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# Irrigating Forage Crops with Saline Waters: 2. Modeling Root Uptake and Drainage

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## ABSTRACT

**The recycling of agricultural drainage water for irrigation is increasingly viewed as a desirable management practice in areas with limited options for drainage disposal. Modeling is potentially a cost-effective approach to examining design and management options for drainage reuse systems, but questions exist about the accuracy of simulated root water uptake in dynamic, highly saline conditions such as those encountered in reuse operations. This study compares HYDRUS-1D simulations of root water uptake and drainage with lysimeter data collected during an experiment in which forage crops (alfalfa [*Medicago sativa* L.] and tall wheatgrass [*Agropyron elongatum* (Host) P. Beauv.]) were irrigated with synthetic drainage waters. A trial-and-error fitting procedure was used to determine uptake reduction parameters for each crop. Good agreement between the model simulations and data was achieved, a noteworthy result given the broad range of experimental conditions considered: irrigation waters with salinities ranging from 2.5 to 28 dS m$^{-1}$ and irrigation rates ranging from deficit to luxurious. The approximations required to derive uptake reduction parameters from published salt tolerance data are examined. Simulations are presented that attempt to account for the uncertainty in derived uptake reduction functions. Overall, we concluded that the general modeling approach captures many essential features of root water uptake under stressed conditions and it may be useful in designing and analyzing reuse operations.**


The recycling of drainage water for irrigation is increasingly viewed as a desirable management practice in areas with limited options for drainage disposal. Scientific and economic questions remain about the development of optimal drainage reuse management practices (Rhoades, 1999). Modeling is potentially a cost-effective approach to examining design and management options (Rhoades, 1999; Oster and Wichelns, 2003). Rhoades (1999) reviewed steady-state model analyses and noted that more comprehensive model calculations are desirable but questioned whether they are justified given the lack of information available about the accuracy of more comprehensive numerical models.

Comprehensive simulation models that could potentially aid in the design of reuse systems include HYDRUS (Šimůnek et al., 1998), SWAP (van Dam et al., 1997), UNSATCHEM (Šimůnek et al., 1996), and HYSWASOR (Dirksen et al., 1993). These models are capable of simulating a wide range of management scenarios and provide detailed computations of soil and drainage conditions. With respect to the accuracy question raised by Rhoades (1999), one critical component of these models that has not been extensively evaluated against experimental data is the root water uptake routines, particularly the parameterized functions used to simulate the reductions in uptake that occur due to water and salt stress.

The numerical models noted above all use a macroscopic description of root water uptake (Feddes and Raats, 2004) in which uptake is modeled by introducing a sink term into the Richards equation:

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

where $\theta$ [L$^3$ L$^{-3}$] is the volumetric water content, $h$ [L] is the water pressure head, $t$ [T] is time, $z$ [L] is the vertical space coordinate, $K$ [L T$^{-1}$] is the hydraulic conductivity, and $S$ [L$^3$ L$^{-3}$ T$^{-1}$] is the sink term. The sink term may be a function of the water pressure head, the osmotic pressure head, root characteristics, and meteorological conditions (evaporative demand). Related and alternative approaches to modeling uptake have been reviewed by Feddes and Raats (2004), Dudley and Shani (2003), and Cardon and Letey (1992).

Typically thet sink term is specified in terms of a potential and an actual uptake rate. The potential uptake is obtained by distributing the potential transpiration rate through the root zone in proportion to the root distribution (Šimůnek et al., 1998; Feddes and Raats, 2004)

$$S_p(z) = \beta(z)T_p \qquad [2]$$

where $S_p$ [L$^3$ L$^{-3}$ T$^{-1}$] and $T_p$ [L$^3$ L$^{-2}$ T$^{-1}$] are the potential uptake and transpiration rates, respectively, and $\beta(z)$ [L$^{-1}$] is the normalized root density distribution such that $\beta(z)\mathrm{d}z$ is the fraction of roots located between $z$ and $z + \mathrm{d}z$. The actual uptake distribution is obtained by introducing a reduction function that depends on the osmotic and water pressure heads (Feddes et al., 1978; van Genuchten, 1987):

$$S(z) = \alpha[h(z),h_\phi(z)]S_p(z) = \alpha[h(z),h_\phi(z)]\beta(z)T_p \qquad [3]$$

where $\alpha$ is the dimensionless uptake reduction function ($0 \le \alpha \le 1$) and $h_\phi$ [L] is the osmotic pressure head. The actual transpiration rate $T$ [L$^3$ L$^{-2}$ T$^{-1}$] is obtained by integrating Eq. [3]:

$$T = \int_{L_R} S\mathrm{d}z = T_p\int_{L_R}\alpha(h,h_\phi)\beta(z)\,\mathrm{d}z \qquad [4]$$

where the integrals are across the depth of the root zone $L_R$.

Feddes and Raats (2004) reviewed the various functional forms for $\alpha$ that have been proposed over the years and noted that most are patterned after whole-plant water use and salt stress relationships, such as the relationship between water use and yield (Hanks, 1974):

$$Y/Y_p = T/T_p \qquad [5]$$

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**Abbreviations:** DOY, Day of Year; EC, electrical conductivity; ET, evapotranspiration.

and the crop yield response to soil salinity (Maas and Hoffman, 1977; Maas, 1990):

$$Y/Y_p(\%) = \begin{cases} 100 & EC_e \le A \\ 100 - B(EC_e - A) & EC_e > A \end{cases} \quad [6]$$

In Eq. [5] and [6], $Y$ is yield, $Y_p$ is potential yield, $EC_e$ (dS m$^{-1}$) is the root-zone-averaged saturation extract electrical conductivity, $A$ (dS m$^{-1}$) is the threshold salinity, and $B$ (% m dS$^{-1}$) is the slope parameter. Linear or piecewise linear models for response functions such as Eq. [5] and [6] have spawned linear and piecewise linear uptake reduction functions; nonlinear models have given rise to nonlinear reduction functions (e.g., van Genuchten, 1987).

Because of the similar forms of uptake reduction functions and whole-plant response functions, it has been anticipated (e.g., van Dam et al., 1997; van Genuchten, 1987; Feddes and Raats, 2004) that uptake reduction parameter values for different crops can be derived from literature studies of whole-plant response, particularly tabulations of plant salt tolerances. Among the difficulties that may be encountered converting plant salt tolerances to uptake reduction parameters is that plant salt tolerances are reported in terms of root-zone-averaged $EC_e$ whereas uptake reduction functions are parameterized in terms of local soil conditions (salt concentration or osmotic pressure head). A recent greenhouse study by Homaee et al. (2002a, 2002b, 2002c) suggests that uptake reduction parameter values derived from the literature on whole-plant response may not yield accurate simulation results.

So while it is envisioned that comprehensive numerical modeling could benefit the design and management of drainage reuse operations, there remains considerable uncertainty about appropriate model parameter values and about the accuracy of model simulations. These uncertainties are particularly acute given that reuse operations may involve irrigation waters and soils with much higher salinities than has traditionally been considered in agronomic research.

Our objectives were to assess HYDRUS-1D's ability to simulate extensive drainage and root water uptake data collected during lysimeter experiments in which forage crops were grown with synthetic saline drainage waters, and to evaluate the uptake reduction parameters required to model the data.

## METHODS AND MATERIALS

### Experiment

In Skaggs et al. (2006) we reported an experiment conducted in a volumetric lysimeter system consisting of 24 volumetric lysimeters, each measuring 81.5 cm wide by 202.5 cm long by 85 cm deep. Drainage was collected in a perforated drainpipe installed at the bottom of each lysimeter. A data acquisition system enabled the nearly continuous measurement of drain flow and drainage water EC for each lysimeter. Twelve lysimeters were planted in 'Salado' alfalfa and 12 were planted in 'Jose' tall wheatgrass. The crops were germinated and established using good quality irrigation water. The experimental treatments started on 2 May 2002 (Day of Year [DOY] 122) and proceeded in two phases. In Phase 1 (DOY 122–237), crops were abundantly irrigated every other day with synthetic drainage waters of varying salinities, ranging from 2.5 to 28 dS m$^{-1}$. In Phase 2 (DOY 247–297), the same irrigation waters and irrigation frequency were used, but irrigation depths were varied such that some lysimeters were deficit irrigated while others received water equal to or in excess of the water consumed in two well-watered "control" lysimeters. A compete description of the experiment is given in Skaggs et al. (2006).

## HYDRUS-1D Simulation Model

We simulated water flow and root uptake in the lysimeters using HYDRUS-1D (Šimůnek et al., 1998). HYDRUS uses a Galerkin finite-element method to solve the Richards equation augmented with a sink term (Eq. [1]–[4]). The soil hydraulic properties were modeled using the van Genuchten–Mualem constitutive relationships:

$$S_e(h) = \begin{cases} (1 + |\alpha_{vg}h|^n)^{-m} & h < 0 \\ 1 & h \ge 0 \end{cases} \quad [7]$$

$$K(h) = K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2 \quad [8]$$

where

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r}, m = 1 - 1/n$$

and where $\theta_s$ is the saturated water content, $\theta_r$ is the residual water content, $K_s$ is the saturated hydraulic conductivity, and $n$, $\alpha_{vg}$, and $l$ are shape parameters.

