.33% (542.61 mm). The water balance error was 9.2%. After irrigation, soil water primarily discharged via infiltration to groundwater, raising the water table, which then drained through open ditches or lateral flow, causing secondary water waste and river salinization. Therefore, determining rational irrigation volumes for "water-saving and salt-control" is essential.

2.2 Soil Salt Balance Analysis

The calibrated model analyzed salt balance during the growing season (Table 5). Spring irrigation effectively controlled salt accumulation, with salt discharge reaching 44.258 $mg \cdot cm^{-2}$ in April. Maximum discharge occurred in July (95.091 $mg \cdot cm^{-2}$). Although irrigation ceased in September-October, strong evaporation continued. With shallow groundwater, capillary action transported groundwater salts to the surface, causing accumulation (21.63 $mg \cdot cm^{-2}$). Total salt input through irrigation and groundwater recharge was 199.99 $mg \cdot cm^{-2}$, total salt discharge was 267.78 $mg \cdot cm^{-2}$, and desalination efficiency reached 33.89%, demonstrating significant salt removal.

2.3 Model Application and Field Irrigation System Optimization

Water-salt balance analysis revealed that field irrigation aims to meet crop water demand and leach salts, particularly through "spring irrigation." Using 2022 field data and Aksu Agricultural Technology Extension Center' s cultivation calendar, crop water consumption patterns were divided into growth stages (Figure 10). Total crop transpiration was 422 mm and inter-plant evaporation was 121.15 mm, requiring 543.15 mm irrigation water for the entire growing period. Evaporation at different stages was measured by micro-lysimeters, while transpiration was allocated using crop coefficients and the Penman formula.

Using the validated model and downstream irrigation area soil salinity data, root zone salinity changes under varying irrigation depths were simulated (Figure 9). When irrigation depth was below 70 cm, root zone salinity decreased rapidly; above 70 cm, the reduction was minimal, indicating water waste. Therefore, 70 cm is the optimal irrigation depth.

Soil salinity constrains cotton relative yield. In the Aksu River irrigation area, an "S-shaped" salt tolerance function describes the relationship (Figure 12). When soil salinity is below 2.5 $g \cdot kg^{-1}$, cotton yield does not decline. The relationship between groundwater depth and root zone salinity shows that salinity decreases rapidly with increasing depth when groundwater is shallower than 220 cm; between 220–300 cm, the change is minimal; beyond 300 cm, salinity stabilizes. Therefore, maintaining groundwater depth at approximately 220 cm during regulation can effectively reduce root zone salinity while ensuring crop yield.

2.5 Stable and Critical Groundwater Evaporation Depths in Riparian Zones

During non-irrigation periods (spring and autumn), shallow groundwater (~120 cm) drives soil salt return through evaporation. Determining stable and critical evaporation depths is crucial for understanding salinization processes. Riparian soil structure varies due to floodplain transverse gradients, causing the loam interlayer position to gradually lower away from the riverbank (Figure 13). To study this effect, simulations were conducted with the loam layer at different positions (10 cm, 20 cm, 30 cm, 40 cm, 50 cm, 60 cm, 70 cm, 80 cm, 90 cm, 100 cm, 110 cm).

Research indicates the limiting evaporation depth for single-structure sandy loam in Aksu is ~2.5 m. Simulations started from 10 cm depth with 10 cm increments to 2.5 m. Potential evaporation was constant (calculated by Penman formula), while actual evaporation varied with groundwater depth. The relationship between actual and potential evaporation transitioned from linear to exponential with increasing depth (Figure 14). The inflection point marks the stable evaporation stage, with different scenarios showing different stable evaporation depths.

When the loam layer is below the groundwater depth, stable evaporation depth increases with loam layer depth but the increment gradually diminishes, reaching maximum at 80 cm (Figure 15a). Beyond this, stable evaporation depth remains unchanged despite further loam layer deepening. Actual evaporation also increases with loam layer depth but with decreasing increments (Figure 15b). The loam layer position has minimal effect on critical evaporation depth (150 cm) but significantly affects stable evaporation depth and actual evaporation.

In unsaturated zones, water content and unsaturated hydraulic conductivity can be discontinuous, but soil suction must be continuous. When groundwater depth is below the loam layer, water from underlying fine sand moves to the loam interface. At the same water content, fine sand suction (S_1) is lower than loam suction (S_2), allowing water entry into the loam layer. However, fine sand hydraulic conductivity is higher than loam, slowing the wetting front in the loam layer and controlling water transmission from below. As water continues moving upward, at the same water content, silty sand suction (S_3) is lower than loam suction (S_2), and loam conductivity is lower than silty sand, causing water to accumulate in the loam layer with difficulty moving upward. Therefore, evaporation-available water is primarily controlled by the upper silty sand layer. As the loam layer moves down, silty sand thickness increases, enhancing water supply capacity and evaporation, but capillary rise limitations eventually stabilize evaporation.

Stable evaporation depth is defined as the maximum depth where potential evaporation equals actual evaporation. Continuous water supply is crucial—when stable evaporation depth is below the loam layer, silty sand water supply is limited by loam permeability. The loam' s low permeability restricts water replenishment, causing silty sand water consumption to exceed supply. As the loam layer rises, silty sand water supply further decreases, intensifying water deficit. To maintain new water balance, stable evaporation depth must decrease to enhance groundwater replenishment and compensate for surface water shortage. Therefore, farmland management should combine groundwater level control with measures like straw mulching and deep tillage to create evaporation barriers, improve water retention, and inhibit salt accumulation.

3 Conclusions

Based on field dynamic monitoring and survey data, this study used the HYDRUS model to simulate groundwater depth effects on water-salt transport in salinized riparian irrigation areas of arid regions, proposing rational regulation schemes and discussing stable and critical evaporation depths under different scenarios. Main conclusions are:

1. During the simulation period, irrigation infiltration accounted for 85.66% of soil water recharge. Soil water discharge occurred primarily through bottom boundary recharge to groundwater (59.68% of total discharge). The soil reservoir had limited regulation capacity, and the water balance error was 9.2%.
2. Spring irrigation effectively controlled seasonal salt return, with salt discharge of 44.258 $\mathrm{mg \cdot cm^{-2}}$. Total salt input through irrigation and groundwater recharge was 199.99 $\mathrm{mg \cdot cm^{-2}}$, total salt discharge was 267.78 $\mathrm{mg \cdot cm^{-2}}$, and desalination efficiency reached 33.89%, demonstrating significant salt removal.
3. Based on the relationship between root zone salinity and irrigation depth, the optimal irrigation depth for cotton was determined as 70 cm. Combined with the relationship between groundwater depth and soil salinity during regulation and cotton salt tolerance thresholds, the reasonable groundwater control depth for downstream irrigation areas is 220 cm.
4. In sandy loam interlayer structures, loam layer position has minimal influence on critical evaporation depth (150 cm) but significantly affects stable evaporation depth and actual evaporation. When the loam layer is closer to the surface, stable evaporation depth becomes shallower and actual evaporation decreases.

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