Simulation of Soil Water and Salt Transport under Different Brackish Water Utilization Modes in the North China Low Plain Using the HYDRUS-1D Model: A Postprint

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Abstract

Continuous over-exploitation of deep groundwater in the North China Low Plain has not only caused depletion of freshwater resources, but also triggered a series of ecological and environmental problems such as land subsidence and soil salinization. The utilization of brackish water in agriculture has become a research focus for alleviating the water resource crisis. To investigate the sustainability of different saline water irrigation patterns, this study takes Nanpi County, Hebei Province, in the North China Low Plain as a case study, and uses the Hydrus-1D model to simulate variations in water-salt flux in the 2 m soil profile under a winter wheat-summer maize rotation system from 2008 to 2013, based on eight different brackish water irrigation schemes. Simulation results indicate that the salt accumulation zone in the soil profile is mainly concentrated in the lower soil layer (100-200 cm); the salt concentration of the soil solution in the upper layer (0-100 cm) remains at approximately 2 g · L-1 for most of the time, which can sustain normal crop growth; however, the salt concentration in the soil profile peaks during the late grain filling stage of winter wheat and gradually increases with the salt concentration of irrigation water. Adequate leaching of soil salt is critically dependent on rainfall intensity, with July rainfall intensity being the main factor determining whether soil desalination occurs; meanwhile, appropriate irrigation with seedling emergence water for salt leaching after summer maize sowing in wet years is crucial for achieving effective soil desalination. By comprehensively analyzing the influences of three factors on soil salt transport—hydrological year type, dynamic distribution characteristics of soil profile salt, and freshwater amount for salt leaching combined with seedling emergence water for summer maize—this study proposes two suitable brackish water irrigation regimes for the North China Low Plain: (1) irrigating winter wheat with wintering water of less than 2 g · L-1 before winter, and applying brackish water of 2-4 g · L-1 once at the jointing stage of winter wheat after spring; (2) no wintering water irrigation before winter, and applying 2 g · L-1 brackish water at both the jointing and grain filling stages of winter wheat after spring. For both irrigation regimes, the annual average freshwater amount for salt leaching combined with seedling emergence water for summer maize and the total water consumption are 60-70 mm and 250-260 mm, respectively. The results of this study provide theoretical guidance for the water-saving potential and sustainability of brackish water utilization in the North China Low Plain.

Full Text

Preamble

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HYDRUS-1D Model Simulation of Soil Water and Salt Movement Under Various Brackish Water Use Schemes in the North China Lowplain*

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Abstract

Continuous overexploitation of deep groundwater in the North China Lowplain has not only depleted freshwater resources but also triggered a series of ecological and environmental problems, including land subsidence and soil salinization. The agricultural use of brackish water has become a research priority for alleviating the water crisis. To evaluate the sustainability of different saline water irrigation regimes, this study employed the Hydrus-1D model to simulate water and salt fluxes in the 0–2 m soil profile under eight different brackish water irrigation schemes during a six-year winter wheat–summer maize rotation system (2008–2013) in Nanpi County, Hebei Province. Simulation results revealed that salt accumulation primarily occurred in the subsoil layer (100–200 cm). The salt concentration in the upper soil layer (0–100 cm) remained around 2 g · L^{-1} for most of the time, ensuring normal crop growth. However, soil profile salinity peaked during the late winter wheat grain-filling stage, with peak values increasing as irrigation water salinity increased. Effective salt leaching depended critically on rainfall intensity, particularly in July, which was the main factor determining whether desalination occurred. Additionally, appropriate irrigation for salt leaching combined with summer maize seedling water in wet years played a crucial role in achieving effective soil desalination. By comprehensively analyzing three factors—hydrological year type, dynamic distribution characteristics of soil profile salinity, and freshwater usage for salt leaching combined with summer maize seedling water—this paper proposes two suitable brackish water irrigation regimes for the North China Lowplain: (1) pre-winter irrigation with $<2\ \text{g} \cdot \text{L}^{-1}$ brackish water for winter wheat winter survival, followed by spring irrigation with 2-4 $\text{g} \cdot \text{L}^{-1}$ brackish water at the jointing stage; (2) no pre-winter irrigation, with spring applications of 2 $\text{g} \cdot \text{L}^{-1}$ brackish water at both the jointing and grain-filling stages. Under these two regimes, the average annual freshwater consumption for salt leaching combined with summer maize seedling water and the total water consumption are 60–70 mm and 250–260 mm, respectively. These results provide theoretical guidance for the water-saving potential and sustainability of brackish water utilization in the North China Lowplain.

