SIMULATION OF SOIL WATER WITH DIFFERENT WATER TABLE DEPTHS UNDER DRIP IRRIGATION ALONG THE TARIM DESERT HIGHWAY, CHINA

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ABSTRACT

The Tarim Desert Highway is the main transportation artery in China for oil and gas exploration and development, and is in fact the first and longest graded highway (across the Taklimakan Desert) in the world. It suffers from continual sandstorms, and shelterbelts have been built along the road to ensure the smooth, uninterrupted operation of the highway. Recent research on the distribution of soil water under drip irrigation in the shelterbelts has great significance for the robust performance of these shelterbelts. To study the role of water table depth in the soil water distribution of the shelterbelts, we established a 2-D saturated-unsaturated flow model, using the software PetraSim, based on TOUGH2. The model was calibrated by sampling data from where the water table depth was 3 m (under drip irrigation conditions) in the center of the Taklimakan Desert. In addition, several scenarios were simulated using different water table depths. By analyzing the simulation results, some useful conclusions were reached.

Our findings showed that soil water distribution is influenced by the irrigation water and groundwater in the shelterbelts along the Tarim Desert highway. Furthermore, the soil-water content with depth takes the form of the letter ‘‘C”; that is, the water content first decreases and then increases in descending from the surface to the water table. The study emphasizes the profound effect of water table depth on the distribution of moisture in the vadose zone, and thus supplies important reference data and provides useful guidelines for research into building an effective irrigation system.

INTRODUCTION

The Tarim Basin, located in northwest China, is very rich in oil and gas resources (Lu et al., 2004). A large part of the basin is occupied by the Taklimakan Desert, which is the largest active desert in China and the second largest in the world (Zhu et al., 1980). With the enlargement of oil exploration, transportation problems severely constricted the development of the resource (Xia et al., 1995); consequently, the Tarim Desert Highway came into being, extending across the center of the desert. The Tarim Desert Highway starts from north of Lunnan, about 35 km to the Tarim River, and extends south to connect with the 315 National Road, 15 km east of Minfeng, for a total length of 519 km (Han et al., 2004). However, the highway is facing serious sand-drift encroachment problems, caused by its 447 km long passage of sand—including crescent dunes, barchan chains, compound transverse dune ridges, and complex megadunes (Han et al., 2003). Shelterbelts, green corridors 436 km in length on both sides of the highway, were constructed to control the windblown sand and ensure the long-term - uninterrupted operation of the highway (Li et al., 2008; Zhu et al., 2010). Shelterbelt plants, such as Tamarix taklamakanensis, Haloxylon ammodendron and Calligonum caput-medusae, which are strong stress-resistant shrubs with excellent windbreak and sand-fixation properties, were irrigated with saline groundwater bumped from local wells (Han et al., 2012).

Over the past 40 years, many researchers around the world have investigated drip irrigation using analytical solutions (Raats, 1971; Warrick, 1974) and numerical solutions (Bresler et al., 1971; Brandt et al., 1971). Moreover, many studies in the Taklimakan Desert have been carried out on soil-water distribution and dynamics (Zhou et al.,

2000; Wang et al., 2008), the laws of soil-water movement (Huang et al., 2003; Zhou et al., 2010), and the mechanisms of water-salt regulation (Li, 2010) in the Taklimakan desert. There has been little research, however, on how water table depth affects soil-water distribution. In this paper, we describe a numerical model based on the software PetraSim and demonstrate its ability to capture the distribution of soil water for different water table depths, thus providing useful guidelines for building effective irrigation systems in the future.

MATERIALS AND METHODS

Field description

The study area lies in the remote reaches of the Taklimakan Desert, which has an extremely dry continental climate. The average temperature is 12.4℃, with a high temperature of 45.6℃ and a low temperature of -22. The annual precipitation is 11.05 mm; annual rainfall is characterized by an uneven distribution, concentrated between May and August. Average annual relative humidity is 29.4%. Evaporation per year is 3638.6 mm, with a maximum of 563.2 mm in June and a minimum of 34.4 mm in November. With respect to vegetation, types are poor, community structure is simple, and the coverage is extremely low.

Large, mobile, composite sand dunes are the typical landscape in the area. Soil characteristics change with the geomorphology, with the predominant drift sand soil having a salt content of ~1.26–1.63 g/kg. Clay can occasionally be found in the lower layer of sand soil, with a thickness of ~20–60 cm (Zhou et al., 2002).

