Simulation soil water–salt dynamics in saline wasteland of Yongji Irrigation Area in Hetao Irrigation District of China
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ABSTRACT
In order to explore the regional water–salt balance mechanism in Hetao Irrigation District, field experiments were conducted in 2018 and 2019 in the Heji canal study area. The SWAP model was calibrated and validated based on field experiments’ observed data. The SWAP model was used to simulate soil water–salt dynamics in saline wasteland after calibration and validation. The results showed that model simulation results of soil water content and soil salt concentration agreed well with the measured values. Soil water content and soil salt concentration changed obviously under the effect of farmland irrigation in the crop growing period. Soil salt was accumulated in saline wasteland. The soil salt accumulation of each soil layer in saline wasteland was 0.164, 0.092, –0.890 and –1.261 mg/cm³, respectively. Soil water content gradually increased and soil salt concentration gradually decreased in the autumn irrigation period. Soil salt was leached in the saline wasteland. The soil salt accumulation of each soil layer in saline wasteland was –1.011, –1.242, –1.218 and –1.335 mg/cm³, respectively. The saline wasteland became a drainage and salt drainage region for cultivated land. The saline wastelands had an obvious role in adjusting salt balance and maintaining salt dynamic balance in Hetao Irrigation District.

Key words | Hetao Irrigation District, saline wasteland, soil salt concentration, soil water content, SWAP model

HIGHLIGHTS
● Soil water–salt transport is concentrated in saline wasteland.
● Soil water content and soil salt concentration changed obviously in crop growing period.
● Soil salt was accumulated in saline wasteland in crop growing period.
● Soil water content gradually increased and soil salt concentration gradually decreased in autumn irrigation period.
● Saline wasteland became a drainage and salt drainage region.

INTRODUCTION
Soil salinization has been one of the main factors impacting agricultural production all around the world (Wang et al. 2007; Muyen et al. 2011). Global salinization land area is 9.5×10⁶ hm², which approximately accounts for 10% of the Earth’s land area, and these salinity lands are mainly distributed in arid and semi-arid areas (Ghassemi et al. 1995; Abbas et al. 2015). In China, with a total area of about 3.6×10⁷ hm², salinity land accounts for 4.9% of the available land area. Especially, there is much salinity land in northwest China, with the arid climate. (Yang 2009; Wang et al. 2011). The Hetao Irrigation District (Hetao) located in the upper reach of Yellow River Basin, is a typical
salinization irrigated district because of the dry climate and shallow groundwater. The area affected by salinization in the whole irrigated district has reached to $3.9 \times 10^6$ ha$^2$, accounting for 69% of the total land area (Huang et al. 2018). The soil salinity in the crop root zone should be maintained within the reasonable range to avoid harming crop growth. Engineering drainage and irrigation leaching were two major ways to control soil salinization (Tedeschi & Menenti 2002; Wu et al. 2009). From the end of the 1980s to the middle of the 1990s, a drainage-oriented irrigating supporting project was constructed for the whole of Hetao and effectively alleviated the soil salinization. A traditional engineering drainage project was difficult to carry out due to high economic cost and environmental restrictions. Dry drainage was an alternative method for effective drainage and control of salinity in the irrigation district (Wichelns & Oster 2006; Wu et al. 2009). Dry drainage was to set for a certain part of idle land (non-cultivated land) in the irrigated district, inputting the surplus irrigating water and salinity of cultivated land into the non-cultivated land through the movement of groundwater. The surplus water would be discharged and salinity would be stored in the non-cultivated land under soil evaporation, so as to maintain the water–salt balance of the cultivated land (Wichelns & Oster 2006). There were $5.74 \times 10^5$ ha$^2$ of cultivated land and $2.09 \times 10^5$ ha$^2$ of salt wasteland in Hetao Irrigation Area, and the salt wasteland was scattered in gaps of cultivated land, which has the conditions to realize dry drainage. Dry drainage played an important role in maintaining salt balance in Hetao irrigation area (Wang et al. 2019). At present, research on soil water–salt transport has mostly been concentrated on cultivated land (Tang et al. 2007; Feng et al. 2017; Yuan et al. 2019), while there has been little research on soil water–salt transport in saline wasteland in the irrigated district. The Soil–Water–Atmosphere–Plant (SWAP) model has been the popular tool to simulate soil water–salt transport in arid or semi-arid areas. It has been widely used in simulating soil water and salt transport in arid or semi-arid areas at home and abroad (van Dam et al. 2008). Singh et al. (2010) used the SWAP model to simulate soil water dynamics and water balance under different wheat planting conditions in Minqin County, Gansu Province. The results showed that the SWAP model could simulate soil water dynamics well and was an effective tool for analyzing soil water balance. Xu et al. (2013) simulated soil water and salt dynamics and spring wheat yield under different groundwater depth and irrigation water conditions in Qingtongxia Irrigation Area of Ningxia by using the SWAP model. The results showed that under the condition of maintaining the existing irrigation quota, the increase of groundwater depth would lead to a slight reduction of spring wheat yield due to soil salt stress. Yin (2013) combined one-dimensional soil water and salt transport model SWAP-EPIC and ArcGIS software to build a distributed model of Nanxiaozhao experimental area in Jiefangzha Irrigation Area of Hetao Irrigation District, and carried out distributed simulation of soil water and salt dynamics and crop yield in the experimental area. According to the dynamic law of soil water and salt in the saline wasteland of an irrigation area, the SWAP model was applied to the saline wasteland soil in Hetao Irrigation Area of Inner Mongolia, and the dynamic changes of soil water and salt in the crop growth period and autumn irrigation period were studied. The results provide a theoretical basis for water and salt management and prevention of soil salinization in Hetao Irrigation Area.