Keywords
brackish water use; irrigation regime; Hydrus-1D model; water and salt movement; hydrological year; winter wheat–summer maize rotation

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Introduction

The North China Plain is a crucial grain production region in China but suffers from severe water scarcity. Massive overexploitation of groundwater resources has caused a series of ecological and environmental crises, including groundwater contamination, land subsidence, seawater intrusion, and soil salinization. To address the increasingly prominent water crisis, developing various water resources, improving water use efficiency, and formulating sustainable water resource strategies have become important research topics. In semi-arid regions, shallow saline and brackish groundwater holds significant development potential, and the use of brackish water for agricultural irrigation has gained increasing attention, particularly in freshwater-scarce areas where it has become an important water-saving strategy. In Hebei Province, the exploitable resources of brackish and saline water amount to nearly 4.2 billion m^3 annually, accounting for approximately 36% of the total groundwater exploitable resources. Increasing the development and utilization rate of brackish water resources for agricultural irrigation plays a vital role in ensuring sustainable water resource use and agricultural development in the North China Lowplain.

The application of brackish water irrigation requires theoretical and technical guidance based on experiments and simulations. Currently, brackish water irrigation technology has been applied in many arid regions, and appropriate irrigation regimes can achieve water-saving and yield-increasing goals. Existing irrigation experiments have shown that irrigation amount and water quality are the main factors affecting soil salt accumulation, with the objective of brackish water irrigation being to control salt accumulation in the root zone. Appropriate brackish water irrigation can promote crop growth and development. Chen et al. demonstrated in a Nanpi County experiment that irrigation with 2 g ·

L^{-1} and 4 g · L^{-1} brackish water at the jointing stage increased yields by 16.7% and 7.4% compared to rain-fed crops, respectively. However, salt accumulation during the wheat season could reduce the yield of the subsequent maize crop, indicating that crop type and irrigation timing must be considered in brackish water irrigation. Experimental studies have shown that wheat is more sensitive to salinity during germination and booting stages, while grain-filling and jointing stages are relatively less affected, and soil salinity should be controlled below 6 dS · m^{-1}. Maize is highly sensitive to salt stress, particularly during germination and seedling stages. Maize begins to suffer damage when soil salinity exceeds 1.7 dS · m^{-1}, and yield is reduced by half at 5.9 dS · m^{-1}. Therefore, reasonable irrigation regimes must be determined based on different crop types, soil characteristics, and saline water resources to meet crop water requirements while effectively controlling soil salt accumulation.

The dynamic changes of soil water and salt in farmland under different brackish water irrigation scenarios have long been a research challenge. The Hydrus-1D model is widely used to simulate soil water and solute transport processes, enhancing mechanistic understanding through simulation. Developed by the U.S. Salinity Laboratory, Hydrus-1D is a numerical model for simulating water, heat, and solute transport in variably saturated porous media. It can comprehensively simulate atmospheric processes (evapotranspiration, rainfall, irrigation), soil water and solute transport, crop root water uptake, and groundwater level changes, with multiple boundary condition settings and extensive parameter databases for reference. This study uses the Hydrus-1D model to simulate soil water and salt flux changes under different brackish water irrigation scenarios in a winter wheat-summer maize rotation system. By investigating the effects of different hydrological year types, irrigation water salinity concentrations, and freshwater amounts for salt leaching combined with summer maize seedling water on soil salt transport, this research clarifies salt accumulation patterns in the soil profile and salt leaching cycles under brackish water irrigation, proposes two suitable brackish water irrigation schemes for the North China Lowplain, and provides theoretical guidance for the water-saving potential and sustainability of brackish water utilization in the region.

1.1 Study Area

The study area is located in Nanpi County, Hebei Province (37°50 -38°11 N, 116°32 -117°02 E, elevation 7-12 m). The main soil types are fluvo-aquic soil, salinized fluvo-aquic soil, and de-salinized fluvo-aquic soil, with salinized fluvo-aquic soil accounting for 22% of the area. The soil texture is primarily loam, with salt content of 0.8-1.5 g · kg^{-1}, bulk density of 1.42 g · cm^{-3}, and field capacity of 24.1%. This region belongs to a coastal water-deficient salinization zone with scarce surface water for irrigation but abundant shallow saline groundwater resources. Nanpi County is part of the ancient river plain groundwater system, with groundwater depth of 5-7 m. Shallow groundwater resources with salinity <2 g · L^{-1} account for 18%, 2-3 g · L^{-1} for 33%, 3-5 g · L^{-1} for 24%, and >5 g ·

L^{-1} for 25%. The region has an average annual precipitation of 550 mm and a typical warm temperate semi-humid continental monsoon climate, characterized by spring and autumn droughts, summer rainfall with flooding risk, and distinct seasonal salt accumulation or desalination phenomena.

