Optimizing drip irrigation with alternate use of fresh and brackish waters by analyzing salt stress: The experimental and simulation approaches

Yuehong Zhang\textsuperscript{a}, Xianyue Li\textsuperscript{a,c,*}, Jirí Šimůnek\textsuperscript{b}, Haibin Shi\textsuperscript{a}, Ning Chen\textsuperscript{a}, Qi Hu\textsuperscript{a}

\textsuperscript{a} College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Huhhot 010018, China
\textsuperscript{b} Department of Environmental Sciences, University of California Riverside, Riverside, CA 92521, USA
\textsuperscript{c} Collaborative Innovation Center for Integrated Management of Water Resources and Water Environment in the Inner Mongolia Reaches of the Yellow River, Hohhot 010018, China

\textbf{A R T I C L E   I N F O}

Keywords:
Alternate drip irrigation
Duration and area of salt stress
HYDRUS (2D/3D)
Crop sensitivity function
Yield

\textbf{A B S T R A C T}

Drip irrigation with alternate use of fresh and brackish waters is an excellent irrigation strategy to overcome salt stress problems induced by brackish water. Understanding salt stresses in the soil profile and their relationship with crop growth is critical when optimizing irrigation strategies with alternate use of fresh and brackish waters. The HYDRUS (2D/3D) model was calibrated and validated using experimental data collected in 2019 and 2020, respectively. The calibrated model was then used to evaluate the effects of different irrigation strategies involving the use of only freshwater (FW) or brackish water (BW), or the alternative use of brackish and fresh waters (1B1F, one irrigation with brackish water and one with fresh water; 2B1F, two irrigations with brackish water and one with fresh water; and 3B1F, three irrigations with brackish water and one with fresh water) on the soil electrical conductivity (EC\textsubscript{sw}), salt stress, crop growth, and yield. In general, the model performed well, with the average RMSE, MRE, and \textit{R}\textsuperscript{2} for EC\textsubscript{sw} of 0.12 dS m\textsuperscript{-1}, 6.85\%, and 0.97, respectively. The average EC\textsubscript{sw} in the 0–40 cm soil layer (the main root zone) showed large differences between different alternate irrigation strategies, increasing by 55.9\% between FW and BW. There was a strong linear relationship between salt stress (EC\textsubscript{sw} of 3.4–11.8 dS m\textsuperscript{-1}, SS) in the main corn root zone and salts introduced by irrigation water. The SS duration and area increased with the frequency of irrigations with brackish water, while the opposite was observed for the average desalination rate (DR) after irrigation during the entire growth stage. The SS duration was 90, 111, 115, 121, and 121 days for FW, 1B1F, 2B1F, 3B1F, and BW, respectively, while the corresponding values for the duration of high salt stress (EC\textsubscript{sw} of 7.6–11.8 dS m\textsuperscript{-1}, HSS) were 4, 24, 32, 37, and 46 days, respectively, and the average DRs were 4.3\%, 2.4\%, 1.9\%, 1.7\%, and 0.8\%, respectively. Average fractions of the SS and HSS areas to the main root zone area for BW increased by 5.3\% and 26.6\% compared with FW, respectively. When the HSS duration increased by 42 days from the FW to BW scenarios, corn yield, plant height, stem diameter, and leaf area index decreased by 8.8\%, 10.4\%, 17.7\%, and 19.6\%, respectively. Additionally, the quantitative relationship between SS and corn yield, i.e., a sensitivity function of the crop yield to soil water and salt stresses, was proposed based on HYDRUS (2D/3D) simulations. The 2B1F scenario can be recommended as the optimal strategy for the studied region, using most brackish water with only a 4\% decrease in the corn yield.

1. Introduction

Irrigation is critical to guarantee food security in most arid regions and countries. However, a freshwater shortage is becoming a critical problem in most of these regions (Jennifer Clapp, 2017; Dinar et al., 2019; Shilpa et al., 2019). Generally, there is often an abundant amount (about 13.86 million km\textsuperscript{2} worldwide) of brackish water available, with a conductivity of 2–5 dS m\textsuperscript{-1} (McMahon and Price, 2011; Rozema and Flowers, 2008). The evidence shows that freshwater can often be securely replaced by brackish water in irrigated agriculture in most water-deficient countries, e.g., Israel (Kaner et al., 2017), Iran (Noshadi et al., 2013), Spain (Aparicio et al., 2019), and Mexico (Ozturk et al., 2018), if appropriate irrigation management is used (Xie et al., 2017; Hassanli et al., 2016; Cucci et al., 2019; Ahdab et al., 2020). In the western regions of China, due to severe drought, less rain, and an extreme shortage of freshwater (Yuan et al., 2019), brackish water has...
be used for large-scale agricultural irrigation in an area of about 3 million hectares (Hu et al., 2020; Wang and Qin, 2017; Chen et al., 2010).