### Solute Transport

Solute transport was modeled in HYDRUS using the convection–dispersion model:

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial z}\left(\theta D \frac{\partial c}{\partial z}\right) - \frac{\partial qc}{\partial z} \quad [9]$$

where $c$ is the solute (salt) concentration, $q$ is the volumetric water flux density, and $D$ is the dispersion coefficient. The dispersion coefficient was specified as $D = \alpha_L q$, were $\alpha_L$ is the dispersivity. We used the value $\alpha_L = 8$ cm, an estimate based on the 80-cm soil depth in the lysimeters and a rule of thumb that suggests that observed dispersivities are often about one-tenth of the transport distance (Skaggs and Leij, 2002). The results presented below were not very sensitive to this parameter value.

The relationship between salt concentration $c$ and osmotic pressure head $h_\phi$ was given by

$$h_\phi = -0.31c \quad [10]$$

where $h_\phi$ has units of meters and $c$ (expressed as the cation concentration) has units of milliequivalents per liter. Equation [10] was determined using UNSATCHEM (Šimůnek et al., 1996) to compute $h_\phi$ for the irrigation water compositions reported in Skaggs et al. (2006) and fitting a line to the computed values (Fig. 1). The relationship between solution EC and solution salt concentration was determined similarly using both UNSATCHEM computations of EC and measured EC data reported in Skaggs et al. (2006, Table 1). The relationship was found to be (Fig. 1)

$$EC = 0.168c^{0.866} \quad [11]$$

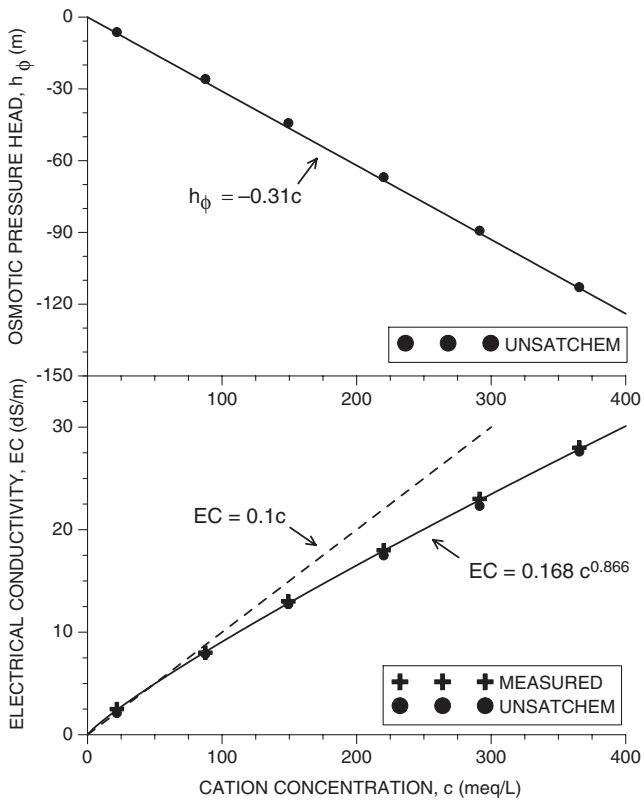


**Fig. 1. Relationship between solution salt concentration $c$ (1 meq $L^{-1}$ = 1 $mmol_c$ $L^{-1}$), osmotic pressure head $h_\phi$, and electrical conductivity EC. The plotted data are EC measurements made on the irrigation waters used in Skaggs et al. (2006) and UNSATCHEM (Šimůnek et al., 1996) computations of EC and $h_\phi$ based on the composition of the same waters. The solid lines are fits to the data. A common dilute-solution approximation, EC = 0.1$c$, is shown for reference (dashed line).**

where EC has units of deciSiemens per meter and $c$ has units of milliequivalents per liter. McNeal et al. (1970) previously suggested a power law form for this relationship. Equation [11] was not required to perform the simulations but was used in post-processing to convert simulated salt concentrations to ECs.

## Potential Transpiration

In Skaggs et al. (2006) we speculated that evaporation ($E$) was a non-negligible component of ET (evapotranspiration) in some of the well-watered, high-salt-stressed experimental treatments, but were unable to quantify the evaporative losses. In the simulations, we assumed $E = 0$ throughout ($T$ = ET). We consider below the impact of this possibly erroneous assumption on the simulated water balance and the parameters used in the uptake reduction function.

Located within 3.2 km of the volumetric lysimeter system is CIMIS weather station no. 44 (California Irrigation Management Information System, http://www.cimis.water.ca.gov), which provides hourly measurements and calculations of reference evapotranspiration, $ET_0$. We initially intended to specify the potential transpiration rate at the upper boundary according to

$$T_p(t) = k(t)ET_0(t) \qquad [12]$$

where $ET_0(t)$ is discretized in hourly time steps and the time variation of $k(t)$ is linked to the time variation of a crop canopy variable such as canopy height. We did not have sufficient canopy data, however, to reliably specify $k(t)$ as a function of canopy development. We therefore used a constant $k$ value:

$$T_p(t) = kET_0(t) \qquad [13]$$

where $k$ was based on measurements of $ET/ET_0$ in well-watered control lysimeters, averaged across time. For the time periods simulated here, we used $k = 1.6$ for alfalfa and $k = 2.1$ for tall wheatgrass for DOY 156 to 214, and $k = 2.4$ for both crops for DOY 247 to 297 (Skaggs et al., 2006, Fig. 3). Using a constant $k$ means that the simulated drainage rates and drainage EC will not exhibit some of the temporal fluctuations that were observed in Skaggs et al. (2006) and attributed to variations in ET associated with canopy development.

## Root Distribution

Root distribution data for the simulation periods were not available. Root length measurements made on core samples taken from four lysimeters subsequent to the simulation periods showed that root length distributions for both crops were approximately distributed according to the 40:30:20:10 rule (40% of the root length located in the upper quarter of the root zone, 30% in the second quarter, etc.). We assumed for both crops a linear distribution consistent with the 40:30:20:10 rule:

$$\beta(z) = \frac{1.8}{L_R} - \frac{1.6}{(L_R)^2}z \quad 0 < z < L_R \qquad [14]$$

where $z = 0$ cm is the location of the bottom of the lysimeter and $z = L_R = 80$ cm is the location of the soil surface.

## Hydraulic Properties and Bottom Boundary Condition

The soil material in the lysimeters was 96% sand, 3% silt, and 1% clay, packed to a bulk density of 1.74 g $cm^{-3}$. We input this data to the Rosetta pedotransfer function model (Schaap et al., 2001) to obtain estimates for the van Genuchten–Mualem parameters: $K_s = 530$ cm $d^{-1}$, $\theta_r = 0.05$ $m^3$ $m^{-3}$, $\theta_s = 0.31$ $m^3$ $m^{-3}$, $\alpha_{vg} = 0.034$ $cm^{-1}$, $n = 3.4$, and $l = 0.5$.

We tested these hydraulic property estimates using two sets of data. The first was soil water content data collected in lysimeter no. 67 before the initiation of experimental treatments. On DOY 112 (2002), 10 d before the initiation of the Phase 1 experimental treatments, lysimeter no. 67 was flood irrigated with approximately 24 cm of water applied within 30 min. A neutron probe instrument was used to measure the soil water content at the 15-, 45-, and 60-cm depths as the soil dried during the ensuing hours and days. The second dataset was drainage data collected in lysimeter no. 67 for DOY 209 to 223, which encompassed the final days of Phase 1 and the first few days of the period between experimental phases in which lysimeters were heavily irrigated to leach any salts that may have accumulated. Lysimeter no. 67 was a tall wheatgrass "control" lysimeter that was always irrigated with good quality water, so zero salt stress was assumed in these computations. Comparing model simulations with the data (Fig. 2), we determined that a better fit to the data was obtained if $\theta_s$ was adjusted upward to $\theta_s = 0.34$ $m^3$ $m^{-3}$, and the bottom boundary condition was specified as

$$\text{bottom boundary condition} = \begin{cases} h(z=0) = h_0 & h(z=0) \geq h_0 \\ q(z=0) = 0 & h(z=0) < h_0 \end{cases} \qquad [15]$$

where $h_0 = -30$ cm and $z = 0$ is the location of the bottom boundary. For $h_0 = 0$ cm, this boundary condition is termed a