1.2 Model Description

This study employs the Hydrus-1D software developed by the U.S. Salinity Laboratory to simulate water, heat, and solute transport in saturated-unsaturated soils. The software primarily includes three modules: water flow, root water uptake, and solute transport.

1.2.1 Basic Water Flow Equation

Using the ground surface as the reference plane, the one-dimensional vertical water flow model can be expressed as:

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

where θ is the soil volumetric water content ($\mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$), t is time (d), K is the unsaturated hydraulic conductivity ($\mathrm{cm} \cdot \mathrm{d}^{-1}$), h is the matric potential (cm), S is the root water uptake rate (d^{-1}), and z is the vertical coordinate (positive upward) (cm).

The van Genuchten-Mualem model is used to determine soil hydraulic parameters:

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

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

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

$$m = 1 - \frac{1}{n}$$

where θ_s is the saturated volumetric water content ($\mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$), θ_r is the residual volumetric water content ($\mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$), K_s is the saturated hydraulic conductivity ($\mathrm{cm} \cdot \mathrm{d}^{-1}$), S_e is the effective saturation, α is the inverse of the air-entry pressure head (cm^{-1}), m and n are parameters of the water retention curve, and l is the pore connectivity parameter (generally taken as 0.5).

1.2.2 Root Water Uptake Equation

The Feddes model is used to calculate root water uptake rate:

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

where $\alpha(h)$ is the root water uptake stress coefficient, $b(x)$ is the normalized root water uptake distribution function describing spatial variation of root water uptake, and T_p is the potential crop transpiration rate (cm • d^{-1}). The root water uptake stress coefficient is determined using empirical parameters proposed by Wesseling et al., as shown in .

TABLE:1 Crop root uptake equation parameters

Crop	h_0 (cm)	h_{opt} (cm)	h_{2H} (cm)	h_{2L} (cm)	h_3 (cm)
Winter wheat	-10	-25	-300	-500	-16000
Summer maize	-10	-25	-150	-300	-8000

Root water uptake approaches zero when soil water potential is near saturation (h_0) or below the wilting point (h_3). Water uptake is optimal and the coefficient approaches 1 when pressure heads are between h_{opt} and h_{2H} (or h_{2L}). h_{2H} represents the soil water potential at a potential transpiration rate of 0.5 cm • d^{-1}, while h_{2L} corresponds to 0.1 cm • d^{-1}.

The normalized root water uptake distribution function $b(x)$ is calculated as:

$$b(x) = \frac{N'(x)}{\int_0^{L_r} N'(x)dx}$$

where $N'(x)$ is the measured or simulated root distribution function reflecting root distribution in the soil profile. Crop root growth uses a linear growth function, with winter wheat and summer maize root growth determined according to Zhang' s experimental research.

1.2.3 Solute Transport Equation

The model investigates soil soluble salts (inert, non-adsorptive solutes) using soil water salinity as the main indicator, establishing a mathematical model for solute transport in saturated-unsaturated soils:

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial C}{\partial z} - qC\right) - S \cdot C_r$$

where C is the salt concentration in soil solution ($\mathrm{mg \cdot cm^{-3}}$), q is the water flux ($\mathrm{cm \cdot d^{-1}}$), and D is the hydrodynamic dispersion coefficient ($\mathrm{cm^2 \cdot d^{-1}}$).

