Application of the SWAP model to simulate water–salt transport under deficit irrigation with saline water

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**A B S T R A C T**

The agro-hydrological Soil–Water–Atmosphere–Plant (SWAP) model was calibrated and validated to simulate water–salt transport based on field experiments in an arid region of China. The simulation results show lower soil water content but higher salt concentration under deficit irrigation. Soil water and salinity below 95 cm at 80% evapotranspiration (\(ET_c\)) treatments and 65 cm at 60% \(ET_c\) treatments were hardly affected by irrigation. With deficit irrigation, the maximum water uptake and salt accumulated layer moved upward. The SWAP model was also used to predict long-term deficit irrigation with saline water. The salinization process reached equilibrium after utilization of saline water for a few years. In summary, the numerical model proves to be a useful tool for studying water–salt transport under different scenarios and for evaluating irrigation practices for a long period.

1. **Introduction**

The Shiyang River basin is a typical interior river basin that faces water shortage and environmental deterioration in arid Northwest China \([1]\). Agriculture in this area relies largely on irrigation. The use of saline groundwater for irrigation is unavoidable because of the rising water demand and deterioration in groundwater spread. Shani et al. promoted deficit irrigation for regions using poor-quality water \([2]\). Deficit irrigation with saline water should also be extended to the area. The soil water–salt dynamics is basic in studying the genesis, evaluation, and control of soil salinity \([3–6]\). Saline water management is usually based on maintaining the root zone salinity below its threshold value and on alleviating the effects on crop yield \([7,8]\). Research indicates that deficit irrigation with saline water decreases the water loss and salt accumulation, but it alters the water extraction and salt accumulation pattern in the soil profile \([9]\). Therefore, evaluating the effects of deficit irrigation with saline water on soil water–salt transport is important in establishing appropriate water management practices. The soil water–salt dynamics is complex when crops are irrigated with saline water.

The use of field experiments is the most credible technique for studying soil water movement and salt accumulation, but it is time consuming and expensive. Given this, numerical models have played an increasingly important role in the study of water flow and solute transport process in unsaturated zones \([10–15]\). The Soil–Water–Atmosphere–Plant (SWAP) model is a deterministic one-dimensional model for water, heat, and solute transport \([16]\). It has been applied at different scales in different places around the world to address management practices and their impact on crops and the environment \([17–22]\). However, the SWAP model has not been applied in the simulation of water–salt transport under deficit irrigation with saline water and long-term prediction in arid Northwest China.
Table 1

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Total salt content (g kg$^{-1}$)</th>
<th>Organic matter (g kg$^{-1}$)</th>
<th>Bulk density (g cm$^{-3}$)</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–20</td>
<td>70.12</td>
<td>15.00</td>
<td>14.88</td>
<td>0.68</td>
<td>7.86</td>
<td>1.56</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>20–50</td>
<td>72.12</td>
<td>13.00</td>
<td>14.88</td>
<td>0.64</td>
<td>6.66</td>
<td>1.61</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>50–85</td>
<td>40.12</td>
<td>42.00</td>
<td>17.88</td>
<td>0.75</td>
<td>6.72</td>
<td>1.38</td>
<td>Clay loam</td>
</tr>
<tr>
<td>85–110</td>
<td>52.12</td>
<td>34.00</td>
<td>13.88</td>
<td>0.81</td>
<td>2.64</td>
<td>1.41</td>
<td>Loam</td>
</tr>
<tr>
<td>110–120</td>
<td>52.12</td>
<td>34.00</td>
<td>13.88</td>
<td>0.81</td>
<td>2.64</td>
<td>1.41</td>
<td>Loam</td>
</tr>
</tbody>
</table>

An investigation of soil water–salt dynamics based on the SWAP model is very important for saline irrigation management in this arid area. Therefore, this study aims (1) to calibrate and validate the SWAP model for the simulation of soil water–salt transport under field conditions; (2) to discriminate between sufficient and deficit irrigation with saline water in soil water and salt movement; (3) and to predict the long-term effects of deficit irrigation with saline water on soil water content and salinization.