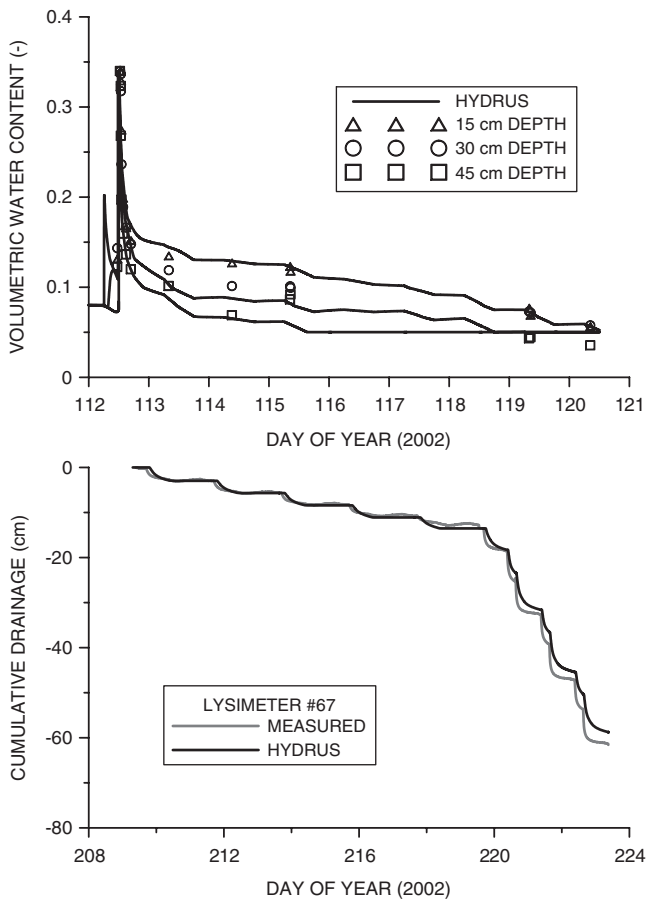


**Fig. 2. Comparison of model simulation and data using final hydraulic parameter estimates.**

*seepage face boundary condition* (Šimůnek et al., 1998) which specifies that drainage occurs when the soil at the lower boundary is saturated ($h \geq 0$) and is a no-flow condition when unsaturated ($h < 0$). Use of $h_0 < 0$ implies that drainage continues somewhat below saturation. Our need for this boundary condition was influenced by the fact that the lysimeter is drained by a single drain line running down the center of the bottom of the lysimeter, which probably leads to deviations from one-dimensional flow in this region. Note that the adjusted $\theta_s = 0.34$ $m^3\ m^{-3}$ corresponds to the soil porosity for the measured bulk density of 1.74 g $cm^{-3}$ (assuming a particle density of 2.65 g $cm^{-3}$). We assumed that the hydraulic properties for all lysimeters were the same as estimated for lysimeter no. 67.

### Uptake Reduction Function

Data reported in Skaggs et al. (2006) showed a linear decrease in yield with increasing irrigation water salinity. We therefore use a linear threshold-type reduction model for the salinity component of the transpiration reduction function. For the water uptake component, we use the S-shaped model introduced by van Genuchten (1987). We assumed that the osmotic and matric effects interact multiplicatively, so the uptake reduction function is

$$\alpha(h,h_\phi) = [1 + b(h_\phi - a)]\frac{1}{1 + (h/h_{50})^p} \qquad [16]$$

where $h_{50}$, $p$, $a$, and $b$ are uptake reduction parameters. The term in square brackets on the right side of Eq. [16] is the salinity reduction component (cf. Eq. [6]) and is defined to be equal to one for $h_\phi \geq a$ and zero for $h_\phi < a - 1/b$. The parameter values used for $a$ and $b$ are discussed below.

In our work, it became apparent that simulations of the Skaggs et al. (2006) experiments were mostly insensitive to the water stress parameters $h_{50}$ and $p$. The parameter $h_{50}$ represents the water pressure head at which transpiration is halved; the exponent $p$ determines the steepness of the transition from potential to reduced uptake rates as $h$ decreases. Values reported or considered for these parameters in the literature have been in the neighborhood of $h_{50} = -1000$ to $-5000$ cm and $p = 1.5$ to 3 (e.g., Dudley and Shani, 2003; Homaee et al., 2002c; Cardon and Letey, 1992; van Genuchten, 1987). In our study, the modeled soil (sand) water retention properties are such that $S_e$ is essentially zero for $h < -250$ cm. Using parameter values for $h_{50}$ and $p$ that are similar to those reported in the literature caused the water reduction component to operate essentially as a step function: when water is present in any appreciable amount, uptake at that depth is at (or very near) the potential rate, and drops rapidly to (effectively) zero when $S_e$ gets very close to zero. In simulations of the deficit irrigation treatments reported in Skaggs et al. (2006), we observed that the upper part of the root zone would be wetted by irrigation while the lower part remained dry. The modeled plant consumed water at near the potential rate in the upper part of the root zone and, for the most part, not at all in the lower part. Integrated across the depth of the root zone, the simulated plant takes up water at less than the potential rate, but locally uptake is at the potential rate or is zero (approximately).

The parameter $h_{50}$ may be viewed as an effective parameter that lumps together in some unspecified way the reduction in uptake due to reduced water potential at the root surface as well as reduced flow of water to the root surface. On the basis of the latter consideration, an $h_{50}$ value considerably lower than reported in the literature seems justifiable for sand. Likewise, a larger value of $p$ could be required to account for the steepness of the soil water retention curve. Data were lacking, however, about the details of uptake within the root zone and it was not possible to reliably determine values for these parameters: agreement between simulations and available data (mostly drainage data) were no better or worse using values similar to those reported in the literature and values drastically different. In the end we used $h_{50} = -1500$ cm and $p = 2$, and concluded that the data from Skaggs et al. (2006) did not allow us to evaluate the performance of the functional form (S-shape) of the water stress component of the uptake reduction function, nor the assumed multiplicative interaction with salinity stress.

## RESULTS

Two time periods were simulated. The first period, DOY 156 to 220, was during Phase 1 experimental treatments in which crops were abundantly irrigated with waters ranging in salinity from 2.5 to 28 dS $m^{-1}$. The second simulation period, DOY 247 to 297, was during Phase 2 treatments in which lysimeters were irrigated with varying amounts of the same waters, including some deficit irrigation treatments. Using trial and error, the salinity uptake reduction parameters $a$ and $b$ were varied until measured and simulated cumulative drainage for all lysimeters and simulation periods were judged to have obtained a best-possible global fit. Since the 12 alfalfa and 12 tall wheatgrass lysimeters were evaluated separately, the fitting produced a single set of uptake reduc-

tion parameter values for each crop. Agreement between measured and simulated drainage EC was also considered but was given less weight owing to the uncertainty in EC data reported in Skaggs et al. (2006). The final parameter values obtained were $a = -25$ m and $b = 0.004\ \mathrm{m}^{-1}$ for alfalfa, and $a = -15$ m and $b = 0.003\ \mathrm{m}^{-1}$ for tall wheatgrass.

The data and simulations using the final uptake reduction parameters are shown in Fig. 3 through 8. Figure 3 shows simulated and measured cumulative drainage for 12 lysimeters during Phase 1. Also shown are the irrigation depths and timings, the irrigation water electrical conductivities ($EC_{iw}$), and the lysimeter numbers. The agreement between measured and simulated drainage is very good across all lysimeters, differing at most by a few percentage points during the 66 d. The experimental treatments in the other 12 lysimeters were replicates of those shown in Fig. 3 and the agreements between the data and the simulations were similar to that shown in Fig. 3 (not shown). The simulated and measured drainage water electrical conductivities ($EC_{dw}$) for the same time period are shown in Fig. 4. The measured data in this figure are daily averaged values. The agreement between the simulations and the data is not as good as that in Fig. 3. First, the measured $EC_{dw}$ exhibits peaks that correspond to crop harvests. Alfalfa was harvested on DOY 171 and 191, wheatgrass on DOY 164 and 190. The peaks occur because of the drop in ET and increase in leaching that follows harvest (Skaggs et al., 2006). The simulations do not show this dynamic because we specified the potential transpiration rate using a constant $k$ factor that averaged across variations in canopy development (see above). A second discrepancy between the data and the simulations is that, in general, the simulated $EC_{dw}$ is lower than the measured $EC_{dw}$. The simulated values are more in line with a steady-state approximation that is shown in Fig. 4 as a solid horizontal line and is defined by (cf. Eq. [11]):

$$EC_{dw} = 0.168(c_{iw}/\mathrm{LF})^{0.866} \qquad [17]$$

where $c_{iw}$ is the salt concentration of the irrigation water and the leaching fraction LF is equal to the ratio of the cumulative drainage depth to the cumulative irrigation depth measured for the time period depicted. We believe that the measured $EC_{dw}$ values may be erroneously high due to instrument calibration problems (Skaggs et al., 2006).

Results for the Phase 2 simulations (DOY 247–297) are shown in Fig. 5 through 8. Phase 2 imposed combinations of water and salinity stress. Figures 5 and 6 show the measured and simulated cumulative drainage for alfalfa and tall wheatgrass, respectively. Again, the agreement between measured and simulated drainage is quite good for the 50 d simulated. In addition to the information given for the Phase 1 simulations, the plots in these figures show, for each lysimeter, the targeted irrigation treatment, expressed as a fraction $f$ of evapotranspiration measured in well-watered control lysimeters. Lysimeters labeled $f = 0.5$ (the top row of plots in Fig. 5–8) received approximately half the volume of water consumed by the crop in the control lysimeters; lysimeters labeled $f = 0.75$ (the second row) received three-fourths that amount, and so on (Skaggs et al., 2006). Results for the control lysimeters (no. 67 and 73) are not shown in Fig. 5 through 8 because the irrigation regimes and agreements with the data were essentially identical to those shown for those lysimeters during Phase 1 (Fig. 3).