1.2.4 Model Input

Initial and boundary conditions for soil water movement:

Initial condition: $h(z,0) = h_{ini}(z)$

Boundary conditions: - Upper boundary: $h(0,t) = h_{sur}(t)$ or $q(0,t) = q_{sur}(t)$ - Lower boundary: $h(L,t) = h_{bot}(t)$ or $q(L,t) = q_{bot}(t)$

Initial and boundary conditions for soil solute transport:

Initial condition: $C(z,0) = C_{ini}(z)$

Boundary conditions: - Upper boundary: $q(0,t)C(0,t) - \theta D \frac{\partial C}{\partial z}|_{z=0} = q_{sur}(t)C_{sur}(t)$ - Lower boundary: $\frac{\partial C}{\partial z}|_{z=L} = 0$

The simulation initial conditions were based on field experience values: initial water content at 65% of field capacity and salt content at 1 $\mathrm{g \cdot kg^{-1}}$. The upper boundary for solute transport was determined by different irrigation water concentrations, while the upper boundary for water flow used an atmospheric boundary with no surface ponding. Potential evapotranspiration (ET_p), potential soil evaporation (E_p), and potential crop transpiration (T_p) were calculated from meteorological conditions and leaf area index. First, reference crop evapotranspiration (ET_0) was calculated using the Penman-Monteith equation, then crop potential evapotranspiration (ET_p) was calculated using crop coefficients, and finally potential evaporation and transpiration were partitioned using Beer' s law:

$$T_p = ET_p \cdot e^{-k \cdot LAI}$$

$$E_p = ET_p \cdot (1 - e^{-k \cdot LAI})$$

where LAI is the leaf area index and k is the canopy extinction coefficient reflecting solar radiation attenuation in the canopy (0.60 for wheat and 0.438 for maize).

A 2 m soil profile was used for simulation. Based on the study area's groundwater depth of 5-7 m, groundwater recharge effects were neglected, and free drainage was used as the lower boundary. The simulation depth was 0–200 cm with a daily time step, minimum time step of 0.00001 d, and maximum time step of 5 d. Considering that roots are mainly distributed in the plow layer, spatial steps were finer in the upper layer and coarser in the lower layer. The 2 m profile was divided into three layers based on soil texture. The Rosetta module in Hydrus-1D was used to input particle size distribution and bulk density for each layer to obtain preliminary soil hydraulic parameters, which were further calibrated using 2004-2005 soil water and salt data from the experimental area. The calibrated soil hydraulic parameters are shown in .

TABLE:2 Calibrated parameters of the van Genuchten model

Soil depth (cm)	θ_r (cm^3 · cm^{-3})	θ_s (cm^3 · cm^{-3})	α (cm^{-1})	n	K_s (cm · d^{-1})	l	D_b (g · cm^{-3})	D (cm^2 · d^{-1})
0-20	0.045	0.43	0.145	2.68	24.96	0.5	1.42	20
20-60	0.045	0.41	0.125	2.68	24.96	0.5	1.42	20
60-200	0.045	0.39	0.105	2.68	24.96	0.5	1.42	20

1.2.5 Scenario Design

Analysis of 19 years of precipitation data (1996-2014) showed that wet years (P=25%) had 658.1 mm precipitation, normal years (P=50%) had 536.4 mm, and dry years (P=75%) had 446.8 mm. The years 2009, 2012, and 2013 were wet years, while 2008, 2010, and 2011 were normal years. Given that water consumption during winter wheat and summer maize growth periods in the North China Plain is 400-450 mm and 350-400 mm, respectively, and that precipitation during the maize growth period exceeded 400 mm in all years from 2008-2013 (), rainfall could meet maize water requirements. Therefore, irrigation research in this region focused on winter wheat with brackish water supplementation. Although the subsequent maize crop was not irrigated with brackish water, salt accumulation from the wheat season could reduce maize yield. Generally, post-sowing irrigation for maize should combine salt leaching with seedling water, meaning the amount of salt-leaching water equals the seedling water amount.

Two scenarios were designed based on different irrigation timings, each with four brackish water treatments. Irrigation amounts and timing were determined based on experimental research and practical experience. Scenario I involved three post-spring irrigations for winter wheat: brackish water at jointing and grain-filling stages, freshwater at heading stage, and salt-leaching water for summer maize after sowing set according to maize salt tolerance threshold (1.7 dS · m^{-1}) but not exceeding 120 mm. Scenario II was based on irrigation experience from the “Bohai Granary” project in Nanpi: three irrigations for winter wheat—fixed 2 g · L^{-1} brackish water in winter, brackish water at jointing stage, freshwater at flowering stage, and fixed 70 mm seedling water for summer maize. Both scenarios used 60 mm irrigation quotas for winter wheat with four salinity treatments: 2, 3, 4, and 5 g · L^{-1}. Specific irrigation treatments are shown in .