2. Materials and methods

2.1. Field experiment

2.1.1. Study area
Field experiments on spring wheat were conducted from 2008 to 2009 at the Experimental Station for Water-Saving in Agriculture and Ecology of the China Agricultural University (102°52′ E, 37°52′ N, and elevation 1557.5 m), located in Gansu Province, Northwest China. The study area lies within the middle reaches of the Shiyang River basin and is characterized as a typical arid climate zone with deep a groundwater table. The average annual rainfall and potential evaporation of the area are 164 mm and 2000 mm, respectively.

2.1.2. Experimental design
The average evapotranspiration ($ET_c$) between 2005 and 2007 was 375 mm. The value was calculated using the Penman–Monteith formula and was used for controlling the irrigation level. Water levels of 100%, 80%, and 60% $ET_c$ (S, D, and DD) in combination with salt concentrations of 0.7, 3, and 6 g l$^{-1}$ (F, 3, and 6) were applied in the experiment. There were nine treatments, with three replicates each. The four irrigations in the spring-wheat growing period was 90 mm, 97.5 mm, 105 mm, and 82.5 mm under 100% $ET_c$; 72 mm, 78 mm, 84 mm, and 86 mm under 80% $ET_c$; 54 mm, 78 mm, 84 mm, and 86 mm under 60% $ET_c$; respectively. Irrigations were applied on May 4, May 30, June 21, and July 2 in 2008 and on April 26, May 15, June 4, and June 26 in 2009. Freshwater with salt concentration of 0.7 g l$^{-1}$ was obtained from the local well, whereas saline water with salt concentration of 3 and 6 g l$^{-1}$ were obtained by adding NaCl, MgSO$_4$, and CaSO$_4$ (mass ration 2:2:1) into fresh water. Plots of 3 m × 4 m areas were separated by smaller buffer blocks and randomly placed.

2.1.3. Field data collection
Spring wheat was sown on March 19 and harvested on July 15 each year for two years. The physical and chemical properties of the soil before the experiment are presented in Table 1. The volumetric water content of the soil was measured every 3–7 days at 10 cm intervals from the surface to a depth of 120 cm using a portable soil moisture monitoring system (Diviner 2000, Sentek Pty. Ltd., Australia). The soil samples from each plot were investigated with an electrical conductivity meter (SevenGo SG3, Switzerland) to measure the soil salinity every 15–20 days at intervals of 0–10, 10–20, 20–40, 40–60, 60–80, and 80–120 cm. A ruler was used to measure the plant height. The leaf area index (LAI) was measured using the SUNSCAN Canopy Analysis System (SUNSCAN, Delta, UK), and the soil water retention curve was determined using a high-speed refrigerated centrifuge (HITACHI, CR22G-). The VGM (van Genuchten–Mualem) hydraulic parameters analyzed by the RETC (RETention Curve) program are presented in Table 2. The molecular diffusion coefficient and dispersion length were 0.5 cm$^2$ d$^{-1}$ and 15 cm, respectively. Daily meteorological data were obtained from an automatic weather station in the experimental station.

2.2. The SWAP model

2.2.1. Model description
The SWAP model, developed by the Water Resources Group of Wageningen University, is described by van Dam et al. as a physically based and detailed agro-hydrological model [16]. Water flow is based on an implicit finite difference solution of the nonlinear partial differential Richards equation. Solute transport is computed by the advection dispersion equation, which is solved by an explicit, central finite difference scheme. A simple crop model is selected in the simulation. Wheat development is modeled linearly or with a fixed length of the crop cycle. The maximum root water extraction rate is equal to the potential transpiration rate $T_p$ (cm d$^{-1}$). The potential root water extraction rate at a certain depth, $S_p(z)$ (d$^{-1}$), may
be determined by the root density, \( \pi_{\text{root}}(z) \) (cm\(^3\) cm\(^{-3}\)), at this depth as a function of the total root length density:

\[
S_p(z) = \frac{\pi_{\text{root}}(z)}{\int_{0}^{D_{\text{root}}} \pi_{\text{root}}(z) \, dZ} \, T_p, \tag{1}
\]