The objectives of this study were: (1) to calibrate and validate the SWAP model with two-year field observation data of water and salt in the soil profile; (2) to simulate soil water–salt dynamics of the saline wasteland in the crop growing period and autumn irrigation period using the calibrated SWAP model.

**MATERIALS AND METHODS**

**General situation of the experiment area**

The study area was selected in the Heji study area of the Yongji Irrigation Area in Hetao Irrigation District of Inner Mongolia (Figure 1), and was located in Minzhu village, Ganzhao Town, Linhe District, Bayannaoer City, Inner Mongolia Autonomous Region of northwest China. The geographical coordinates are $107^\circ 15'–107^\circ 18' \ E$ and $40^\circ 43'–40^\circ 46' \ N$. The study area was located in northwest China inland, belonging to the mid-temperate semi-arid continental climate, dry and with less rain, where evaporation is strong, the annual average rainfall is 160 mm and the
annual average evaporation is 2,240 mm \((\text{Ren et al. } 2018)\). The average buried depth of groundwater level in the study area was 1.6–2.2 m, and the groundwater level was shallow. The terrain of the study area was relatively gentle. The terrain was high in the southeast and low in the northwest in the study area. The elevation was between 1,040 and 1,042 m, and the total area was about 507 hm\(^2\). It was mainly controlled by two land-use types: cultivated land and salt wasteland. It was controlled by one main canal (Heji branch canal) and two branch canals (Xinli branch canal and Xinzhang branch canal). The distribution of salt wasteland in the study area was relatively concentrated, mainly concentrated in the central and northwest regions of the study area. The east, south and west sides were surrounded by cultivated land and the saline wasteland was lower than the cultivated land. Saline wasteland had the function of drainage and salt discharge, and was a typical ‘dry drainage’ area in Hetao Irrigation Area.

**Experiment layout and observation items**

Field experiments were carried out from July 2018 to October 2019. Three groundwater observation wells (Figure 2) were arranged in the saline wasteland of the study area. The depth of each observation well was 3 m and the diameter was 10 cm. The three observation wells were used to monitor the groundwater depth in the study area. Soil sampling points were arranged near the observation wells, and the distance between the soil sampling points and the observation well was 3–5 m. In the study area, soil samples were obtained from soil sampling points by soil drill before and after crop irrigation. The soil layers were divided into four layers: 0–10 cm, 10–20 cm, 20–40 cm and 40–60 cm. The soil water content was determined by the drying method, and the electrical conductivity of saturated extraction solution \(EC_{1.5}\) was determined by conductivity meter (DDSJ-308A, Shanghai Leici Instrument Company), and the soil electrical conductivity was converted into soil salt content according to the formula \((S = 2.882EC_{1.5} + 0.183)\) (Xu et al. 2019). During the observation period, the groundwater depth of the observation wells was observed every seven days. The groundwater depth was measured by steel ruler water level gauge (JK 22924, Beijing Jingkaida Instrument Company). The soil particle composition of the 0–60 cm soil layer in the saline wasteland was determined by Laser Particle Sizer (Mastersizer 2000, Malvern, UK). The soil particle classification was based on the international soil texture classification standard. The soil physical parameters of the saline wasteland are shown in Table 1. According to the soil physical properties of each soil layer, the soil hydraulic characteristic parameters of each soil layer were generated.
by using the neural network soil transfer function of Rosetta Software. The initial soil hydraulic characteristic parameters of the saline wasteland are shown in Table 2. The meteorological data during the experimental observation period from 2018 to 2019 were downloaded from the meteorological station of Hetao experimental base of China Agricultural University in the study area.

