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Modeling multiyear observations of soil moisture recharge in the semiarid American Southwest

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Abstract. The multiyear, root zone soil moisture redistribution characteristics in a semiarid rangeland in southeastern Arizona were evaluated to determine the magnitude and variability of deep-profile, wintertime soil moisture recharge. Intermittent observations from 1990 to 1998 of average volumetric soil moisture under shrub and grass cover showed that significant recharge beyond 0.30 m principally occurs only in the wintertime when the vegetation is senescent and does not use the infiltrating water. Using the physically based, variably saturated flow model HYDRUS, wintertime observations were modeled to determine the recharge of soil moisture at different depth intervals in the vadose zone. Two approaches were carried out to estimate the soil model parameters. The first was to use basic soils data from detailed profile descriptions in conjunction with pedotransfer functions. The second parameter estimation strategy was to use an automatic parameter search algorithm to find the optimal soil parameters that minimize the error between the model-computed volumetric water content and observations. Automatic calibration of the model was performed using the shuffled complex evolution algorithm (SCE-UA), and it proved possible to satisfactorily describe the vadose zone observations using a simplified description of the soil profile with optimal model parameters. Simulations with the optimized model indicate that significant recharge of vadose zone does occur well beyond 0.30 m in winter but that such recharge is highly variable from year to year and appears correlated with El Niño episodes. This water could serve as a source of plant water for deeper-rooted plants that are active during the subsequent spring season, thereby exploiting a niche that the more abundant, shallower-rooted plants that are active during the summer rainy season do not. However, the year-to-year variability of the winter precipitation and consequent deep soil moisture recharge indicates that the deeper-rooted vegetation in this region must retain the ability to obtain moisture from the near surface in order to meet its water demands if necessary.

1. Introduction

In this paper, we document the root zone soil moisture redistribution processes that occurred during an 8 year time period at two rangeland sites in the semiarid southwestern United States. Our approach was to use a variably saturated hydrological flow model to represent intermittent soil moisture profile observations and in this way to determine the wintertime soil moisture recharge rates. To model the observations accurately, it is necessary to derive effective parameters for the model. An additional facet of this work therefore is to demonstrate the feasibility of using an optimization methodology and to compare this parameter estimation approach with a traditional one that uses basic soils data in conjunction with pedotransfer functions. On the basis of our modeling study we examine the hydrologic feasibility of the proposition that wintertime soil moisture recharge in southeastern Arizona can support plants with a water use strategy that favors the use of water from deeper regions of the root zone (e.g., C_3 shrubs) and can rely less on the summer precipitation retained in the upper root zone. Such a strategy would differ from the strategy of warm season vegetation (e.g., C_4 grasses), which heavily competes for near-surface moisture from summer rains. Last, we note that the wintertime root zone recharge may be related to global-scale climate phenomena.

In much of the Southwest the annual precipitation regime is bimodal. The majority of annual precipitation typically occurs during the summer under the influence of the North American monsoon [*Adams and Comrie*, 1997]. During this July to September monsoon season, precipitation is often of high intensity and short duration. Rainfall excess (rainfall minus runoff) is quickly removed from the soil via plant transpiration and bare soil evaporation; thus soil moisture recharge of the deeper root zone (beyond ~0.3 m) is generally considered insignificant. However, the gentler rains associated with longer duration frontal systems during the wintertime recharge soil moisture at greater depth in the root zone [e.g., *Cable*, 1969; *Caldwell*, 1985; *Cable*, 1980; *Kemp*, 1983] when lower atmospheric demand (lower potential evaporation) and cooler temperatures (inactive vegetation) reduce the evapotranspiration loss. In general terms, cool season precipitation is posited to control woody plant growth, whereas summer rains drive the annual grass production [e.g., *Culley*, 1943; *Cable*, 1975; *Kemp*, 1983; *Swetnam and Betancourt*, 1998].

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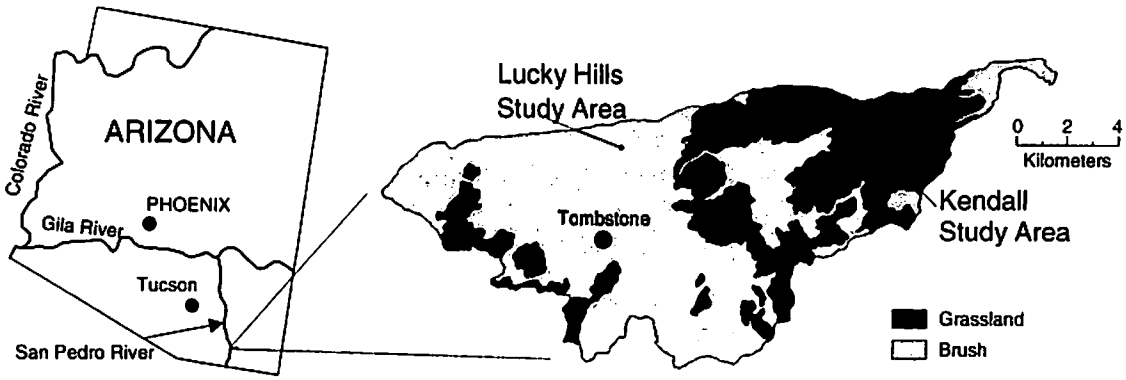

Figure 1. The Walnut Gulch Experimental Watershed of southeastern Arizona and the two study sites where the soil moisture observations were made. The shrub-covered profile was made from three trenches at Lucky Hills in the mixed desert shrub community. The other profile was the grass-covered profiles made at three trenches nearby the Kendall study site, which is in the grassland community.

Soil resource partitioning is often cited as a mechanism for the stable coexistence of grasses and shrubs/trees in savanna and woodlands around the world [*Walter*, 1954, 1979]. According to this "two-layer" model of savanna plant distribution, deeper-rooted woody plants access water from farther down in the root zone, whereas shallow-rooted grasses utilize a separate shallow moisture source. This hypothesis has been used to model functioning of savanna ecosystems [*Walker et al.*, 1981; *Noy-Meir*, 1982; *Walker and Noy-Meir*, 1982; *Eagleson and Segarra*, 1985; *Skarpe*, 1990].

There is observational evidence that the particular rainfall patterns (and its corresponding infiltration and redistribution in the root zone) of the Southwest have led to different plant water acquisition strategies. In a desert scrub community in Utah, *Ehleringer et al.* [1991] found that all species used winter-spring precipitation for spring growth but the utilization of the summer rains was life-form dependent. Annuals and succulent perennials used summer precipitation exclusively. Herbaceous and woody perennials used both the summer rains and any remaining winter-spring recharged soil moisture, with herbaceous species being much more reliant on summer precipitation. A few woody perennial species did not respond to the summer rains. Such opportunistic and varied adaptation to the partitioning of shallow and deep soil moisture sources has also been confirmed by other observational studies in the Southwest [e.g., *Cable*, 1980; *Weltzin and McPherson*, 1997; *Williams and Ehleringer*, 2000]. In addition to a plant's rooting strategy, *Kemp* [1983] stressed the importance of a plant's photosynthetic pathway in determining which water sources are exploited at different times of the year by different species in southern New Mexico. For annual plants, C_3 plants were found to be dominant at the end of the winter-spring, and C_4 annuals prevailed at the end of summer. For perennial species, C_3 forbs and shrubs showed only small seasonal changes, but C_4 perennials showed a marked decrease in density and cover during the winter-spring season and increase during the warm summer season.

In areas where water is a limited resource the depth of root water extraction depends ultimately on the depth of moisture recharge. *Andraski* [1997] found that the maximum depth to which temporal changes in water content were observed over 5 year period was 0.75 m under vegetated soil. *Kemp et al.* [1997] performed a comparative modeling study of soil water dynamics in a desert ecosystem and concluded that over the course of their 1 year study, rainfall recharge penetrated to a depth of 0.45–0.55 m. *Cable* [1980] reported that water infiltrated past the 0.25 m depth eight times and to a depth of at least 1.0 m only three times in a 3 year study in southern Arizona.

The work cited above suggests that root zone soil moisture distribution and water balance are important to ecosystem function. The primary purpose of the present study was to document soil moisture recharge. Section 2 describes the 8 year intermittent observations of the average time domain reflectrometry (TDR)-measured soil moisture profiles at two rangeland sites with different types of vegetation cover. Section 3 describes our methods for estimating how much wintertime precipitation percolates into the soil each year by calibrating a variably saturated flow model, forced by observed precipitation, to match the observations. Section 4 presents the results of the calibration procedure and compares them with model simulations made by using parameters determined on the basis of soil data and pedotransfer functions. Section 5 gives our estimates of the wintertime soil moisture water balance and discusses the implications of this distribution on the plant water acquisition strategies. Section 6 summarizes the results.

2. Site Description and Data Collection

Weather and soil moisture data were collected near the town of Tombstone, Arizona, in the Walnut Gulch Experimental Watershed (see Figure 1). The watershed monitoring is performed by the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) [*Renard et al.*, 1993]. The 148 km^2 watershed is an ephemeral tributary of the San Pedro River and is heavily instrumented with rain gages and runoff-measuring devices. The vegetation is a mixed Sonoran-Chihuahuan desert grass-shrub rangeland typical of southeastern Arizona and southwestern New Mexico. As indicated in Figure 1, brush cover prevails on the lower western half of the watershed with primarily grass cover on the higher-elevation eastern half of basin.