However, the use of brackish water often leads to high soil salinization (Zhang et al., 2021). Secondary soil salinization inevitably occurs when irrigation with brackish water is applied continuously without any other measures (Bakker et al., 2010; He et al., 2017; Aragüés et al., 2015), resulting in a decrease in soil productivity (Khan et al., 2004) and sustainability (Brouwer et al., 1985). When soil salinity exceeds a certain threshold (Ayers and Westcot, 1976), crop physiological drought occurs (Li et al., 2015a, 2015b), resulting in a low crop yield (Ben Ahmed et al., 2012; Yang et al., 2020). Therefore, excess brackish water has usually been used to leach salts from the root zone, decrease soil salinity, and prevent salt stress (SS) (Zeng et al., 2014; Libutti and Montelone, 2012). However, it is impossible to thoroughly leach salts from the soil profile by irrigation with brackish water. Soil salts usually accumulate at the edge of the main root zone after irrigation concludes, resulting in crop growth still being restrained by SS (Zhang et al., 2019a, 2019b; Groenveld et al., 2013).

Drip irrigation under plastic film is used worldwide due to its advantageous agronomic, water conservation, and economic aspects (Lazarovitch et al., 2009; Jia et al., 2020). However, since drip irrigation applies water at single points in space, salts are frequently pushed towards the fringes of the wetting area (Chen et al., 2009) and accumulate in the root zone. The conjunctive use of brackish water and freshwater for irrigation, such as blending and alternate irrigation (Dudley et al., 2008; Kulkarni, 2011; Ghermandi et al., 2014), is an important way to overcome SS problems caused by the exclusive use of brackish water (Rhoades, 1984; Kondash et al., 2016). Some studies have indicated that the alternate use of brackish water and freshwater is better than blending, having high efficiency in decreasing soil salinity and increasing crop yield (Bradford and Letey, 1992; Naresh et al., 1993a; Minhas et al., 2007; Li et al., 2019). For instance, when freshwater was used at the corn jointing stage, the desalination rate (DR) increased by 59% under brackish water drip irrigation (Zhang et al., 2021). Furthermore, sunflower’s average yield and water productivity increased by 8.2% and 7.6%, respectively, for alternate irrigation with brackish and fresh waters compared to irrigation with freshwater only (Xue and Ren, 2017).

Although soil desalination can be effectively improved by increasing the amount or frequency of freshwater irrigation (Raij et al., 2016), freshwater is often a very scarce resource in arid and semi-arid regions (Li et al., 2015). It is thus necessary to limit the use of freshwater as much as possible without significantly reducing crop growth. Research needs to be carried out to reveal the relationship between irrigation, SS, and crop yield. At present, many field experiments have been conducted, but they are very time-consuming, labor-intensive, and costly (Zhang et al., 2018). Fortunately, physical and mathematical models can partially replace experimental work (Liu et al., 2019; Wan et al., 2021; Li et al., 2018). Different irrigation strategies of conjunctive use of brackish and fresh waters on soil water and salt movement have been successfully evaluated by many models, such as SWAP (Kroes et al., 2000; Kumar et al., 2015; Yuan et al., 2019), SALTMED (Karandish and Simunek, 2019), and HYDRUS (Kanzari et al., 2018; Yang et al., 2019). There also exist models (i.e., yield reduction models) that directly relate soil salinity and crop yield (Ayers and Westcot, 1976; van Genuchten and Hoffman, 1984; Qiu et al., 2017), and CropSyst (Stockle et al., 1994). These SS crop sensitivity functions indicate that yield decreases (non) linearly with increased salinity and percent water depletion (Walland Yitayew, 2016) and, due to their simplicity and effectiveness, have been standard FAO tools (Doorenbos and Kassam, 1979; Allen et al., 1998). Some comprehensive models, such as DSSAT (Garibay et al., 2019), SIMDualKc (Anupoju and Kambhammettu, 2020), or AquaCrop (López-Urrea et al., 2020) even directly simulate soil salt dynamics and crop yield. However, the above-discussed comprehensive models cannot simulate the alternate use of brackish and fresh waters. Thus, numerical models need to distinguish between different irrigation water qualities and simulate detailed distributions of soil water and salts in the soil profile and their effects on root water uptake and crop yield.

HYDRUS (2D/3D) is likely the most popular model that can carry out such simulations due to its comprehensive nature and flexibility in accommodating different types of boundary and initial conditions (Phogat et al., 2012; Simunek et al., 2016; Mao et al., 2020). However, optimizing an irrigation strategy of alternate use of brackish and fresh waters requires the knowledge of SS in the soil profile and the relationship between SS and yield. Currently, studies evaluating alternate drip irrigation with brackish and fresh waters are rare, especially those jointly applying HYDRUS (2D/3D) and water and SS crop sensitivity functions. Hence, the main objectives of this study are: (1) to calibrate and validate HYDRUS (2D/3D) and a crop sensitivity function using measured soil water contents, soil salinities, and corn yields, (2) to evaluate electrical conductivities and SS in the root zone under alternate drip irrigation, (3) to analyze the effects of SS on crop growth and yield under alternate drip irrigation, and (4) to optimize an alternate drip irrigation strategy.

