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Simulation of soil water and salt transfer under mulched furrow irrigation with saline water

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ABSTRACT

A mathematical model for simulating soil water and salt transfer under mulched furrow irrigation with saline water was presented. The model performance was evaluated by comparing the simulated values with observed data from the field experiment. The results demonstrated that the model performed reliably in the simulation of water and salt transfer under field conditions. In addition, the model was also used to simulate the process of soil water and salt transfer after saline water irrigation. The simulation demonstrated that the increment of soil water storage below the bottom of the furrow was nearly equal to the value below the top of the ridge immediately after the end of the irrigation (17 h) when the downward movement of irrigation water was restricted by the clay interlayer in soil. However, during the irrigation interval (192 h and 384 h after the irrigation), more water was maintained below the top of the ridge due to a considerable reduction of evaporation under mulched furrow irrigation. Soil salt mainly comes from saline water irrigation and the soil salt below the top of the ridge mainly increased at the redistribution phase (17 h). During the irrigation interval, soil conductivity in surface soil layer below the top of the ridge was smaller than that below the bottom of the furrow, which indicated that the distribution of soil salt below the top of the ridge was more uniform than below the furrow. The model presented here offers an efficient approach to estimate environmental effects of mulched furrow irrigation technology associated to saline water utilization.

1. Introduction

Saline water, which is in plentiful supply in the world (Mantell et al., 1985), is an important substitutable resource for fresh water in regions with scarce irrigation water of good quality (Pereira et al., 2002). In most arid regions of northwest China, saline water utilization for agriculture is generally combined with surface irrigation. Furrow irrigation with plastic mulching is currently the most common irrigation practice for this combination.

Evaluation of environmental impacts of the combined irrigation practices requires accurate estimation of water and salt fluxes within soil (Crevoisier et al., 2008). In traditional furrow irrigation, salts tend to accumulate in surface soil layers below the ridges (Saggu and Kaushal, 1991) because leaching occurs primarily below the furrows. For mulched furrow irrigation, however, the plastic mulching may induce pronounced changes in soil water flow and salt transfer paths (Zhou et al., 2009; Bezborodov et al., 2010). Based on this consideration, we carried out field experiments to investigate the distributions of soil water and salt under mulched furrow irrigation with saline water. The result showed that salt concentration in surface soil below the ridge was smaller than that below the bottom of the furrow. However, the experiments could not completely explain the cause of the result because of its restriction of observation. Therefore, specialized and efficient methods which could elaborate soil water and salt transfer process are necessary.

Numerical simulation is a proper approach for investigating the process of water and salt movement laterally and vertically away from the bottom of the furrow and allows more flexible representation of the flow domain, boundary conditions, and soil properties than can be achieved in field tests (Warrick, 2003). Numerous models have been developed for simulating water flow and solute transfer under furrow irrigation (e.g., Burguete et al., 2009; Abbasi et al., 2004; Mailhol et al., 2001), but not much is concerning about the effect of plastic covering on the soil, especially under the condition of saline water irrigation. Humberto and Lal (2007) showed that saturated hydraulic conductivity of mulched treatments was 123 times greater and retained 40 to 60% more water than the un-mulched treatment. This modified soil microenvironment which is caused by plastic mulching needs to be recognized when estimating the wetted soil volume and the accumulation of salts in the root zone. Therefore, it is essential to construct a model that accurately represents the actual patterns of soil water flow and salt transfer when using mulched furrow irrigation with saline water.

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The objective of the study is to establish a mathematical model which is used for simulating soil water and salt transfer under mulched furrow irrigation with saline water. The performance of the model was evaluated by comparing the simulated values with the experimental data. Finally, the process of soil water and salt transfer after irrigation was elaborated in order to explain the differences of soil water and salt distributions below the top of the ridge and the bottom of the furrow. The model could be then used to estimate the environmental effects of mulched furrow irrigation technology associated to saline water utilization.

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′03.4″E, 38°42′40.2″N) in Minqin County, Gansu Province, China, from April 22 to September 25, 2013. The experimental site is located at the boundary of Tengger Desert, where average annual evaporation (more than 2664 mm) is twenty four times greater than the annual precipitation (110 mm). The average annual temperature is 7.8 °C, and winter temperature minima can fall to −27.3 °C whereas summer maxima rise to 41.1 °C. The groundwater table is generally below 18 m. The experimental soil is classified as sandy loam in the upper 60 cm with an average bulk density of 1.55 $g \cdot cm^{-3}$, clay in the 60–100 cm layer with an average bulk density of 1.46 $g \cdot cm^{-3}$ and sand in the 100–120 cm layer with an average bulk density of 1.63 $g \cdot cm^{-3}$.