Trenches were excavated in the summer of 1990, prior to the MONSOON'90 field experiment [*Kustas and Goodrich*, 1994], to install TDR probes to measure root zone soil moisture. Each trench was designed to have six TDR probes installed horizontally into a vertical trench face to define a soil moisture profile from the surface to 0.5 m depth. The 0.15 m probes were calibrated in situ at the trench site by relating TDR

Table 1. USDA-NRCS Soil Profile Data for Pedons at the Lucky Hills and Kendall Study Sites

Horizon	Depth, cm	Clay, %	Silt, %	Sand, %	CF,[a] %	Bulk Density, g cm^{-3}	θ at 33 kPa, cm^3 cm^{-3}	θ at 1.5 MPa, cm^3 cm^{-3}
				Lucky Hills				
A	0–2	10.8	20.9	68.3	59	NA	NA	6.6
EB	2–4	12.8	25.2	62	55	1.35	18.4	7.7
BK1	4–24	16.9	25	58.1	58	1.19	22.9	10.1
BK2	24–36	19.6	29.7	50.7	46	1.25	21.3	10
2BtK1	36–46	21.9	36.7	41.4	33	1.23	20.7	12.5
2BtK2	46–109	21.2	27.3	51.5	8	1.66	13.4	9
2BtK3	109–138	59.6	22.8	17.6	16	1.54	31.2	22.2
3BtkM	138–170	23.8	31.1	45.1	70	1.32	23.3	9.9
				Kendall				
A	0–4	15.8	16.9	67.3	64	1.26	23.9	7.5
BT1	4–9	28.7	10	61.3	43	1.41	22.7	13.5
BT2	9–16	44.2	13.2	42.6	44	1.48	28.1	16.3
BT3	16–35	45.9	10.8	43.3	53	1.41	32	17.4
BT4	35–62	28.8	14.5	56.7	32	1.56	26.5	11.9
2CK	62–150	11	21.8	67.2	45	1.38	21.9	6.7

Here θ is the volumetric water content, and NA is not available.
[a]Coarse fraction >2 mm by weight

measurements to the volumetric water content of the same soil determined by combined water content/bulk density sampling [*Amer et al.*, 1994]. At Lucky Hills, three profiles were made directly under shrub cover of *Larrea tridentata* (creosote) and *Acacia constricta* (whitethorn acacia). Each of the three profiles is defined by TDR probes at 0.05, 0.10, 0.15, 0.20, 0.30, and 0.50 m, and measured samples are averaged for these depths. One trench has an additional single probe at 0.12 m. Similarly, at another study location, Kendall, the TDR probes were installed in three trenches under a grass cover (north facing aspect). Sensor installation in these trenches was hindered owing to rocks and a calciferous layer. In each trench, probes were installed at 0.05, 0.10, 0.15, and 0.20 m. Additional probes were installed at 0.25 and 0.50, 0.30 and 0.50 m, and 0.30 and 0.75 m in the three trenches, respectively. The grass at this site was periodically grazed by cattle. Since July 1990, TDR measurements at each of the trenches have been made about every 2 weeks using a Tektronix 1502B cable tester. (Note that the use of this and other commercial names in this paper is not intended as an endorsement of the product.)

Figure 1 shows that Lucky Hills lies in the lower shrub-dominated region, while Kendall lies in the eastern, grass-covered part of the watershed. The vegetation at Lucky Hills consists mainly of the C_3 shrubs and forbs: *Larrea tridentata* (creosote bush), *Flourensia cernua* (tarbush), *Acacia constricta* (whitethorn acacia), and *Zinnia pumila* (desert zinnia). There is little understory vegetation at Lucky Hills. Kendall is covered mainly by perennial C_4 grasses, specifically, *Hilaria belangeri* (curly mesquite), *Bouteloua eriopoda* (black grama), *Bouteloua hirsuta* (hairy grama), and *Aristida hamulosa* (three-awn) [*Weltz et al.*, 1994]. Kendall is also interspersed with the C_3 shrubs: *Calliadra eriophylla* (fairy duster), *Dalea formosa* (feather plume), *Krameria parvifolia* (range ratany), and *Haplopappus tenvisectus* (burroweed). *Prosopis velutina* (mesquite) shrubs are scattered throughout the Walnut Gulch watershed, although they are most dense along drainage channels. The majority of the perennial grass forage production on southern Arizona ranges is produced from summer rainfall [*Culley*, 1943; *Cable*, 1975]. In a nearby southern New Mexico rangeland, C_3 plants were most active in spring or autumn, while the C_4 grasses and forb activity was confined mainly to the summer and autumn [*Kemp*, 1983].

The dominant soil in the Lucky Hills study area is the Lucky Hills–McNeal complex formed from mixed calcareous alluvium. These are mainly very gravelly sandy loams or loamy sand. Soils around Kendall are generally very gravelly sandy loams of the Tombstone, Stronghold-Bernardino, and Elgin-Stronghold complexes [*Breckenfeld et al.*, 2000]. The soil profiles in individual trenches were observed to differ from each other to varying degrees. One soil profile at Kendall and one at Lucky Hills was extensively described in 1990 by the USDA National Resource Conservation Service with a number of soil properties being measured from field samples collected at each soil horizon observed in the profiles. Table 1 presents the depth, percent clay/silt/sand, coarse fragment percent by weight, bulk density (<2 mm), and volumetric water content θ at 33 kPa and 1.5 MPa for the Lucky Hills and Kendall profiles.

Precipitation and weather data (net radiation, ground heat flux, wind speed, wind direction, air temperature, and relative humidity) were collected near the soil moisture observations at both Kendall and Lucky Hills. The 1964–1994 average annual, summer (July–September), and winter (November–February) precipitation for both sites are given in Table 2. Climate variability is high in this region, so Table 2 also gives the standard deviation of these values in parentheses. About 60% of the annual precipitation arrives between the July through September period when the region is normally under the influence of the North American monsoon. About 25% of the annual pre-

Table 2. 1964–1994 Average and Standard Deviation of Annual, Monsoon, and Winter Precipitation for the Lucky Hills and Kendall Study Sites

Site	Annual	July–September	November–February
Lucky Hills (gage 80)	338 (91)	200 (69)	80 (55)
Kendall (gage 68)	351 (77)	200 (58)	86 (58)

Standard deviations are in parentheses. Values are given in millimeters.

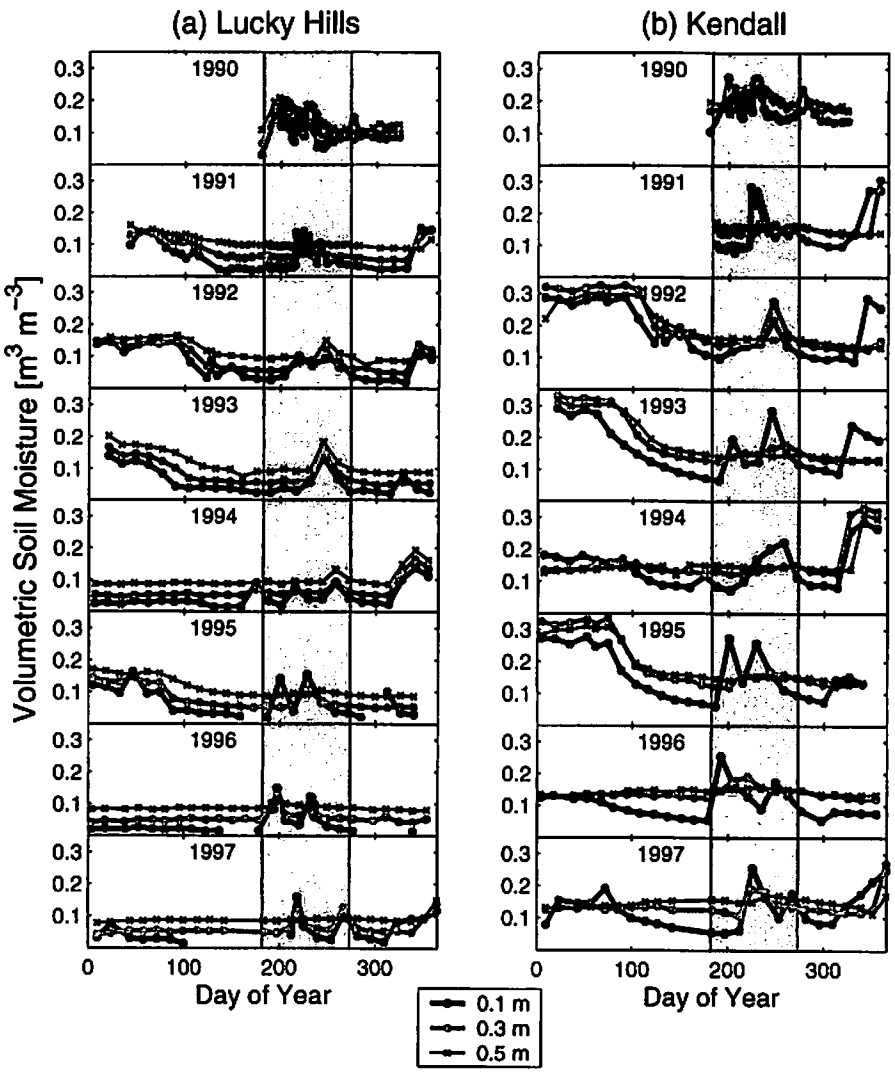

Figure 2. (a) Average time domain reflectometry (TDR) observations of volumetric soil moisture at 0.1, 0.3, and 0.5 m depth for the shrub-covered profile at the Lucky Hills study area for the years 1990–1997. Deeper wetting occurs primarily during the wetter winter years rather than the ranier monsoon season (shaded region). (b) Average TDR observations of volumetric soil moisture at 0.1, 0.3, and 0.5 m depth for the grass-covered profile near the Kendall study area for the years 1990–1997. Results are similar to the observations at Lucky Hills, but the changes in soil moisture are more pronounced.

cipitation comes during the longer duration and less intense winter frontal storms in the period of November through February when most of the vegetation is senescent. The elevation of the Kendall site is 1526 m, while that at Lucky Hills is 1371 m. The coefficient of variation (the ratio of the standard deviation to the mean) indicates that the wintertime experiences more year-to-year variability in precipitation.

