# Comparison of HYDRUS-2D Simulations of Drip Irrigation with Experimental Observations

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**Abstract:** Realizing the full potential of drip irrigation technology requires optimizing the operational parameters that are available to irrigators, such as the frequency, rate, and duration of water application and the placement of drip tubing. Numerical simulation is a fast and inexpensive approach to studying optimal management practices. Unfortunately, little work has been done to investigate the accuracy of numerical simulations, leading some to question the usefulness of simulation as a research and design tool. In this study, we compare HYDRUS-2D simulations of drip irrigation with experimental data. A Hanford sandy loam soil was irrigated using thin-walled drip tubing installed at a depth of 6 cm. Three trials (20, 40, and 60 $L \cdot m^{-1}$ applied water) were carried out. At the end of each irrigation and approximately 24 h later, the water content distribution in the soil was determined by gravimetric sampling. The HYDRUS-2D predictions of the water content distribution are found to be in very good agreement with the data. The results support the use of HYDRUS-2D as a tool for investigating and designing drip irrigation management practices.

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**CE Database subject headings:** Trickle irrigation; Subirrigation; Soil water movement; Computer models; Simulation.

## Introduction

As the population grows and urban water use increases, irrigated agriculture is being called on to produce more food using less water, and to do so without degrading soil and water resources. Drip irrigation technology can help meet this challenge by giving growers greater control over the application of water, fertilizers, and pesticides. Realizing the full potential of drip technology requires optimizing the operational parameters that are available to irrigators, such as the frequency and duration of irrigation, the emitter discharge rate and spacing, and the placement of drip tubing.

Numerical simulation is an efficient approach to investigating optimal drip management practices (e.g., Meshkat et al. 1999; Schmitz et al. 2002; Cote et al. 2003). However, there have been very few, if any, studies showing that numerical simulations of drip irrigation agree with field data, thus bringing into question the value of conclusions drawn from numerical simulations.

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The objective of this work was to compare HYDRUS-2D (Šimůnek et al. 1999) simulations of water infiltration and redistribution with field data, and to assess the utility of using simulation in design drip management practices. HYDRUS-2D is a well-known Windows-based computer software package for simulating water, heat, and/or solute movement in two-dimensional, variably saturated porous media.

## Methods and Materials

### *Field Experiment*

A study of water infiltration and redistribution under drip irrigation was conducted on a Hanford sandy loam soil (coarse-loamy mixed thermic Typic Durizeralf) at the San Joaquin Valley Agricultural Sciences Center, a U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS) research facility located southeast of Fresno, Calif. The experimental site was slip plowed to 1.5 m to thoroughly mix the profile and eliminate any compacted layers, then chiseled to 30 cm, disked, and harrowed. A 30 m run of commercial drip tubing was installed approximately 6 cm below the soil surface [Fig. 1(a)]. The subsurface installation was consistent with ''surface'' drip irrigation practices in the San Joaquin Valley, where drip lines may be buried at shallow depths to protect the lines and hold them in place. The tubing was RO-DRIP 08-12-24 16 mm drip tape (Roberts Irrigation Products, Inc., San Marcos, Calif.), which has a 16 mm inside diameter, a wall thickness of 8 mm, and an emitter spacing of 30 cm. (Mention of products and trade names are for the benefit of the reader and do not imply a guarantee or endorsement of the product by USDA.)

The installed tubing was subsequently cut into three equal sections, with water supplied separately to each segment. This permitted the study of a different water application on each segment. The three water applications were 5, 10, and 15 h irrigations. During irrigation, a Sensus displacement-type water flow meter showed that each segment applied water at a steady rate of 4

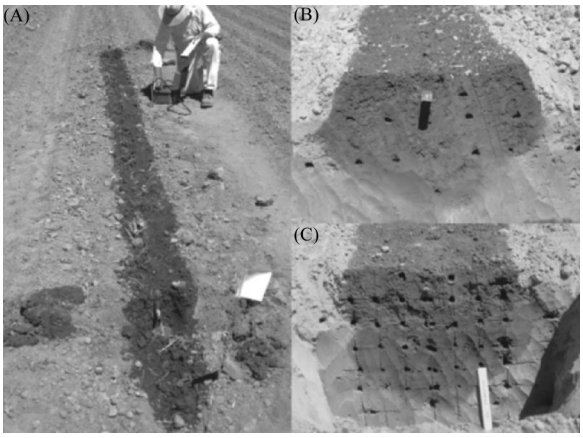


**Fig. 1.** Wetting pattern observed at the soil surface (A) and within the soil (B and C). In B and C, the sampling grids are visible, as is the drip tubing (6 cm below the soil surface in the center of the wetted region).