TABLE:3 Precipitation during wheat and corn growth periods (2007-2013)

Year	Wheat period	Corn period	Annual
2007-2008	63.9	401.5	465.4

Year	Wheat period	Corn period	Annual
2008-2009	124.8	533.4	658.2
2009-2010	63.9	533.4	597.3
2010-2011	124.8	401.5	526.3
2011-2012	63.9	533.4	597.3
2012-2013	124.8	533.4	658.2

TABLE:4 Irrigation water quality and amount of winter wheat-summer maize system at different growth stages under different modeling scenarios in Nanpi County, Hebei Province

Scenario I			Scenario II		
Wheat	**Corn**	**Wheat**	**Corn**		
Irrigation time	Water quality	Salinity (g · L^{-1})	Irrigation amount (mm)	Irrigation time	Water quality
Jointing	Saline water	2-5	60	Winter period	Saline water
Heading	Fresh water	<1	60	Jointing	Saline water
Grain filling	Saline water	2-5	60	Flowering	Fresh water
Before sowing	Fresh water	<1	Variable	Before sowing	Fresh water

The simulation period covered six years from 2007-2013. Winter wheat was sown on October 13 and harvested on June 7 (238-day growth period), while summer maize was sown on June 10 and harvested on October 2 (115-day growth period). Irrigation timings for winter wheat winter survival, jointing, heading, flowering, and grain-filling stages were December 1, early March, mid-April, late April, and mid-May, respectively, with specific dates adjusted based on monthly rainfall timing and intensity.

2.1 Model Calibration and Validation

Data from Nanpi experiments in 2004 and 2005 were used for model calibration and validation, respectively, comparing simulated and measured soil water and salt contents in the 0-40 cm main root zone of winter wheat.

The 2004 experiment consisted of a 195 mm irrigation quota for winter wheat: 60 mm pre-sowing water (freshwater, 0.84 $g \cdot L^{-1}$), 45 mm jointing water (freshwater, 0.84 $g \cdot L^{-1}$), 45 mm heading water (freshwater, 0.84 $g \cdot L^{-1}$), and 45 mm grain-filling water (brackish water, 3 $g \cdot L^{-1}$). Four observation points were set at 10, 20, 30, and 40 cm depths in the main root zone, with simulated values taken as weighted averages. Calibration results are shown in [Figure 1: see original paper]. The results indicated good agreement between simulated and measured soil water content and soil solution salinity before and after the first two irrigations, with larger deviations around grain-filling irrigation. The root mean square error and coefficient of determination for water content were 0.0418 $cm^3 \cdot cm^{-3}$ and 0.7264, respectively, while those for salt content were 0.9271 $g \cdot L^{-1}$ and 0.5023, respectively.

FIGURE:1 Comparison between simulated and measured water contents (A) and salt contents (B) of 0–40 cm soil of winter wheat in Nanpi County, Hebei Province in 2004

The 2005 experiment included three post-spring irrigations (jointing-heading-grain-filling) with three treatments: fresh–fresh–fresh, fresh–saline–saline, and fresh–fresh–saline. The concentrations of pre-sowing, fresh, and saline water and irrigation amounts were the same as in the 2004 experiment. Validation results are shown in [Figure 2: see original paper]. Water content simulation was satisfactory, with minimum root mean square error of 0.029 and maximum coefficient of determination of 0.9587. For salt content, although deviations between simulated and measured values were larger around grain-filling irrigation, the overall simulation effect was acceptable and generally reflected the dynamic change trend of soil salinity in the main root zone. Overall, the model performance was acceptable, parameters were reliable, and the model could be used for practical simulation applications.

FIGURE:2 Comparison between simulated and measured water contents and salt contents at different irrigation modes during the validation in 2005 (F: freshwater irrigation, water salinity 0.84 $g \cdot L^{-1}$; S: saline water irrigation, water salinity 3.0 $g \cdot L^{-1}$; three irrigations at jointing, heading, and grain-filling stages)

2.2 Simulation Results Analysis

The calibrated soil water and salt transport model was used to simulate soil water and salt transport processes for Scenarios I and II.