Figure 2a shows the average volumetric soil moisture θ for the period of 1990–1997 at 0.10, 0.30, and 0.50 m depth under shrub cover at Lucky Hills. During the summer monsoon (day of year 182–273), soil wetting occurs with lower frequency at 0.5 m depth, and there is often little response even at 0.3 m depth. However, during the winter, wetting does occur to a depth of at least 0.5 m, although the year-to-year variability of this deeper wetting process is high. During the dry winters of 1993/1994, 1995/1996, and 1996/1997, very little vadose zone recharge occurred. During the remaining winters, there is evidence of significant recharge, especially during the winters of 1991/1992, 1992/1993, and 1994/1995.

Figure 2b shows the average volumetric soil moisture for the same period and depths under the grass at Kendall. A similar behavior is exhibited at this site. Again, wetting infrequently occurs at 0.5 m depth during the monsoon, and there is often little response at 0.3 m. Here monsoon percolation is even shallower than at Lucky Hills, presumably because there are more grass roots to take up the available moisture. Contrast this behavior with the wintertime, when the percolation appears more significant. Figures 2a and 2b both suggest that there may be significant water to the depth of at least 0.5 m in the soil profile available during the spring growing season for deeper-rooted plants.

Redmond and Koch [1991] have shown that there is a strong correlation between the tropical ocean/atmosphere phenomena El Niño/La Niña and southern Arizona winter precipitation. On the basis of a reanalysis at the National Centers for Environmental Prediction/Climate Prediction Center and at the United Kingdom Meteorological Office (available on the World Wide Web at http://www.nnic.noaa.gov/products/

analysis_monitoring/ensostuff/ensoyears.html) the winters of 1990/1991, 1991/1992, 1992/1993, 1993/1994, 1994/1995, and 1997/1998 were preceded by anomalous warming in the eastern tropical Pacific (El Niño). The winters of 1995/1996 and 1996/1997 were normal. With exception of the 1993/1994 winter, the deeper root zone recharge appears highly correlated with these global phenomena. *Trenberth and Hoar* [1996] indicated that the number of El Niño events since 1976, culminating in the 1990–1995 El Niño, is unusual and should occur only once every thousand years.

To provide quantitative estimates of how much recharge occurred at these two sites from the intermittent soil moisture observations, we used these observations to calibrate a physically based soil hydraulic model. In section 3 we discuss the model and the calibration procedure used.

3. Overview of Model and Calibration Procedure

3.1. HYDRUS Soil Model

We used the one-dimensional, variably saturated flow model HYDRUS (version 6.0 [*Šimunek et al.*, 1997]) to model the observations presented in section 2. HYDRUS solves for one-dimensional water movement in a partially saturated rigid medium using Richards' equation. Assumptions include that the air phase plays an insignificant role in the liquid flow process and that water flow due to thermal gradients can be neglected. The model is also capable of simulating heat and solute transport, although this capability was not used in this study. The governing equation in the model is

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

where h is the pressure head $[L]$, θ is the volumetric water content $[L^3L^{-3}]$, t is time $[T]$, z is the spatial coordinate positive upward $[L]$, and S is the sink term $[L^3L^{-3}T^{-1}]$. The unsaturated hydraulic conductivity function K $[LT^{-1}]$ is a known function of the pressure head h, the van Genuchten soil water retention parameters [*van Genuchten*, 1980], and the saturated hydraulic conductivity K_s $[LT^{-1}]$. The conductivity function is derived from the pore-size distribution model of *Mualem* [1976]. The model runs on a variable time step and solves the equation numerically for defined initial and boundary conditions.

In this paper, the goal is to represent the winter recharge process by modeling observations made each year between November and February. During this period we need not estimate the parameters that control the strength and the location of the plant transpiration sink S. Skirting that difficult task, we optimize only the parameters in the model that describe the soil hydraulic properties. This simplification is allowed because the vegetation is normally senescent during these winter months in southern Arizona at the elevations of the study sites. Thus the only parameters to be specified are the saturated hydraulic conductivity K_s and the van Genuchten soil model parameters [*van Genuchten*, 1980], θ_r, θ_s, α^i, n^i, and K_s^i, where the index i runs from 1 to the number of different soils chosen for the simulation N_{soils}. In our calibration runs we deliberately sought to represent the profiles with as few soil layers as possible, providing that most of the observed behavior was represented. Given the soil data presented in Table 1, this representation is clearly a simplification of the complex, heterogeneous soils at the study sites. Nevertheless, as discussed in section 3.2, this simplification was necessary and did result in a good calibration.

In the model, we simulated a 2.0 m vertical profile discretized into 101 nodes with a node spacing of 0.02 m. Each simulation included eight 120 day periods (i.e., the months November through February for each winter). At the beginning of each new winter period, the initial soil moisture (or, alternatively, matric potential) conditions were initialized from the first measurements in the month of November. The surface node was initialized to the nearest measurement (at 0.05 m); the bottom node was initialized to the lowest observation (either at 0.50 or 0.74 m depending on the profile being simulated). Initialization of the intermediate nodes was to the initial moisture conditions provided by linear interpolation between the observations.

In order to solve (1), boundary conditions must be defined. At the bottom boundary a unit hydraulic gradient was imposed to simulate a freely draining profile. At the top boundary a specified flux boundary condition was used. We forced the model with daily total precipitation and daily average Penman potential evaporation E_p $[LT^{-1}]$, as calculated from the local measurements of net radiation, ground heat flux, vapor pressure deficit, and wind speed following *Shuttleworth* [1993]. With these boundary conditions at the surface the actual surface flux is not defined a priori; rather, it depends on the transient soil conditions at the surface. HYDRUS computes the surface flux by limiting its value by the following conditions [*Šimunek et al.*, 1997]:

$$\left| -K\frac{\partial h}{\partial z} - K \right| \le E_p \qquad z = 0 \qquad (2)$$

$$h_A \le h \le h_s \qquad z = 0, \qquad (3)$$

where h_A and h_s are the minimum and maximum pressure head at the soil surface allowed under the prevailing soil conditions $[L]$. The value for h_A is determined assuming equilibrium between soil water and atmospheric water vapor [*Feddes et al.*, 1974]. Thus, under drying conditions, HYDRUS defines the outgoing evaporative flux either to be the maximum rate at which water can be brought to the surface against gravity by capillary forces or potential evaporation, whichever is least. In practice, we found that the simulated evaporation was insensitive to the value of h_A, and in our simulations we used $h_A = -1000$ m (varying this value by 2 orders of magnitude gave little change in the computed evaporation). Here h_S represents a small layer of ponded water on the surface. In the model a small layer of water is allowed to build up over the surface during heavy rain, and no water is allowed to runoff. In practice, this assumption is reasonable in the context of this wintertime study at these study sites because neither overland flow nor stream channel runoff occur during the moderate winter rains at these sites. Additionally, the water table is very deep, and the sites are only slightly sloped. Lateral surface and subsurface flow can therefore safely be assumed to be negligible, and the use of a one-dimensional model is entirely appropriate.

HYDRUS only accounts for isothermal water flow. Hence our simulations do not account for possible vapor flow. It has been argued that vapor flow may be significant, especially under the dry soil conditions that are often found in semiarid areas [*Noy-Meir*, 1973]. However, according to *Scanlon and Milly* [1994], the upward flux of water is vapor dominated only in the top several millimeters of the soil during periods of

evaporation in a numerical simulation of a Chihuahuan desert site that included liquid and vapor fluxes. Their results showed that water fluxes in the upper 0.3 m of the soil were dominated by both upward and downward liquid fluxes. Below this upper layer, vapor fluxes forced downward by thermal gradients again dominated, but the amount of water that moved in this way was extremely small relative to fluxes in the upper 0.3 m. *Saravanapavan and Salvucci* [2000] found that cumulative evaporation is mainly limited by the liquid water flux from the deeper, wetter soils below the drying front for all cases except those in which the soil is so dry that total evaporation is essentially negligible. This result is a plausible explanation for why other modeling studies which did account for vapor movement have shown little improvement in their prediction of soil water redistribution in dry soils [*Hanks et al.*, 1967; *Jackson et al.*, 1974]. As will be shown in this paper, HYDRUS with calibrated model parameters can capably model the observations (as quantified by low root-mean-square errors). While this does not in itself justify neglecting vapor flow, it does imply that an isothermal model can be configured (by calibration) to compensate for any vapor flow that might be occurring in this case. However, the model did seem less capable of representing soil drying in the drier winters. Perhaps this weaker performance might be linked to neglecting vapor flow: We discuss this point in further detail below.