Figures 7 and 8 show the measured and simulated $EC_{dw}$ for alfalfa and tall wheatgrass, respectively. In these figures, gaps or breaks in the simulated and measured $EC_{dw}$ data occur because $EC_{dw}$ was plotted only when drainage occurred. Both crops were harvested on DOY 262 and 297. It is difficult to generalize about the agreement between the simulated and measured $EC_{dw}$ because of the considerable variability among the lysimeters. Many of the lysimeters show fairly good agreement while in other cases significant discrepancies exist. Note that in many of the treatments—especially the deficit irrigation ($f < 1$) treatments— $EC_{dw}$ was very large, at times exceeding 50 dS $\mathrm{m}^{-1}$, which is roughly the conductivity of seawater at 20°C. If the measured $EC_{dw}$ values were in fact higher than the true drainage conductivity (as suggested by the Phase 1 results), then the good agreement for several of the Phase 2 lysimeters actually implies that the model calculations were above the true $EC_{dw}$. Overestimation of $EC_{dw}$ in the model calculations is not unexpected because, at such high salt concentrations, it is anticipated that precipitation reactions will remove salt from solution and lower the solution EC (e.g., Rhoades, 1999).

## DISCUSSION

Overall, good agreement was achieved between lysimeter measurements and HYDRUS simulations made with uptake reduction parameters $a$ and $b$ fitted for alfalfa and for tall wheatgrass. That the model could be fitted to the data is especially noteworthy given the broad range of experimental conditions: irrigation waters with salinities ranging from 2.5 to 28 dS $\mathrm{m}^{-1}$ and irrigation rates ranging from deficit to luxurious.

Some questions remain about the modeling approach. Although the model was able to simulate deficit irrigation experimental treatments, a lack of data on uptake dynamics within the root zone combined with the low water-holding capacity of the coarse-textured soil in the lysimeters prevented us from evaluating the specific form of the water stress component of the uptake reduction function. Sand is commonly used in plant salt-tolerance trials because it is easily leached and a high-volume, high-frequency irrigation regime can be used to effectively minimize the role of the soil in determining growth conditions, with plant response being mainly a function of irrigation water quality. Such an experimental setup is useful for screening plants for salt tolerance, but it does not lend itself to testing process models of the effects of soil conditions on plant growth.

The linear threshold-type reduction function used for the salinity component of the uptake reduction function performed well. We noted above the interest in iden-

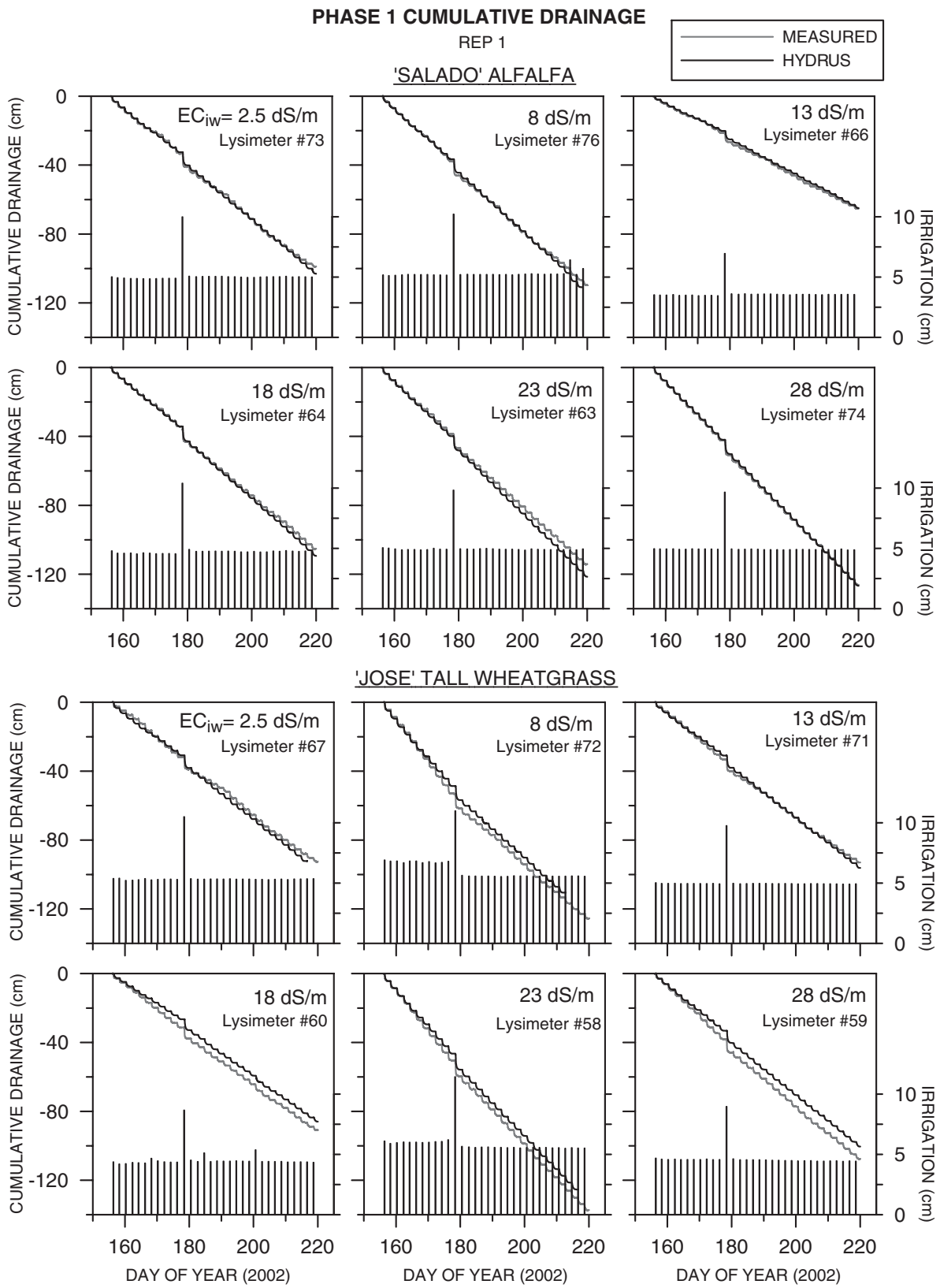


**Fig. 3. Measured and simulated cumulative drainage for Phase 1 experimental treatments in which all lysimeters where luxuriously irrigated with various irrigation water salinities ($EC_{iw}$). Irrigation timings are shown on the bottom of each plot and the irrigation depth is indicated on the axes on the right side of each plot.**