The peripheral mountain area is the formation region of the Tarim Basin water resources. The alluvial plain and the flood plain in front of the mountains are the phreatic recharge and discharge areas. The desert in the middle is the phreatic runoff discharge area, and the Lop Nor Lake Basin in the east is the phreatic confluence hub (Wang et al., 2004). Within the desert area, the phreatic flow is basically from south to north, turning east at the Tarim alluvial plain. The groundwater is Quaternary loose pore water. The rivers close to the desert highway include the Tarim River (north of the highway), the Niya River, the Yatonggusi River, and the Andiel River (south of the highway). The three rivers south of the highway are the few rivers that flow into the desert (Fan et al., 2008).

The shrubs Tamarix, Haloxylon, and Calligonum are the preferred tree species, considering the harsh desert environmental conditions (Huang, 2002). The configurations can be described as mixed planting between rows with spacing. Groundwater with total dissolved solids of ~3–30 g/L are extracted for drip irrigation at intervals of ~8–12 days, and the irrigation volume is 300 m^3/ha over 8 hours.

Field sampling

Sampling sites shown in Figure 1 were located at the K359 km mark on the desert highway in October 2009. In order to fully consider the influence of irrigation water, sampling took place just after irrigation. The horizontal spacing was 2 m every two sampling points in an east-west direction, and every sampling point was placed next to the emitter and the plant. The vertical spacing between sampling points was 20 cm from the surface to the saturated zone. There were 6 sampling points labeled pm01-06 in the field, and 15 soil samples at each sampling point where the water table depth was at 3 m. All of the samples were sealed in aluminum boxes and weighed on the spot.

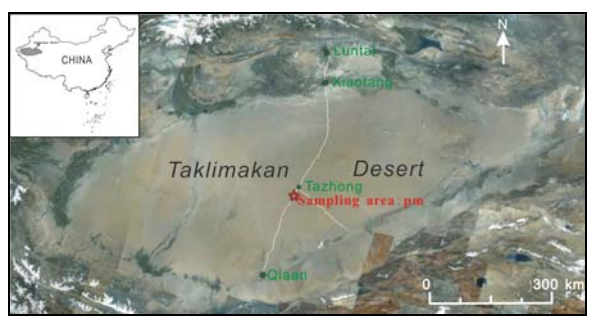

Figure 1. Geographic location of sampling sites

Measurement and calculation methods

Measurement of the water content was conducted in November 2009 by means of oven-drying method, which involved drying the samples in a vacuum oven to a constant weight under 65℃. Volumetric water content was then calculated by Equation (1)

$$\theta_V = \frac{\rho_b}{\rho_w}\theta_m = \frac{\rho_b}{\rho_w}\frac{M - M_s}{M_s} \times 100\% \qquad (1)$$

where θ_V is the volumetric water content (%); ρ_b is the soil bulk density (g/cm^3), with a value of 1.5 in the related literature (Huang, 2002); ρ_w is the density of pure water (g/cm^3), with a value of 1; θ_m is the mass water content (%); M is the mass of wet soil (g); and M_s is the mass of dry soil (g).

NUMERICAL MODELING

EOS9 in the PetraSim software package (Thunderhead Engineering, 2007) based on the well-known simulator TOUGH2 (Pruess et al., 1999) was used to simulate the vertical variation in soil water content after drip irrigation under different water table depths (set at 1 m, 3 m, and 5 m).

Concept and mathematical model

The soil-water flow is axially symmetric in the irrigation period, so that it is treated as a 2-D (vertical plane) water flow process (Skaggs et al., 2004). The vertical plane is determined by x and z axes. TOUGH2 is used to simulate the water flow in the unsaturated-saturated zone, with the water flow under isothermal conditions described by Equation (2), which represents a generalization of the Richards' equation (3).

$$\frac{\partial}{\partial t}\varphi S\rho = div[k\frac{k_r}{\mu}\rho\nabla\left(P + \rho gz\right)] \qquad (2)$$

where ϕ is porosity; S is water saturation; ρ is water density; k is the absolute permeability; k_r is the relative permeability to water, varying between 0 and 1; μ is the viscosity; P is the fluid pressure in water (the sum of the reference gas pressure and capillary pressure); g is the vector of gravitational acceleration; and z is the defined positive upward.

$$\frac{\partial\theta}{\partial t} = div[K\nabla h] \qquad (3)$$

where $\theta = \varphi S$ is the specific volumetric water content, $K = kk_r\rho g/\mu$ is the hydraulic conductivity, and $h = z + P/\rho g$ is the hydraulic head.