3.2. Parameter Specification

3.2.1. Pedotransfer functions. Specifying parameters in physically based soil water models often involves an attempt to make detailed measurements using laboratory and/or field techniques. Laboratory measurements might include estimating soil model parameters by fitting the model to a laboratory-measured soil water characteristic curve [*van Genuchten et al.*, 1991] and using the constant head method for estimating saturated hydraulic conductivity [*Klute and Dirksen*, 1986]. Field parameter estimation techniques include disk permeameter measurements of zero- or moderate-tension hydraulic conductivity and simultaneous [*Green et al.*, 1986] in situ measurements of water content and matric head to develop a soil water characteristic curve which is later fit with the parameters of a soil water model [e.g., *Kemp et al.*, 1997]. Using either laboratory or field approaches, measurements are needed for each distinct layer of soil in the profile if the soil profile is heterogeneous (often the case at natural sites). If such measurements are available, the estimated parameters are used in the model, simulations are performed, and results are compared against observations. Seldom is rigorous model calibration made to improve the simulated results.

Another approach for estimating model parameters is to use more readily obtainable soil information (such as soil texture, percent sand/silt/clay, bulk density, organic matter, and points on the soil characteristic curve, etc.) and to relate these via a regression model to the parameters used in the model (in our case, the van Genuchten parameters). Such descriptive data may be available from sources like the USDA National Resource Conservation Service's National Soil Characterization Database (available on the World Wide Web at http://www.statlab.iastate.edu/soils/ssl/natch_data.html). Regression models that relate this more common soil information to soil hydraulic parameters are generally referred to as pedotransfer functions, and we adopt this nomenclature here. They can be as simple as linear regression models or as complex as neural networks [e.g., *Rawls and Brakensiek*, 1985; *Schaap et al.*, 1998].

Prior to calibrating the model using parameter optimization techniques (discussed below), we assessed HYDRUS's ability to simulate the observed profiles using parameters developed from measurements. Although soils data from each individual TDR profile were not available, we did have USDA-NRCS data from two described trenches located near the Kendall and Lucky Hills study sites. We used these data (given in Table 1) in the hierarchical neural network of *Schaap et al.* [1998] to obtain relevant model parameters for each of the soil layers. (We used a prerelease version of M. Schaap's ROSETTA model.) Since there was a large fraction of coarse fragments in the profile, a measurement that is not accounted for in this neural network model, we adjusted the resultant residual water content θ_r and saturated water content θ_s using the relation given by *Bouwer and Rice* [1984]:

$$\theta_{r,s} = \theta^*_{r,s}(1 - V_f), \tag{4}$$

where the asterisk indicates water content obtained from the neural network. V_f is the volume fraction of coarse fragments >2 mm, calculated by

$$V_f = W_f\left(\frac{\rho_b}{\rho_{2\mathrm{mm}}}\right), \tag{5}$$

where W_f is the weight fraction of coarse fractions, ρ_b is the bulk density of the field soil including particles >2 mm, and $\rho_{2\mathrm{mm}}$ is the mass of particles >2 mm divided by the volume of particles >2 mm. We assumed that $\rho_{2\mathrm{mm}} = 2.65$ g cm^3. Additionally, the saturated hydraulic conductivity of the gravelly field soil K_s was computed from the estimated conductivity of the soil alone K^*_s following *Brakensiek et al.* [1986] from

$$K_s = K^*_s(1 - W_f). \tag{6}$$

The parameters calculated from the pedotransfer functions of *Schaap et al.* [1998] using the input data given in Table 1 and (4)–(6) are given in Table 3. The simulated profiles given with these parameters are compared with those using calibrated parameters in section 4.

3.2.2. Calibrated parameters. Model calibration using parameter estimation techniques can be used to define model/soil parameters as an alternative to estimating them from field or laboratory techniques. (A review is given by *Kool et al.* [1987].) This approach typically involves the coupling of a variably saturated flow model with a parameter optimization algorithm. Parameter estimation techniques were first used in conjunction with laboratory experiments where the homogeneity of the soil and the initial and boundary conditions are controlled [e.g., *Kool et al.*, 1985; *van Dam et al.*, 1992, 1994; *Eching and Hopmans*, 1993; *Ciollaro and Romano*, 1995; *Santini et al.*, 1995; *Šimunek et al.*, 1998]. Soil heterogeneity and uncertain initial and boundary conditions complicate the application of parameter estimation techniques to field conditions. Examples of field applications include the instantaneous profile method [*Dane and Hruska*, 1983], water flow into a tensiometer [*Timlin and Pachepsky*, 1998], disk infiltrometers [*Šimunek and van Genuchten*, 1996, 1997], the extraction method [*Inoue et al.*, 1998], and cone penetrometers [*Gribb*, 1996; *Šimunek et al.*, 1999].

Previous studies that have modeled field observations of soil moisture have shown the utility of the calibration process [e.g., *Camillo et al.*, 1986; *Burke et al.*, 1997; *Stähli et al.*, 1999], but they also illustrate a need for a robust methodology when multiple parameters are involved. The literature on calibrating

Table 3. Soil Model Parameters Derived From Soil Data in Table 1 and the Neural Network Model of *Schaap et al.* [1998]

Layer	Depth, cm	α, cm^{-1}	n	K_s, cm d^{-1}	θ_r, cm^3 cm^{-3}	θ_s, cm^3 cm^{-3}
			Lucky Hills			
A	0–2	0.033	1.41	17.0	0.024	0.215
EB	2–4	0.022	1.46	25.3	0.031	0.263
BK1	4–24	0.017	1.46	31.2	0.038	0.292
BK2	24–36	0.013	1.48	21.1	0.046	0.324
2BtK1	36–46	0.009	1.53	18.9	0.057	0.371
2BtK2	46–109	0.022	1.31	6.7	0.051	0.336
2BtK3	109–138	0.018	1.23	5.1	0.086	0.396
3BtkM	138–170	0.012	1.48	6.0	0.033	0.206
			Kendall			
A	0–4	0.024	1.45	31.1	0.031	0.248
BT1	4–9	0.022	1.36	18.7	0.054	0.313
BT2	9–16	0.022	1.25	7.2	0.061	0.302
BT3	16–35	0.023	1.26	8.5	0.058	0.286
BT4	35–62	0.023	1.29	8.7	0.054	0.310
2CK	62–150	0.028	1.47	36.9	0.032	0.289

Adjustments to K_s, θ_r, and θ_s were made according to (4)–(6). Here α and n are empirical parameters, K_s is saturated hydraulic conductivity, θ_r is residual water content, and θ_s is saturated water content.

other types of hydrologic models is extensive (see *Gupta et al.* [1998] for review), and research has led to the development of sophisticated population-evolution–based search strategies. The shuffled complex evolution method (SCE-UA [*Duan et al.*, 1992]) has proven consistent, effective, and efficient in locating globally optimal values for model parameters in hydrologic models [e.g., *Thyer et al.*, 1999]. The ability to determine a global minimum is directly related to the number and quality of the calibration data points [*Sorooshian and Gupta*, 1983]. Also, in the case of the present study, increasing the number of soil types N_{soils} in the model results in more model parameters to calibrate. As the number of parameters increase, finding a unique parameter set that defines a true, global minimum can be difficult, if not impossible. Thus our approach sought to limit the number of soil layers in the profile. In reality, Table 1 infers that the soil profiles are more complex than a system composed of only two or three layers. Consequently, the resulting calibrated parameters for the soils in the modeled profile are best interpreted as being effective values of the heterogeneous field parameters that optimally reflect the soil texture and structure properties (e.g., preferential flow paths) which actually control the soil moisture redistribution process.

We calibrated the parameters for HYDRUS using a single objective function. Specifically, the results of each eight-winter simulation were evaluated by comparing the daily average, model-computed volumetric moisture θ_{model} with the TDR-measured soil moisture θ_{TDR} for each level and on each day for which observations were available. We defined a single objective function, namely, the total root-mean-square errors function for all layers, RMS. It is given by

$$\mathrm{RMS} = \left[\frac{1}{N_{day} N_{lev}} \sum_{i=1}^{N_{day}} \sum_{j=1}^{N_{lev}} (\theta^j_{i,\mathrm{Model}} - \theta^j_{i,\mathrm{TDR}})^2 \right]^{0.5}, \quad (7)$$

where N_{day} is the number of days for which observations exist and N_{lev} is the number of levels where TDR measurements were made. (At Lucky Hills, N_{day} = 65. At Kendall, N_{day} = 62.) Consequently, the optimization problem is to find the set of model parameters for the selected number of soil layers N_{soils} which minimize the objective function defined in (7).