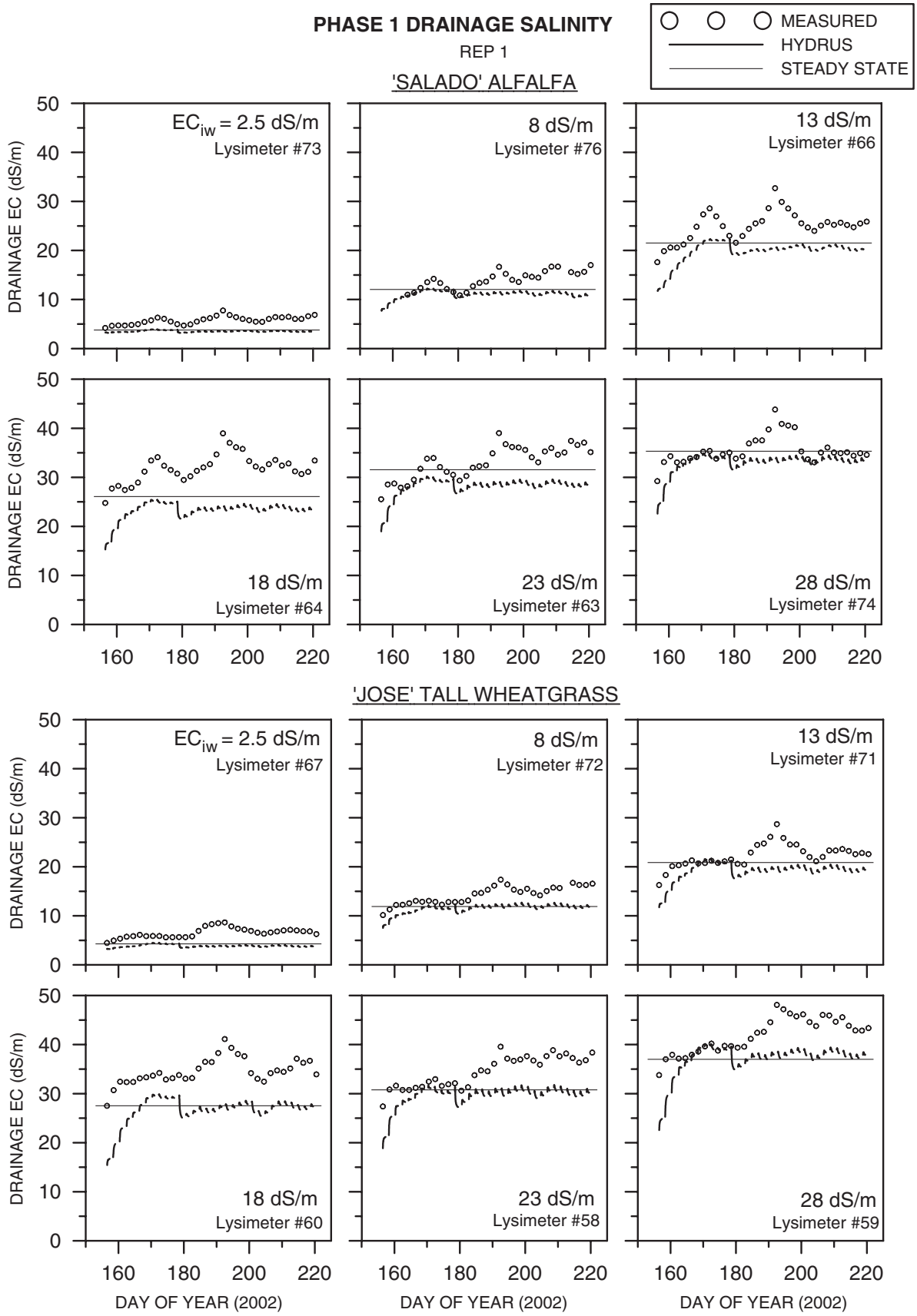


**Fig. 4. Measured and simulated drainage electrical conductivity for Phase 1 experimental treatments using various irrigation water salinities ($EC_{iw}$). The open circles in each plot are measured daily averages and the solid lines are the simulated drainage EC. The horizontal line in each plot is a steady-state approximation (see Eq. [17]). Drainage was not continuous in the simulations, leading to the broken appearance of the solid lines. The irrigation for each lysimeter is shown in Fig. 3.**

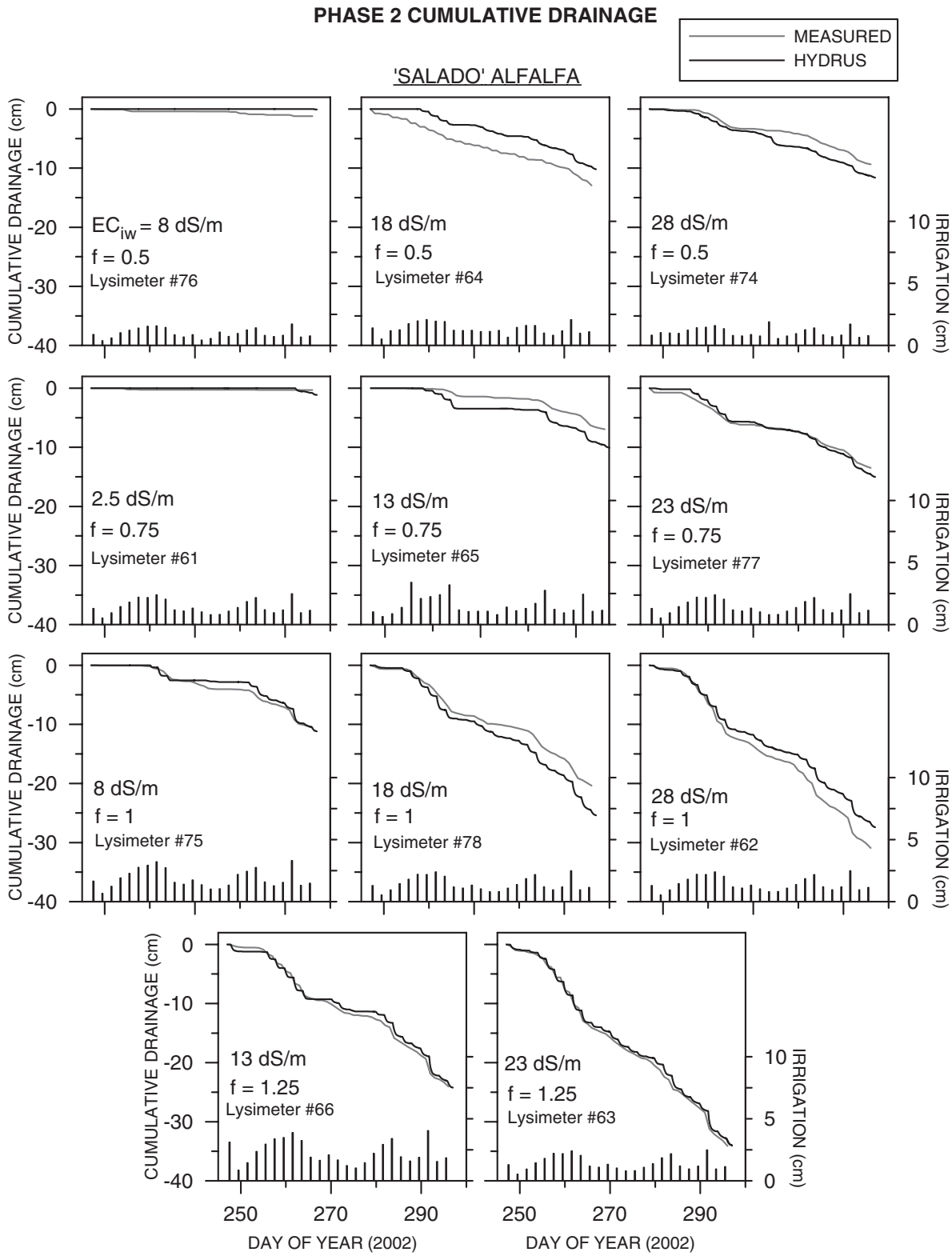


**Fig. 5. Measured and simulated cumulative drainage for alfalfa lysimeters during Phase 2 experimental treatments using various irrigation water salinities ($EC_{iw}$) and target irrigation depths *f*. Irrigation timings are shown on the bottom of each plot and the irrigation depth is indicated on the axes on the right side of each plot.**

tifying parameter values for uptake reduction functions based on whole-plant salt-tolerance data. Figure 9 compares the uptake reduction functions used here with functions calculated from literature data. The literature-derived reduction functions were obtained by substituting Eq. [10] and [11] into Eq. [4] of Skaggs et al.

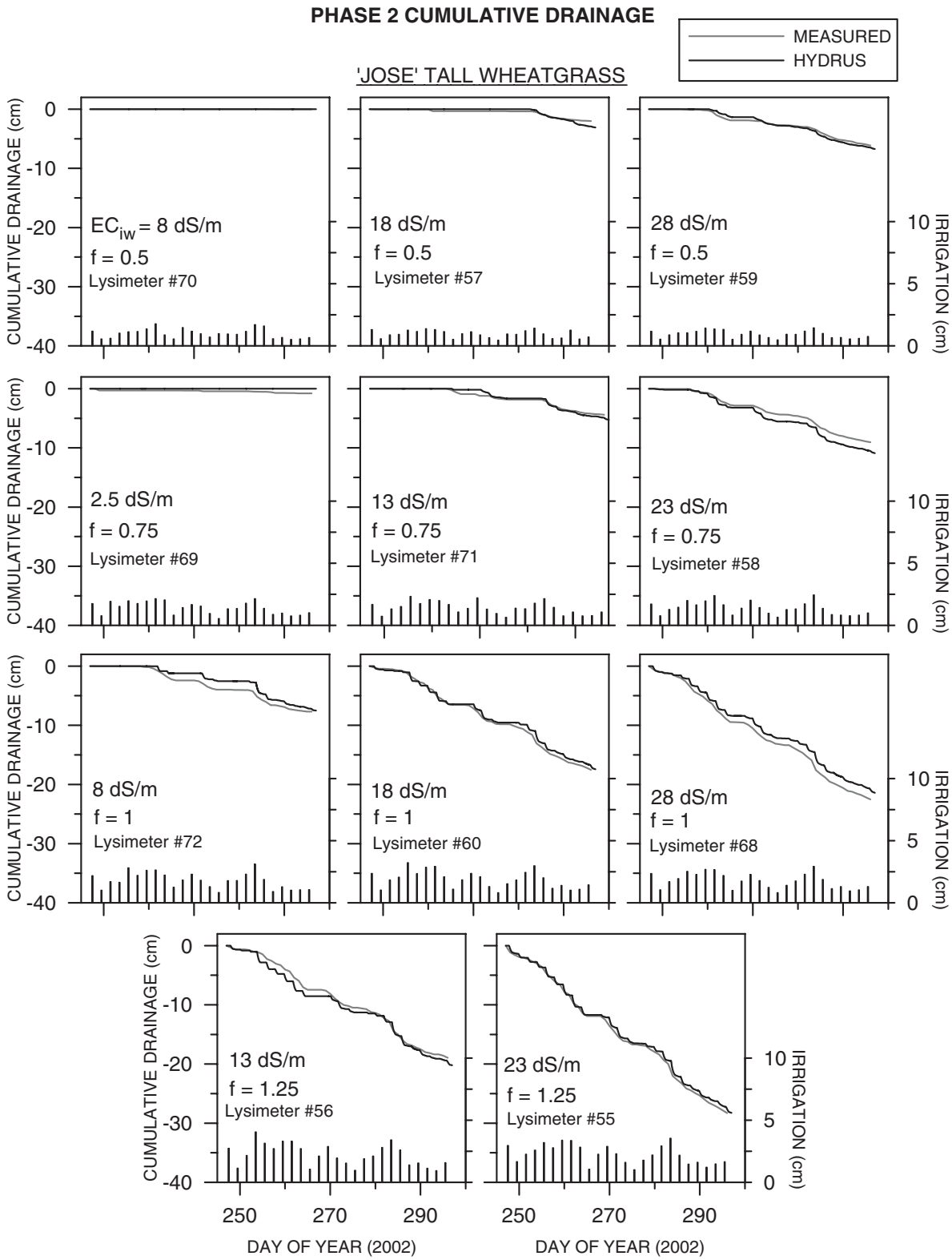


**Fig. 6. Measured and simulated cumulative drainage for tall wheatgrass lysimeters during Phase 2 experimental treatments using various irrigation water salinities ($EC_{iw}$) and target irrigation depths *f*. Irrigation timings are shown on the bottom of each plot and the irrigation depth is indicated on the axes on the right side of each plot.**