2. Material and methods

2.1. Experimental site

The experiments were conducted in 2019 and 2020 at the Jiuzhuang Water Saving Comprehensive Station in the middle of the Hetao Irrigation District, in the Yellow River basin of Northwest China (40°1’ N, 107°18’ E). The region has a temperate continental monsoon climate with annual sunlight of 3230 h and an average air temperature of 6.8°C. Mean annual rainfall and open water surface evaporation are 137.6 and 2332 mm, respectively. Total 2019 and 2020 rainfalls at the site during the crop growth were 87.9 and 144.7 mm, respectively (Fig. 1). The average clay, sand, and silt contents in the top 0–100 cm soil layer are 4.3%, 70.3%, and 25.4%, respectively. The soil type was classified as silt loam (e.g., United States Department of Agriculture, 2010) with an average bulk density of 1.42 g cm$^{-3}$ and field capacity ($\theta_{fc}$) of 0.41 cm$^3$.
The salinity conditions were classified as low (Abrol et al., 1988). The groundwater table depth was 1.3–2.4 m during the experiment, with an average electrical conductivity of 0.96 dS m\(^{-1}\).

### 2.2. Experimental design and arrangement

Five irrigation strategies were considered: (a) irrigation with freshwater only (FW), (b) alternating one irrigation with brackish water and one with freshwater (1B1F), (c) two irrigations with brackish water and one with freshwater (2B1F), (d) three irrigations with brackish water and one with freshwater (3B1F), and (e) irrigation with brackish water only (BW). All treatments had the same irrigation frequencies and amounts. A detailed irrigation schedule is shown in Fig. 1. The experimental scheme considered three repetitions per treatment, using a complete randomized block design with 15 field plots. Each plot had a length of 20 m and a width of 7 m.

Corn seeds (Z mays L.) were sown on May 1 and May 4 and harvested on September 17 and September 25 in 2019 and 2020, respectively. Drip irrigation under plastic film was performed with a single line of drip tape with an emitter discharge of 2.4 L h\(^{-1}\). The plastic film with drip tape was installed by a specialized machine. The average electrical conductivities of fresh and brackish waters were 0.31 and 3.7 dS m\(^{-1}\), respectively. The irrigation quota was 22.5 mm per irrigation event, and the total irrigation amount during the corn growth stage was 270 mm in each treatment in both 2019 and 2020. Before sowing, based on the soil analysis recommendation, basal fertilizer with 140 kg ha\(^{-1}\) of diammonium phosphate ((NH\(_4\))\(_2\)HPO\(_4\), N \(\geq\) 18%), 140 kg ha\(^{-1}\) of potassium sulfate (K\(_2\)SO\(_4\)), and 50 kg ha\(^{-1}\) of carbamide (CO(NH\(_2\))\(_2\), N \(\geq\) 32%) was applied. The solubilized topdressing fertilizer was carbamide (CO(NH\(_2\))\(_2\), N \(\geq\) 32%), which was applied during the elongation stage (30% of the total N-fertilizer) and the grain-filling stage (30% of the total N-fertilizer), each time accompanied with drip irrigation.

### 2.3. Measurements and methods

#### 2.3.1. Measurements

Meteorological data, including air temperature, air humidity, atmospheric pressure, wind speed, and precipitation, were obtained from an automatic meteorological station (Onset Computer Inc.; U30, Hobo, USA). Reference crop evapotranspiration (\(ET_0\)) was calculated using the Penman-Monteith approach (Allen et al., 1998). Potential
evapotranspiration ($ET_p$) was obtained by multiplying $ET_0$ with the crop coefficient ($K_c$), which was obtained for corn from the FAO paper 56 (i.e., 0.7, 1.2, and 0.35 during the early, middle, and late growth stages, respectively) (Allen et al., 1998). Additionally, $ET_p$ was divided into potential evaporation ($E_{vp}$, mm day$^{-1}$) and transpiration ($T_p$, mm day$^{-1}$) using Beer’s law (Campbell and Norman, 1989):

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

(1)

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

(2)

where $k$ is the extinction coefficient of corn (0.39), and $LAI$ is the leaf area index.

Soil water contents (SWC) and soil potentials were measured by TDR probes (IMKO GmbH Inc.; IPH, TRIME-PICO, Germany) and tensiometers (Zhonghui Inc.; ZKNT-100, China), respectively, which were installed under the drip tape and bare area (Fig. 2). SWCs were taken once every 5–7 days at soil depths of 0–10, 10–30, 30–50, 50–70, and 70–100 cm, while soil potentials were measured only at depths of 90 and 110 cm. Soil sample measurements verified the TDR probe at periodic intervals. The soil samplings were divided into two groups, one for measuring SWCs and another for electrical conductivities of the saturation extract ($EC_s$).

$EC_s$ were measured once every two weeks at the same locations as SWCs. $EC_s$ values were determined in a laboratory (Rhoades, 1993). From each sample, approximately 300 g of soil was air-dried and saturated with distilled water for 24 h. A vacuum system extracted soil solutions through a No. 1 Whitman paper filter in Buchner funnels. Ultimately, $EC_s$ was measured by a conductivity meter (Shanghai Youke Instrument and Meter Co., ltd.; DDS-307A, CHN). $EC_{sw}$ is assumed to be twice as large as $EC_s$ (Ayers and Westcot, 1976). The titration method was used to determine the soil salt concentrations (i.e., contents of Ca$^{2+}$, Mg$^{2+}$, Cl$^-$, SO$^2-$, HCO, and CO$^2-$) based on the specification of soil tests, SL237–1999 (Ministry of Water Resources of the People’s Republic of China, 1999).