In practice, we determined the number of soil layers in the model by first modeling the system with a single soil layer. After this calibration, we reviewed the model performance at each observation level along with the profile data in Table 1 and included one then, eventually, two more additional layers in the model to account for significant discrepancies between the observations and the model at certain depths in the profile. Additional layers were included in a manner consistent with the described soil horizons in Table 3. The resultant optimized soil profile at Lucky Hills consisted of the major soil horizons (A-EB, BK, and 2BtK) at 0–0.04, 0.04–0.36, and 0.36–2.0 m, as indicated in Table 3. For Kendall the three soil horizons (consistent with the A, BT, and 2CK horizons) were prescribed at 0–0.04, 0.04–0.62, and 0.62–2.0 m. For the calibrations using just one or two soil layers we prescribed θ_r to be 0.01 less than observed minimum volumetric soil moisture to reduce the number of optimized parameters. For our final three layer calibrations we prescribed both θ_r and θ_s using the information in Table 3 and thereby limited the parameter set to nine (α, n, and K_s for each soil). The parameter values were limited to the range for the parameters presented by *Carsel and Parrish* [1988], who presented the calculated values of the van Genuchten parameters and saturated conductivity for a wide range of soils. These limits were $0.5 < K_s < 700$ cm d^{-1}, $.005 < \alpha < .15$ cm^{-1}, and $1.1 < n < 2.7$. In section 4 we discuss the site-specific results.

4. Modeling Results

4.1. Field/Laboratory Parameters

We first developed two baseline runs (one at Lucky Hills and another for Kendall) by running HYDRUS with the soil layering and parameters given in Table 3. These runs were used to evaluate the approach of using available soil data along with pedotransfer functions when simulating observed profiles. Poor simulation of observations could imply either that the observations were in error, that the profiles where the TDR measurements were made were different to the nearby profiles described by the NRCS, and/or that the pedotransfer functions of *Schaap et al.* [1998] used in companion with (4)–(6) are invalid.

Table 4. Lucky Hills Shrub Profile Simulation Performance

Source of Parameters in Simulation	Depth of Observation, m							Total RMS
	0.05	0.10	0.12	0.15	0.20	0.30	0.50	
Table 3	0.046 (0.54)	0.030 (0.59)	0.030 (0.65)	0.033 (0.68)	0.041 (0.65)	0.025 (0.73)	0.015 (0.90)	0.0329
Calibration	0.030 (0.71)	0.026 (0.77)	0.016 (0.85)	0.022 (0.83)	0.031 (0.80)	0.021 (0.81)	0.013 (0.89)	0.0237

Root-mean-square error (RMS) and the coefficient of determination R^2 (in parentheses) are given for each observation level in the profile.

As described in section 2, HYDRUS was run over eight November through February winter periods between 1990 and 1997 with the initiation to the first November observation each year. In fact, some of the residual water contents θ_r given in Table 3 are greater than the minimum observed at certain levels. In these cases θ_r was set equal to 0.01 m^3 m^{-3} less than the minimum observation. The results of the Lucky Hills simulation using the prescribed parameters are summarized in Table 4 in terms of the root-mean-square (RMS) error and the coefficient of determination R^2 of the model output relative to observations for each observation level and the value of the objective function, or total root-mean-square error for all levels. In general, the model was able to simulate the profile fairly well; RMS errors for each level ranged from 0.015 to 0.046 m^3 m^{-3}, and the coefficient of determination ranged from 0.54 to 0.90. Overall, the RMS error for this run was 0.0329 m^3 m^{-3}. Although not shown, we mention that the model seems to be less able to simulate the drier winters of 1993/1994 and 1995/1996 than in the other years, especially in the middle levels.

Table 5 summarizes the results of the simulation of the soil profile under grass at Kendall using the parameters given in Table 3. It is apparent that at this site the prescribed parameter approach gives a poorer model performance relative to the Lucky Hills simulation. The higher RMS errors and lower R^2 values in Table 5 confirm this. The total RMS objective function value of 0.0433 m^3 m^{-3} is indicative of the poor result. Remarkably, the best agreement between the model and the observations for both simulations is at the deepest observation level, but this is likely a chance result. Above 0.75 m, the model results clearly differ from observations.

In summary, the results for this preliminary study suggest that the traditional approach to prescribing model parameters on the basis of pedotransfer functions worked reasonably well for the Lucky Hills site but performed worse for the Kendall site. Assuming that the errors in the observations were not systematic (arguably, the errors in the TDR observations for one average profile might be assumed equal to the errors for another profile) and that the pedotransfer approach is not biased toward particular types of soils (there is no bias reported by *Schaap et al.* [1998]), it seems plausible that profile heterogeneity (the differences in one profile to the next) was greater at Kendall than at Lucky Hills. In other words, the pit description at Kendall is not as representative of all the profiles at the site as that at Lucky Hills.

4.2. Calibration Results

We explored whether the performance of HYDRUS can be improved by model calibration using SCE-UA of *Duan et al.* [1992]. Prior to using SCE-UA, we attempted to use the simplex algorithm of *Nelder and Mead* [1965]. However, despite many random, restarts of the model, the simplex algorithm always resulted in a finding a higher (local) minimum on the error function response surface than the minimum found by SCE-UA. As the number of calibration parameters in the model increases, the harder it is to find a true, global minimum. As described earlier, we sought to reduce the total parameter space by limiting the number of different soil types to two or three and by prescribing the residual water content θ_r and the saturated water content θ_s to the average value for the given horizon listed in Table 3. If the minimum (maximum) water content was observed to be less (greater) than this average value, then it was prescribed to be 0.01 m^3 m^{-3} less (greater) than the minimum (maximum) observation; thus the parameter set was reduced by 2 per soil type. Prescribing θ_r was also suggested by *Zurmühl and Durner* [1998] and *Šimunek et al.* [1998], who found their optimizations least sensitive to this parameter. With three soil layers, there are nine unknowns, and the SCE-UA algorithm made ~6000 objective function evaluations prior to finding a minimum with a 1% stopping criteria. Each objective function evaluation which was 960 simulated days long took ~ 100*K* to 200*K* iterations of the variable time step model and around 1.2 min (real time) on a SUN UltraSPARC server running at a 336 MHz clock rate. This resulted in a total of ~5 days (real time) for the algorithm to finish. The determination of unique parameters for a layered profile also can be made difficult owing to parameter interaction/correlation. We performed some preliminary numerical experiments to determine how identifiable the parameters from a single-layered, double-layered, and triple-layered system using a 14 day sampling of water content at seven vertical nodes are. For all three systems the optimization routine was able to determine the true parameters to within a very small limit.

Figure 3 presents the results after calibration for soil profile under shrub at Lucky Hills. The RMS and the coefficient of determination R^2 for each level and the value of the objective function are given in Table 4. The calibration gives an improved model performance relative to the simulation using the

Table 5. Kendall Grass Profile Simulation Performance

Source of Parameters in Simulation	Depth of Observation, m								Total RMS
	0.05	0.10	0.15	0.20	0.25	0.30	0.50	0.75	
Table 3	0.038 (0.52)	0.040 (0.74)	0.051 (0.81)	0.050 (0.87)	0.039 (0.84)	0.048 (0.87)	0.050 (0.70)	0.022 (0.68)	0.0433
Calibration	0.020 (0.81)	0.034 (0.90)	0.020 (0.95)	0.021 (0.96)	0.020 (0.94)	0.020 (0.98)	0.029 (0.85)	0.023 (0.65)	0.0239

Root-mean-square error (RMS) and the coefficient of determination R^2 (in parentheses) are given for each observation level in the profile.

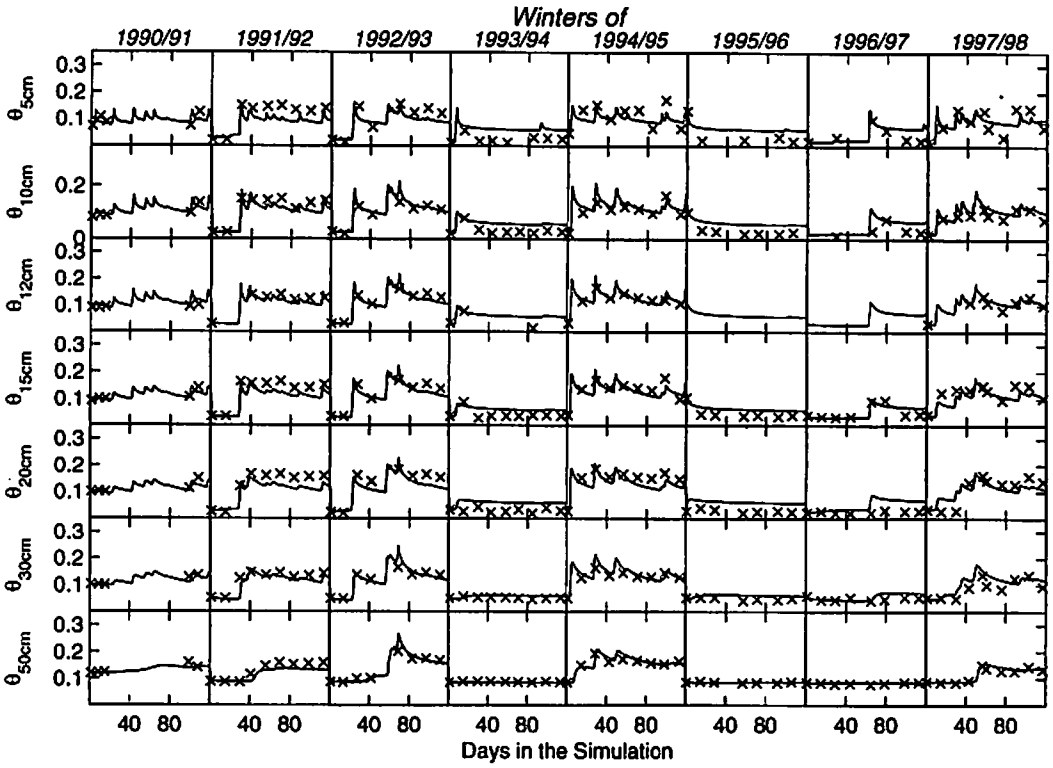

Figure 3. Lucky Hills simulated (solid line) versus observed (crosses) volumetric soil moisture θ at different depths for the winter months of November through February for the eight winter periods of 1990–1997. This simulation used the parameters derived from calibration that minimized the squared differences between the simulated and observed values. Root-mean-square (RMS) errors and the coefficient of determination for each level are given in Table 4.

