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A bidirectional model for simulating soil water flow and salt transport under mulched drip irrigation with saline water

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ABSTRACT

Here, we present a mathematical model for simulating both soil water flow and salt transport in two directions (perpendicular and parallel to the drip tubing) under mulched drip irrigation with saline water. We evaluated the effectiveness of this model by comparing the simulated values with observed data from the field experiment (one treatment with three replications was imposed with irrigation water electrical conductivity of 4.0 dS m^{-1} and amounts of 2400 m^3 ha^{-1} under mulched drip irrigation system). The results demonstrated that the model performed reliably in the simulation of water flow and salt transport under field conditions. In addition, the model was also used to simulate the spatial distribution patterns of soil water and salt in the two directions in relation to different treatments of irrigation quantity and quality. The simulation demonstrated that the volume of wetted soil was affected by both the plastic mulching and irrigation amount. The wetted region was expanded to the middle of the plastic mulching when the irrigation amount was high and the uniformity of irrigation increased with increasing irrigation volume. Soil water content in the direction parallel to the drip tubing was higher than that perpendicular to the tubing at the same distance, indicating that the wetting fronts overlapped more rapidly in the direction parallel to the drip tubing. The soil salt concentration was high at the edges of the wetting front, with a fairly large desalinated area immediately underneath and adjacent to the drippers. The model presented here offers an efficient approach to investigating the mechanisms underlying soil water flow and salt transport and for designing mulched drip irrigation systems with saline water.

1. Introduction

Scarcity of fresh water constrains irrigated agriculture worldwide (Beltran, 1999; Mantell et al., 1985); consequently, farmers in many irrigated areas are being encouraged to use saline water for agricultural production. However, salt accumulation in soil profiles due to saline water irrigation typically leads to salinization and sodification, producing soils that cannot sustain crop yields. In this context, specialized and efficient methods of irrigation that can attain the twin objectives of higher productivity and optimum use of saline water are indispensable.

Mulched drip irrigation, with beds and drip tubing covered with plastic film, is able to maintain high soil matric potential in the root zone as well as promoting weed control and crop production. Furthermore, because this type of irrigation allows application of water at a low rate and high frequency over extended periods of time, the soil salt introduced during the early stages of saline water irrigation can be leached effectively by subsequent applications (Goldberg et al., 1976; Kang, 1998). Thus, mulched drip irrigation is more profitable than other techniques for saline water irrigation (Ayers et al., 1986; Burt and Isbell, 2005; Saggu and Kaushal, 1991).

Successful utilization of mulched drip irrigation with saline water depends primarily on effective system design and management. By adjusting the number of drippers, discharge rate, and irrigation frequency, a mulched drip irrigation system can be designed so that the wetted soil volume coincides with the crop rooting pattern as closely as possible (Patel and Rajput, 2008). In addition, accumulation of salts in the root zone should not exceed the tolerance limits of the crop. Therefore, improvements in our understanding of soil water flow and salt transport and their spatial distributions play an important role in the design and performance of such systems.

Numerical simulation is an efficient approach for investigating the extent to which water and salt move laterally and vertically away from a dripper and allows more flexible representation of the flow domain, boundary conditions, and soil properties than can be

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achieved in field tests (Warrick, 2003). Numerous models for analyzing water flow and solute transport under drip irrigation have been developed over the last 40 years (e.g., Annandale et al., 2003; Arbat et al., 2013; Brandt et al., 1971). Most of these models assume that the wetted regions on both sides of the vertical plane (i.e., the plane perpendicular to the horizontal plane of the drip source) are symmetrical. It has also been a common practice to conceptualize the drip tubing as a line source rather than representing individual drippers along the drip line (Skaggs et al., 2004), ignoring the wetting pattern in the direction parallel to the drip tubing. For mulched drip irrigation, however, the plastic film covers an asymmetric pattern of individual drippers and the plastic mulching may induce pronounced changes in soil water flow and solute transport paths (Amayreh and Al-Abed, 2005). Therefore, it is essential to construct a model that accurately represents the actual patterns of soil water flow and salt transport when using mulched drip irrigation with saline water.

Here, we describe a mathematical model using HYDRUS-2D that calculates soil water flow and salt transport both perpendicular and parallel to the drip tubing under mulched drip irrigation with saline water. The performance of the model was evaluated by comparing the simulated values with experimental data. Finally, the spatial distribution patterns of soil water and salt under various irrigation conditions are discussed.

2. Materials and methods

2.1. Field experiment

We conducted a field experiment at the test and demonstration base for agricultural water-saving and ecological construction (103°12′3.4″E, 38°42′40.2″N) in Minqin County, Gansu Province, China from April 25 to October 15, 2013. The experimental soil was classified as sandy loam, with bulk densities of 1.57 and 1.55 g cm^{-3} in the 0–25-cm and 25–50-cm layers, respectively. Further details of the experimental site can be found in Chen and Feng (2013).