where \( D_{\text{root}} \) is the root layer thickness in cm. The water stress in the SWAP model is described by the function proposed by Feddes et al. [23]. The response function of Maas and Hoffman is used for salinity stress [24]. The water and salinity stress are assumed to be multiplicative. The actual root water flux density, \( S_p(z) \) (d\(^{-1}\)), is calculated from

\[
S_p(z) = \alpha_{\text{rw}} \alpha_{\text{zn}} S_p(z), \tag{2}
\]

where \( \alpha_{\text{rw}} \) and \( \alpha_{\text{zn}} \) are the reduction factors due to water and salt stresses, respectively.

The input parameters required by the SWAP model are soil data, meteorological data, \( ET_c \) rate, bottom boundary condition, and crop information. In this study, the soil water pressure head transformed from the initial soil water content is regarded as the initial condition. Free drainage is assumed as the bottom boundary condition. A 120 cm depth soil profile was represented in the model by 33 soil compartments in the vertical plane. The nodal spacing increased from 1 cm near the soil surface to a maximum of 10 cm. A fixed irrigation schedule is defined by the time and depth of irrigation, as given in Table 1. The plant height and LAI were obtained from field measurements, whereas the maximum root depth was set to 120 cm. The critical pressure values for root water uptake were set at \( h_1 = 0.1 \), \( h_2 = -1.0 \), \( h_{3\text{a}} = -500 \), \( h_{3\text{b}} = -900 \), and \( h_4 = -160.00 \). A threshold soil salinity (electrical conductivity of soil-water saturated paste) of 6.0 dS m\(^{-1}\) and a 3.0% per dS m\(^{-1}\) slope of relative yield response to salinity were used for the salt tolerance response. The minimum canopy resistance was set at 20 s m\(^{-1}\).

### 2.2.2. Model calibration and validation

The VGM and salt transport parameters derived from measurements were used as the initial values for model calibration and were modified in a “trial and error” process in order to obtain the optimal calibration results. The data sets of DF treatment in 2008 and 2009 were used for model calibration and validation. Two statistical variables, namely the root mean squared error (RMSE) and mean relative error (MRE), were used to quantify the deviation in modeling results from the data observed. The RMSE and MRE were calculated according to the following equations:

\[
\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (P_i - O_i)^2} \tag{3}
\]

\[
\text{MRE} = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{P_i - O_i}{O_i} \times 100\% \right), \tag{4}
\]

where \( N \) is the total number of observations, and \( O_i \) and \( P_i \) are the observed and predicted values, respectively.

### 3. Results and discussion

#### 3.1. Model calibration and validation

##### 3.1.1. Soil water content

The simulated and predicted soil water contents at depths of 15, 35, 65, and 95 cm of the DF treatment were compared with the measured values in 2008 for calibration and with the values in 2009 for validation. As shown in Figs. 1 and 2, the simulated and predicted soil water contents agree reasonably well with the measured values at various soil depths. The RMSE and MRE values in the calibration and validation are presented in Table 3. The maximum RMSE was 0.07 cm\(^3\) cm\(^{-3}\) in the calibration and 0.05 cm\(^3\) cm\(^{-3}\) in the validation. The maximum MRE was 32.41% in the calibration and 27.62% in the validation. The model performed very well in heterogeneous soils except at the conjunction layer. The SWAP model efficiently described the soil water content variation for heterogeneous soils during the spring-wheat growing period. The calibrated soil hydrological parameters are shown in Table 3.
Fig. 1. Comparison of the measured and simulated soil water content in the calibration.

Fig. 2. Comparison of the measured and predicted soil water content in the validation.