pedotransfer function-derived parameters (both simulations' performances are presented in Table 4). Calibration improved the total RMS error from 0.033 to 0.024 $m^3\ m^{-3}$. Soil in the upper model layers do not track well the observed dry down during the dry winters of 1993/1994 and 1995/1996. This inability of HYDRUS to dry out the surface soil with already low moisture contents resulted from the model's top soil node quickly reaching its minimum pressure head (as defined by h_A given in (3)) within a few days after wetting. Bare soil evaporation is not allowed at this limit. Simply decreasing the already very low value of the minimum pressure head did not increase the bare soil evaporation because the conductivity is too small to conduct significant upward water flow at these very high capillary pressures. The inclusion of vapor flow might improve the model performance for these occasions. *Saravanapavan and Salvucci* [2000] reported that water stored in very dry profiles can only escape efficiently through vapor flow, although the magnitude of this drying via vapor transport is very small. An alternative explanation is that a small amount of root water uptake (also neglected in these simulations) contributed to the drying out of the soil profile during these warmer winter periods. The values of the final calibrated soil parameters at this site are listed in Table 6.

Figure 4 gives the calibration results for the grazed grass site at Kendall. Calibration resulted in substantially better model performance, although the profile is too dry at lower levels in 1991/1992 and 1997/1998. At Kendall, three layers were needed, corresponding to a less permeable soil horizon between more permeable layers above and below. The RMS and R^2 values for each level along with the total objective function value are given in Table 5. RMS errors ranged from 0.020 to 0.034 $m^3\ m^{-3}$ at each level, and the total RMS error was

Table 6. Calibrated Soil Model Parameters Using SCE-UA Algorithm for the Lucky Hills and Kendall Profiles

Depth, cm	α, cm^{-1}	n	K_s, cm d^{-1}	θ_r, $cm^3\ cm^{-3}$	θ_s, $cm^3\ cm^{-3}$
			Lucky Hills		
0–4	0.148	1.31	3.2	0.002	0.23
4–36	0.066	1.50	143.7	0.004	0.30
36–200	0.141	1.45	95.1	0.04	0.36
			Kendall		
0–4	0.147	1.12	22.1	0.03	0.25
4–62	0.013	1.12	12.9	0.06	0.34
62–200	0.073	1.25	140.3	0.03	0.28

Here θ_r and θ_s were fixed, and α, n, K_b were found by optimization.

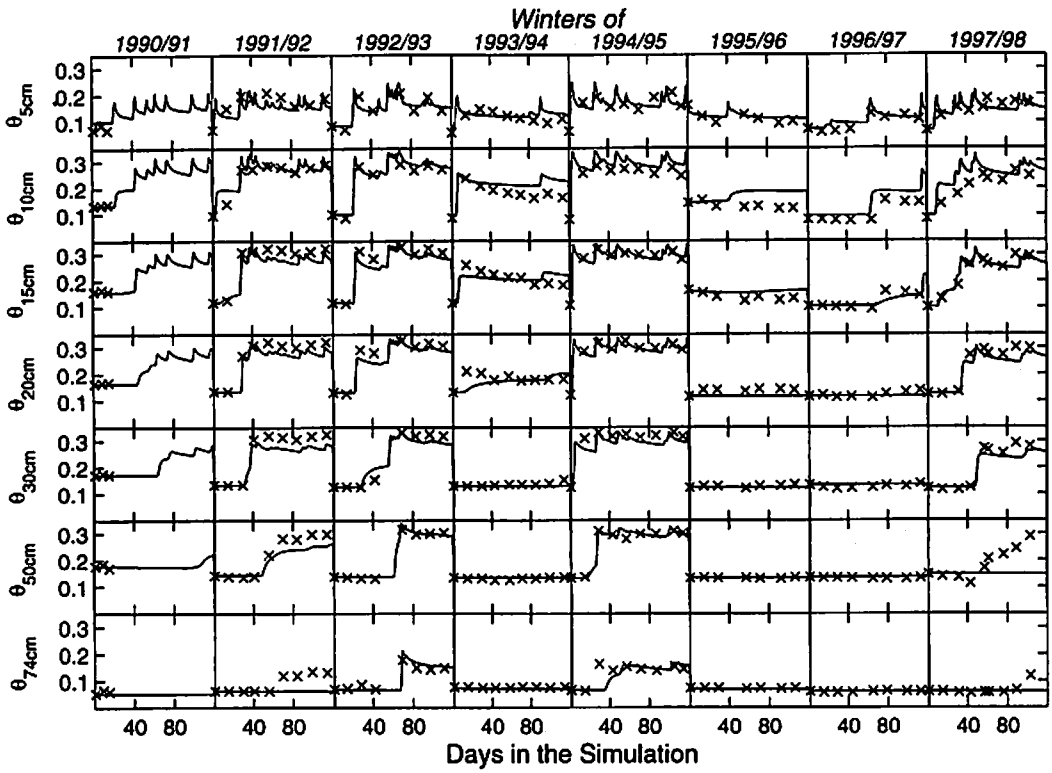

Figure 4. Kendall simulated (solid line) versus observed (crossed) volumetric soil moisture θ at different depths for the winter months of November through February for the eight winter periods of 1990–1997. This simulation used the parameters derived from calibration that minimized the squared differences between the simulated and observed values. RMS errors and the coefficient of determination for each level are given in Table 5.

substantially improved (relative to the prescribed parameter approach) from 0.0433 to 0.0239 $m^3\ m^{-3}$. This overall goodness of fit is comparable to that found at Lucky Hills.

A visual comparison of the calibrated parameter and pedotransfer approach is given in Figure 5 to complement the numerical comparison given in Tables 4 and 5. Figure 5 compares the model output of volumetric soil moisture from the two approaches versus observations for three consecutive winters at the Kendall site. For the wetter winters of 1992/1993 and 1994/1995 the improvement due to using the automatic calibration approach is dramatic. Not surprisingly, the differences are less obvious in the dry winter of 1993/1994, when there is not enough precipitation input to sufficiently activate the states in the model that are sensitive to the chosen model parameters.

The calibrated parameter values are presented in Table 6. They differ considerably from the pedotransfer-derived values (Table 3). At Lucky Hills the upper layer K_s is unexpectedly low, even though the large α and the soil textural data indicate a sandy soil. Perhaps, this low value for K_s in the model is to compensate for weakness in the measurement of precipitation, which was taken from the nearby gage. In reality, some portion of the precipitation may be intercepted by the shrub and shrub litter above the profile, and this was not represented in the model. Below this upper layer the calibrated parameters K_s and α values follow a trend similar to the parameters in Table 3 (K_s and α decrease with depth and moving into the finer textured soil). For Kendall the pit description (Table 1) indicates finer-textured (less permeable) layers bounded by coarser-textured soils above and below. The calibrated hydraulic conductivities (Table 6) seem consistent with this description. The saturated hydraulic conductivity at the lowest layer seems dramatically higher than those at the layers above it. This is probably a compensation for the lowest layer being too dry. Not enough water is getting past the second layer to account for the observed increase in water content at the lowest level. Thus the model tries to compensate by making the lowest level very permeable. The calibrated values of α seem to follow the same trend as those in Table 3, but the range of values is much larger. For both Kendall and Lucky Hills, the shape parameter n does not appear to follow any trend. The calibrated α values for the uppermost layer at both sites were only just within the range of acceptable values in the optimization ($0.005 < \alpha < 0.15\ cm^{-1}$ from *Carsel and Parrish* [1988]). An increase in this upper boundary did result in calibrated values that were higher than $0.15\ cm^{-1}$.

In the optimization simulations, there are a number of parameter sets which would result in objective function values very close to the minimum calculated using the parameters in Table 6. The progression of the SCE-UA algorithm's search indicates that the shape parameter n was the most quickly determined parameter in the search, which is an indication that the model was more sensitive to it. However, the algorithm took much longer to identify an optimal value of α and an even greater time to optimize K_s. Although further research into parameter identification and the limitations of this approach is warranted, these results are consistent with our preliminary numerical experiments. *Šimunek et al.* [1998] also found their optimizations were most sensitive to n and θ_s and much less sensitive to α and especially to K_s. They obtained relatively large differences in calibration-derived K_s versus that obtained from the laboratory estimation technique (Wind's method).