$L \cdot h^{-1} \cdot m^{-1}$. Additionally, during each irrigation, soil was excavated around two emitters and volumetric discharge measurements were made. These measurements confirmed the 4 $L \cdot h^{-1} \cdot m^{-1}$ water application rate. Thus, the 5, 10, and 15 h trials correspond to 20, 40, and 60 $L \cdot m^{-1}$ applied water.

At the end of each irrigation and approximately 24 h later, a vertical soil profile perpendicular to the drip tubing was exposed. A coordinate system was established on the profile with the origin at the soil surface directly above the drip tubing. Soil samples were taken by pressing a 30 cm long, 2 cm inside diameter steel soil sampling tube horizontally into the profile at selected coordinate positions [Figs. 1(b and c)]. Note that the length of the soil sample was equal to the distance between emitters. The profile for the second sampling of each trial was exposed by shaving 30 cm of soil off the first profile. Between the first and second sampling, the soil surface and profile face were covered with plastic sheeting to minimize evaporation.

The observed soil wetting had a high degree of horizontal symmetry [Figs. 1(b and c)], and when analyzing the data we averaged the two samples taken from "mirror" coordinate positions on opposite sides of the drip tubing [i.e., we combined the two samples taken at $(x,z)$ and $(-x,z)$, where $z$=vertical coordinate and $x$=horizontal coordinate centered at the drip tubing]. The gravimetric water contents of the samples were determined by recording the weight of water lost after oven-drying the samples. Soil bulk density was determined at several locations in the soil profile with a Soilmoisture Model 0200 soil sampler (5.7 cm diameter×6 cm long double ring manually inserted into the profile wall). Bulk density measurements ranged from 1.45 to 1.65 $g \cdot cm^{-3}$. There were no obvious trends in the bulk density measurements, so the average value of 1.55 $g \cdot cm^{-3}$ was used to convert the gravimetric water content data to volumetric water content. Mass balance calculations for the six volumetric water content profiles gave an average recovery of 96% of the applied water (ranging from a high of 109% to a low of 85%).

### Numerical Modeling

Because the length of the soil samples was equal to the emitter spacing (30 cm), the sampling effectively integrated over any variability in water content that existed in the direction of the tubing. It is therefore possible to ignore individual emitters and conceptualize the drip tubing as a line source, with infiltration and redistribution being a two-dimensional (vertical plane) process. The wetting pattern shown in Fig. 1(a) also supports the notion that the drip tubing operated as a line source.

We simulated water infiltration and redistribution using HYDRUS-2D (Šimůnek et al. 1999). Assuming a homogeneous and isotropic soil, the governing equation for water flow is the 2D Richards equation

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

where $\theta$=volumetric water content; $h$=soil water pressure head; $t$=time; $x$=horizontal space coordinate; $z$=vertical space coordinate; and $K$=hydraulic conductivity. The soil hydraulic properties were modeled using the van Genuchten-Mualem constitutive relationships

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{(1+|\alpha h|^n)^m} & h<0 \\ \theta_s & h \geqslant 0 \end{cases} \tag{2}$$

$$K(h) = K_s S_e^l [1-(1-S_e^{1/m})^m]^2 \tag{3}$$

where

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

and where $\theta_s$=saturated water content; $\theta_r$=residual water content; $K_s$=saturated hydraulic conductivity; and $n$, $\alpha$, and $l$=shape parameters.