Table 3
RMSE and MRE values of the DF treatment in soil water calibration and validation.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>5</th>
<th>15</th>
<th>25</th>
<th>35</th>
<th>45</th>
<th>55</th>
<th>65</th>
<th>75</th>
<th>85</th>
<th>95</th>
<th>105</th>
<th>115</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE (cm³ cm⁻³)</td>
<td>0.03</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.06</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.07</td>
</tr>
<tr>
<td>Validation</td>
<td>0.04</td>
<td>0.04</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>MRE (%)</td>
<td>27.31</td>
<td>27.62</td>
<td>13.82</td>
<td>16.94</td>
<td>3.27</td>
<td>15.22</td>
<td>6.06</td>
<td>6.78</td>
<td>14.13</td>
<td>8.88</td>
<td>20.66</td>
<td>25.36</td>
</tr>
</tbody>
</table>

3.1.2. Salt concentration

The soil salinity was measured at seven sampling dates during the spring-wheat growing period each year. As illustrated in Figs. 3 and 4, the simulated and predicted salt concentrations were in reasonable agreement with the measured values except for the calibration on July 9 and the validation on July 4. The RMSE and MRE values at various dates for each treatment in the calibration and validation are presented in Table 4. Most RMSE and MRE values were less than 4.0 mg cm⁻³ and 40%, respectively. The discrepancy between the simulated and measured values in later growth stages may be attributed to the fact that some processes, such as adsorption, decay, proportional salt in root uptake, and hysteresis in the retention curve, were not taken into account. The lower soil water content in the later periods may also affect the prediction of salt concentration. The calibrated model described the temporal and vertical variations in salt concentration of the heterogeneous soils in most growth stages of spring wheat. The calibrated molecular diffusion coefficient and dispersion length were 0.5 cm² d⁻¹ and 12 cm, respectively.

3.2. Simulation of soil water content and salt concentration

3.2.1. Soil water content

Due to restrictive conditions, the soil water content after irrigation can hardly be measured immediately in the field. Model simulation, however, can achieve the required output. The effect of irrigation water quantity on soil water content was similar at three salinity levels. As presented in Fig. 5, the soil water content increased with irrigation water quantity. The soil water content of the DD3 treatment was relatively low in the late growth stages for all layers. The temporal variation of the soil water content at 65 cm showed a declining trend. The soil moisture changed slightly below 95 cm depth for the D3 treatment and 65 cm for the DD3 treatment.
Fig. 3. Comparison of the simulated and measured salt concentration in the calibration.

Fig. 4. Comparison of the predicted and measured salt concentration in the validation.

Table 4
RMSE and MRE values of the DF treatment in salt concentration calibration and validation.

<table>
<thead>
<tr>
<th></th>
<th>Date</th>
<th>April 14</th>
<th>April 27</th>
<th>May 12</th>
<th>May 28</th>
<th>June 11</th>
<th>June 19</th>
<th>July 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>RMSE (cm² cm⁻³)</td>
<td>0.77</td>
<td>1.09</td>
<td>2.51</td>
<td>1.77</td>
<td>1.63</td>
<td>2.91</td>
<td>4.83</td>
</tr>
<tr>
<td></td>
<td>MRE (%)</td>
<td>10</td>
<td>15.49</td>
<td>21.68</td>
<td>16.98</td>
<td>24.57</td>
<td>28.73</td>
<td>44.73</td>
</tr>
<tr>
<td>Validation</td>
<td>Date</td>
<td>May 3</td>
<td>May 14</td>
<td>May 22</td>
<td>June 1</td>
<td>June 12</td>
<td>June 22</td>
<td>July 4</td>
</tr>
<tr>
<td></td>
<td>RMSE (cm² cm⁻³)</td>
<td>1.48</td>
<td>3.81</td>
<td>2.25</td>
<td>4.1</td>
<td>3.4</td>
<td>4.55</td>
<td>5.06</td>
</tr>
<tr>
<td></td>
<td>MRE (%)</td>
<td>18.4</td>
<td>22.26</td>
<td>24.43</td>
<td>29.65</td>
<td>45.8</td>
<td>33</td>
<td>55.21</td>
</tr>
</tbody>
</table>

Fig. 5. Comparisons of soil water content at three irrigation levels.