The position of the groundwater table and its electrical conductivity were obtained using an automatic water level logger (Onset Computer Inc.; U20L-01, Hobo, USA) and an automatic water conductivity data logger (Onset Computer Inc.; U24-001, Hobo, USA), respectively, installed in an observation well in the field.

Five corn plants from each plot were selected to measure the plant height, stem diameter, leaf length, and leaf width once every 7–14 days. The corn leaf area was calculated as: 0.75 $\times$ leaf length $\times$ leaf width, and the leaf area index ($LAI$) was calculated using the FAO method (Allen et al., 1998). Ten corn plants from each plot were randomly selected at harvest to measure the grain number per cob and the 100-grain drying weight. The corn yield for each treatment was obtained from the mean value of three replicates (Chen et al., 2021a, 2021b; Mueller and Vyn, 2018).

2.3.2. Desalination rate, relative salt stress, and duration

The crop root zone was divided into four regions for exploring salt stress (SS) and desalinization in more detail. The mulched (0–30 cm) and non-mulched regions (30–50 cm) were distinguished in the horizontal direction, and the main (0–40 cm) and secondary (40–100 cm) root zones were distinguished in the vertical direction (Fig. 2), resulting in regions I (top left, 30 $\times$ 40 cm$^2$), II (top right, 20 $\times$ 40 cm$^2$), III (bottom left, 30 $\times$ 60 cm$^2$), and IV (bottom right, 20 $\times$ 60 cm$^2$).

In the study, SS was considered to be low, moderate, and high, with an average $EC_{sw}$ in the zone of 3.4–5.0 dS m$^{-1}$ (LSS), 5.0–7.6 dS m$^{-1}$ (MSS), and 7.6–11.8 dS m$^{-1}$ (HSS), which corresponds to about 10%, 25%, and 50% corn yield reduction, respectively (Rhoades et al., 1989). The SS area was calculated using Image J-1.6 (National Institutes of Health, USA).

The SS duration was defined as the number of days when the average $EC_{sw}$ in the zone exceeds 3.4 dS m$^{-1}$ during the growth period. The desalination rate ($DR$, %) was calculated as a fraction of the $EC_{sw}$ difference before and after irrigation and the $EC_{sw}$ before irrigation in the zone as follows:

$$DR = \frac{EC_s - EC_{sw}}{EC_s} \times 100$$

(3)

where $EC_s$ and $EC_{sw}$ are $EC_{sw}$ before and after irrigation (dS m$^{-1}$) in the zone, respectively.

2.3.3. Crop sensitivity function to water and salt stress

The sensitivity function of the crop yield to soil water and salt stresses was described by Doorenbos and Kassam (1979) and Allen et al. (1998) as follows:

$$Y_s = (1 - K_s) \cdot Y_{max}$$

(4)

where $Y_s$ is actual corn yield under SS, $Y_{max}$ is the maximum corn yield without SS, $K_s$ is the crop sensitivity to water stress (1.25 according to Allen et al., 1998), and $K_s$ is the combined salt and water stress coefficient, i.e., 0.82–0.78 (Doorenbos and Kassam, 1979; Allen et al., 1998).

2.4. HYDRUS (2D/3D)

2.4.1. Model description

The HYDRUS (2D/3D) model simulates the two-dimensional movement of soil water and salts by solving the Richards (Richards, 1931) and convection-dispersion equations, respectively. A detailed description can be found in Simaneck et al., 2016.

Root water extraction was computed according to the Feddes model (Feddes et al., 1978; Simanek et al., 2018) adapted for two-dimensional conditions and simultaneous water and salinity stresses:

$$S(h, h_s) = a(h, h_s)J(x, z, t)LT_p$$

(5)

where $a(h, h_s)$ is the water and osmotic stress function ($\sigma$), $J(x, z, t)$ is the normalized spatial root water uptake distribution (cm$^{-2}$), $L$ is the width of the soil surface associated with transpiration (cm), and $T_p$ is the potential transpiration rate (cm day$^{-1}$). The multiplication model was used to account for combined water and salinity stresses. The root water uptake reduction due to water stress was simulated using the piece-wise linear function of Feddes et al. (1978), with default HYDRUS (2D/3D) parameters for corn. The root water uptake reduction due to salinity stress was simulated using the salinity threshold ($EC_s$) and slope function (Mans, 1990). The salinity threshold and slope for corn were set to 3.4 dS m$^{-1}$ and 12%, respectively (Karandish and Simaneck, 2019).

