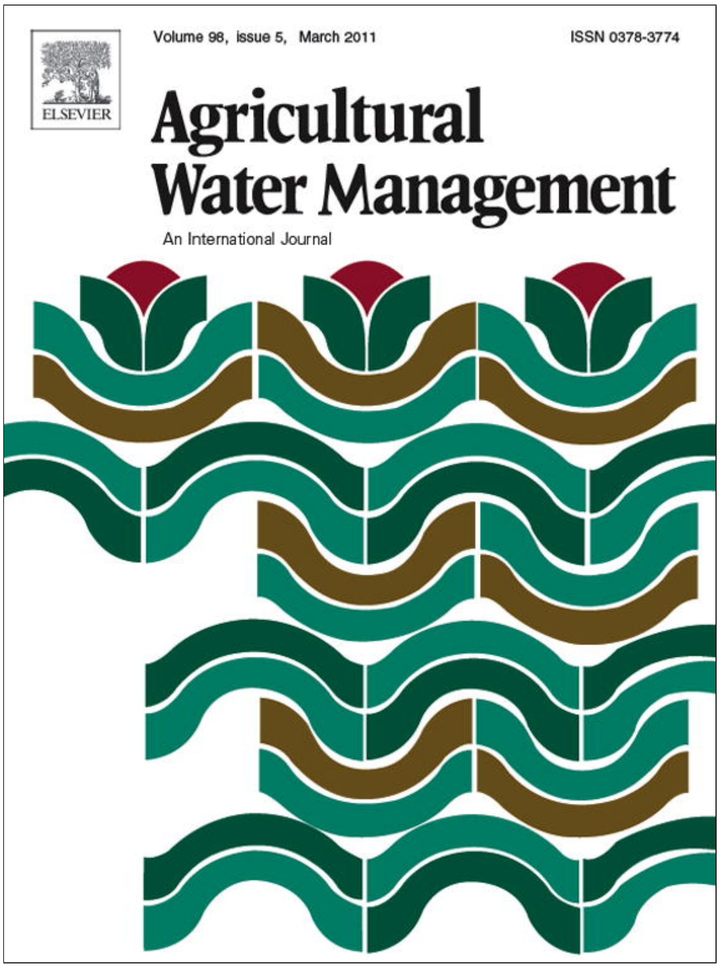
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Simulating root water uptake from a shallow saline groundwater resource

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ABSTRACT

Disposal of saline drainage water is a significant problem for irrigated agriculture. One proposal to deal with this problem is sequential biological concentration (SBC), which is the process of recycling drainage water on increasingly more salt tolerant crops until the volume of drainage water has been reduced sufficiently to enable its final disposal by evaporation in a small area. For maximum effectiveness this concept will require crop water reuse from shallow groundwater. To evaluate the concept of sequential biological concentration, a column lysimeter study was used to determine the potential crop water use from shallow groundwater by alfalfa as a function of ground water quality and depth to ground water. However, lysimeter studies are not practical for characterizing all the possible scenarios for crop water use related to ground water quality and depth. Models are suited to do this type of characterization if they can be validated. To this end, we used the HYDRUS-1D water flow and solute transport simulation model to simulate our experimental results. Considering the precision of the experimental boundary and initial conditions, numerical simulations matched the experimental results very well. The modeling results indicate that it is possible to reduce the dependence on experimental research by extrapolating experimental results obtained in this study to other specific sites where shallow saline groundwater is of concern.

1. Introduction

Irrigated agriculture, especially in the western United States and specifically California, is facing dual challenges for water resource allocation. Firstly, water resources that historically have been dedicated to agriculture are dwindling because increased population has drastically increased the demand for good quality drinking water. Industry also wants its share, and environmental and recreational water use needs are finally being addressed (Postel, 1999). Secondly, disposal of saline drainage water represents a substantial economic and environmental liability. Traditional salinity control measures have employed the concept of leaching, enabled by artificial subsurface drainage, to reduce the negative impact of over-irrigation and to remove excess salts (United States Salinity Lab Staff, 1954). Until half a century ago, saline drainage water was discharged to rivers and streams without any consideration of the environmental impacts. This is no longer a viable option and alternative methods have to be developed (Ayars and Tanji, 1999). Drainage water disposal from vast areas of cropland on the west side of the San Joaquin Valley of California is now relegated to on-farm, because of increased regulation of receiving surface water quality. As a result, irrigated agriculture in the West must find new water resources and reduce saline drainage water volumes to remain sustainable and profitable.