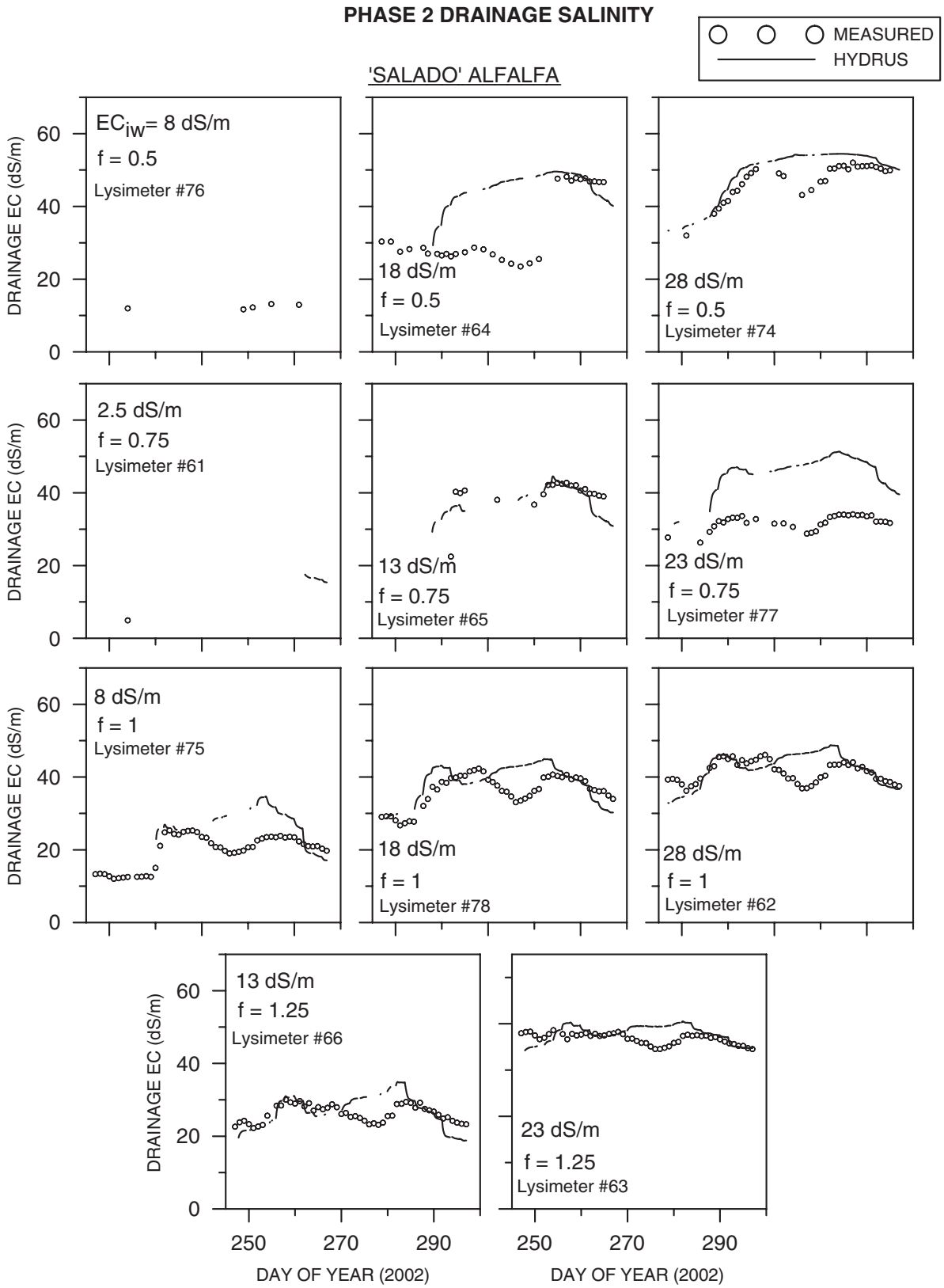


**Fig. 7. Measured and simulated drainage electrical conductivity for alfalfa lysimeters during Phase 2 experimental treatments using various irrigation water salinities ($EC_{iw}$) and target irrigation depths *f*. The open circles in each plot are measured daily averages and the solid lines are the simulated drainage EC. The simulated and measured drainage EC appears broken or missing in some plots because drainage did not occur or occurred infrequently in some lysimeters (see Fig. 5).**

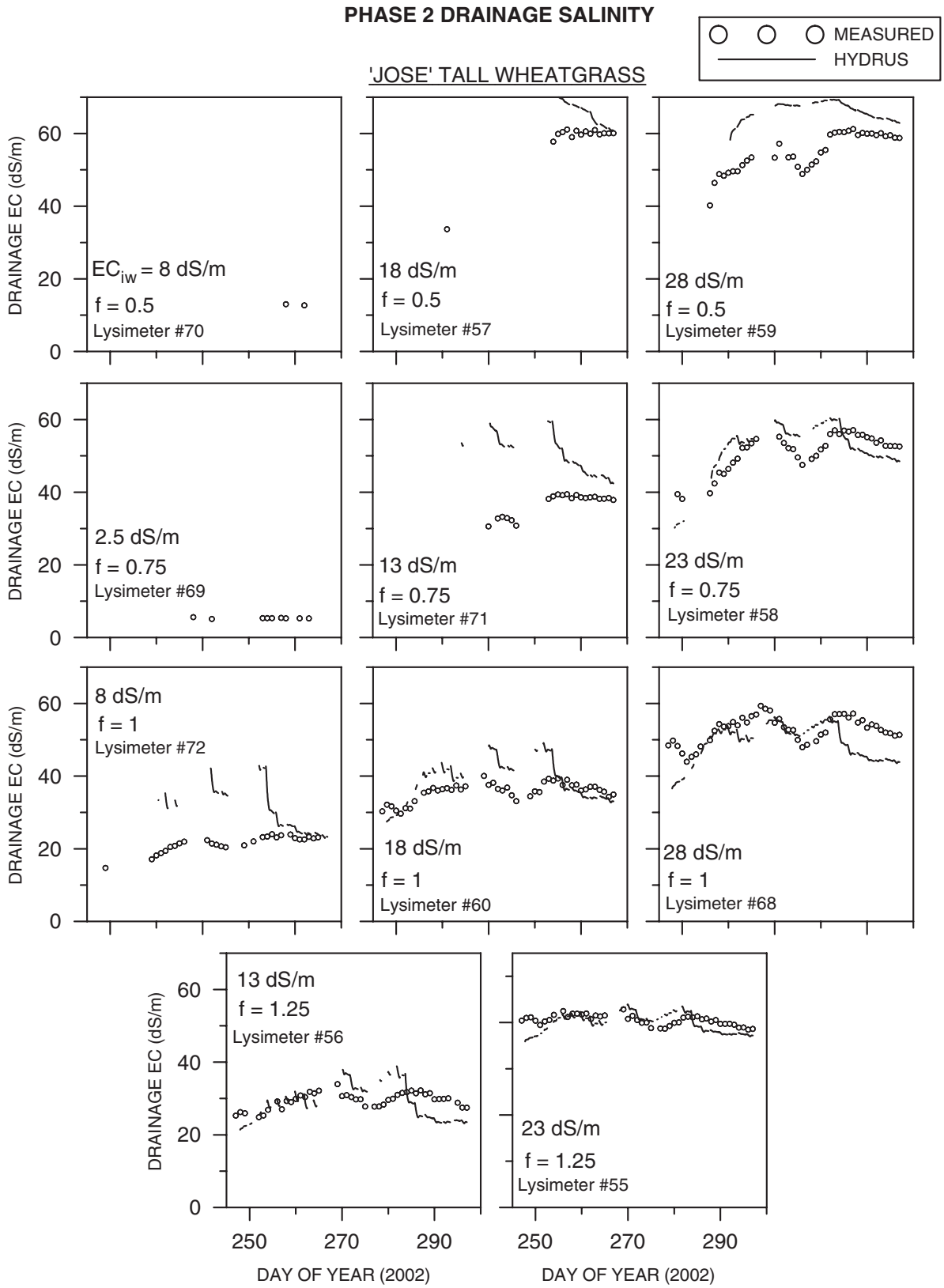


**Fig. 8. Measured and simulated drainage electrical conductivity for tall wheatgrass lysimeters during Phase 2 experimental treatments using various irrigation water salinities ($EC_{iw}$) and target irrigation depths *f*. The open circles in each plot are measured daily averages and the solid lines are the simulated drainage EC. The simulated and measured drainage EC appears broken or missing in some plots because drainage did not occur or occurred infrequently in some lysimeters (see Fig. 6).**