The soil hydraulic properties (i.e., $\theta(h)$ and $K(h)$) are represented in the HYDRUS (2D/3D) model using the analytical functions of van Genuchten (1980):

$$\theta(h) = \left\{ \begin{array}{ll}
\theta_r + \frac{\theta_i - \theta_r}{\left[ 1 + \left( \frac{|ah|}{s_h} \right) \right]^{m}} & \text{if } h < 0 \\
\theta_r & \text{if } h \geq 0
\end{array} \right.$$  

(6)

$$K(h) = K_s \left[ 1 - \left( 1 - \frac{h}{S_h} \right)^{-\frac{1}{\alpha}} \right]^{-\frac{m}{\alpha}}, m = \frac{1}{n}, S_h = \frac{\theta_i - \theta_r}{\theta_i - \theta_r}$$

(7)

where $\theta_r$ is the residual volumetric water content (cm$^3$ cm$^{-3}$), $\theta_i$ is the saturated volumetric water content (cm$^3$ cm$^{-3}$), $K_s$ is the saturated hydraulic conductivity (cm day$^{-1}$), $a$ (cm$^{-1}$), $n$ (c), and $m$ (c) are empirical parameters, $S_h$ is the effective saturation ($\sigma$), and $I$ is the pore connectivity parameter.

2.4.2. Initial and boundary conditions

A rectangular two-dimensional transport domain (50 cm wide and 250 cm deep) was defined between the dripper and the middle of the
bare area (Fig. 2). The modeled domain was discretized using the non-uniform triangular finite element mesh generated by the HYDRUS (2D/3D) model. SWCs and \( E_{\text{SWC}} \) (twice \( E_{\text{FW}} \)) measured at the beginning of the experiment of each year were used as initial conditions. The top and bottom SWCs were 0.19 and 0.35 cm\(^3\) cm\(^{-3}\), respectively, and \( E_{\text{SWC}} \) were 3.14 and 3.2 dS m\(^{-1}\), respectively. The no-flux and atmospheric (to apply precipitation/irrigation and potential evaporation \( E_{\text{P}} \)) boundary conditions (BCs) were assigned to the top 0–30 and 30–50 cm boundaries (Fig. 2), respectively, depending on whether plastic film mulching at the soil surface was used or not. A 0.8-cm wide variable flux BC was specified at the left corner of the soil surface to represent the dripper. The potential transpiration \( T_{\text{P}} \) flux was specified to account for plant water uptake. A variable head BC was used at the bottom boundary to represent the position of the groundwater table. Left and right boundaries were assigned a no-flux BC. Additionally, a third-type BC was used to describe \( E_{\text{SWC}} \) fluxes along the top and bottom boundaries.

### 2.4.3. Model parameters

Soil hydraulic parameters (i.e., \( \theta_s, \theta_r, \alpha, n, \) and \( K_s \)) were obtained using the soil bulk density and percentage contents of sand, silt, and clay using the Rosetta module of HYDRUS (2D/3D). These values of soil hydraulic parameters were further manually calibrated by comparing simulated and observed values of SWCs and \( E_{\text{SWC}} \) (Zhang et al., 2021). The longitudinal dispersivities for the two soil layers were 50 and 28 cm. The transversal dispersivities for the two soil layers were 4 and 3 cm. Since molecular diffusion can usually be neglected, the molecular diffusion coefficient was set to zero (Radcliffe and Simůnek, 2010).

### 2.5. Scenario simulation

The soil salinity \( (E_{\text{SWC}}) \) for different drip irrigation strategies involving the use of only freshwater (FW) or brackish water (BW), or the alternative use of brackish and fresh waters (1B1F, 2B1F, and 3B1F), corresponding to the two-year field experiments, was simulated using the HYDRUS (2D/3D) model. Additionally, \( E_{\text{SWC}} \) and salt stress were analyzed using HYDRUS (2D/3D) for three additional scenarios (without corresponding experiments) involving alternating three irrigations with fresh water and one with brackish water (3F1B), two irrigations with fresh water and one with brackish water (2F1B), and one irrigation with fresh water and one with brackish water (1F1B). Meanwhile, corn yields for all eight scenarios were predicted using the crop yield sensitivity function to soil water and salt stresses.

### 2.6. Model performance criteria

The agreement between simulated and measured values of each treatment was evaluated using the root mean square error (RMSE), the mean relative error (MRE), and the coefficient of determination \( (R^2) \) (Gong et al., 2021; Chen et al., 2021a, 2021b):

\[
RMSE = \left[ \frac{1}{N} \sum_{i=1}^{n} (S_i - M_i)^2 \right]^{1/2}
\]

\[
MRE = \frac{1}{N} \sum_{i=1}^{n} \left| \frac{S_i - M_i}{S_i} \right| \times 100
\]

\[
R^2 = \frac{\sum_{i=1}^{n} (M_i - \overline{M})(S_i - \overline{S})}{\sqrt{\sum_{i=1}^{n} (M_i - \overline{M})^2 \sum_{i=1}^{n} (S_i - \overline{S})^2}}
\]

where \( n \) is the number of data points, \( S_i \) and \( M_i \) are simulated and measured values, respectively, and \( \overline{S} \) and \( \overline{M} \) are the mean values of simulated and measured values, respectively.