Worldwide, between 70% and 80% of the developed water supply is dedicated to irrigation (Postel, 1999). In the Central Valley of California, surface irrigation is the predominant method of water application, with an efficiency of 60–70% (Ayars and Schrale, 1989). In the near term, irrigation efficiencies will have to increase to between 80% and 85% to make up for demands on water resources by municipalities, industry, the environment, and recreation. In the longer term, irrigated agriculture will have to rely on poorer quality water to meet crop water use demands, and at the same time reduce saline drainage water emissions to surface water sources. These are formidable challenges. Solutions under study include source control measures via improved irrigation management, more efficient water application methods such as drip and/or sprinkler, and drainage water reuse for irrigating salt tolerant crops (San Joaquin Valley Drainage, 1990; Ghassemi et al., 1995). Additionally, irrigation management needs to be modified to maximize in situ crop water use from the shallow groundwater and correspondingly reduce irrigation water application and drainage water volumes to be disposed (Ayars et al., 2006).

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Research quantifying crop water use from shallow groundwater as a function of crop salt tolerance, groundwater quality and depth to groundwater has shown that the potential for meeting crop requirements from shallow groundwater ranges to 50% of the total irrigation requirement (Ayars et al., 2006, 1999). Perennial forage crops, such as alfalfa and forage grasses, may offer a more continuous water uptake pattern from shallow groundwater because of their long growing season and their deep and robust root systems (Ayars et al., 2009). Sensitivity to saline conditions may be the major limitation to uptake of shallow groundwater by forage species. Using alfalfa, a moderately salt tolerant forage species, as a test crop, we quantified the effect of groundwater quality on the in situ water use from a shallow water table (Ayars et al., 2009). While our results confirm results of other studies (Wallender et al., 1979; Ayars and Hutmacher, 1994; Hutmacher et al., 1996), we need to generalize or further extrapolate these site-specific results to other soils and cropping systems. The most obvious way to extrapolate these results is through simulation modeling.

Using simulation to extrapolate experimental findings to new conditions is not a new concept (Otten, 1994; Heinen, 1997; Hopmans and Bristow, 2002), but success without model calibration involving adjusting various model parameters is a rare occurrence (Anderson and Woessner, 1992). We believed that if we could simulate using a numerical model the results of well-conducted experiments where initial conditions are known, and boundary conditions are simple and controlled, then we should be able to predict the results for similar conditions, but involving different soils, crops, or weather, thus reducing our need to conduct experiments for every situation. By simulating well-controlled experiments rather than field observations we also reduce our risk of failure due to imprecise knowledge of initial and boundary conditions, soil heterogeneity, and other factors. If successful, simulation can be used to evaluate the efficacy of various crop, soil, and shallow groundwater scenarios in managing irrigation water and minimizing drainage water disposal. The objective of this research was to illustrate this point using the initial and boundary conditions from our alfalfa experiment (Ayars et al., 2009) and simulate results from 8 treatments over a 4-year period.

2. Materials and methods

2.1. Experimental

A detailed account of the experimental procedures can be found in Ayars et al. (2009) and Ayars and Shouse (2007), only a brief summary will be presented here.

Alfalfa (Medicago savitia var SW9720) was grown in large aboveground hydraulic pillow lysimeters made from 45-cm diameter polyvinyl chloride (PVC) pipes of two heights: 180 cm (short columns) and 260 cm (tall columns) (Robbins and Willardson, 1980; Ayars and Hutmacher, 1994; Hutmacher et al., 1996).

By using a Marriotte bottle we could precisely control the water table depth (at 120 cm for short columns and 200 cm for tall columns) and measure groundwater use directly. The hydraulic pillows were used to measure changes in water storage in each column. Crop evapotranspiration (ET_c) was calculated by summing the groundwater use and storage changes. The lysimeters were located outdoors in a field at the USDA-ARS, San Joaquin Valley Agricultural Sciences Center in Parlier, CA.

Each lysimeter was packed with Panoche clay loam soil (Typic Torriorthents) to a bulk density of 1.4 Mg m^{-3} (Nielsen et al., 1973). This soil dominates much of the cropland affected by shallow groundwater in the central San Joaquin Valley, California. The soil was initially non-saline ($EC_{sw} < 1$ dS/m).

Short column groundwater quality treatments included: no groundwater (T1), non-saline (0.3 dS/m) groundwater (T2), 2 dS/m groundwater (T3), 4 dS/m groundwater (T4), 6 dS/m groundwater (T5), and 8 dS/m groundwater (T6). Tall column groundwater quality treatments included: 2 dS/m groundwater (T3T) and 4 dS/m groundwater (T4T). There were four replications of each treatment.