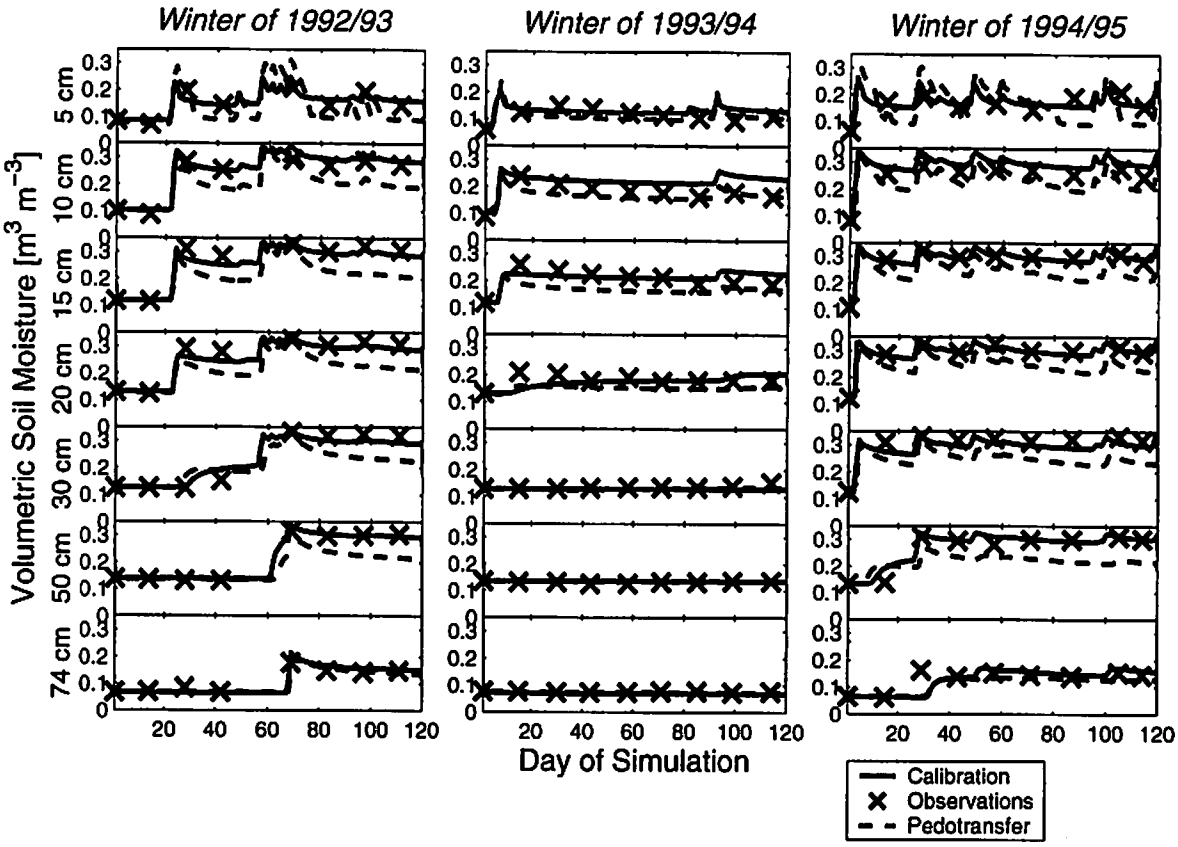

Figure 5. The 1992/1993, 1993/1994, and 1994/1995 wintertime volumetric water content for the simulation using parameters determined by calibration (solid line) and the simulation using parameters determined by pedotransfer functions (dashed line) at the Kendall site. Each TDR observation is indicated by a cross. The multiparameter calibration improved the total root-mean-square error between the simulated and observed water content from a value of 0.043 to 0.024 $m^3\ m^{-3}$ (see Table 5).

Zurmühl and Durner [1998] also indicated that the determination of K_s was subject to great uncertainty owing to its lower sensitivity. In contrast, *Gribb* [1996], in determining hydraulic properties from cone penetrometer data, showed that inverse solution was most sensitive to K_s and α and least sensitive to θ_s and n. The sensitivities (summarized above) largely depend on the type of simulation, the data, and the chosen objective function; thus different soil model applications likely give different parameter sensitivities.

The value of the soil model calibration was also evident when HYDRUS was calibrated over a reduced number of winter periods and then validated against the remaining winter periods. The results are summarized in Table 7, where we compare model predictions with parameters determined by the SCE calibration using a limited calibration period with those derived using the pedotransfer functions. The results shown are for the Lucky Hills site where the pedotransfer function approach worked best and where the test is therefore more exacting. Even using a four-winter calibration time period, SCE is capable of finding a parameter set that results in improved model performance (as measured by the overall root-mean-square error). Just as remarkable, the 8 year calibration was only slightly better than the 4 or 6 year calibrations.

5. Wintertime Soil Moisture Water Balance

The ability to successfully calibrate HYDRUS gave us confidence in the use of the calibrated model to quantitatively estimate the root zone recharge during the winter months, this being the primary motivation for this study. In this section, we determine how much soil moisture recharge occurred in the November to February wintertime period each year and how this recharge was distributed in the soil profile. This amount and its distribution determine the water source available to plants adapted to take advantage of it. Ultimately, the ratio of deep- to shallow-rooted plants, if such stratification in species

Table 7. Validation for the Lucky Hills Site Shuffled Complex Evolution (SCE) Calibration

Winter Calibration Period	Winter Validation Period	SCE RMS, $cm^3\ cm^{-3}$	Pedotransfer RMS, $cm^3\ cm^{-3}$
1990–1993	1994–1997	0.026	0.030
1994–1997	1990–1993	0.028	0.035
1990–1995	1996–1997	0.026	0.033
1992–1997	1990–1991	0.024	0.038
1990–1997	1990–1997	0.024	0.033

Results are the root-mean-square error (RMS) of the predicted versus the observed volumetric soil moisture for all levels using a mutually exclusive calibration/validation data set (the final values, which utilize all eight winters as a calibration data set, are shown for comparison). The calibration results are compared with the model predictions using pedotransfer function-derived parameters from Table 3. Even with limited calibration periods, the SCE method was able to determine parameters that improved the model predictions relative to using pedotransfer function-derived parameters.

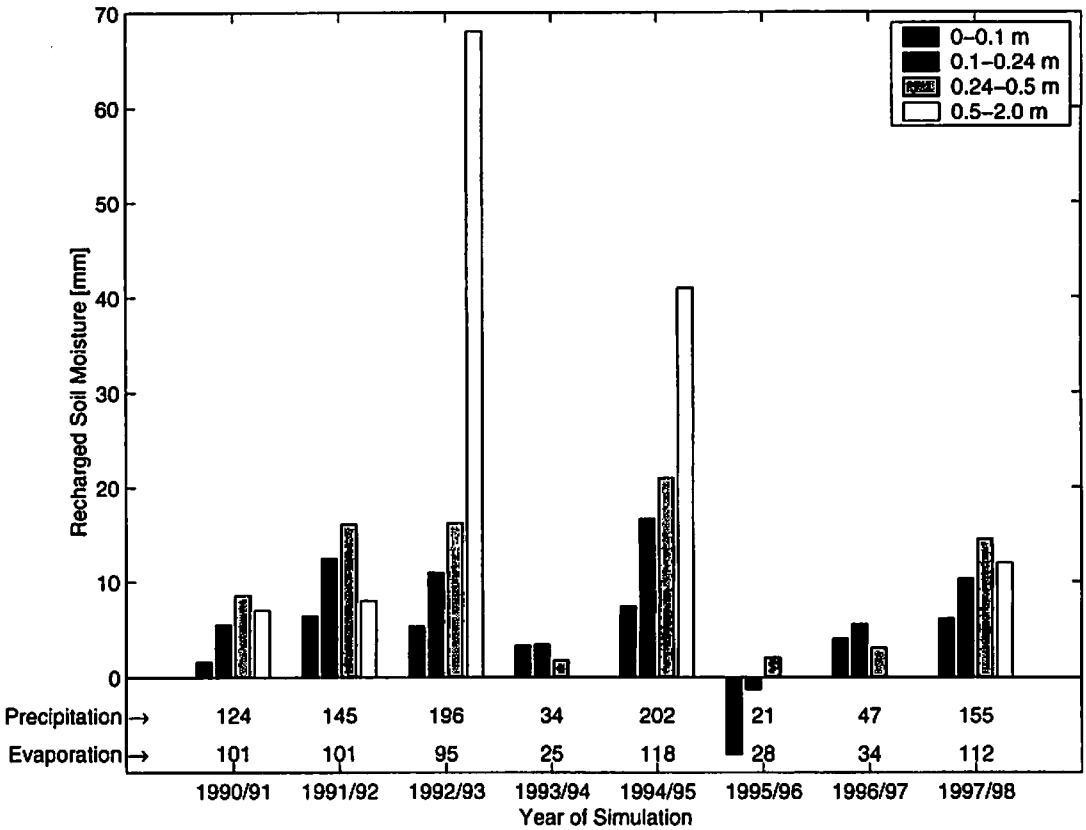

Figure 6. Accumulated 1990–1997 winter recharged soil moisture (mm) over the profile depth intervals of 0–0.1, 0.1–0.24, 0.24–0.5, and 0.5–2.0 m for the Lucky Hills profile. Total precipitation (mm) and model-computed evaporation (mm) for each winter are also given below the bars.

exists in a particular ecosystem, should be correlated with the ratio of deep to shallow recharge.