HYDRUS-2D uses the Galerkin finite-element method to solve Eqs. (1)–(3). Šimůnek et al. (1999) explain the solution procedure in detail. We simulated only the right side of the presumed symmetric profile. Thus, the boundary of the finite-element mesh is rectangular except on the left edge near the upper left hand corner where the drip tubing is located. The tubing is represented as a half-circle on the boundary, curved inward toward the interior of the mesh. The half-circle has a 1 cm radius and is located on the left edge 6 cm below the top boundary. During water application, the drip tubing boundary had a constant water flux of $q = 6.37\ cm \cdot h^{-1}$, which was calculated based on the measured 4 $L \cdot h^{-1} \cdot m^{-1}$ water application rate and the modeled drip tube surface area:

$$q = \frac{\text{flow rate}}{\text{surface area}} = \frac{4{,}000\ \ cm^3 \cdot h^{-1}}{2\pi(1\ cm)(100\ cm)} = 6.37\ \ cm \cdot h^{-1}$$

When irrigation ended, the drip tube boundary became a zero-flux boundary condition. The remaining portion of the left boundary was a zero-flux boundary condition during and after irrigation (due to the symmetry of the profile), as was the upper boundary (reflecting our assumption that surface evaporation was insignificant—evaporation was less than 5% of the water application rate during irrigation and was reduced to low levels with plastic mulch after irrigation). The computational flow domain was made large enough to ensure that the right and bottom boundaries did not affect the simulations.

Running the model required the hydraulic parameters $\theta_s$, $\theta_r$, $K_s$, $n$, $\alpha$, and $l$, as well as the initial water content distribution. We estimated the hydraulic parameters using ROSETTA (Schaap et al. 2001), a pedotransfer function software package that uses a neural network model to predict hydraulic parameters from soil texture and related data. ROSETTA contains a hierarchy of pedotransfer functions that can be used depending on the soil char-