2.2.1 Scenario I

1) Irrigation water consumption

In Scenario I, all four brackish water treatments used 120 mm of brackish water (two irrigations at jointing and grain-filling stages). Freshwater consumption included pre-sowing irrigation for wheat (only needed in 2007–2008), heading water (60 mm), and maize seedling water. As shown in [Figure 3: see original paper], because 2008, 2010, and 2011 were normal years, salt-leaching water consumption combined with summer maize seedling water was relatively large, mostly reaching 120 mm. In contrast, 2009, 2012, and 2013 were wet years, where rainfall conditions reduced salt-leaching water requirements. For example, at 3 $g \cdot L^{-1}$, the maize seedling water amounts were 0, 120, and 30 mm in the three wet years. To ensure root zone salinity remained below the maize salt tolerance threshold during the seedling stage, freshwater consumption increased with brackish water concentration, as evident from the trend in freshwater consumption in the sixth year. The six-year average salt-leaching water consumption combined with summer maize seedling water for the 2, 3, 4, and 5 $g \cdot L^{-1}$ treatments was 64, 101, 105, and 118 mm, respectively ([Figure 4: see original paper]).

2) Actual evapotranspiration

After four irrigation treatments with 2–5 $g \cdot L^{-1}$ salinity, actual evapotranspiration of winter wheat did not vary with irrigation water salinity, indicating minimal salt stress impact on wheat. Interannual variation in wheat evapotranspiration was mainly affected by rainfall during the growth period. For example, rainfall during the 2009–2010 and 2010–2011 wheat growth periods was 124.8 mm and 63.9 mm, respectively, while evapotranspiration was 474 mm and 409 mm. However, summer maize evapotranspiration was more significantly affected by salt stress, particularly in the normal year 2010–2011, where evapotranspiration decreased from 363 mm and 342 mm to 351 mm and 325 mm as salinity increased from 2–5 $g \cdot L^{-1}$ ([Figure 5: see original paper]).

3) Salt accumulation increment

During 2007-2011, soil salt accumulation increased with irrigation water salinity and accumulated over time. During 2012–2013 (wet years), salt accumulation increments began to decrease due to salt leaching by heavy rainfall, and after two years of rainfall leaching, soil salt accumulation was substantially reduced ([Figure 6: see original paper]). The final salt accumulation per unit area in the 2 m soil profile for the 2, 3, 4, and 5 $g \cdot L^{-1}$ treatments was 25.36, -4.88, 28.24, and 12.82 $mg \cdot cm^{-2}$, respectively. Except for the 3 $g \cdot L^{-1}$ treatment which showed desalination, all other treatments exhibited slight salt accumulation. The 2 $g \cdot L^{-1}$ treatment did not achieve desalination because the salt-leaching water consumption combined with seedling water was relatively small (64 mm).

4) Soil profile salinity concentration changes in the 2 m profile

As shown in [Figure 7: see original paper], salt accumulation mainly occurred below 1 m depth because most surface salts migrated to deeper soil layers through irrigation and rainfall leaching. Higher irrigation salinity resulted in higher salt content and more obvious accumulation in deeper layers. The 0–100 cm layer maintained relatively low salt content, staying below 4 $g \cdot L^{-1}$ from June each year to April of the following year. After two brackish water irrigations at jointing and grain-filling stages, soil salinity increased significantly, and strong evapotranspiration caused continuous upward salt movement. The period from April to June had the highest soil salinity concentrations, with peaks exceeding 8 $g \cdot L^{-1}$. Salinity in the lower layer (100–200 cm) increased continuously over time, with the high-concentration zone (~9 $g \cdot L^{-1}$) gradually moving upward during the first five years, particularly prominent under 4 and 5 $g \cdot L^{-1}$ treatments. The boundary of the 9 $g \cdot L^{-1}$ concentration zone rose from 140 cm to 100 cm during 2008-2012. In 2012-2013, influenced by rainfall, the soil profile began to show obvious desalination trends, with the high-concentration zone descending below 180 cm by the end of the 2013 maize season.

2.2.2 Scenario II

1) Irrigation water consumption
This scenario represents the existing brackish water irrigation pattern and salt leaching method in Nanpi: 2 $g \cdot L^{-1}$ brackish water irrigation during winter survival period, brackish water irrigation at jointing stage (2, 3, 4, and 5 $g \cdot L^{-1}$ treatments), freshwater irrigation at flowering stage, and fixed 70 mm seedling water for maize each year. Except for 60 mm freshwater pre-sowing irrigation in the first year, wheat received freshwater only at flowering stage in other years. Except for rainfall at maize sowing in the second year, maize received 70 mm seedling water in other years. Annual freshwater consumption was 190 mm in 2007-2008, 60 mm in 2008-2009, and 130 mm in the remaining four years. Annual brackish water consumption was 120 mm. The multi-year average salt-leaching water consumption combined with seedling water and brackish/fresh irrigation amounts are shown in [Figure 4: see original paper].