### 3. Results

#### 3.1. Calibration and verification

Measured values of SWC and \( E_{\text{SWC}} \) for different alternate irrigation strategies at different locations during 2019 and 2020 were used for model calibration and validation, respectively. Generally, HYDRUS (2D/3D) can well capture SWC and \( E_{\text{SWC}} \) under alternate irrigation strategies (Table 1). The average RMSE, MRE, and \( R^2 \) for SWC were 0.02 and 0.05 cm\(^3\) cm\(^{-3}\), 7.11% and 9.16%, and 0.90 and 0.95 during calibration (2019) and validation (2020) periods, respectively. Average RMSEs for the 0–10, 10–40, 40–60, and 60–100 cm soil layers were 0.13, 0.11, 0.09, and 0.07 dS m\(^{-1}\) during the calibration period, and 0.14, 0.11, 0.11, and 0.09 dS m\(^{-1}\) during the validation period, respectively. The MREs of \( E_{\text{SWC}} \) were 3.7–11.5% and 3.2–9.9% during the calibration and validation periods, respectively. The coefficients of determination \( R^2 \) of \( E_{\text{SWC}} \) were 0.95–0.98 and 0.97–0.98 during the calibration and validation periods, respectively. Additionally, visual inspection (Fig. 3) showed that there was also strong consistency between simulated and measured \( E_{\text{SWC}} \) for different alternate irrigation strategies.

### 3.2. Effects of alternate irrigation strategies on \( E_{\text{SWC}} \)

There were apparent differences between \( E_{\text{SWC}} \) in the 0–40 cm soil layer (the main root zone) under different alternate irrigation strategies. However, only small differences appeared in the 40–100 cm soil layer due to irrigation or precipitation events, especially in the 0–10 cm soil layer. In general, \( E_{\text{SWC}} \) increased from sowing to harvest for all alternate irrigation strategies, but the differences were quite apparent among different treatments. For example, the average \( E_{\text{SWC}} \) in the 0–10 cm soil layer increased by 0.042, 0.056, 0.060, 0.059, and 0.077 dS m\(^{-1}\) day\(^{-1}\) for the FW, 1B1F, 2B1F, 3B1F, and BW strategies in both years, respectively. The average \( E_{\text{SWC}} \) in the main root zone for FW, 1B1F, 2B1F, and 3B1F was 27.7%, 13.3%, 8.7%, and 6.7% lower, respectively, than for BW during both years. Additionally, \( E_{\text{SWC}} \) in the main root zone significantly decreased after irrigation with freshwater, while an obvious decrease in \( E_{\text{SWC}} \) only appeared during the late crop growth stage due to higher \( E_{\text{SWC}} \) in the 0–40 cm soil layer after irrigation with

### Table 1

The root mean square errors (RMSE), mean relative errors (MRE), and coefficients of determination \( (R^2) \) for soil water contents (SWC) and soil water electrical conductivities \( (E_{\text{SWC}}) \) during 2019 (calibration) and 2020 (validation) under alternate drip irrigation strategies with fresh and brackish waters, i.e., scenarios FW, 1B1F, 2B1F, 3B1F, and BW.

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>SWC (RMSE cm(^3) cm(^{-3}))</th>
<th>2019 (calibration)</th>
<th>2020 (validation)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MRE (%)</td>
<td>1B1F</td>
<td>2B1F</td>
</tr>
<tr>
<td>2019</td>
<td>FW</td>
<td>0.05</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>1B1F</td>
<td>8.13</td>
<td>7.52</td>
<td>7.32</td>
</tr>
<tr>
<td></td>
<td>2B1F</td>
<td>0.93</td>
<td>0.95</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>3B1F</td>
<td>0.09</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>BW</td>
<td>7.99</td>
<td>6.16</td>
<td>5.89</td>
</tr>
</tbody>
</table>

- RMSE: root mean square error
- MRE: mean relative error
- \( R^2 \): coefficient of determination

Y. Zhang et al. Soil & Tillage Research 219 (2022) 105355
brackish water (Fig. 3). Average desalination rates (DR) increased with frequency of freshwater irrigation, and average DR after 12 irrigation events were 4.3%, 2.4%, 1.9%, 1.7%, and 0.8% for FW, 1B1F, 2B1F, 3B1F, and BW, respectively.

3.3. The effects of alternate irrigation strategies on salt stress

Only salt stress (SS) in the soil profile during the 2020 season was analyzed in our study because of the high similarity between 2019 and 2020. There was an apparent difference in SS ($EC_{sw}$ of 3.4–11.8 dS m$^{-1}$) among different alternate irrigation strategies after the last irrigation during 2020. SS increased in response to an increase in the frequency of brackish water irrigation (Fig. 4). Also, the SS duration in the 0–40 cm soil layer (the main root zone) increased with an increase in brackish water irrigation frequency, being 90, 111, 115, 121, and 121 days for FW, 1B1F, 2B1F, 3B1F, and BW, respectively (Fig. 5). Larger differences appeared in high salt stress ($EC_{sw}$ of 7.6–11.8 dS m$^{-1}$, HSS) and middle salt stress ($EC_{sw}$ of 5.0–7.6 dS m$^{-1}$, MSS). The HSS duration for 1B1F,
water salinity was FW, respectively, and decreased by 5, 10, 12, and 20 days for MSS. 2B1F, 3B1F, and BW increased by 20, 28, 33, and 42 days compared to Fig. 4. Additionally, the relationship between the HSS duration and irrigation water salinity was $y = 12.1x - 3.7$ ($R^2 = 0.99$).