The SWAP model

The SWAP model, developed by the Water Resource Group of Wageningen University, is a one-dimensional agricultural hydrological model that is used to simulate vertical soil water flow, solute and heat transport and crop growth (van Dam et al. 1997; van Dam et al. 2008). It has been widely applied to simulate irrigation, soil water–salt transport, crop evapotranspiration, crop growth, drainage, and groundwater tables in semi-arid and arid areas around the world (Vazifedoust et al. 2008; Noory et al. 2011). Soil water flow is based on the Richards’ equation for vertical flow in the SWAP model, which is given by:

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

where \( C(\theta) \) is differential water capacity (\( \ell/\ell^3 \)); \( \theta \) is soil water content (\( \ell^3/\ell^3 \)); \( h \) is soil water pressure head (\( \ell \)); \( t \) is time (\( \ell \)); \( z \) is the vertical coordinate (\( \ell \), positive uptake); \( K(h) \) is the hydraulic conductivity (\( \ell/\ell^1 \)); \( S(h) \) is the soil water extraction rate by plant roots (\( \ell^3/(\ell^3/\ell^1) \)).

Solute transport is based on the convective–dispersive equation in the SWAP model, which is given by:

\[
J = q c - \theta(D_{\text{diff}} + D_{\text{disp}}) \frac{\partial c}{\partial z}
\]

where \( J \) is total solute flux density (\( \ell^3/(\ell^2/\ell^1) \)); \( q \) is vertical flow at the bottom (\( \ell/\ell^1 \)); \( c \) is solute concentration in the soil liquid phase (\( \ell^3/\ell^3 \)); \( D_{\text{diff}} \) is the diffusion coefficient (\( \ell^2/\ell^1 \)); \( D_{\text{disp}} \) is the dispersion coefficient (\( \ell^2/\ell^1 \)).

The SWAP model has two crop growth modules to simulate the crop growth process, a simple one and another detailed one based on the WOFOST model (Hijmans et al. 1997). Due to the first crop model requiring fewer parameters and simple crop data inputs, the simple crop growth module was applied in this study. For a more detailed introduction to the SWAP model, reference can be made to the SWAP model theory book (van Dam et al. 1997).

The SWAP model requires various data as inputs, which includes meteorological data, soil data, crop growth data, and initial and boundary conditions. The meteorological data was obtained from an automatic meteorological station in the study area. The meteorological data calculated by the model were the daily meteorological data observed by the weather station of Hetao experimental base of China.

### Table 1 | Soil physical properties of saline wasteland

| Soil depth (cm) | Clay (\(<0.002\ \ell,\ %)\) | Silt (0.002–0.02 mm, %) | Sand (0.02–2 mm, %) | Soil bulk density (g/\(\ell^3\)) | International soil texture |
|----------------|-----------------|-----------------|-----------------|-----------------|------------------|
| 0–10           | 3.47            | 18.61           | 77.93           | 1.56            | Silty sandy loam  |
| 10–20          | 3.11            | 17.86           | 79.03           | 1.54            | Silty sandy loam  |
| 20–40          | 2.78            | 14.14           | 83.07           | 1.58            | Silty sandy loam  |
| 40–60          | 3.29            | 16.15           | 80.57           | 1.55            | Silty sandy loam  |

### Table 2 | Soil hydraulic parameters for different soil layers of saline wasteland

| Soil depth (cm) | Residual water content \( \theta_r \) (\( \ell^3/\ell^3 \)) | Saturated water content \( \theta_s \) (\( \ell^3/\ell^3 \)) | Saturated hydraulic conductivity \( K_s \) (\( \ell/\ell^1 \)) | Shape factor \( \alpha \) (-) | Shape factor \( \beta \) (-) | Shape factor \( \lambda \) (-) |
|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0–10           | 0.0338          | 0.3916          | 87.81           | 0.0451          | 1.6015          | 0.5             |
| 10–20          | 0.0352          | 0.3903          | 97.6            | 0.0449          | 1.6693          | 0.5             |
| 20–40          | 0.0347          | 0.3910          | 100.76          | 0.0455          | 1.6821          | 0.5             |
| 40–60          | 0.0379          | 0.3886          | 142.65          | 0.0439          | 1.9163          | 0.5             |
Agricultural University where the research area was located. Because there was no crop in the salt wasteland, it was not necessary to input irrigation data and crop growth information. Soil water content was transformed into soil water pressure head by the soil water retention curve. The soil water pressure head and soil salinity before crop sowing were regarded as the initial condition. The measured dispersion length and molecular diffusion coefficient were 12 cm and 0.5 cm²/d, respectively. A 60 cm depth soil profile divided into five horizons in the model was represented by 33 soil compartments in the vertical plane in the cultivated land soil layer. A 60 cm depth soil profile divided into five horizons was represented by 33 soil compartments in the vertical plane in the saline wasteland soil layer. The upper boundary condition was described by the irrigation, daily rainfall and the potential ET. Groundwater level was given as the bottom boundary condition.