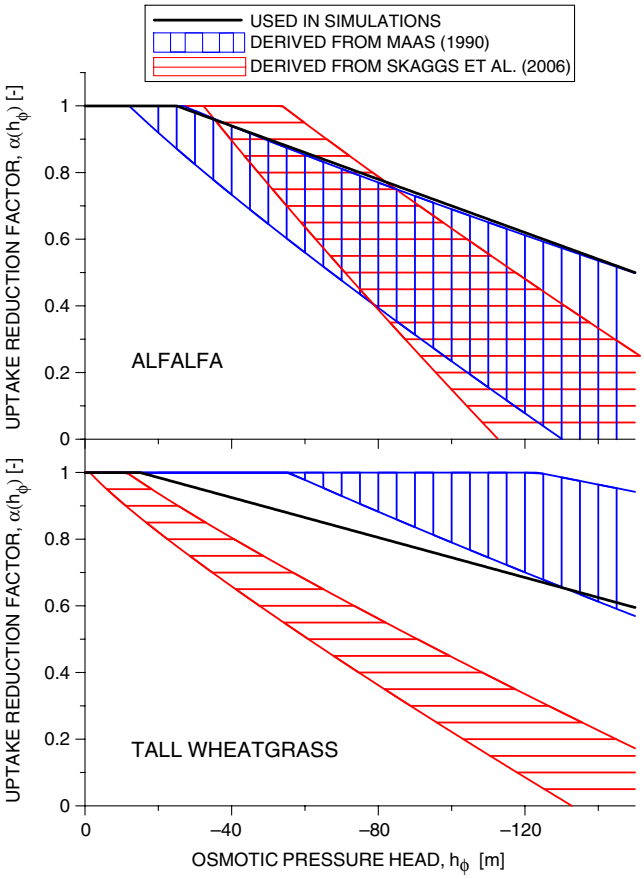


**Fig. 9. Comparison of uptake reduction functions used in the simulations with functions derived from published plant salt tolerances.**

(2006) and assuming $Y/Y_p = T/T_p = \alpha$. The resulting reduction functions are

$$\alpha(h_\phi) = \begin{cases} 1 & h_\phi \geq -(a')^{1/0.866} \\ 1 - b'[(-h_\phi)^{0.866} - a'] & h_\phi < -(a')^{1/0.866} \end{cases} \quad [18]$$

where

$$a' = \frac{k_{EC}(.31)^{0.866}}{0.168} A = 2.159A'$$

$$b' = \frac{0.168}{k_{EC}(.31)^{0.866}} 10^{-2} B = 4.632 \times 10^{-3} B'$$

and where $A$ (dS m$^{-1}$) and $B$ (% m dS$^{-1}$) are Maas–Hoffman salt-tolerance parameters, $A' = k_{EC}A$, $B' = B/k_{EC}$, and $h_\phi$ has units of meters. The parameter $k_{EC}$ is the ratio of the electrical conductivity of the in situ soil water at field capacity, and the electrical conductivity of the saturation extract, $k_{EC} = EC_{fc}/EC_e$. Note that Eq. [11] leads to a slight nonlinearity in Eq. [18]. We considered two sets of literature salt-tolerance values. In a tabulation of plant salt tolerances, Maas (1990) reported $A$ = 7.5 dS m$^{-1}$ and $B$ = 4.2% m dS$^{-1}$ for tall wheatgrass and $A$ = 2.0 dS m$^{-1}$ and $B$ = 7.3% m dS$^{-1}$ for alfalfa. Following Skaggs et al. (2006; also see below), we assumed $k_{EC}$ had a value between 2 and 4 and we used those bounds to compute the lower and upper confidence limits shown in Fig. 9 for the Maas (1990) data. The second dataset is from Skaggs et al. (2006), who reported $A'$ = 2.2 ± 1.6 dS m$^{-1}$ and $B'$ = 2.9 ± 0.29% m dS$^{-1}$ for tall wheatgrass, and $A'$ = 12 ± 2.6 dS m$^{-1}$ and $B'$ = 4.5 ± 0.96% m dS$^{-1}$ for alfalfa. Since $A'$ and $B'$ were reported (rather than $A$ and $B$), $k_{EC}$ was not needed to calculate α in Eq. [18]. The intervals shown in Fig. 9 for the Skaggs et al. (2006) data were derived from the reported 95% confidence limits for $A'$ and $B'$.

Several things are notable in Fig. 9. For alfalfa, there is considerable overlap between the two reduction functions derived from the Maas (1990) and Skaggs et al. (2006) salt-tolerance parameters. The "fitted" reduction function used in the alfalfa simulations lies near the upper edge of the region demarcated by the two derived functions, and in fact follows almost exactly the upper bound derived from the Maas parameters. For tall wheatgrass, there is no overlap between the two derived functions. The fitted function for tall wheatgrass lies mostly between the two derived functions, although with its small slope, the fitted function is closer in appearance to the Maas function. It is noteworthy that for both alfalfa and tall wheatgrass, the slopes (i.e., the rates of uptake decline) used in the simulations were substantially smaller than was derived from the Skaggs et al. (2006) data. A couple of factors may have contributed to this result. Skaggs et al. (2006) reported relatively high water use and speculated that the dry atmospheric conditions led to a non-negligible evaporative component in ET. Also, as discussed above, our neglect of precipitation reactions may have led to unrealistically high simulated osmotic pressure heads. Additionally, determining potential transpiration using an average $k$ value in Eq. [13] that was based on data for control lysimeters would tend to overestimate the potential transpiration rate in high $EC_{iw}$ treatments where there is less canopy development. All of these factors would favor a smaller slope parameter in the simulations than would be deduced from yield data.

It is of interest to consider briefly how the uncertainty contained in the literature-derived reduction functions would translate to uncertainty in drainage predictions. For one Phase 2 treatment ($f$ = 1.2, $EC_{iw}$ = 13 dS m$^{-1}$), Fig. 10 compares the measured cumulative drainage with the drainage that would have been predicted using uptake reduction functions derived from Maas (1990) salt-tolerance parameters. For alfalfa, the uncertainty in the reduction function resulted in cumulative drainage being between 22 and 35 cm at the end of the 55-d simulation (vs. 24 cm measured); for tall wheatgrass, drainage was between 12 and 19 cm (vs. 20 measured). During the 50 d, the measured drainage in both instances lies near the edge of the predicted confidence regions, at the upper bound predicted for alfalfa and slightly below the lower bound predicted for tall wheatgrass.

The question of whether the predictions and bounds shown in Fig. 10 are sufficiently accurate or precise will, of course, depend on the particular problem being addressed. In assessing these predictions, however, we should recall that the uncertainty in the drainage computations was generated by assigning uncertainty to the

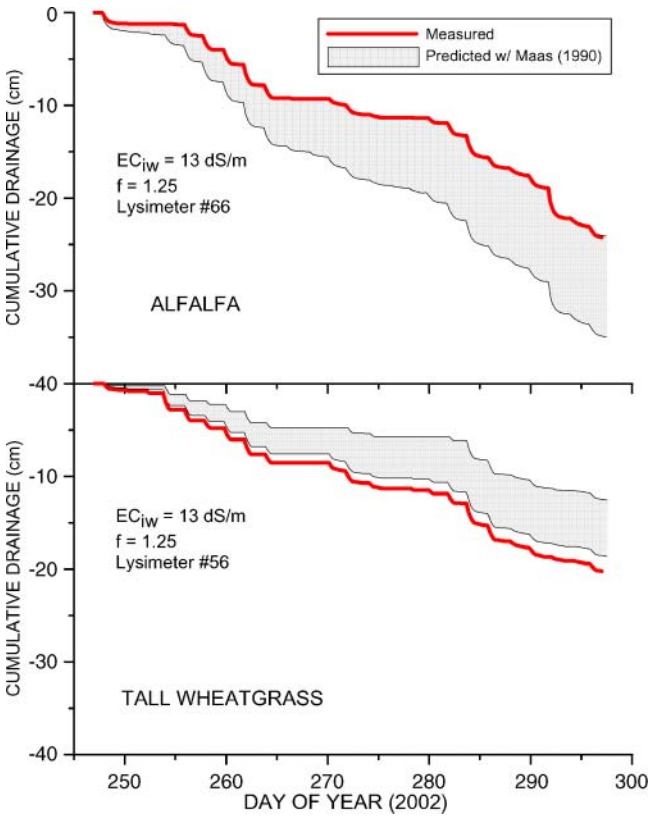


**Fig. 10. Comparison of measured cumulative drainage with cumulative drainage simulated using uptake reduction functions derived from Maas (1990) salt-tolerance data. Electrical conductivity of the irrigation water ($EC_{iw}$) was 13 dS $m^{-1}$ and the target irrigation depth *f* was 1.25 for both crops.**

uptake reduction functions arbitrarily; namely, by assuming that $k_{EC} = EC_{fc}/EC_e$ had a value between 2 and 4. A basis for this estimate is found in U.S. Salinity Laboratory Staff (1954), where measured data and other observations were presented demonstrating for various soil textures' relationships between field capacity water content, wilting point water content, and the water content of saturation pastes. The data presented for medium-textured soils, plus the assumptions that the dissolved salt mass is unaffected by dilution and that the salt concentration is proportional to solution EC, leads to a common approximation for soil water contents near field capacity, $k_{EC} = 2$ (e.g., Rhoades, 1999; Homaee et al., 2002a). The data for coarse-textured soils suggests $k_{EC}$ is larger in sands, say 3 or more, leading to our supposition that $k_{EC}$ could range from 2 to 4. Conceptually, though, there is some ambiguity. If it is the EC of the in situ soil water, $EC_{sw}$, that determines the yield response, then it could be argued that it is not the texture of the soil for which a prediction is desired that is relevant, it is the texture of the soil used in the literature's salt-tolerance trial; that is, we should convert the literature's $EC_e$ to the $EC_{sw}$ that was operational during that trial, and derive an uptake reduction function for the prediction based on that $EC_{sw}$ value.