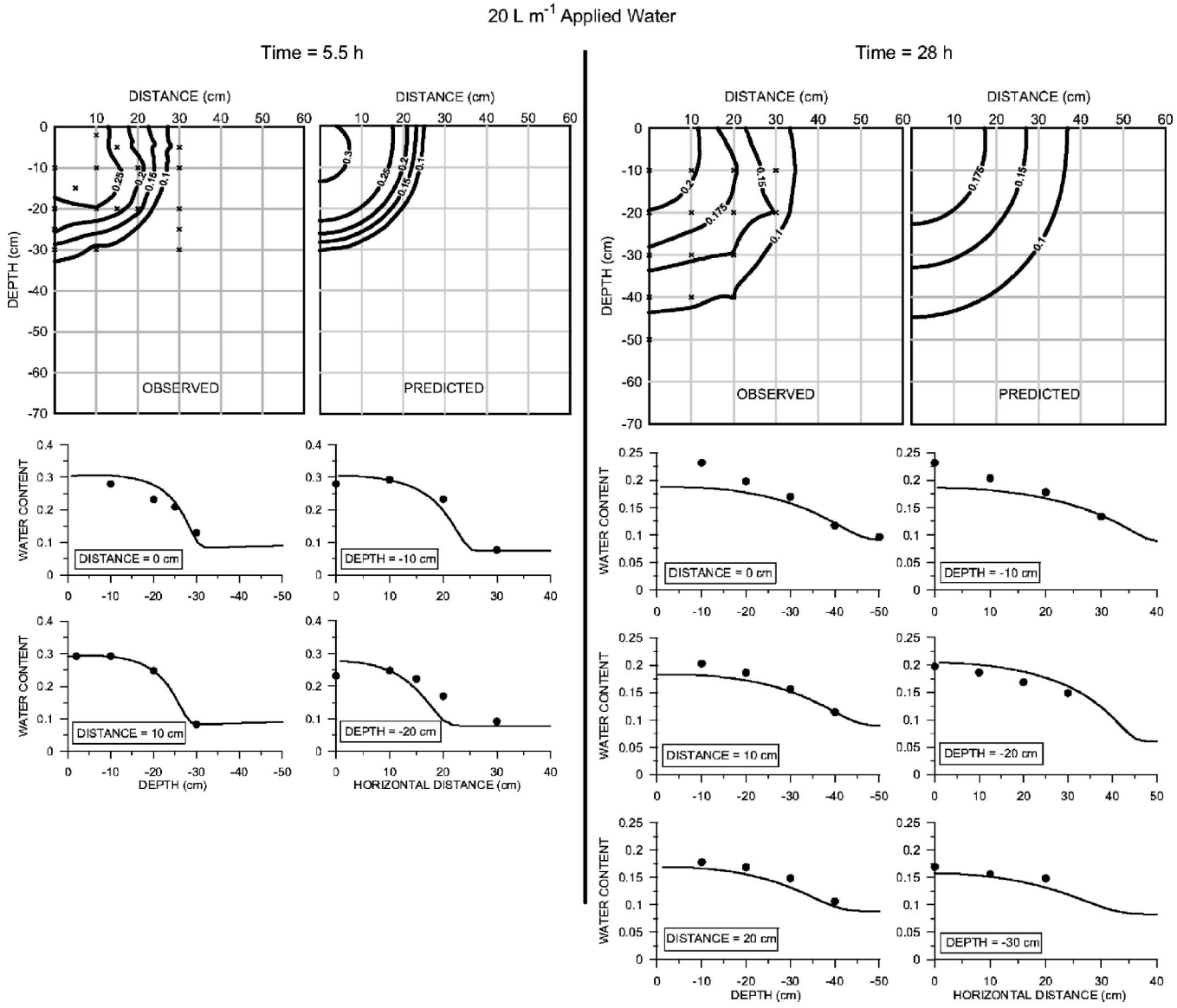


**Fig. 2.** Measured and predicted volumetric water contents for Trial 1. Water application was from $t=0$ to $t=5$ h. The hash marks in the ''observed'' contour plot indicate the location of a measurement. The line plots compare the measured (filled circles) and predicted (solid line) water contents along selected transects.

acterization data that are available. The lowest-order model makes predictions of hydraulic parameters based on the soil textural class. The most complex model predicts hydraulic parameters based on bulk density, percentages of sand, silt, and clay, and 33 and 1,500 kPa water contents. We previously measured at the experimental site the following soil physical properties: 54.8% sand, 39.6% silt, 5.6% clay, 17% water content at 33 kPa suction, and 5.4% water content at 1,500 kPa suction. Inputting these data to ROSETTA, along with our measured bulk density of 1.55 $g \cdot cm^{-3}$, resulted in the following parameter estimates: $\theta_s = 0.34$, $\theta_r = .021$, $K_s = 1.6\ cm \cdot h^{-1}$, $n = 1.4$, $\alpha = 0.023\ cm^{-1}$, and $l = -0.92$. The initial water content distribution was estimated based on the water content of samples taken outside the wetted region during each sampling [Figs. 1(b and c)]. Based on those measurements, we assumed the initial volumetric water content was uniform in the horizontal direction and varied linearly with depth, from about $\theta = 0.06$ at the soil surface to about $\theta = 0.09$ at the bottom of the profile.

## Results and Discussion

Figs. 2–4 show the measured and simulated water content distributions for each of the three trials. Each figure contains contour plots of the measured and simulated water content profiles, as well as comparisons of the measured and simulated water contents along selected profile transects.

The contours in the measured profiles were drawn using a kriging interpolation algorithm. However, because the data are relatively sparse, one should not attach too much significance to the contour details. Nevertheless, it is clear from the contour plots in Figs. 2–4 that in general the predicted pattern of wetting is in excellent agreement with the data; the depths and widths of the wetted regions are similar, as are the spatial distributions of the water content.

The transect plots in Figs. 2–4 permit a more objective comparison. While there is some disagreement between the predictions and observations, overall the predictions are very good, par-