Low salt irrigation water (0.3 dS/m) was applied at the soil surface once or twice per week depending on the required depth of application. As the depth of application increased it became necessary to use two irrigations a week to facilitate the irrigation in a single day to all treatments. The depth of application was determined using the average weight loss between irrigation for all lysimeters in a treatment. After a harvest and during periods of low ET_o there was only a single irrigation per week, and as the crop water requirement increased the irrigation frequency was increased to twice a week. Climatic data collected at the California Irrigation Management Information System (CIMIS) station located approximately 1 km from the lysimeters were used to calculate reference crop evapotranspiration. Because of the atypical conditions of a crop surrounded by dry land, an advection correction similar to Skaggs et al. (2006a) was used.

We harvested the alfalfa every four to six-weeks during the season, and the dry masses were used to calculate yield (kg m^{-2}).

2.2. Simulation

We used the HYDRUS-1D model (version 3.00, Šimůnek et al., 2005; Šimůnek et al., 2008) for several reasons: (1) availability: the latest version of the model can easily be downloaded from the internet (http://www.pc-progress.com/en/Default.aspx?hydrus-1d); (2) ease of use: the user friendly interface is intuitive with good help files; (3) support: rapid customer technical support; (4) widely tested: it was used in hundreds of peer-reviewed journal articles; (4) processes included: the current version has a compensatory root water uptake feature (Jarvis, 1989; Šimůnek and Hopmans, 2009) where root water uptake reduced by water or salinity stress in one part of the root zone is fully or partially compensated by root water uptake from a non-stressed part of the root zone.

2.3. Model input

Main processes included in HYDRUS-1D are one-dimensional water flow, Eq. (1) (the Richards equation), and one-dimensional solute transport, Eq. (2) (the convection–dispersion equation), through a homogeneous, isotropic soil:

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

and

$$\frac{\partial(\theta R c)}{\partial t} = \frac{\partial}{\partial z}\left(\theta D\frac{\partial c}{\partial z} - qc\right) - \phi, \tag{2}$$

where θ is the volumetric water content (–), h is the soil water pressure head (L), t is time (T), z is depth (L), K is the hydraulic conductivity (LT^{-1}), R is a retardation factor accounting for sorption or exchange (–), c is the solute concentration of the liquid phase (ML^{-3}), D is the solute dispersion coefficient (L^{2}T^{-1}), q is the Darcy–Buckingham volumetric water flux (LT^{-1}), S (T^{-1}) is the sink or source for water, and ϕ (ML^{-3} T^{-1}) is the sink or source for solutes. In our simulations ϕ is considered negligible (Bresler and Hoffman, 1986; Bresler et al., 1982), R is equal to 1 (i.e., no retardation as overall salinity was simulated), and S is associated exclusively with root water uptake (Dudley and Shani, 2003).

The root water uptake sink term, S, has been defined as the volume of water removed from a unit volume of soil per unit of time (Šimůnek et al., 2005). Feddes et al. (1978) defined S in terms of pressure head h to account for water stress and van Genuchten (1987) expanded that formulation by including dependence upon osmotic pressure to account for osmotic stress:

$$S(h,\pi) = \alpha(h,\pi)\,\beta(z) T_p, \tag{3}$$

where T_p is the potential transpiration rate (LT^{-1}), β is the root spatial distribution (L^{-1}), α is the root water uptake stress reduction function (–), h is the soil water pressure head (L), and π is the osmotic head (L). The stress reduction is a function of both water and salinity stress. The functional form of the water stress reduction function proposed by Feddes et al. (1978) is a piecewise linear function parameterized by four critical values of the water pressure head (Skaggs et al., 2006b; Feddes and Raats, 2004), $h_4 < h_3 < h_2 < h_1$,

$$\alpha_h(h) = \begin{cases} \dfrac{h - h_4}{h_3 - h_4} & h_3 > h > h_4 \\ 1 & h_2 \geq h \geq h_3 \\ \dfrac{h - h_1}{h_2 - h_1} & h_1 > h > h_2 \\ 0 & h \leq h_4 \quad \text{or} \quad h \geq h_1 \end{cases} \tag{4}$$

and this is the function we used in our simulations (Šimůnek et al., 2005).

We used a salinity stress reduction function consistent with the Maas and Hoffman (1977) model for crop salt tolerance. The effects of salinity stress on root water uptake were described using a piecewise linear (threshold-slope) function:

$$\alpha_\pi(\pi) = \begin{cases} 1 & 0 \leq \pi \leq a \\ 1 + b(\pi - a) & a < \pi < a - 1/b \\ 0 & a - 1/b \leq \pi \end{cases}, \tag{5}$$

where the threshold a and the slope b are adjustable parameters that mirror the terminology used for the Maas–Hoffman parameters A and B (Maas and Hoffman, 1977). Note, however, that the parameter sets are not necessarily the same: A and B parameterize total yield reductions as a function of average root zone salinity, whereas a and b parameterize local reductions in the root water uptake rate as a function of osmotic head (Skaggs et al., 2006a,b,c). It should also be pointed out the parameter sets would be the same if and only if the uptake process would be homogeneous over the entire root zone. Piecewise Feddes et al. (1978) and Maas and Hoffman (1977) functions were used, rather than the S-shape functions of van Genuchten (1987), since HYDRUS provides parameters for these functions for many agricultural crops.