Additionally, the predictions in Fig. 10 ignore another significant source of uncertainty, namely uncertainty associated with the salt-tolerance parameters themselves. The salt-tolerance tables in Maas (1990) and elsewhere do not provide confidence intervals for the parameters, but in reviewing the original sources for a number of the tabulated values, it is apparent that the data used to estimate *A* and *B* for various crops were not sufficient to determine these parameters with great precision, especially the threshold parameter *A*. Additionally, Maas (1990) notes that the parameters in the tables are intended to "serve only as a guideline to relative tolerances among crops" and that "absolute tolerances vary, depending on climate, soil conditions, and cultural practices." Hence with respect to the estimation of uptake reduction parameters, tabulated salt-tolerance parameters must be regarded as carrying significant uncertainty.

So while our specifying a range for $k_{EC}$ was arbitrary, allowing for variability in $k_{EC}$ could nevertheless be a useful method of lumping and accounting for various uncertainties, including the conversion of $EC_e$ to $EC_{sw}$, salt-tolerance parameter values, potential uptake rates, and other sources of uncertainty not discussed here (example: calculating $h_\phi$ as a function of salt concentration for different water compositions). Future research is needed to demonstrate the utility of such an approach and identify appropriate ranges for $k_{EC}$. Additionally, it would helpful if future salt-tolerance studies would report data for $EC_{sw}$ in addition to $EC_e$, as well as provide confidence bounds for salt-tolerance parameters. This would greatly assist in the estimation of appropriate uptake reduction parameters for various soil textures.

## CONCLUSIONS

This study compared HYDRUS-1D simulations of root water uptake and drainage with lysimeter data collected during an experiment in which forage crops (alfalfa and tall wheatgrass) were irrigated with synthetic drainage waters. A trial-and-error fitting procedure was used to determine uptake reduction parameters for each crop. Good agreement between the model simulations and data was achieved, a noteworthy result given the broad range of experimental conditions considered: irrigation waters with salinities ranging from 2.5 to 28 dS $m^{-1}$ and irrigation rates ranging from deficit to luxurious.

Deriving uptake reduction parameters from tabulated plant salt tolerances would allow the model to be used without extensive calibration, but the derivation poses a number of challenges. Plant salt-tolerance parameter values recorded in literature tables are approximate and carry significant uncertainty. Additionally, salt tolerances are normally reported in terms of root-zone-averaged $EC_e$, whereas uptake reduction functions are parameterized in terms of osmotic pressure head. We presented simulations showing that it may be possible to account for various uncertainties by assuming a range of values for $k_{EC} = EC_{sw}/EC_e$, although additional work is needed to verify the utility of this approach and identify appropriate bounds for $k_{EC}$. When plant salt-tolerance data is reported in terms of $EC_{sw}$ instead of $EC_e$, the conversion of salt-tolerance parameters to uptake reduction param-

eters is simplified, especially when confidence intervals for salt-tolerance parameters are provided.

Despite the difficulties and uncertainties highlighted here, our results demonstrate that the transpiration reduction modeling approach used in HYDRUS captures many essential features of root water uptake under salt and water stress. In this regard, it is our view that advanced simulation models such as HYDRUS can be useful tools for assessing drainage reuse operations, especially when used as a complement to more basic, steady-state analyses such as those discussed by Rhoades (1999).

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## REFERENCES

Cardon, G.E., and J. Letey. 1992. Plant water uptake terms evaluated for soil water and solute movement models. Soil Sci. Soc. Am. J. 32:1876–1880.

Dirksen, C., J.B. Kool, P. Koorevaar, and M.Th. van Genuchten. 1993. HYSWASOR—Simulation model of hysteretic water and solute transport in the root zone. p. 99–122. *In* D. Russo and G. Dagan (ed.) Water flow and solute transport in soils. Springer-Verlag, New York.

Dudley, L.M., and U. Shani. 2003. Modeling plant response to drought and salt stress: Reformulation of the root-sink term. Vadose Zone J. 2:751–758.

Feddes, R.A., P.J. Kowalik, and H. Zaradny. 1978. Simulation of field water use and crop yield. Simulation Monogr. Pudoc, Wageningen, the Netherlands.

Feddes, R.A., and P.A.C. Raats. 2004. Parameterizing the soil–water–plant root system. p. 95–141. *In* R.A. Feddes et al. (ed.) Unsaturated-zone modeling: Progress, challenges and applications. Wageningen UR Frontis Ser., Vol. 6. Kluwer Acad. Publ., Dordrecht, the Netherlands.

Hanks, R.J. 1974. Model for predicting plant yield as influenced by water use. Agron. J. 66:660–664.

Homaee, M., R.A. Feddes, and C. Dirksen. 2002a. Simulation of root water uptake: I. Non-uniform transient salinity using different macroscopic reduction functions. Agric. Water Manage. 57:89–109.

Homaee, M., R.A. Feddes, and C. Dirksen. 2002b. Simulation of root water uptake: II. Non-uniform transient water stress using different reduction functions. Agric. Water Manage. 57:111–126.

Homaee, M., R.A. Feddes, and C. Dirksen. 2002c. Simulation of root water uptake: III. Non-uniform transient combined salinity and water stress. Agric. Water Manage. 57:127–144.

Maas, E.V. 1990. Crop salt tolerance. p. 262–304. *In* K. Tanji (ed.) Agricultural salinity assessment and management. ASCE Manuals and Rep. on Eng. Practice no. 71. Am. Soc. Civ. Eng., New York.

Maas, E.V., and G.J. Hoffman. 1977. Crop salt tolerance—current assessment. J. Irrig. Drain. Div. 103(IR2):115–134.

McNeal, B.L., J.D. Oster, and J.T. Hatcher. 1970. Calculation of electrical conductivity from solution composition data as an aid to in-situ estimation of soil salinity. Soil Sci. 110:405–414.

Oster, J.D., and D. Wichelns. 2003. Economic and agronomic strategies to achieve sustainable irrigation. Irrig. Sci. 22:107–120.

Rhoades, J.D. 1999. Use of saline drainage water for irrigation. p. 615–657. *In* R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural drainage. Agron. Monogr. 38. ASA, CSSA, and SSSA, Madison, WI.

Schaap, M.G., F.J. Leij, and M.Th. van Genuchten. 2001. ROSETTA: A computer program for estimating soil hydraulic properties with hierarchical pedotransfer functions. J. Hydrol. 251:163–176.

Šimůnek, J., M. Šejna, and M.Th. van Genuchten. 1998. The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media. Version 2.0. Int. Ground Water Model. Ctr., Golden, CO.

Šimůnek, J., D.L. Suarez, and M. Šejna. 1996. The UNSATCHEM software package for simulating one-dimensional variably saturated water flow, heat transport, carbon dioxide production and transport, and multicomponent solute transport with major ion equilibrium and kinetic chemistry. Version 2.0. Res. Rep. no. 141. U.S. Salinity Lab., Riverside, CA.

Skaggs, T.H., and F.J. Leij. 2002. Solute transport: Theoretical background. p. 1353–1380. *In* J. Dane and C. Topp (ed.) Methods of Soil Analysis. Part 4. SSSA, Madison, WI.

Skaggs, T.H., J.A. Poss, P.J. Shouse, and C.M. Grieve. 2006. Irrigation of forage crops with saline drainage waters. 1. Volumetric lysimeter studies. Vadose Zone J. 5:815–823 (this issue).

U.S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and alkali soils. USDA Agric. Handbk. 60. U.S. Gov. Print. Office, Washington, DC.

van Dam, J.C., J. Huygen, J.G. Wesseling, R.A. Feddes, P. Kabat, P.E.V. van Walsum, P. Groenendijk, and C.A. van Diepen. 1997. Theory of SWAP version 2.0: Simulation of water flow, solute transport, and plant growth in the soil–water–atmosphere–plant environment. Wageningen Agric. Univ., Dep. Water Resour. no. 71. DLO Winand Staring Centre, Wageningen, the Netherlands.

van Genuchten, M.Th. 1987. A numerical model for water and solute movement in and below the root zone. Res. Rep. 121. U.S. Salinity Lab., Riverside, CA.