Boundary and initial conditions

The simulated flow domain is shown in Figure 2. The horizontal range of the flow domain is 1.0 m, i.e., half of the space between two irrigation tubes, and the vertical range is 5.0 m. The drip tubing can be represented as a small circle with a 0.01 m radius placed at the top boundary on the plane of symmetry between two plant rows.

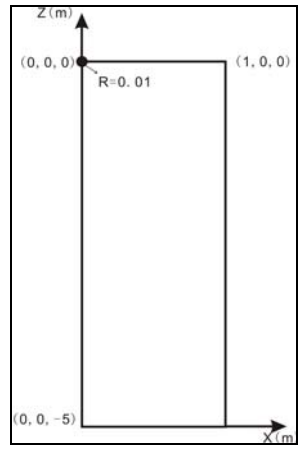

Figure 2. The 2-D model region

The upper boundary is divided into two parts. In the range of the point source (the radius of the point source is 0.01 m), the flux q is constant and calculated by the total irrigation volume divided by the irrigation period—in the modeling, the value is 2.83×10^{-3}kg/s. Outside the irrigation source of the upper boundary, a no-flow boundary condition is employed, i.e., evapotranspiration is ignored.

The lower boundary is set as a free drainage condition, while the lateral boundaries are set to be zero-flux boundary conditions. The pressures at the lower boundary change with water table depth as follows:

$P_l(x, 0, z) = 1.013\times10^5 + 10^3\times9.81\times4 = 1.4054\times10^5$Pa $\quad 0\leqslant x\leqslant1.0, z=-5.0,$
the water table is 1 m below the surface;

$P_l(x, 0, z) = 1.013\times10^5 + 10^3\times9.81\times2 = 1.209\times10^5$ Pa $\quad 0\leqslant x\leqslant1.0, z=-5.0,$
the water table is 3 m below the surface;

$P_l(x, 0, z) = 1.013\times10^5$Pa $\quad 0\leqslant x\leqslant1.0, z=-5.0,$
the water table is 5 m below the surface.

The initial condition of the drip simulation is obtained by running the model to steady state.

Soil hydraulic properties

Soil hydraulic properties could be described with the nonlinear functions (4)–(6) of van Genuchten (1980):

$$k_r = S_e^{1/2}\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \quad (4)$$

$$P_c = -\alpha^{-1}\left(S_e^{-1/m}-1\right)^{1/n} \quad (5)$$

$$S_e = \frac{S-S_r}{S_s-S_r} \quad (6)$$

where S_e is the effective saturation; n is the pore-size distribution characteristic parameter, m=1-1/n; α^{-1} is the entry pressure; and S_r and S_s denote the residual and saturated water saturation, respectively.

The soil parameters S_r, S_s are taken from measurements, whereas n and α are based on the neural network estimates for sand. The values are listed in Table 1.

Table 1. Soil parameters.

φ	k /m^2	n	α/pa	S_r	S_s
0.37	5×10^{-10}	3.62	2.2×10^{-4}	0.0016	1

RESULTS AND DISCUSSION

Comparing simulated with observed water content

Comparison between simulated data and observed data at the trickle (x=0, z=0) after irrigation (8h) is shown in Figure 3, when the saturation depth is 3 m below the surface. The observed data are mean values of sampling points pm01–06 for the error reduction. Figure 3 shows that the observed and simulated water content match well. Volumetric content decreased from the surface to a depth of about 1.2 m, then increased until it reaches the water table at a depth of 3 m. The water saturation distribution for different times after the beginning of irrigation is shown in Figure 4. Soil water mainly moves downward around the emitter, and the water content has increased over the irrigation period.

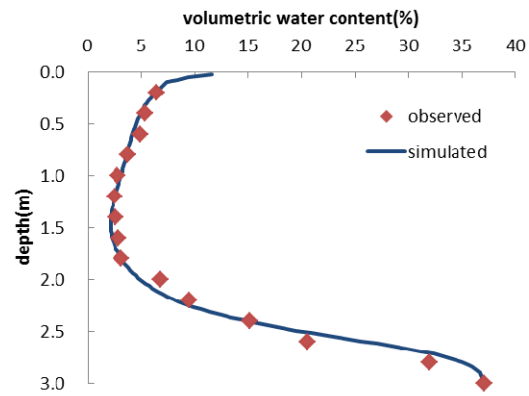

Figure 3. Comparison of simulated and observed soil water content along the depth