2) Actual evapotranspiration
Trends in evapotranspiration with irrigation water salinity and hydrological year type in Scenario II were similar to Scenario I: wheat was less affected by salt stress, with interannual variation influenced by rainfall; maize was more affected by salt stress, with evapotranspiration decreasing as salinity increased in 2010 and 2011 ([Figure 8: see original paper]).

3) Salt accumulation increment
After six years, salt accumulation increments for the four treatments (2, 3, 4, and 5 $g \cdot L^{-1}$) were -62.29, -38.32, -15.49, and 5.90 $mg \cdot cm^{-2}$, respectively. The 2-4 $g \cdot L^{-1}$ treatments achieved desalination in the 2 m profile, while the 5 $g \cdot L^{-1}$ treatment showed slight salt accumulation. Overall, the 2 m soil profile basically did not accumulate salt under the four brackish water treatments in Scenario II ([Figure 9: see original paper]).

4) Soil profile salinity concentration changes in the 2 m profile
Upper layer (0-100 cm) salinity remained around 2 $g \cdot L^{-1}$, with peak periods occurring from April to June each year. Interannually, lower layer (100-200 cm) salinity gradually increased during 2008-2012, but the high-concentration zone (~10 $g \cdot L^{-1}$) did not move significantly upward, remaining below 120 cm. Intra-annually, salinity in the 100-160 cm zone showed a continuous decreasing trend from June to April of the following year ([Figure 10: see original paper]). Overall, Scenario II resulted in lower salinity in the upper layer and more stable salt accumulation in the lower layer.

3.1 Soil Water and Salt Dynamics Under Different Hydrological Year Types

Whether soil accumulates salt depends critically on desalination amount, which is mainly affected by natural rainfall. During the six-year simulation period (2008-2013), the soil was in a salt accumulation state every winter wheat season, while salt leaching mainly occurred during the summer maize season. In normal years (2008, 2010, and 2011), salt accumulation occurred during the maize season, while in wet years (2009, 2012, and 2013), desalination occurred with increasing amounts. Salt-leaching water consumption was closely related to bottom water leakage. Using Scenario II as an example, maize season leakage was 13 mm in 2009 (maximum 0.055 $\mathrm{cm \cdot d^{-1}}$), while in 2012 and 2013 it was 50 mm and 109 mm, respectively (maximum 0.14 and 0.61 $\mathrm{cm \cdot d^{-1}}$). This indicates that significant desalination mainly occurred during the 2012 and 2013 maize seasons.

Whether soil leakage occurs depends on rainfall and evapotranspiration during the period. In 2009, maximum rainfall intensity occurred in August (), with leaching mainly in September. In 2012 and 2013, maximum rainfall intensity was in July, but leaching occurred in August and September, indicating a time lag between peak rainfall and leaching. According to maize water demand patterns, soil evaporation and crop transpiration peaked in June and August, respectively ([Figure 11: see original paper], using 2009 as an example), indicating peak water demand in these months. If rainfall concentrated in these months, leakage might be smaller and shorter in duration. If rainfall concentrated in July or September, leakage might be larger and longer due to lower water consumption. Compared to September, heavy rainfall in July had better leaching effects because August rainfall was much greater than October rainfall, and leaching had a time lag requiring continuous rainfall of certain intensity.

3.2 Effects of Different Salinity Irrigation Water on Soil Profile Salt Distribution and Leaching Effect

Both scenarios shared common characteristics: during 2008-2011 (salt accumulation period), lower layer (100-200 cm) salinity exceeded 8 $\mathrm{g \cdot L^{-1}}$ and increased over time; upper layer (0-100 cm) salinity remained around 2 $\mathrm{g \cdot L^{-1}}$ from July to March, generally ensuring normal maize growth. A brief peak phenomenon occurred in late May to early June, reaching over 8 $\mathrm{g \cdot L^{-1}}$, coinciding with late winter wheat grain-filling stage when salt stress impact was significant. Therefore, two points require attention in brackish water irrigation: (1) controlling salt accumulation in the lower layer (salt accumulation zone) to facilitate rainy season desalination; (2) preventing excessively high upper layer salinity during late wheat grain-filling stage (above 6 $\mathrm{dS \cdot m^{-1}}$ affects wheat growth), which would not only impact wheat yield but also increase maize post-sowing salt-leaching water consumption, hindering water conservation.