The root mean square error (RMSE), mean relative error (MRE) and the coefficient of determination (R²) were used to quantify the deviation of the simulated and observed data in calibration and validation. These indicators were defined as follows:

\[
RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (P_i - O_i)^2}
\]

\[
MRE = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{P_i - O_i}{O_i} \right| \times 100\% 
\]

where \(N\) is the total number of observations in the experiments, \(P_i\) and \(O_i\) are the \(i\)th model predicted and observed values \((i = 1, 2, \ldots, N)\), respectively.

**RESULTS AND DISCUSSION**

**Calibration and validation of SWAP model**

The average groundwater depth, soil water content and soil salt concentration of three groundwater observation wells were used to calibrate and validate the parameters of the SWAP model. The observation data in 2019 were used to calibrate the model parameters, and the observation data in 2018 were used to validate the model parameters. The simulation period in 2019 was from June 7 to September 28, with a total of 113 days. The simulation period in 2018 was from July 13 to October 1, with a total of 80 days.

The comparison between simulated and measured values of soil water content in saline wasteland is shown in Figures 3 and 4 during calibration and validation. It can be seen from the figure that the simulated values of soil water content of each soil layer was basically consistent with the measured values. The calibration effect of surface soil moisture was slightly poor. This was mainly due to the influence of rainfall and evaporation on the surface soil, and the change was relatively violent, but the simulated values of soil water basically reflected the change process of the measured values. The statistical analysis of the soil water content simulation results is shown in Table 3. The RMSE value of soil water content in each soil layer was below 0.06 cm³/cm³, and the MRE was less than 25%, which was within the allowable error range of 25%. The simulation results were basically feasible. The results of soil hydraulic characteristic parameters after calibration of the soil water module are shown in Table 4.

The comparison between simulated and measured values of soil salt concentration in saline wasteland during calibration and validation is shown in Figures 5 and 6. It can be seen from the figure that the simulated values of soil salt concentration in each soil layer were basically consistent with the measured values. Due to the influence of rainfall and evaporation, the calibration effect of surface soil salt concentration was slightly poor, but the simulated values of soil salt concentration basically reflected the change process of the measured values. The statistical analysis of soil salt concentration simulation results is shown in Table 5. The RMSE values of soil salt concentration in each soil layer were less than 1.5 mg/cm³. The MRE values were all lower than 25%, which was within the allowable error range of 25%. The simulation results were basically feasible. After the calibration of the soil solute transport module, the molecular diffusion coefficient was 5.0 cm²/d, and the solute dispersion was 10 cm. The calibration and validation results show that the SWAP model can simulate the soil water–salt dynamics in saline wasteland.
The soil water–salt dynamics of saline wasteland during April 10 to September 30 (crop growth period) and October 1 to November 20, 2019 (autumn irrigation period) were simulated by using the SWAP model after calibration of parameters.
Table 4  | Soil hydraulic parameters for different soil layers after calibration

| Soil depth (cm) | Residual water content $θ_r$ (cm$^3$/cm$^3$) | Saturated water content $θ_s$ (cm$^3$/cm$^3$) | Saturated hydraulic conductivity $K_s$ (cm/d) | Shape factor $α$ (-) | Shape factor $n$ (-) | Shape factor $λ$ (-) |
|-----------------|---------------------------------------------|---------------------------------------------|--------------------------------------------|----------------------|----------------------|----------------------|
| 0–10            | 0.0312                                      | 0.3956                                      | 51.65                                      | 0.0162               | 1.659                | 0.5                  |
| 10–20           | 0.0785                                      | 0.4195                                      | 74.49                                      | 0.0383               | 1.436                | 0.5                  |
| 20–40           | 0.0290                                      | 0.4169                                      | 70.12                                      | 0.0349               | 1.423                | 0.5                  |
| 40–60           | 0.0639                                      | 0.390                                       | 125.60                                     | 0.0323               | 1.8063               | 0.5                  |

Figure 5  | Calibration for soil salt concentration in saline wasteland (2019).