SS mainly appeared in the main root zone (top 0–40 cm of the mulched region (zone I) and the non-mulched region (zone II)). An average fraction of the SS area to the main root zone area under FW, 1B1F, 2B1F, 3B1F, and BW was 39.0%, 44.2%, 45.2%, 46.0%, and 47.9%, respectively, during the entire crop growth season (Fig. 5). In zone I, a fraction of the HSS area increased with increasing brackish water irrigation frequency by 1.2, 1.6, 1.7, and 3.5 for 1B1F, 2B1F, 3B1F, and BW compared with FW. In zone II, it increased by 1.0, 1.4, 1.5, and 2.2, respectively. The MSS area behaved similarly to the HSS area; its fraction increased by 6.0%, 7.4%, 8.2%, and 10.1% for 1B1F, 2B1F, 3B1F, and BW compared with FW in zone I, respectively, and 1.1%, 1.4%, 2.1%, and 2.5% in zone II. Additionally, only low salt stress ($EC_{sw}$ of 3.4–5.0 dS m$^{-1}$, LSS) occurred in zone III (bottom 40–100 cm of the mulched region) and IV (bottom 40–100 cm of the non-mulched region). Additionally, the relationship between the HSS area and irrigation water salinity was $y = 0.11x + 0.06$ ($R^2 = 0.93$).

### 3.4. Response of corn growth and yield to salt stress

The corn height, stem diameter, LAI, and yield decreased with an increase in the average fraction of the SS area (Fig. 6). When this fraction increased by 5.2%, 6.1%, 7.0%, and 8.8% for 1B1F, 2B1F, 3B1F, and BW compared with FW, the corn yield decreased by 2.4%, 3.8%, 4.9%, and 18.8%, respectively. Additionally, the corn height, stem diameter, and LAI decreased by 10.4%, 17.7%, and 19.6%, respectively, for BW compared with FW. When the average fraction of the HSS area increased by 2.9% compared with FW, the corn height, stem diameter, LAI, and corn yield decreased by 38.5 cm, 0.59 cm, 1.0, and 2.3 t ha$^{-1}$, respectively. Meanwhile, the SS duration also significantly affected corn growth and yield. When the SS duration increased by one day, the corn yield, height, stem diameter, and leaf area decreased on average by 0.07 t ha$^{-1}$, 1.24 cm, 0.02 cm, and 0.03, respectively (Fig. 6). However, when the HSS duration increased by one day, the corn yield, height, stem diameter, and leaf area decreased by 0.05 t ha$^{-1}$, 0.92 cm, 0.01 cm, and 0.02, respectively. Moreover, the corn yield for 2B1F only decreased by 3.8% compared with that for FW, yet the corresponding average fraction of the SS area and the SS and HSS duration increased by 5.2%, 21, and 28 days, respectively (Fig. 6a, i, m).

### 4. Discussion

#### 4.1. Soil salt and its stress dynamics under different irrigation strategies

Irrigation with brackish water usually temporarily reduces soil salinity and salt stress (SS) in saline soils (Zhang et al., 2019a, 2019b). However, SS inevitably reappears under continuous irrigation with brackish water (Holthusen et al., 2012). The conjunctive use of brackish and fresh waters for irrigation can effectively reduce or avoid SS (Rhoades, 1984). The salt accumulation after irrigation is mainly related to irrigation water salinity and irrigation amount. The Food and Agriculture Organization of the United Nations (FAO) proposed a leaching strategy based on accumulated scientific knowledge. The FAO manual defined the minimum leaching fraction as the amount of water, in excess of consumptive use, necessary to leach accumulated soil salts below the root zone (Ayers and Westcott, 1976). However, a large amount of irrigation water would be required for the proposed leaching strategy. This strategy would not only waste freshwater resources, but would also not be able to remove salt stress in time. In fact, a relatively small amount of freshwater can relieve SS, e.g., alternate or blending irrigation strategies with brackish and fresh waters can effectively control soil salinity and shorten the SS duration (Hassanli and Ebrahimian, 2016; Ramos et al., 2012).

In this study, the average $EC_{sw}$, a fraction of the SS area to the main root zone area, and the SS duration decreased by 9.7%, 3.7, and 10 days, respectively, under an alternate irrigation strategy 1B1F compared with BW (Figs. 3 and 4). However, the alternate (1–1) irrigation strategy still cannot save enough freshwater in a water-shortage area. The frequency of using brackish water for irrigation is thus frequently increased, inevitably leading to an increase in the soil salinity. For example, the average soil salinity in the root zone increased by 45.5% when brackish water was used during the sixth-leaf to tasseling stages, while freshwater was used during the remaining growth stages, resulting in significantly inhibited crop growth (Huang et al., 2019). In this study, average soil salinity increased by 31.9% when the irrigation frequency with brackish water increased three times (3B1F).