A furrow irrigation system mulched with plastic film (black polyethylene) was used to deliver saline water with an electrical conductivity (EC_w) of 4.46 $dS \cdot m^{-1}$ to Maize (*Yu 22*). Three replications were adopted for the test, and irrigation water was obtained by mixing the water from two wells in specified proportions. One well was located at the experimental station (fresh water (FW), $EC_w = 1.09$ $dS \cdot m^{-1}$) and the other was in Huanghui Village (103°36′11.9″E, 39°02′56.4″N) in the Minqin County (saline water (SW), $EC_w = 15.92$ $dS \cdot m^{-1}$). The ion concentrations of the source water are presented in Table 1. The desired salinities were obtained as follows:

$$M = \frac{M_f \times Q_f + M_s \times Q_s}{Q_f + Q_s} \quad (1)$$

where M is the salinity of the irrigation water after mixing ($dS \cdot m^{-1}$), M_f is the salinity of the FW ($dS \cdot m^{-1}$), M_s is the salinity of the SW ($dS \cdot m^{-1}$), Q_f is the amount of FW ($m^3 \cdot ha^{-1}$), and Q_s is the amount of SW ($m^3 \cdot ha^{-1}$).

Three large tanks were used to store the irrigation water: the first and second tanks were filled with water from FW and SW, respectively, and the third was filled with mixing water. The irrigation water was supplied by a pump in amounts that were controlled by valves, with the exact amounts of water supplied monitored by water meters (Fig. 1). The total irrigation volume was 360 mm of irrigation depth (3600 $m^3 \cdot ha^{-1}$), which was applied in five irrigation events. According to local irrigation practice, the source water of the first irrigation event was surface water which was supplied from Hongyashan Reservoir by channels ($EC_w = 0.52$ $dS \cdot m^{-1}$, see Table 1). The date for this irrigation was on June 2 and the volume of water applied was 45 mm of irrigation depth. The schedule for other four irrigation events with saline water ($EC_w = 4.46$ $dS \cdot m^{-1}$) was: June 21, 75 mm; July 9, 75 mm; July 25, 90 mm; and August 12, 75 mm. The average irrigation interval was 17.75 days.

After the experimental field was divided into plots (3 plots, each 12 m long and 3 m wide; Fig. 1), three groups of mulched furrow irrigation system were arranged on each plot. The furrows were closed at the end of the plot to withhold the water. The ridge and furrow for any group were 60 cm wide (30 cm high) and 40 cm wide (30 cm high), respectively. After the plots were mulched with a plastic film (extending for a width of 90 cm), two rows of maize were planted on any ridge with dibblers (the plant density was approximately 45 $kg \cdot ha^{-1}$). The plastic film was joined at the bottom of the furrow and a 10 cm space without plastic film was maintained for water infiltration. This is a common irrigation practice followed by the farmers of the locality. Irrigation was applied in the furrow and the date of application, amount of fertilizer used, use of pesticides, and the undertaking of other necessary operations were prescribed according to typical local practices and general recommendations.

Data relating to precipitation were obtained from the standard meteorological observation station of the base. During each irrigation period, the depth of irrigation water in furrow was recorded once in every 10 min. Soil samples were collected using an auger in the center of each plot before and after each irrigation event. The depth of sampling ranged from 30 cm to 120 cm below the bottom of the furrow (30–40 cm, 40–60 cm, 60–80 cm, 80–100 cm, 100–120 cm) and 0 cm to 120 cm below the top of the ridge (0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm, 100–120 cm, Fig. 2). All soil samples were divided into two parts. One part was used for measuring soil water contents by the gravimetric method and another part was used for preparing dilute soil extract solutions. Samples for the solutions 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 ($EC_{1:5}$, $dS \cdot m^{-1}$). Soil samples with a wide range of $EC_{1:5}$ values were selected to measure the conductivity of saturated paste extract (EC_e) and the relationship between EC_e and $EC_{1:5}$ was developed subsequently. The conductivities were highly correlated ($R^2 = 0.966$). Thus, EC_e was estimated for all samples using Eq. (2):

$$EC_e = 5.8605 \times EC_{1:5} + 1.3542. \quad (2)$$

The EC_e was converted to salt concentration (C_{sw}, $g \cdot L^{-1}$) using the relationship according to Xin et al. (1986):

$$C_{sw} = 0.67 \times EC_e. \quad (3)$$

Salt concentrations were converted to solute densities ($g \cdot cm^{-3}$) using the measured soil bulk density and volumetric water content.

Soil evaporation was measured using microlysimeters, which were installed at the bottom of the furrow. The microlysimeters were made of two iron tubes with an internal diameter of 15 cm and a depth of 35 cm for the inner and 20 cm and 40 cm for the outer. For each inner tube, the bottom was beveled and a hand auger coupled to the upper part made for easy insertion and removal. After each irrigation event and significant precipitation, the inner tube was inserted into the soil

Table 1
Chemical composition of source water used in the experiment.

Water	HCO_3^- ($mg \cdot L^{-1}$)	Cl^- ($mg \cdot L^{-1}$)	SO_4^{2-} ($mg \cdot L^{-1}$)	Ca^{2+} ($mg \cdot L^{-1}$)	Mg^{2+} ($mg \cdot L^{-1}$)	Na^+ ($mg \cdot L^{-1}$)	K^+ ($mg \cdot L^{-1}$)	TDS ($mg \cdot L^{-1}$)	EC_w ($dS \cdot m^{-1}$)
FW	267	93	307	97	40	109	7.0	921	1.09
SW	689	2906	6334	438	1043	2655	33.6	14,099	15.92
Surface water	150	29	126	41	13	64	2.0	425	0.52

FW is the fresh water from the well located at the experimental station; SW is the saline water from the well located at Huanghui Village; TDS is the total dissolved solids; and EC_w is the electrical conductivity.