We used the multiplicative model for combining the effects of water and salinity stresses:

$$\alpha(h,\pi) = \alpha_a(h)\alpha_\pi(\pi) \tag{6}$$

according to a recent review of root water uptake modeling (Skaggs et al., 2006c).

Šimůnek et al. (2005) and Šimůnek and Hopmans (2009) recently implemented into HYDRUS-1D the compensatory root water uptake model of Jarvis (1989), modified by using soil water pressure head as the controlling variable. To formulate a compensatory uptake model, they defined the dimensionless water stress index, ω:

$$\frac{T_a}{T_p} = \int_{L_R} \alpha_h(h)\alpha_\pi(\pi) b(z)\,dz \equiv \omega, \tag{7}$$

where T_a is the actual non-compensated transpiration rate (LT^{-1}), T_p is the potential transpiration rate (LT^{-1}), $\alpha_h(h)$ is the water stress reduction factor (–), $\alpha_\pi(\pi)$ is the salinity stress reduction factor (–). The dimensionless water stress index, ω, sometimes also called the root adaptability factor (Jarvis, 1989), provides a measure of total plant stress. A value of ω equal to 1 indicates that there is no stress in the soil root zone and that the actual transpiration rate T_a is equal to the potential transpiration rate T_p.

The transpiration rate for compensatory water uptake is now given by

$$\frac{T_{ac}}{T_p} = \begin{cases} \dfrac{T_a}{T_p}\dfrac{1}{\omega} = 1 & \omega_c < \omega \leq 1 \\ \dfrac{T_a}{T_p}\dfrac{1}{\omega_c} = \dfrac{\omega}{\omega_c} & \omega < \omega_c \end{cases}, \tag{8}$$

where T_a is the actual compensated transpiration rate (LT^{-1}), and $0 < \omega_c \leq 1$. Transpiration occurs at the potential rate ($T_{ac} = T_p$) only when total root zone stress is low, i.e., when ω is greater than some critical value ω_c. For actual root water uptake to remain equal to the potential rate, uptake is increased throughout the root zone by a compensatory factor of $1/\omega$. Although on a relative basis uptake is increased uniformly throughout the root zone, in absolute terms the biggest increase occurs in those parts of the root zone where stress is low. Root water uptake from stressed parts of the root zone is then compensated by uptake from less stressed parts. When stress becomes higher and $\omega < \omega_c$, compensation is only partial, with uptake increased throughout the root zone by a factor of $1/\omega_c$ (Skaggs et al., 2006a,b,c; Šimůnek and Hopmans, 2009). Notice that Jarvis (2010) recently showed that his 1989 model (Jarvis, 1989) can be considered as a simplified, dimensionless form of the physically based de Jong van Lier et al. (2008) model, which uses a concept of the matric flux potential to describe radial flow to roots. Consequently, the dimensionless parameters in the empirical model of Jarvis (1989) can be explicitly related to measurable system properties such as root length density and soil hydraulic characteristics (Jarvis, 2010).

2.4. Model parameters

We assumed the soil profiles were a uniform and isotropic clay loam soil with a bulk density of 1.4 Mg/m^3 (either 180 cm or 260 cm deep). The soil hydraulic properties were taken from the HYDRUS soils catalog for a generic clay loam soil, for which the van Genuchten–Mualem (van Genuchten, 1980) parameters were as follows: the saturated water content $\theta_s = 0.41$, the residual water content $\theta_r = 0.095$, the retention curve shape parameters $\alpha = 0.019\ \text{cm}^{-1}$ and $n = 1.31$, the saturated hydraulic conductivity $K_s = 6.24$ cm/d, and the tortuosity and pore connectivity parameter $l = 0.5$. Soil longitudinal dispersivity was assumed to be 10 cm. The parameters for the Feddes water stress reduction function (Feddes et al., 1978) were $h_1 = 0$ cm, $h_2 = -10$ cm, $h_3 = -5000$ cm, and $h_4 = -17{,}000$ cm. The salinity stress reduction parameters were $a = 2$ dS/m and $b = 7$, with a critical stress index, $\omega_c = 0.25$ (Jarvis, 1989).