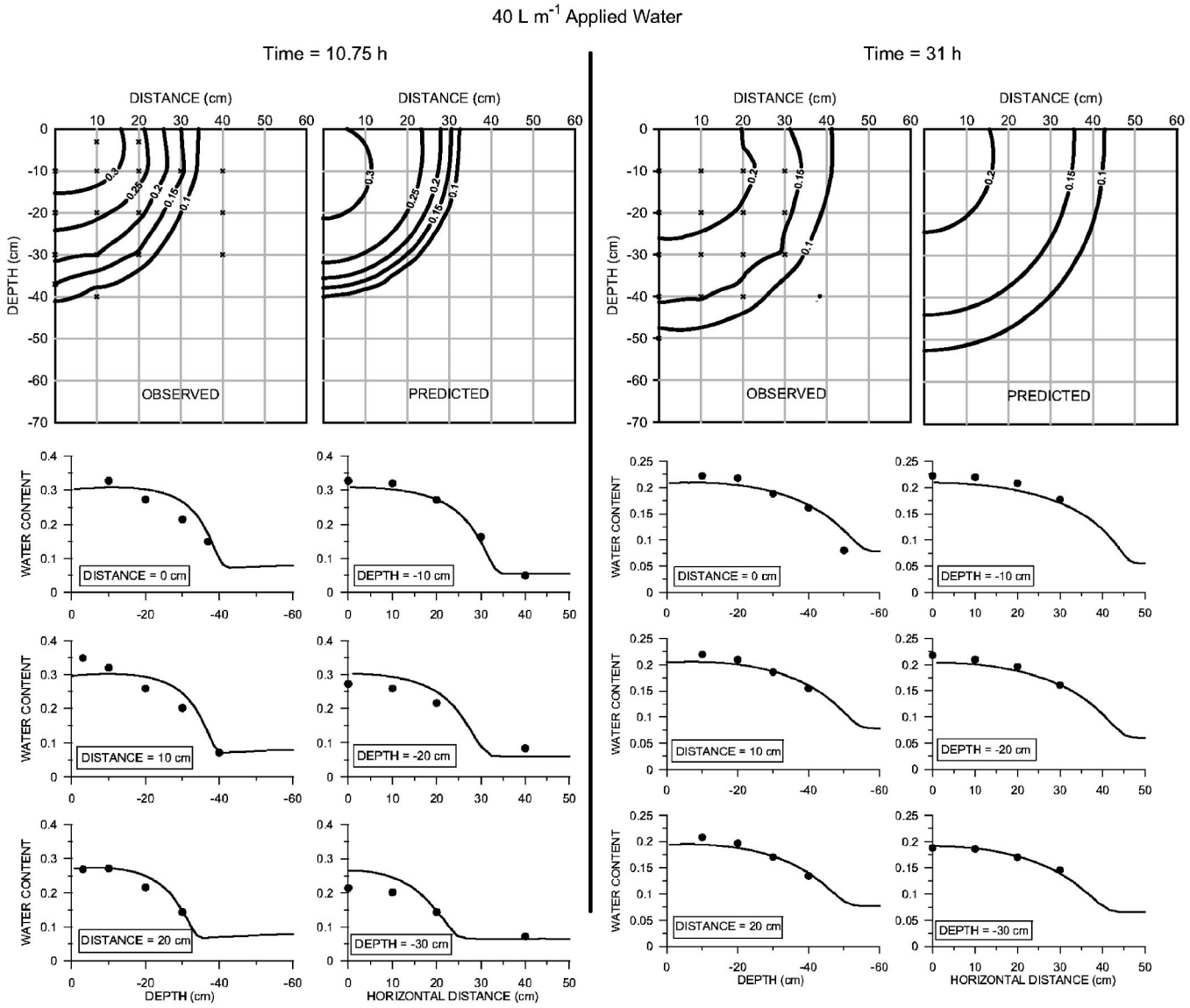


**Fig. 3.** Measured and predicted volumetric water contents for Trial 2. Water application was from $t=0$ to $t=10$ h. (See Fig. 2 for an explanation of symbols.)

ticularly considering that the simulations were done without any fitting to the water content data, and without characterizing in detail the soil at each experimental site.

The root-mean-square-error (RMSE) for the simulated and measured volumetric water contents provides a quantitative measure of the goodness-of-fit between the data and the simulation. The RMSE value for each simulation is given in Table 2. The RMSE values range from 0.02 to 0.04 $m^3 \cdot m^{-3}$ for the sampling immediately after irrigation, and from 0.01 to 0.03 $m^3 \cdot m^{-3}$ for the second sampling.

Overall, we judge the accuracy of the HYDRUS-2D simulations to be very good, and certainly accurate enough to justify using HYDRUS-2D as a tool for designing drip management practices for the soil investigated here.