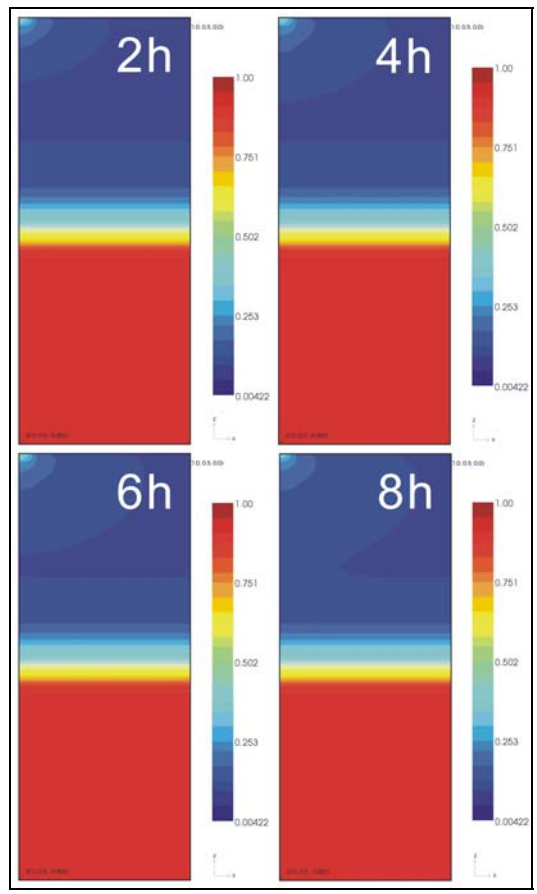

Figure 4. Water saturation distribution for different times of the profile XZ

Scenario simulations

Considering the different locations of the water table along the Tarim Desert Highway, we simulated another two scenarios. Soil-water saturations were calculated by changing the assumed water table depth to 1 m and 5 m. Figures 5 and 6 show variations in volumetric content along the depth at the trickle, as well as

water saturation of the profile XZ under different water table depths.

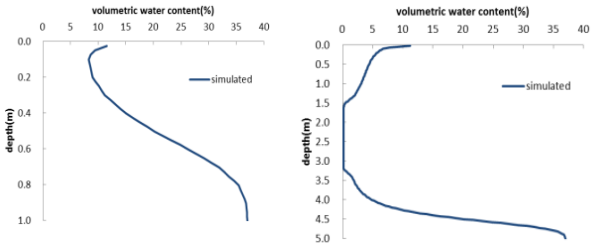

Figure 5. Simulated soil water content along the depth when the water tale depths are 1 m and 5 m

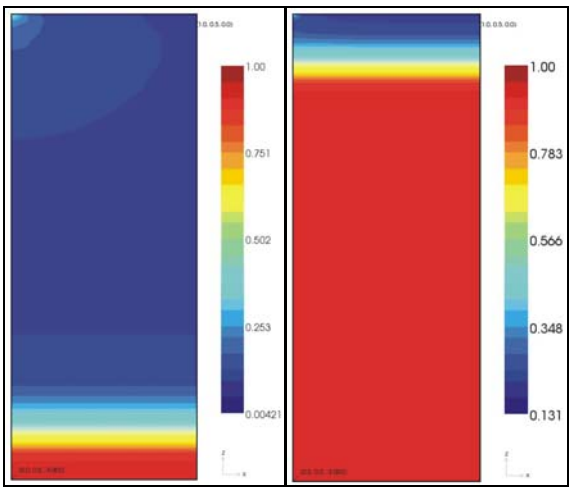

Figure 6. Water saturation distribution of the profile XZ when the water tale depths are 1 m and 5 m

From Figures 5 and 6, it can be seen that at different water table depths, soil moisture first decreases, then increases. The distribution of water soil is affected by the groundwater and irrigation. Water content decreases descending from the surface, mainly because of the effect of irrigation water, and increases again as the top of the capillary fringe zone is reached. Water moves upward from the water table, so that water content becomes greater closer to the saturated zone.

CONCLUSIONS

To study the water table under the Tarim Desert Highway, we established a 2-D unsaturated-saturated model, based on the well-known simulator TOUGH2. By making the simulated soil-water content match the measured data, soil parameters were identified so that the model could be used to simulate the variation in soil water content after drip irrigation under different water table depths (set as 1 m, 3 m and 5 m). The modeling results show that the distribution of soil water is affected by the irrigation water and groundwater in the shelterbelts along the Tarim Desert Highway, with the water content first decreasing and then increasing from the surface to the water table.

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