For water flow upper boundary condition we used an atmospheric boundary, which was the daily Penman–Montieth ET_0 from CIMIS weather station data and measured precipitation and irrigation. The solute flux at the top was deduced from the irrigation water salinity (0.3 dS/m) and the rate of irrigation. The free drainage bottom boundary condition was used for both water flow and solute transport for the treatments without a groundwater table (T1). For the treatments with groundwater, a constant pressure head (corresponding to the position of the water table) and a constant concentration, equal to the concentration of the groundwater treatment (e.g., T2 = 0.3 dS/m, T3 = 2 dS/m), were used as bottom boundary conditions.

The initial conditions for water flow for 2002 were considered to be uniform with depth and equal to −50 cm pressure head, except in the vicinity of groundwater where hydrostatic conditions were assumed. The initial conditions for solute transport for 2002 was a uniform salinity of 0.3 dS/m, except for runs with the water tables for which the initial concentrations were taken to be the concentrations of the groundwater. The growing season and therefore the simulation season was approximately 250 days from day of the year (DOY) 45 to DOY 295 (mid-February to mid-October). For subsequent years, the initial conditions were determined from the previous year's pressure head and salt concentration distributions, so any salt build-up or residual water stress was taken into account. The off season was not simulated since all major processes in the Central Valley usually occur during the growth season. During the off season the land is either fallow or the plants are dormant. Any precipitation is usually significantly lower that potential E and, consequently, there are no major changes in the water content or salinity profiles during the off season.

3. Results and discussion

Table 1 summarizes the experimentally measured crop water use as well as simulation results for each treatment. The presence of a shallow groundwater table in T2 led to a higher water use by the alfalfa crop, implying that the crop was under-irrigated in T1. The alfalfa may have undergone a substantial water deficit during part of the growing season reducing water use. Table 1 also shows that the total range of measured water use values was within 20–25% of the mean value. With a few exceptions, the simulated values for water uptake fell within the range of the measured values for each treatment. One notable exception is the T1 in 2004. The simulated value is 1000 mm less than the measured value. The reason for this discrepancy is not known, but in that year the experimental water use for T2 was also higher than other years by about 1000 mm. This leads us to speculate that weather conditions, disease or insect pressures were more favorable in 2004 for the growth and yield of alfalfa than in other years. According to Ayars et al. (2009), the yield vs. water use function was linear with no apparent abnormalities, further adding to the circumstantial evidence that this was indeed an exceptional year for alfalfa. Table 1 also shows that, with the exception of T2, water use was reduced during the course of the experiment, implying that perhaps salinity may have been building up in the root zone, and reducing root water uptake. Ayars et al. (2009) show some soil salinity data at the end of the experiment that do indicate that salinity did build up with time. This is due to the fact that there was no leaching. The higher groundwater salinity treatments were affected to a greater extent than the lower groundwater salinity treatments. The simulation of these measured conditions confirms that the root water uptake reduction functions are performing well enough to simulate the experimental results.

The general results from measurement and simulation of water uptake from the groundwater are shown in Table 2. As with the total crop water use, the simulation results for the ground water contribution were within the range of measured values, indicating that the simulations were as accurate as the measurements.

Fig. 1 shows for T1 during the 2002 season (DOY 50-284) the time course of cumulative ET_0 (CIMIS data), measured ET_a, simulated ET_a, and irrigation. ET_0 for the 2002 growing season was approximately 3000 mm, however the ET_a measured during the season was around 66% of that amount. Regardless, the HYDRUS simulation of T1-2002 showed a very good approximation of the measured values. The simulation was able to follow the general dynamic of the measurements, starting slowly, leveling off after DOY 75, increasing after DOY 150 during increased irrigation, and then paralleling the irrigation rate until the end of the season. Similar simulation results were obtained for T1 during 2003 and 2005. As noted before, 2004 was an odd year, alfalfa growth and water use were higher in that year than other years, especially for T1 (Ayars et al., 2009). At this time we cannot explain the increase in the water use and yield, and we are not sure if this is just a local phenomenon or if the 2004 San Joaquin Valley alfalfa crop in general was affected.

Simulation and measurement results for T2-2002 are shown in Fig. 2. As with T1-2002 simulations, major features of the measured *ET* are preserved in the simulations, although the *ET* was over-predicted between DOY 100 and DOY 150. After DOY 150 the simulated *ET* was parallel with the measured *ET* indicating the accuracy of the simulation during this period. Simulated groundwater use also tracked the measured values until DOY 200, where there was a slight divergence until the end of the season.