For soils with low hydraulic conductivities (i.e., fine textured soils), or for simulations with high water application rates, it may be necessary to improve upon our drip tubing boundary condition, which specified a constant water flux during irrigation. When irrigating a low permeability soil, substantial positive pressure can build up around the drip tape as the soil becomes saturated. The water flux should then decrease in response to the pressure buildup, rather than remain constant. The constant flux boundary condition in HYDRUS-2D maintains the prescribed water flux by raising the pressure at the drip tube boundary. This increase in boundary pressure is physically unrealistic and, if the increase becomes too large, may lead to numerical problems. In our simulations, the pressure buildup required to maintain the flux was minimal (the drip tubing boundary pressure never exceeded 0.6 kPa). Numerically, it would be straightforward to implement an improved boundary condition where the flux depends on the water pressure inside the tape and the pressure in the soil.

Another consideration when extrapolating our findings to other soils and locations is soil hydraulic parameter estimation. Clearly, the accuracy of a simulation depends on the quality of the hydraulic parameter estimates. Making detailed measurements of soil hydraulic properties is expensive and time consuming, thus diminishing a primary advantage of simulation. The ROSETTA neural network model uses more easily obtained data (bulk density, percentages of sand, silt, and clay, 33 and 1,500 kPa water contents) and it worked very well for our field site, but it may not