Figure 6  | Validation for soil salt concentration in saline wasteland (2018).
Figure 7 shows the dynamic changes of soil water content in different soil layers of saline wasteland in the crop growth period. In the study area, the soil began to melt in the middle of April, and soil water content of each soil layer gradually increased. In early May, the spring irrigation was carried out in the study area. Affected by the spring irrigation of cultivated land, the soil water content of each soil layer in saline wasteland was higher, which was mainly because the saline wasteland was located in the low-lying area. Due to the ‘dry drainage’ effect, soil water content of each soil layer in the saline wasteland was relatively high. In the irrigation season, the soil water content of the saline wasteland changed obviously. After irrigation, the soil water content of the saline wasteland gradually increased, and the soil water content of the deep layer soil was the highest, and the surface water content was relatively low from May to August. From the middle of August to the end of September, the soil water content of the saline wasteland gradually decreased due to no irrigation in the cultivated land, and the soil water content of each soil layer reached the lowest values before autumn irrigation. Figure 8 shows the dynamic changes of soil salt concentration in different soil layers of saline wasteland in the crop growth period. It can be seen from the figure that the soil salt concentration of each soil layer in the saline wasteland was quite different, and soil salt concentration in the surface soil was the highest in the crop growth period. With the increase of soil depth, soil salt concentration gradually decreased, and the soil salt content of the saline wasteland mainly accumulated in the surface soil, and the change of soil salt concentration in each soil layer was obvious in the farmland irrigation season, which was mainly caused by farmland irrigation and leaching of salt, which flowed to the saline wasteland through groundwater flow. Under the action of soil evaporation, soil salt accumulated in the surface soil. At the end of the growth period, compared with the early growth stage, soil salt accumulation in each soil layer was 0.164, 0.092, –0.890 and –1.261 mg/cm³, respectively. The surface soil (0–20 cm) accumulated salt, and the lower soil (20–60 cm) desalinated. Therefore, the saline wasteland was in the state of storing salt in the crop growth period. After irrigation and leaching, soil salt flowed to the saline wasteland through groundwater flow, and salt accumulated in the surface soil of the saline wasteland. The saline wasteland had a role as drainage and salt drainage area for the cultivated land, which reduced the degree of soil salinization and created favorable conditions for crop growth in the cultivated land.

Simulation of soil water–salt dynamics in autumn irrigation period

Figure 9 shows the dynamic changes of soil water content in different soil layers of saline wasteland in the autumn irrigation period. The autumn irrigation period was from early October to mid-November in the study area. Autumn irrigation was a period of large irrigation amount in the year. The

**Table 5 | The statistical results for soil salt concentration in calibration and validation**

| Soil depth (cm) | Calibration (2019) | Validation (2018) |
|-----------------|-------------------|------------------|
|                 | RMSE (mg/cm³) | MRE (%) | RMSE (mg/cm³) | MRE (%) |
| 0–10            | 1.09 | 22.76 | 1.25 | 22.77 |
| 10–20           | 0.84 | 19.16 | 0.78 | 21.76 |
| 20–40           | 0.53 | 15.91 | 0.6  | 18.32 |
| 40–60           | 0.49 | 16.18 | 0.52 | 13.46 |
The main purpose of autumn irrigation was to leach soil salt in cultivated land and saline wasteland. Soil water content in saline wasteland increased gradually with the autumn irrigation of cultivated land, and soil water content of each soil layer increased gradually. In the first ten-day period of November, soil water content of each soil layer reached the maximum, and the soil reached saturation state. Figure 10 shows the dynamic changes of soil salt concentration in each soil layer of the saline wasteland in the autumn irrigation period. With the progress of autumn irrigation, soil salt concentration of each soil layer gradually decreased. After autumn irrigation, soil salt concentration of each soil layer reached the minimum values, and soil salt concentration of the saline wasteland was reached. After autumn irrigation, compared with that before autumn irrigation, the soil salt accumulation in each soil layer of saline wasteland was −0.164, −0.092, −0.890 and −1.261 mg/cm³, respectively in the crop growth period. Saline wasteland was in the state of storing salt in the crop growth period, which was the drainage and salt drainage area for cultivated land. Soil water content gradually increased and soil salt concentration gradually decreased in the autumn irrigation period. Soil salt accumulation in each soil layer of saline wasteland was −1.011, −1.242, −1.218 and −1.335 mg/cm³, respectively. The saline wasteland played an important role in maintaining the soil salt balance in the study area. The saline wasteland played an important role in maintaining the soil salt balance in the study area. This study will provide a theoretical basis for soil water and salt management and prevention of soil salinization in Hetao Irrigation Area of China.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.
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