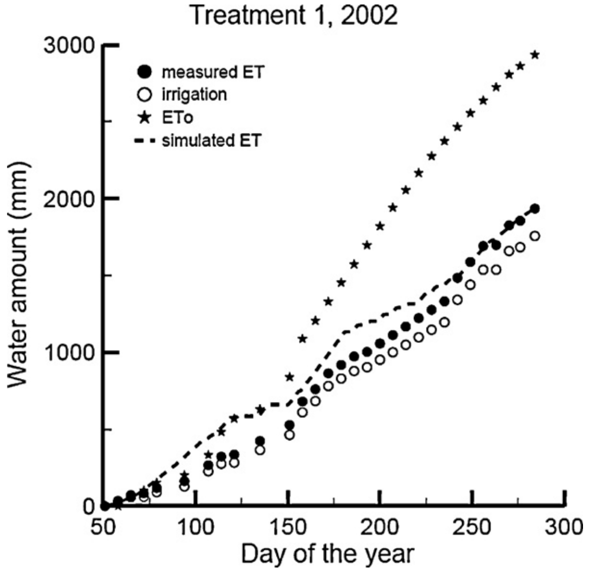

Fig. 1. Measured and simulated water use for T1-2002.

The data and simulations shown in Fig. 1 and Table 1 imply that the alfalfa crop in T1 may have been undergoing moderate water deficit compared to T2 in Fig. 2 and Table 1. One reason for simulating experimental results is that insight into factors not measured during the experiment can be gained by looking at specific simulation output. Considering the case of contrasting water use between T1 and T2, we speculate that T1 may have been affected by water deficit during part of the growing season. But can our model substantiate our theory? We know from Figs. 1 and 2 that we have good simulation results for these treatments during 2002 (for 2003, 2004, and 2005 also, data not shown). HYDRUS allows us to look inside the soil column at the average root zone soil water pressure head during the season (Fig. 3). By comparing the time course of the

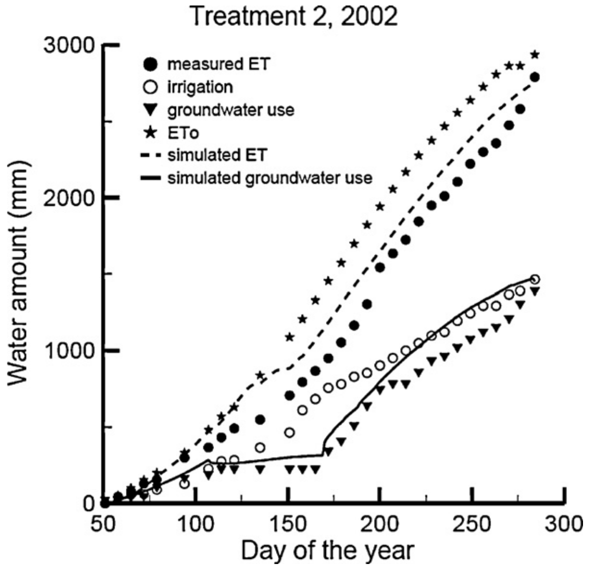

Fig. 2. Measured and simulated water use for T2-2002.

Table 1
Measured and simulated overall water uptake for 8 treatments (in columns) and 4 years (rows).

Year	Data set	Treatments							
		T1 (mm)	T2 (mm)	T3 (mm)	T4 (mm)	T5 (mm)	T6 (mm)	T3T (mm)	T4T (mm)
2002	Measured	1924 ± 230	2379 ± 210	2502 ± 250	2269 ± 125	2261 ± 350	1907 ± 112	2358 ± 250	2282 ± 75
	Simulated	1940	2457	2800	2510	2109	2023	2485	2484
2003	Measured	1947 ± 210	2688 ± 350	2507 ± 225	2299 ± 175	2363 ± 325	1979 ± 150	2475 ± 285	2286 ± 175
	Simulated	1752	2655	2513	2102	1904	1685	2342	2105
2004	Measured	2805 ± 250	3467 ± 500	2126 ± 125	1657 ± 150	1101 ± 200	784 ± 10	2368 ± 200	1425 ± 300
	Simulated	2080	3036	2103	1559	1297	822	2205	1521
2005	Measured	1236 ± 150	2403 ± 200	1384 ± 200	1074 ± 250	767 ± 150	660 ± 15	1667 ± 100	1129 ± 75
	Simulated	1117	2271	1212	979	898	625	1518	947

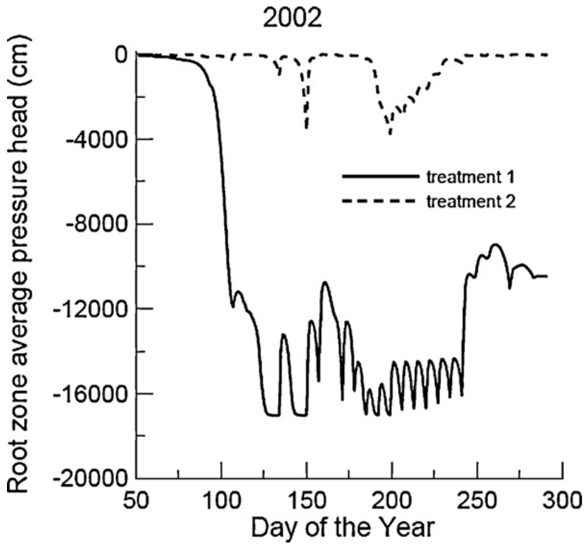

Fig. 3. Simulated average root zone soil pressure heads for T1 and T2-2002.