The effect of irrigation water salinity on the soil water content was unobvious for two years. Ben-Asher et al. reported that the higher soil water content in saline treatments results from the relatively low water consumption of vines under medium and high salinity [25]. Jiang et al. found that severe salt stress markedly inhibits the spring-maize water uptake and that more water is left in the soil [9]. This unobvious phenomenon in the study might be due to the short-term simulation and salt tolerance of spring wheat in the area.
3.2.2. Salt concentration

Salt concentration is related to soil water content. The salt concentration was high prior to irrigation when the soil water content was low (Fig. 6). Taking SF, S3, and S6 as examples (Fig. 6(a)), the salt concentration at 15, 35, and 65 cm increased with water salinity at the same water quantity. The difference became obvious with crop development. The salt concentration at 15 and 35 cm increased after irrigation due to water extraction in the irrigation period. At 65 cm, the salt concentration for all treatments showed a constantly increasing trend from the middle stage. There was a slight increase in the salt concentration at 95 cm during harvest, but the difference among the three salinity levels was minor.

At the same water salinity, the salt concentration increased with a decreasing water quantity at 15, 35, and 65 cm. Using SF, DF, and DDF as examples (Fig. 6(b)), the salt concentration of DDF at 65 cm was higher than for the SF and DF treatments from the middle stage; this corresponds to the decreased soil water content. At 95 cm depth, however, the salt concentration of DF treatments was highest during harvest. Some salts may be leached downward 95 cm under 100% ETc treatments but not reach 95 cm under 60% ETc treatment; most accumulate around 95 cm under 80% ETc treatments.

3.3. Simulation of cumulative water and salt exchange

3.3.1. Cumulative water exchange

Cumulative water and salt exchange values at certain depths were obtained by cumulating water or salt flux daily. As presented in Fig. 7, the main process of water exchange at 15, 35, 65, and 95 cm was supplemented into the upper layer before the first irrigation. After the second irrigation, the cumulative water exchange at 15, 35, and 65 cm increased with an increase in water quantity when downward but decreased with an increase in water quantity when upward. At 15 cm, the main process of water exchange was percolation into the lower layer after the first irrigation. The main downward process in DD3 at 35 cm and D3 at 65 cm appeared after the third irrigation. Cumulative water exchange was always upward from 65 cm in DD3 and 95 cm in D3. The main water uptake layer concluded above 65 cm at 60% ETc and above 95 cm at 80% ETc treatments. The cumulative water exchange for all treatments at 95 cm was performed upward, indicating that the water transport process below this depth was mainly supplemented into the upper layer of the wheat growth period. Accumulation curves with no significant inflections indicate that supplementation of irrigation water cannot reach these depths. The corresponding depths of D3 and DD3 were 65 cm and 95 cm, respectively. The difference in water exchange at various soil depths in water salinity was not obvious at the same water quantity.

3.3.2. Cumulative salt exchange

The difference in salt exchange between water quantity and salinity was apparent, as shown in Fig. 8. Within the same salinity, the temporal variety of salt exchange was consistent with water exchange. The salt exchange of DD3 at 65 cm depth
Fig. 7. Comparisons of cumulative water exchange at different soil depths.

Fig. 8. Comparisons of cumulative salt exchange at different soil depths.

and that of D3 at 95 cm depth showed a small upward trend, so most of the salt accumulated above 65 cm in DD3 and 95 cm in D3. The amount of salt leached to the lower soil layer at various depths increased with irrigation water quantity. For the same water quantity, the differences in cumulative salt exchange among the three salinity levels were not obvious at 15 cm. The salt was mainly leached to the lower layer at 35 cm as the amount of leaching increased with water salinity. At 65 cm depth, however, the largest amount of leaching was with the S3 treatment. On the one hand, saline water with salt concentration of 3 g l\(^{-1}\) brought salt into the 65 cm soil layer; on the other hand, more accumulated salt in the upper layer was leached from saline water. The cumulative salt exchange of all treatments at 95 cm depth was performed upward, which was consistent with water exchange.