A drip irrigation system mulched with plastic film (black polyethylene) was used to deliver saline water with an electrical conductivity (EC) of 4.0 dS m^{-1} to cotton plants (*Gossypium hirsutum* L. cv. Xinluzao 7). Irrigation water was obtained by mixing water from two wells in specified proportions. One well was located at the experimental station (fresh water (FW), EC = 1.09 dS m^{-1}) and the other was in Huanghui Village (103°36′11.9″E, 39°02′56.4″N) in Minqin County (saline water (SW), EC = 15.92 dS m^{-1}). The ion concentrations of the source water are presented in Table 1. The desired salinities were obtained as follows:

$$M = \frac{M_f \times Q_f + M_s \times Q_s}{Q_f + Q_s} \tag{1}$$

where M is the salinity of the irrigation water after mixing (dS m^{-1}), M_f is the salinity of the FW (dS m^{-1}), M_s is the salinity of the SW (dS m^{-1}), Q_f is the amount of FW (m^3 ha^{-1}), and Q_s is the amount of SW (m^3 ha^{-1}). The ion concentrations of the mixed water are also presented in Table 1.

Three tanks were used for the irrigation system. The first and second tanks were filled with FW and SW, respectively, and the third was used for mixing the water. The irrigation water was supplied by a pump controlled by valves, with the exact amounts of water supplied monitored by water meters (Fig. 1). The total irrigation amount was 2400 m^3 ha^{-1} (8 applications of 30 m^3 ha^{-1} each). The irrigation interval was determined based on soil moisture and crop growth requirements.

After the experimental field was divided into plots (3 replicate plots, each 15 m long and 3.4 m wide; Fig. 1), two groups of the mulched drip irrigation system were arranged on each plot and a 30-cm space without plastic film was maintained between each group. Two rows of drip tubing were laid in each group, with an 80-cm spacing maintained between the two irrigation lines. After each group was mulched with plastic film (140 cm width), four rows of cotton were planted (plants on either side of an irrigation line were 30 cm apart, while plants adjacent to paired irrigation lines were 50 cm apart; see Fig. 1). The plant spacing along the line was 20 cm and an average seeding rate of 58.8 seeds per m^2. The dripper spacing and discharge rate were 30 cm and 2.0 L h^{-1}, respectively. The dates of irrigation, amounts of fertilizer and pesticides used, and other necessary operations were conducted according to typical local practices and recommendations.

Tube access probes (TRIME, Germany) based on time domain reflectometry (TDR; Cichota et al., 2008) were used to measure soil water content. The sensors were installed vertically at three depths (0, −25, and −50 cm) and horizontally at five points (−40, −20, 0, and 20 cm in the direction perpendicular to the drip tubing and at 15 cm in the direction parallel to the drip tubing; see Fig. 2). Measured values were calibrated using the gravimetric method and bulk density. Soil samples used to prepare dilute soil extract solutions were collected using an auger in the same location at which the sensors were installed. Samples were collected before sowing the cotton and before and after each irrigation and significant precipitation event throughout the growing season. The samples were air dried and sieved through a 1-mm mesh. Soluble salt estimates were based on extracts with a 1:5 soil:water ratio, determined using a conductivity meter (EC$_{1:5}$). All data were analyzed using PASW Statistics 18.0 and Surfer 8.0.

2.2. Model development

2.2.1. Mathematical model

We simulated soil water flow and salt transport using HYDRUS-2D (Simunek et al., 1999). Assuming homogeneous and isotropic soil, the governing equation for water flow can be written as follows:

$$\frac{\partial \theta}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[rK(h)\frac{\partial h}{\partial r}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] + \frac{\partial K(h)}{\partial z} - S \tag{2}$$

where θ is the volumetric water content of the soil (cm^3 cm^{-3}), t is time (d), r is the radial coordinate (cm), $K(h)$ is the hydraulic conductivity (cm d^{-1}), h is the pressure head (cm), z is the vertical coordinate with positive upwards (cm), and S is a distributed sink function representing water uptake by the roots (1 d^{-1}).

In HYDRUS-2D, solute transport was described as follows:

$$\frac{\partial(\theta c)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\theta D_r\frac{\partial c}{\partial r}\right) + \frac{\partial}{\partial z}\left(\theta D_z\frac{\partial c}{\partial z}\right) - \frac{1}{r}\frac{\partial}{\partial r}(rq_r c) - \frac{\partial}{\partial z}(q_z c) \tag{3}$$

where c is the concentration of the solute in the soil solution (dS m^{-1}), D is the dispersion coefficient (cm^2 d^{-1}), and q is the volumetric flux density (cm d^{-1}).

2.2.2. Initial and boundary conditions

The origin of the coordinates (r = 0 and z = 0) was placed at the center of the dripper, as illustrated by the schematic diagram presented in Fig. 3.

Perpendicular to the drip tubing, the measured soil water pressure heads $h_0(r,z)$ and soil salinities $c_0(h,z)$ before the experiment were used as initial conditions within the flow domain. Then:

$$h(r, z, t) = h_0(r, z),\ c(r, z, t) = c_0(r, z),\ t = 0,\ -R' \le r \le R',\ 0 \le z \le Z \tag{4}$$

where R' and Z are the maximum radial and vertical extents of the simulated domain (cm).