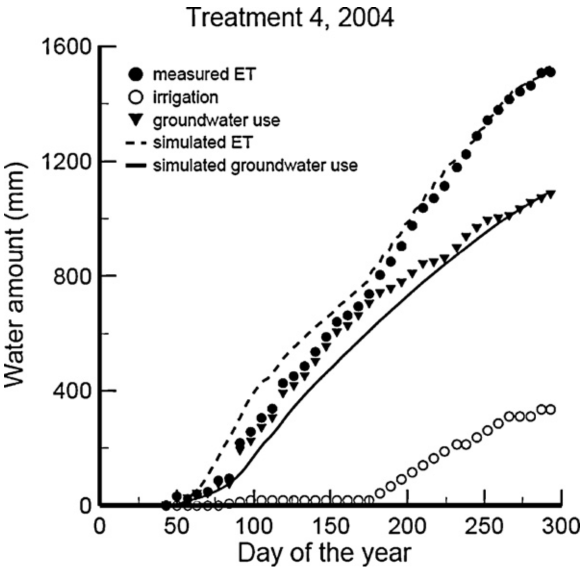

Fig. 4. Measured and simulated water use for T4-2004.

average pressure head, we can see substantial differences between T1 and T2. While T2 never had pressure heads less than −4000 cm, T1 had pressure heads less than −10000 cm for a major part of the growing season. The specific values of the simulated pressure heads are less important than the relative differences between the two simulated treatments. Skaggs et al. (2004) showed the accuracy of the HYDRUS model for simulating water content distributions during and after drip irrigation, which leads us to believe that these simulated results are reasonable.

To illustrate the effect of salinity on water uptake, Fig. 4 shows simulation and experimental results of crop water use from T4-2004 with 4 dS/m salinity in the groundwater. The salinity is twice the Maas–Hoffman (1977) threshold value for alfalfa salt tolerance. Moreover, during the 3 years of the experiments there was no leaching, so that salts were building up in the lysimeter. Therefore reductions in water uptake were to be expected. The seasonal ET_0 for 2004 was 3100 mm, and T4 *ET* was reduced by approximately 50% due to the salinity of the groundwater and in the soil profile. Our simulation of T4-2004 slightly over-estimated the crop *ET* for DOY's 70 to 175, most likely due to a mismatch of initial soil water storage between the simulation and the experiment. For the remainder of the season, simulated *ET* tracked measured *ET* very well. Simulated groundwater use under-estimated actual groundwater use for approximately the same duration as the *ET* was over-estimated. This leads us to think that these two simulation results are linked and that one will compensate for the other, but both simulated variables were on track during the latter part of the season, indicating that the mismatch of initial conditions only had a transient effect and that after some time the mismatch had less effect on the results (Skaggs et al., 2006b).

To look more closely at the effect of soil and groundwater salinity on root water uptake by alfalfa, we again employ the HYDRUS output. This time we look specifically at the root water uptake dis-

Table 2
Measured and simulated water uptake from the shallow groundwater for 8 treatments (in columns) and 4 years (rows).

Year	Data set	Treatments							
		T1 (mm)	T2 (mm)	T3 (mm)	T4 (mm)	T5 (mm)	T6 (mm)	T3T (mm)	T4T (mm)
2002	Measured	–	1385 ± 250	1135 ± 180	978 ± 175	650 ± 300	408 ± 112	812 ± 125	782 ± 105
	Simulated	–	1297	1500	975	594	484	950	948
2003	Measured	–	1438 ± 200	1327 ± 205	1089 ± 145	763 ± 120	523 ± 110	986 ± 85	743 ± 107
	Simulated	–	1533	1393	1048	832	559	1209	801
2004	Measured	–	2874 ± 350	1626 ± 155	1009 ± 150	655 ± 150	414 ± 50	1889 ± 150	971 ± 250
	Simulated	–	2299	1625	1215	991	512	1931	1089
2005	Measured	–	1973 ± 220	808 ± 200	510 ± 200	767 ± 150	101 ± 15	1190 ± 100	514 ± 75
	Simulated	–	1922	826	701	620	348	1276	710