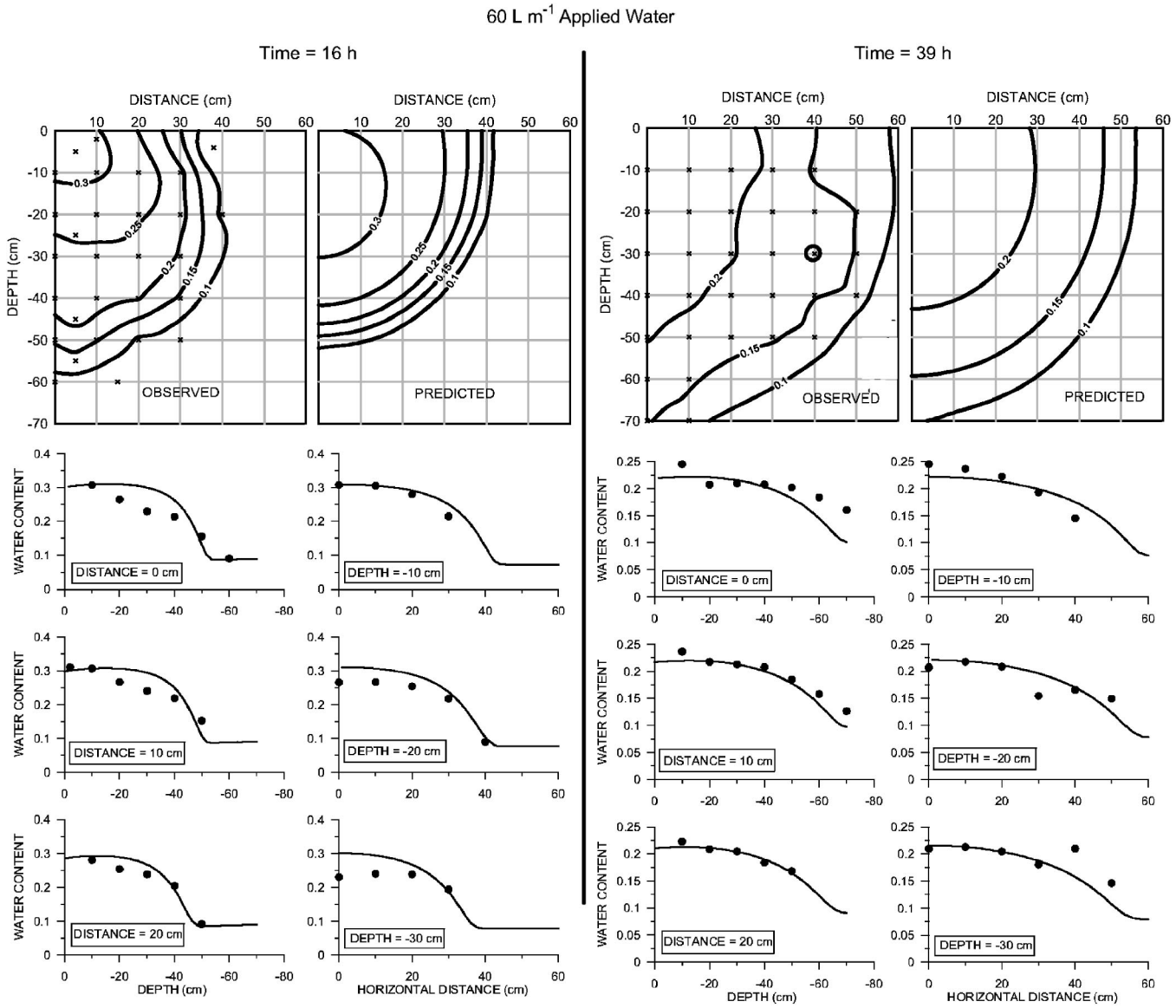


**Fig. 4.** Measured and predicted volumetric water contents for Trial 3. Water application was from $t=0$ to $t=15$ h. (See Fig. 2 for an explanation of symbols.)

work equally well for other sites. One might also wonder about the accuracy of simulations when the data needed to use the full neural network model are unavailable.

With these considerations in mind, we reran the 40 $L \cdot m^{-1}$ simulation assuming we knew only the soil textural class (sandy loam). We considered three pedotransfer function estimates for the hydraulic parameters: the ROSETTA texture class average values, the ROSETTA Lite class average values [these values are the same as the ROSETTA class average values except that $l$ is fixed at Mualem's (1976) recommended value of $l=0.5$], and the Carsel and Parrish (1988) class average values. The ROSETTA Lite and Carsel and Parrish parameter values are included in the HYDRUS-2D software package. As shown in Table 1, the ROSETTA class average parameter values are very similar to the estimates obtained with the full ROSETTA model, except for a higher saturated water content ($\theta_s=0.39$ for the class average versus $\theta_s=0.34$ for the neural network). The Carsel and Parrish estimates differ considerably from the ROSETTA estimates, in-

**Table 1.** Hydraulic Parameters Estimated with Different Pedotransfer Function Models

| Pedotransfer function | $\theta_r$ | $\theta_s$ | $K_s$ ($cm \cdot h^{-1}$) | $n$ | $\alpha$ ($cm^{-1}$) | $l$ |
|---|---|---|---|---|---|---|
| ROSETTA (complete model) | 0.021 | 0.34 | 1.6 | 1.4 | 0.023 | −0.92 |
| ROSETTA SaL[a] class average | 0.039 | 0.39 | 1.6 | 1.4 | 0.027 | −0.86 |
| ROSETTA Lite SaL[a] class average | 0.039 | 0.39 | 1.6 | 1.4 | 0.027 | 0.5 |
| Carsel and Parrish (1988) SaL[a] class average | 0.065 | 0.41 | 4.4 | 1.9 | 0.075 | 0.5 |

[a]SaL=sandy loam.