In Scenario I, the 4 and 5 $\mathrm{g \cdot L^{-1}}$ double brackish water irrigation treatments resulted in excessive salt accumulation in the lower layer (upper layer salinity reached 9.1 $dS \cdot m^{-1}$ at wheat grain-filling stage), preventing salt leaching during subsequent wet-year maize seasons. Even in the normal year 2010-2011, where salt-leaching water consumption combined with seedling water reached 120 mm, leaching effects were still poor, with root zone salinity around 3 $dS \cdot m^{-1}$ during maize seedling stage, exceeding the maize salt tolerance threshold (1.7 $dS \cdot m^{-1}$). Therefore, these two brackish water irrigation patterns are not conducive to normal crop growth. The 2 and 3 $g \cdot L^{-1}$ double brackish water irrigation treatments controlled soil salinity below crop tolerance thresholds. From a water-saving perspective, the 3 $g \cdot L^{-1}$ treatment required more annual salt-leaching water (101 mm) than the 2 $g \cdot L^{-1}$ treatment (64 mm). Therefore, the 2 $g \cdot L^{-1}$ double brackish water irrigation treatment in Scenario I is a sustainable irrigation scheme.

In Scenario II, because one brackish water irrigation (2 $g \cdot L^{-1}$) was applied during winter survival period followed by one 2-5 $g \cdot L^{-1}$ brackish water irrigation at jointing stage, this pattern resulted in less salt accumulation in the lower layer. After subsequent wet-year heavy rainfall, desalination was achieved under 2, 3, and 4 $g \cdot L^{-1}$ treatments, while the 5 $g \cdot L^{-1}$ treatment showed slight salt accumulation with concentration peaks above 9 $dS \cdot m^{-1}$ at grain-filling stage. With fixed annual seedling water of 70 mm, salt concentration in the 100-120 cm zone decreased from 8 $g \cdot L^{-1}$ to about 4 $g \cdot L^{-1}$ during the period from maize seedling stage to wheat regreening stage (July to March), indicating that salt leaching was relatively easy under Scenario II.

3.3 Effects of Salt-Leaching Water Amount Combined with Seedling Water on Soil Salt Leaching

Maize season desalination is affected not only by hydrological year type but also by artificial salt leaching. Under the same hydrological year type and identical salt-leaching water amounts, desalination amounts were basically consistent across the four salinity treatments (). However, under the same hydrological year type but different salt-leaching water amounts, desalination increased with leaching water amount, particularly in wet years where irrigation for salt leaching combined with seedling water was more beneficial. For example, in Scenario I during 2012, the 2 and 3 $g \cdot L^{-1}$ double brackish water treatments had salt-leaching water amounts of 0 mm and 120 mm, with corresponding desalination amounts of 15.51 $mg \cdot cm^{-2}$ and 75.51 $mg \cdot cm^{-2}$. In 2013, the positive correlation was more evident: salt-leaching water amounts of 0, 30, 45, and 110 mm for the 2, 3, 4, and 5 $g \cdot L^{-1}$ double brackish water treatments resulted in desalination amounts of 58.61, 79.38, 98.08, and 162.11 $mg \cdot cm^{-2}$, respectively. Therefore, irrigation for salt leaching combined with seedling water is critical for soil desalination during the maize season, even in wet years.

TABLE:6 Soil salt leaching under different salt concentrations of irrigation water in summer maize period under Scenario II ($mg \cdot cm^{-2}$)

Salinity ($g \cdot L^{-1}$)	2009	2012	2013	Standard deviation
2	-7.96	-34.59	-99.99	46.02
3	-8.31	-36.67	-105.72	48.71
4	-8.75	-39.28	-111.38	51.32
5	-9.30	-42.20	-117.24	54.00

This paper comprehensively proposes suitable conditions and regimes for brackish water irrigation: (1) pre-winter irrigation with 2 $g \cdot L^{-1}$ brackish water for winter survival, followed by spring irrigation with 2-4 $g \cdot L^{-1}$ brackish water at jointing stage; (2) no pre-winter irrigation, with spring applications of 2 $g \cdot L^{-1}$ brackish water at both jointing and grain-filling stages. Under both regimes, the average annual freshwater consumption for salt leaching combined with seedling water (60-70 mm) is less than brackish water irrigation amount (120 mm), and total water consumption (250-260 mm) is relatively low, thereby improving the sustainable utilization of brackish water resources from a water-saving perspective.

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