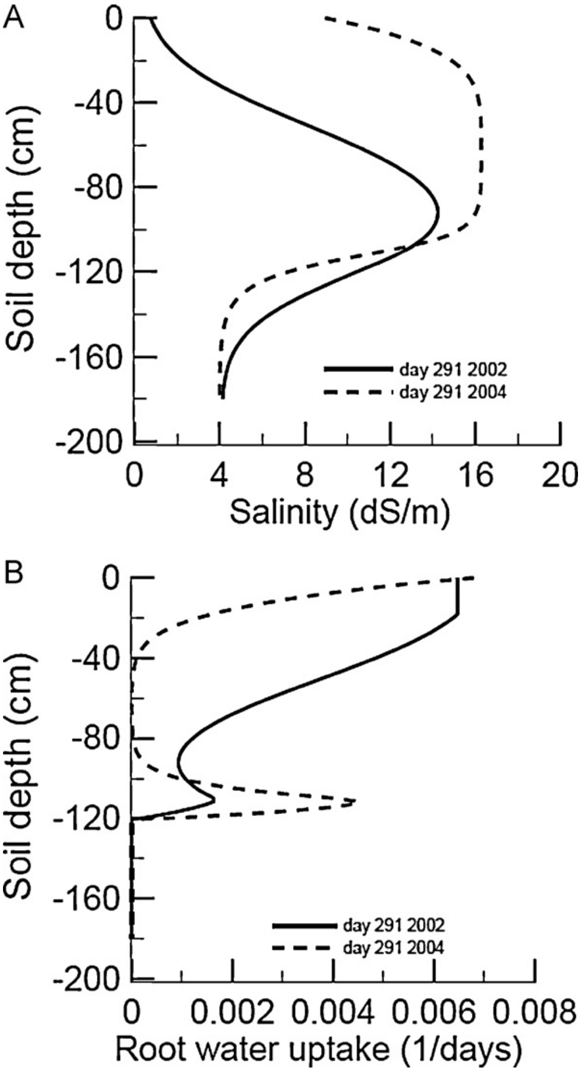

Fig. 5. Simulated root water uptake and salt distributions for T4-2002 and 2005 at the end of the growing season.

tributions at the end of 2002 and 2005 for T4 and at the same time we look at the salinity distributions (Fig. 5). Fig. 5a shows the salinity distribution patterns. According to the simulations, root water extraction was highest near the soil surface during 2002, especially after irrigation, less water was being extracted from the shallow groundwater due to salinity of the groundwater. Little or no root water extraction was occurring in the middle of the profile due to low water pressure head and increased salinities. In the 2004 simulation water was taken up from the soil surface layer but to a lesser extent than in 2002, because of the increased salinity in that region of the soil profile (Figure 5b). Water extraction from the lower part of the profile indicates that conditions are more favorable due to lower salinity levels while little or no extraction occurred in the middle of the profile due to primarily to salinity stress (salinity measured at the end of the experiment showed a value larger than 17 dS/m in the middle of the root zone).

Notice that the compensated root water uptake model performed very well for these, highly stressed conditions. The uncompensated root water uptake model would predict much more dramatic reduction of transpiration due to salinity build up in the middle of the profile. One the other hand, the compensated root water uptake model could compensate for reduced uptake in the middle of the profile by increased uptake close to the surface (with fresh irrigation water) and at the bottom of the root zone (with water from the groundwater). Consequently, the compensated root water uptake model predicted cumulative *ET* almost identical to the measured *ET* (Fig. 4).

Our simulation results are impressive for several reasons: (1) we used internally (within HYDRUS) provided parameter sets for both water flow and solute transport (e.g., soil hydraulic parameters from HYDRUS soil catalog); (2) we used external atmospheric boundary conditions for the simulated location; (3) we used standard parameter sets for compensatory root water uptake, water stress, and salt stress reduction functions taken from HYDRUS database or appropriate literature; and (4) we did no calibration of the model. By choosing to simulate lysimeter experimentals with known, precisely controlled boundary and initial conditions, we effectively reduced the effects of soil spatial heterogeneity inherent in field studies that could blur the interpretation of the results. As a result we are well equipped to extrapolate our experimental results to other specific soils, crop and weather conditions.

4. Concluding remarks

Simulation model development has matured enough in recent years to be helpful in reducing our dependence on experimental research for solving real world problems. Problems facing irrigated agriculture in semi-arid climates are immense. Dwindling water resources and saline drainage water disposal are two problems that can be partially addressed using simulation modeling. Through simulations one can extrapolate experimental results to specific sites where saline shallow groundwater is of particular concern. Our simulations have provided insight into the dynamic character of using shallow groundwater as a resource as well as the ramifications of drainage water reuse. The next challenge is to use our simulations to design shallow groundwater management systems that reduce drainage water volumes and minimize salt redistribution into the root zone.

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