Therefore, it is necessary to optimize alternate irrigation strategies to

![Simulated two-dimensional distributions of $EC_{sw}$ on DAS 106 (before irrigation, top) and DAS 107 (after irrigation, bottom) in a field irrigated using different alternate drip irrigation strategies with fresh and brackish waters, including (left to right) FW, 1B1F, 2B1F, 3B1F, and BW.](image-url)
reduce the amount of freshwater and decrease SS. In this study, HYDRUS (2D/3D) simulations showed that an increase in the frequency of brackish water irrigation resulted in a linear increase in the average ECsw, SS area, and SS duration (Fig. 7). However, the desalination rate (DR) decreased with an increase in the brackish water irrigation frequency. For low, moderate, and high SS levels, the SS duration for 1F1B was shortened by 7, 2, and 2 days compared to 1B1F, while the average fraction of the SS area to the main root zone area was reduced by 2.8%, 2.5%, and 14.3%, respectively. When no fresh water was used for irrigation (BW), the HSS (7.6–11.8 dS m⁻¹) duration in the main root zone during the growth stage reached 20 days (Fig. 7c).

4.2. Effect of soil salinity on crop yield

Root water uptake stress occurs when soil salinity reaches a critical threshold due to the very high osmotic potential in the soil (Maas and Hoffman, 1977; Munns et al., 2006; Estrada et al., 2013). When average ECsw in the root zone reaches 5 dS m⁻¹, the corn yield is reduced by 10%, and no grain harvest is obtained when ECsw is higher than 20 dS m⁻¹ during the entire crop growing season (Ayers and Westcot, 1976). The magnitude of the SS area and its duration in the root zone during the crop growing season directly influence crop yield. For example, when the soil was leached by surface irrigation with freshwater during the corn elongation stage, the HSS duration was reduced by about half, and the corn yield increased by 18.5% compared with no leaching treatment (Zhang et al., 2021). Similar results were obtained in this study when the higher frequency of freshwater irrigations was accompanied by the lower SS area and the shorter SS duration. For instance, the average SS area and duration for 1B1F decreased by 11.0% and 8.3% compared to BW, respectively (Fig. 7a, b, c).

It is necessary to develop a relationship between crop yield and SS or irrigation water salinity to use brackish water for irrigation more...
efficiently (Sepaskhah et al., 2006). However, the effects of irrigation with different alternate uses of fresh and brackish waters on crop yield are still not clear. In the study, the crop sensitivity functions, i.e., the relationships between crop yield and water and salt stresses, were obtained based on the combination of experimental results and HYDRUS (2D/3D) simulations (Waller and Yitayew, 2016). Generally, when the frequency of irrigations with brackish water increased, the SS area and duration increased, and the yield decreased (Fig. 8). Average values of $EC_{sw}$ for 3F1B, 2F1B, 1F1B, 2B1F, 3B1F, and BW during the growth period were 6.1, 6.2, 6.4, 6.5, 6.7, 6.8, and 7.2 dS m$^{-1}$, which was about 0.4, 0.5, 0.7, 0.8, 1.0, 1.1, and 1.5 dS m$^{-1}$ higher than for FW, respectively, while the yield decreased by 0.2, 0.4, 0.8, 1.1, 1.3, 1.5, and 2.4 t ha$^{-1}$, respectively. For the 1F1B alternate irrigation strategy, the average $EC_{sw}$ was 6.4 dS m$^{-1}$ during the growth period, the average fraction of the SS area to the main root zone area was 120.4%, and the yield was reduced by 0.7 t ha$^{-1}$ compared with FW. The relationship
between the SS fraction and yield in both years was $y = -0.06x + 19.8$ ($R^2=0.88$), and the relationship between the SS duration and yield was $y = -0.07x + 19.5$ ($R^2=0.78$).

5. Conclusions

Both experiments and the numerical model were used to evaluate the effects of different alternate drip irrigation strategies with fresh and brackish waters on soil salt dynamics. The results showed that simulated
EC_{sw} was in good agreement with measurements in all irrigation scenarios. An apparent difference in salt accumulation could be found in the 0–40 cm soil layer at the end of the growth stage under different alternate irrigation strategies. The higher the irrigation frequency with brackish water, the greater the average EC_{sw}, the longer duration of salt stress (SS), and the larger the SS area. Both field experiments and numerical simulations showed that crop yield decreased linearly with an increase in the SS duration and area. The scenario with two irrigations with brackish water and one with fresh water represented the optimal strategy for the studied region, using the most brackish water with the least significant yield decrease.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was jointly supported by the National Key Research and Development Program of China (2021YFC3201202), the Transformation Projects of Scientific and Technological Achievements of Inner Mongolia (2021CG0022), the National Natural Science Foundation of China (52079064, 51969024, and 51469022), and the Inner Mongolia Autonomous Region Graduate Education Innovation Plan (SZ2020081).

References

Soil & Tillage Research 219 (2022) 105355