3.4. Simulation of averaged daily water and salt change

3.4.1. Averaged daily water depletion in depth

The averaged daily water depletion was used to understand the water uptake pattern; a tangible difference in the patterns of water extraction from various soil layers is depicted in Fig. 9. Significant differences were found in the soil profile among the three water quantity levels. The root water uptake above 80 cm depth was increased under deficit irrigation. The maximum soil depth of the root water uptake moved upward under deficit irrigation. The differences in water extraction patterns for various salinity levels were not obvious at 100% and 80% \(ET_c\), but were observable at 60% \(ET_c\). Compared with the DDF treatment, the water extraction of DD3 was increased within the 30–90 cm soil layer. Meanwhile, the water extraction of DD6 increased in the 0–50 cm layer and decreased in the 50–100 cm layer. This implies that irrigation water deficit can enhance water extraction from the soil in certain layers; the maximum soil layer of root uptake will be moved upward under severe water and salt stresses.

3.4.2. Daily salt concentration change

To understand the salt accumulation pattern, the averaged daily salt concentration change was examined (Fig. 10). A difference was found in the salt accumulation patterns from individual soil layers. Significant differences in the salt accumulation profile were found among different irrigation practices. At the same salinity level, the maximum salt
Field experiments only simulate limited scenarios, and so are difficult to use for long-term observations. In comparison, numerical model simulation is advantageous for scenario analysis and long-term prediction. Water with salt concentration of 3, 6, 9, and 12 g l\(^{-1}\) in combination with water quantity of 50\%, 60\%, 70\%, 80\%, 90\%, 100\%, 110\%, and 120\% \(ET_c\) was simulated using the calibrated SWAP model. The maximum relative yield at 3, 6, 9, and 12 g l\(^{-1}\) of 0.97, 0.9, 0.85, and 0.8 was obtained in the 90\%, 70\%, 70\%, and 60\% \(ET_c\) levels, respectively. The four treatments were named as T1, T2, T3, and T4. Four treatments were assumed to be utilized for five continuous years. Every winter, two irrigations of 90 mm was applied for water storage and salt leaching.

The temporal change in soil water content for five years appeared similar for all treatments, as seen for T2 and T3 in Fig. 11. Although the water supplement was the same every year, the soil water content increased slightly at the same rate. The higher the water salinity, the more apparent was the increase observed. A higher soil water content appeared under deficit irrigation with saline water, indicating that the increasing salt stress significantly hindered water extraction from soil. Salt stress cannot be compensated by higher soil water content.
As presented in Fig. 12, the long-term simulation of salt concentration indicated that the highest salt concentration value appeared a few days after the harvest, whereas the lowest appeared after winter irrigation. Winter irrigation is important for salt leaching. The simulation results also demonstrated that after a few years’ use of saline water, the salinization process reached a certain equilibrium state. Equilibrium was achieved earlier at a higher irrigation water salinity and larger water quantity. As depicted in Fig. 12, the salinization of treatments T1, T2, T3, and T4 reached equilibrium after three, four, three, and three years, respectively. Smets et al. also found a similar phenomenon in Pakistan; the difference in years of equilibrium was ascribed to soil texture, irrigation practices, and climate [26].

4. Conclusions

The calibrated and validated SWAP model described water and salt transport effectively in spring-wheat growth stages. The use of the SWAP model under different irrigation practices was considered practical. The simulation results credibly discriminate the difference in water–salt transport under saline irrigation. The soil water content decreased with irrigation water quantity, and the salt concentration increased with a decrease in water quantity and an increase in water salinity. Deficit irrigation may change the water extraction pattern from the soil in certain layers; under a severe water deficit, the maximum root uptake soil layer will be moved upward. In conformity with soil water extraction, the maximum salt accumulation layer moved upward with a decrease in irrigation water quantity. In addition, the SWAP model is an effective tool to predict long-term variation in soil water and salt, which can hardly be observed in the field. Finally, the soil water content showed a minor increase annually, and the salinization process reaches a certain equilibrium state after a few years of using saline water.

Further research is required on the use of the SWAP model to study alternative uses of saline water, to evaluate crop growth under various scenarios, and to find a feasible saline irrigation schedule.

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References