Characterization and Modeling of Water and Salt Dynamics in a Sandy Soil Under the Effects of Surface Drip Irrigation

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Abstract

In the global context of water scarcity and salinization, there is a more pressing need for an efficient use of irrigation water through alternative, localized irrigation techniques. Experimental characterization and two-dimensional modeling of water movement and salts transport is important for managing such irrigation systems. However, experimental observations rarely accompany most numerical modeling studies of two-dimensional water flow and solute transport under drip irrigation. For this purpose, two sandy soil monoliths were instrumented with TDR probes to monitor water contents and Watermark sensors to monitor soil pressure heads. Soil salinity was measured using the method of the soil diluted extract (soil/water ratio of 1/5). Preliminary tests on small monoliths were carried out to determine soil hydraulic parameters of this soil. The two monoliths were saturated with either distilled or saline waters (with electrical conductivity of 4 dS m⁻¹). Experimental results show important vertical movement of water and the formation of a saline bulb around a depth of 20 cm.

Modeling of water movement and solute transport was performed with Hydrus-2D. Four sets of soil hydraulic parameters were evaluated against data from the monolith irrigated with distilled water. The best results were obtained with the parameters estimated using the RETC software and the retention curve data measured by the evaporation method. Model validation was performed on the data obtained from the monolith irrigated with saline water. Modeling results showed a good agreement between measured and predicted values. A scenario highlighting the effect of significant evaporation (8 mm day⁻¹) during an irrigation cycle revealed a potential for soil salinization with the formation of a saline bulb of medium salinity (3.5 dS m⁻¹) around the emitter. This bulb extends to a depth of 30 cm. In the long-term, after several cycles of irrigation, the salinity risk can be aggravated and affect the soil physical properties and consequently, crops production.

1. Introduction

In arid and semi-arid regions, soil salinity remains one of the most crucial and widespread environmental problems in agriculture, in addition to an increasing demand on water resources and water quality degradation. To cope with these twin problems, a wide range of irrigation systems, including surface drip irrigation, have been developed. Surface drip irrigation is widely used in agriculture in recent decades because of its many advantages in terms of water economy, water efficiency, and limitation of soil salinization. Thus, increasing water demand, water quality degradation, and soil salinization have aroused a great interest in understanding the processes governing water movement and solute transport in unsaturated soils through numerical modeling. This requires a reliable characterization of soil hydraulic properties and solute transport parameters. However, measuring these parameters is expensive and often difficult to implement.
Indirect methods and laboratory measurements are increasingly used by researchers. Meanwhile, several numerical models have been developed to study water and salts dynamics under drip irrigation (Al-Qinna and Abu-Awwad, 2001). For example, Skaggs et al. (2004) compared measured values of water contents under surface drip irrigation to those simulated using Hydrus-2D. Zhou et al. (2007) also compared simulated values of water contents by Hydrus-2D with those simulated by a two-dimensional model APRI under the dripper. However, these days there are only few studies that focus on soil salinization risks with surface drip irrigation. In Tunisia, there is also a lack of studies that focus on numerical modeling in the management of water and soil salinity under drip irrigation.

The objectives of this paper are to experimentally characterize and model two-dimensional water and solute dynamics in a sandy soil under surface drip irrigation and to study the effects of high evaporation on the distribution of water content and soil salinity.

2. Materials and Methods

2.1. Experimental Design and Measurements

Two monoliths of a sandy soil (93% sand, 4% silt and 3% clay) were used (Fig. 1). Their dimensions were: 60 cm along the $x$-axis, 60 cm along the $z$-axis, and 10 cm along the $y$-axis. In each monolith, given the symmetry of the problem, five TDR probes were placed on the right side at the following coordinates: one probe 45 cm below the emitter axis, two probes at a depth of 30 cm at $x = 0$ cm and $x = 15$ cm, and two probes at a depth of 10 cm depth at $x = 0$ cm and $x = 15$ cm. The dripper was placed in the center ($x = 0$ cm, $z = 0$ cm) at the surface of the monolith. The first monolith was irrigated at a flow rate of 0.316 L h$^{-1}$ with fresh water (0.5 dS m$^{-1}$) and the second monolith at a flow rate of 0.490 L h$^{-1}$ with saline water (4 dS m$^{-1}$). Water was applied for 4 h 45 min and 4 h 25 min to the first and second monoliths, respectively. The water content was monitored using TDR probes. The 2001 Trase model from the Soil Moisture Corp Company was used. The TDR probes were adapted to salinity and previously calibrated. The salinity of the soil was determined on soil samples using the method of the soil diluted extract (soil/water ratio of 1/5) at the same measurement points.