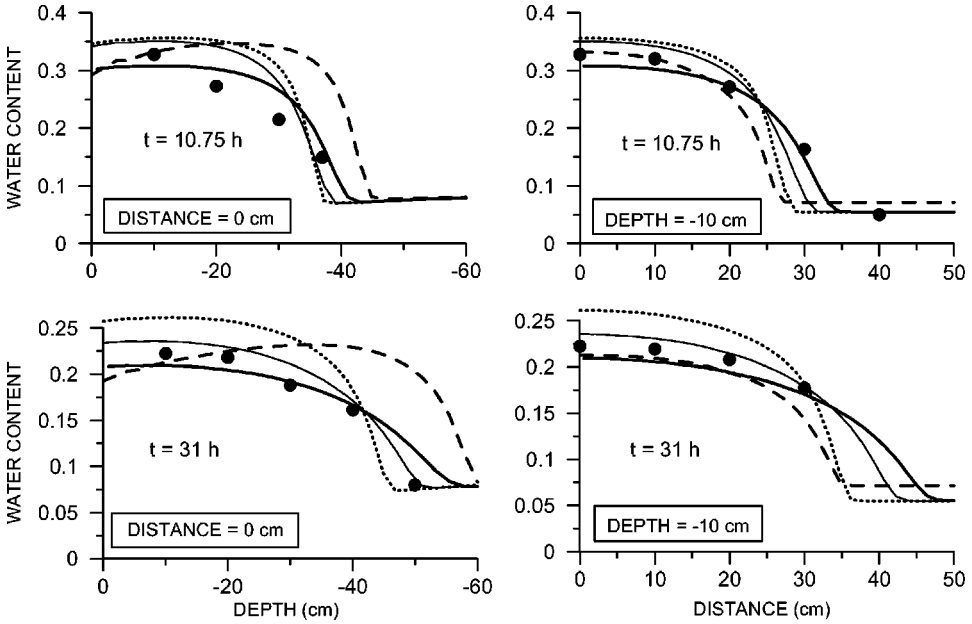


**Fig. 5.** Comparison of data and predictions made using different estimates of the soil hydraulic properties. The water application was 40 $L \cdot m^{-1}$ and the hydraulic properties were estimated with the full ROSETTA model (thick solid line, same as Fig. 3), the ROSETTA Lite texture class average model (dotted line), the ROSETTA texture class average model (thin solid line), and the Carsel-Parrish texture class average model (dashed line). See Table 1 for the hydraulic parameter values and Table 2 for the RMSE values.

cluding a higher saturated hydraulic conductivity ($K_s = 4.6\,cm \cdot h^{-1}$ for Carsel and Parrish versus $K_s = 1.6\,cm \cdot h^{-1}$ for ROSETTA).

Fig. 5 shows the data and model predictions for the $x = 0$ and $z = -10$ cm transects. Table 2 gives the RMSE values for the simulations. Based on the RMSE values and a visual inspection of the simulations, we conclude that the predictions made with the Carsel and Parrish estimates are inferior to those obtained with ROSETTA. The wetted region predicted with Carsel and Parrish is too deep and too narrow. The predictions made using the ROSETTA class average parameters are marginally better than those made using the ROSETTA Lite parameters and are roughly equal in quality to those made using the full ROSETTA model parameters. Because the ROSETTA class average and full ROSETTA model parameters yielded comparable predictions, it appears that little was gained from the additional data required by the full model. This is probably an exception rather than the rule. Our experience with other modeling efforts suggests that it is usually advantageous to collect the additional data needed by the full neural network model. If a more detailed characterization of the hydraulic properties is desired, we recommend focusing on measurements of $K_s$ and $\theta_s$. For most situations, we believe that ROSETTA will give estimates for $\theta_r$, $n$, $\alpha$, and $l$ that are sufficiently accurate for drip irrigation simulation.

## Summary and Conclusions

We evaluated the accuracy of HYDRUS-2D simulations of water infiltration and redistribution under drip irrigation of a sandy loam soil. The soil water content distributions predicted with HYDRUS-2D were found to be in very good agreement with experimental data. The results provide support for using HYDRUS-2D as a tool for investigating and designing drip irrigation management practices. For low permeability soils, it may be necessary to improve upon the drip tubing boundary condition that was used in our calculations. The ROSETTA pedotransfer function software package offers a quick and easy way to estimate the soil hydraulic parameters that are needed for the simulations.

**Table 2.** Root-Mean-Square-Error (RMSE) for HYDRUS-2D Simulations Performed with Hydraulic Parameters Estimated from Different Pedotransfer Function Models

| | RMSE | | | | | |
|---|---|---|---|---|---|---|
| | Applied water and measurement time | | | | | |
| | 20 $L \cdot m^{-1}$ | | 40 $L \cdot m^{-1}$ | | 60 $L \cdot m^{-1}$ | |
| Pedotransfer function | 5.5 h ($m^3\,m^{-3}$) | 28 h ($m^3\,m^{-3}$) | 10.75 h ($m^3\,m^{-3}$) | 31 h ($m^3\,m^{-3}$) | 16 h ($m^3\,m^{-3}$) | 39 h ($m^3\,m^{-3}$) |
| ROSETTA (complete model) | 0.031 | 0.18 | 0.027 | 0.013 | 0.041 | 0.026 |
| ROSETTA SaL[a] class average | — | — | 0.043 | 0.012 | — | — |
| ROSETTA Lite SaL[a] class average | — | — | 0.057 | 0.039 | — | — |
| Carsel and Parrish (1988) SaL[a] class average | — | — | 0.071 | 0.045 | — | — |

[a]SaL = sandy loam.

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