2.2. Modeling of Water Movement and Solute Transport

Only the right side of the monolith was simulated using Hydrus-2D (Šimůnek et al., 1999). The geometric domain is defined for the two monoliths as before: width = 30 cm and height = 60 cm. The emitter, represented by a quarter of a circle with a radius of 1 cm, is placed 1 cm below the origin of the coordinate system, i.e., in the center, 1 cm below the surface of the monolith. The simulations were carried out over periods of 2,685 min and 2,800 min, respectively, for the first and second monolith. The first monolith was used to evaluate the model with four different sets of soil hydraulic parameters, and the second to validate the model. As an initial condition, the average water contents measured by TDR probes in each depth were used. The average water content for the probes located at a depth of 10 cm was 12%. This value was assigned uniformly to the portion of the soil between the soil surface and a depth of 20 cm. The same approach was used for the following 20-cm thick soil layer by taking the average of probes located at a depth
of 30 cm. For the soil profile between depths of 40 and 60 cm, the water content value measured by a probe located at a 45-cm depth was used. The initial electrical conductivity was assumed to be uniform and equal to 0.5 dS m⁻¹.

![Image](image1.png)

Figure 1. Monolith and measurement points.

![Image](image2.png)

Figure 2. Water flow (left) and solute transport (middle) boundary conditions.

Soil hydraulic properties were estimated using either:
- the van Genuchten catalog (1991) (denoted as vG)
- Rosetta pedotransfer functions (Schaap et al., 2001) (denoted as R), and
- the evaporation method (Kanzari et al., 2012), using fresh water (0.5 dS m⁻¹) (denoted as FW) and saline water (4 dS m⁻¹) (denoted as SW).
Table 1. Soil hydraulic parameters determined by the four methods.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\theta_s$ (cm$^3$ cm$^{-3}$)</th>
<th>$\theta_r$ (cm$^3$ cm$^{-3}$)</th>
<th>$\alpha$ (cm$^{-1}$)</th>
<th>$n$ (-)</th>
<th>$K_s$ (cm d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>vG</td>
<td>0.43</td>
<td>0.0001</td>
<td>0.036</td>
<td>1.56</td>
<td>24.9</td>
</tr>
<tr>
<td>R</td>
<td>0.43</td>
<td>0.0001</td>
<td>0.145</td>
<td>2.68</td>
<td>24.9</td>
</tr>
<tr>
<td>FW</td>
<td>0.749</td>
<td>0.134</td>
<td>0.00959</td>
<td>4.34</td>
<td>712.8</td>
</tr>
<tr>
<td>SW</td>
<td>0.831</td>
<td>0.0444</td>
<td>0.001086</td>
<td>2.75</td>
<td>712.8</td>
</tr>
</tbody>
</table>

The results of model simulations were evaluated using graphical and statistical methods. In the graphical approach, the measured and simulated volumetric water contents and soil salinities were plotted as a function of soil depth using Surfer 8.0. The statistical approach involved the calculation of the root mean square error ($RMSE$).

3. Results

3.1. Characterization of Water Movement and Solute Transport

Figure 3 below shows the distribution of the water content and soil salinity for the two monoliths at different times. The vertical movement of water is more important than the lateral movement. For monolith 2, the salts bulb extends down to a depth of 30 cm.

3.2. Hydrus-2D Calibration

Hydrus-2D was calibrated against the experimental data on water and salts dynamics in monolith 1 using four different sets of hydraulic properties. According to the graphical and statistical evaluation, the parameters estimated using the evaporation method with fresh water provided the best agreement between predicted and measured values.
Figure 4. Measured and simulated (using four different sets of soil hydraulic parameters) water content and soil salinity distributions for Monolith 1.

Table 2. RMSE Values.

<table>
<thead>
<tr>
<th>Value</th>
<th>FW</th>
<th>SW</th>
<th>R</th>
<th>vG</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE: Water Contents</td>
<td>0.140</td>
<td>0.206</td>
<td>0.199</td>
<td>0.256</td>
</tr>
<tr>
<td>RMSE: $EC_e$</td>
<td>0.379</td>
<td>0.372</td>
<td>0.388</td>
<td>0.374</td>
</tr>
</tbody>
</table>

3.3. **Hydrus-2D Validation**

Validation of Hydrus-2D was carried out using the experimental results from Monolith 2. Good agreement between measured and simulated values was obtained. The wetting bulb and salts accumulation were more important. At the end of the irrigation cycle, the soil was dry and low soil salinity around the dripper was observed.

3.4. **Effects of High Evaporation**

A scenario with a high evaporation rate (8 mm day$^{-1}$) was studied numerically using the same input parameters for monolith 2 during a 3 month long irrigation cycle (1 irrigation per week) with a 25 mm irrigation volume of 4 dS m$^{-1}$ saline water. 25 mm is approximately the irrigation volume applied to the second monolith. The results show that at the end of the irrigation, soil salinity is low under the dripper down to a depth of about 10 cm and that salts migrated to a depth of 30 cm with an $EC_e$ of 3.5 dS m$^{-1}$. 
4. Conclusions

In this study, a good agreement between simulated and measured soil water contents and salt contents was found using Hydrus-2D. The effect of high evaporation (8 mm day$^{-1}$) during an irrigation cycle revealed a risk of soil salinization. In the long term, after several irrigation cycles, this risk can be aggravated and affect the soil physicochemical properties and crop growth.

References