For each calibrated simulation presented in section 4.2 the amount of accumulated recharge (after evaporation loss) was computed for the intervals of 0–0.1 m, 0.1–0.24 m, 0.24–0.5 m, and 0.5–2.0 m each winter. Figure 6 illustrates recharge for the Lucky Hills profile. The total precipitation and model-computed evaporation for each winter are also shown on Figure 6 below the bars. During the wet winters of 1992/1993 and 1994/1995 a substantial proportion (>60 mm) of the precipitation percolates to depths greater than 0.25 m, while only ~10–20 mm are recharged below 0.24 m in the moderate winters of 1990/1991, 1991/1992, and 1997/1998. As expected, the dry winters of 1993/1994 and 1995/1996 have negligible recharge or even a net loss of water from the soil profile. In this semiarid environment, wintertime evaporation is still significant with around 75–100% of the winter precipitation (less for high precipitation years) returning to the atmosphere via bare soil evaporation.

Figure 7 illustrates the recharge at the Kendall site (wintertime precipitation and evaporation totals are given below the bars). The Kendall site received more precipitation than the Lucky Hills site. Not surprisingly, therefore, Figure 7 shows that recharge was greater than at Lucky Hills with substantially more accumulated recharge below 0.24 m in the wetter-than-normal winters of 1992/1993 and 1994/1995. Total evaporation at the Kendall site was sometimes less than that at the Lucky Hills site, especially in 1990/1991 and 1997/1998. The parameters for the top layer at the Kendall site combine to allow more rapid water movement to depth, thereby inhibiting subsequent soil evaporation. The fact that model calibration forces the model to perform in a way that best reproduces the observations is helpful in this study. In essence, the SCE-derived parameters provide the "best guess" of the upper boundary input (of precipitation minus evaporation) implied by the observations. Thus the calibration process ensures that the impact of possible model deficiencies (such as the neglect of vapor flow or a relatively simple representation of evaporation) on modeled subsurface moisture fields will be minimized.

Figures 6 and 7 show that although significant recharge to deeper levels in the soil profile occurs, the amount of deep recharge varies from year to year. This large interannual variability in deeper root zone recharge indicates that it is probably not hydrologically feasible that there are two separate ecological niches which could sustain plants with nonoverlapping water acquisition strategies. The high variability in the winter rains between 1990 and 1998 is consistent with the variability observed in the longer-term record of 1964–1994 given in Table 2. Although the recharge will be advantageous to plants that have deeper roots and can be active during the cooler temperatures of spring (i.e., C_3 shrubs), these species must also be able to access shallow summer moisture when winter rains fail to produce enough soil moisture recharge. A plant that only had access to soil moisture deep in the profile would face certain mortality given the observed interannual variability in winter recharge. Thus the type of bifurcation in root water extraction seen in other ecosystems of the Southwest [e.g., *Ehleringer et al.*, 1991; *Weltzin and McPherson*, 1997] is not likely to be occurring at these southern Arizona sites. *Kemp* [1983] came to a similar conclusion at a Chihuahuan desert

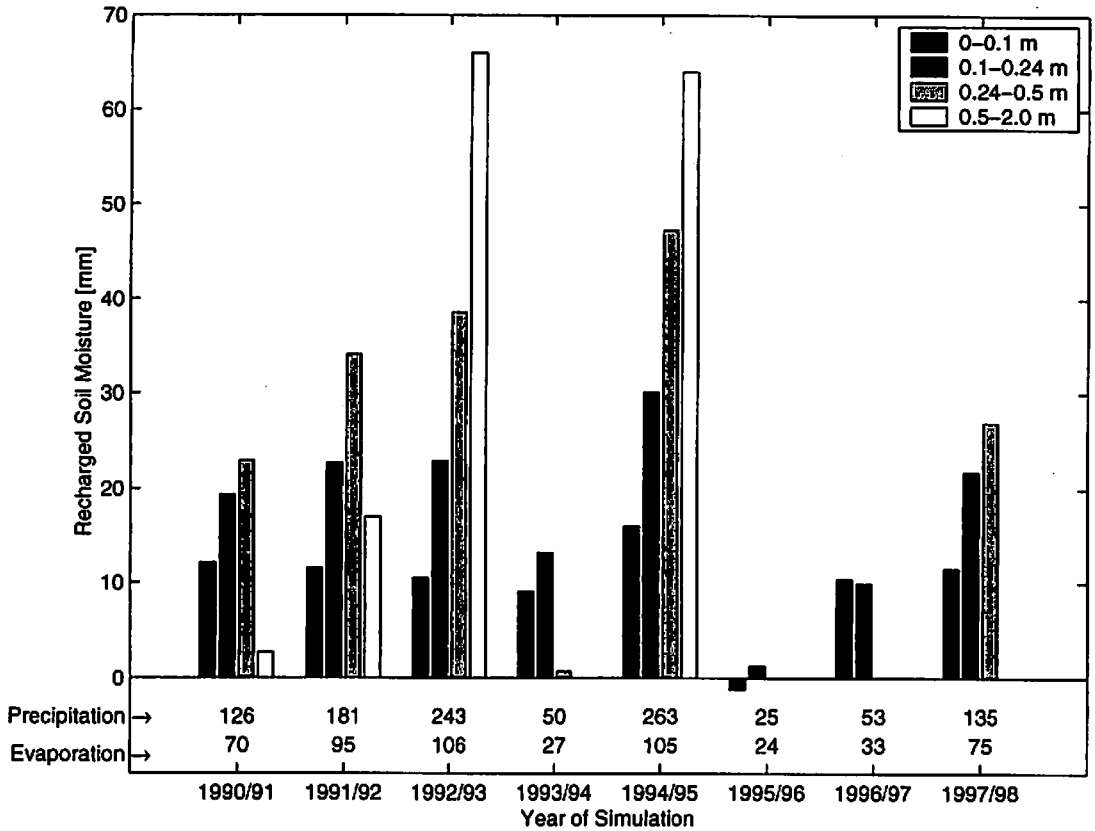

Figure 7. Accumulated 1990–1997 winter recharged soil moisture (mm) over the profile depth intervals of 0–0.1, 0.1–0.24, 0.24–0.5, and 0.5–2.0 m for the Kendall profile. Total precipitation (mm) and model-computed evaporation (mm) for each winter are also given below the bars.

site, where it was found C_3 shrubs and Crassulacean acid metabolism (CAM) shrubs, which were primarily active in spring or autumn, also use summer precipitation in competition with the dominant C_4 grasses.

Finally, we compared the prewinter and postwinter soil moisture profiles to determine the approximate depth of wetting that occurred each winter. We note that these computed moisture front depths are made assuming there is homogeneous soil below the lowest observation level. Both the Lucky Hills and the Kendall profiles showed similar depths of wetting. During the drier winters of 1993/1994, 1995/1996, and 1996/1997 the region of active change in soil moisture was confined to the top 0.3 m. The moisture front penetrated to around 0.6–0.9 m in 1990/1991, 1991/1992, and 1997/1998 and to ~1.3 m in the wet winters of 1992/1993 and 1994/1995. However, even the 1990/1991, 1991/1992, and 1997/1998 winters had greater than average rainfall (see Table 2). Consequently, it is expected that during average winters the profile wetting is confined to the top 0.5 m of soil. Root distribution data at both sites are consistent with this [*Cox et al.*, 1986; M. Weltz, USDA-ARS, Tucson, personal communication, 1999]. While some roots are found down to 1.5 m, the majority of the roots (80–90% of the total roots in one profile) are confined to the upper 0.5 m of soil.

As mentioned in section 2, the wintertime precipitation and the resultant root zone recharge appears correlated with El Niño/La Niña cycles. With the exception of the 1995/1996 and 1996/1997 winters, all the winters examined in this study were preceded by weak to strong El Niño episodes. Except for 1993/1994, precipitation was higher than normal (and recharge was often greater) during these winters. If wintertime precipitation is indeed linked to C_3 shrub growth [e.g., *Cable*, 1980; *Kemp*, 1983], this period with its enhanced root zone recharge could likely contribute to an acceleration of the already ongoing shrub invasions of southwestern grasslands [*Cox et al.*, 1983; *Grover and Musick*, 1990]. This link is intriguing and could have important implications in the management of rangeland resources, but more data are needed before such a link can firmly be established.

6. Summary

This paper has examined the soil moisture redistribution patterns at two different sites in semiarid, southeastern Arizona. Wintertime root zone recharge was examined in further detail to determine if deeper root zone recharge might be an important process in this region. The one-dimensional, Richards' equation–based soil water model HYDRUS was used to model intermittent observations of soil moisture status during the November through February periods in the years 1990–1998. The two profiles were modeled using two different sets of parameters. The first was derived from available soils data and pedotransfer functions, while the second was found by calibration using the automatic parameter search algorithm, SCE-UA. Calibration resulted in improved model performance relative to the traditional prescribed parameter approach. The results of this paper suggest that using an automatic calibration approach can be very useful for improving soil water simula-

tion performance, but further research is needed to determine the limits of parameter estimation when applied at heterogeneous field sites.

It was found that there is substantial root zone recharge during wetter-than-normal winters. Modeled moisture fronts moved as deep as 1.3 m during these years. However, the fact that the long-term variability of wintertime precipitation is quite high in this region means that deeper-profile recharge is not reliable even during the limited (1990–1998) period of study. Hence we infer that some plants in this region would have the ability to access this substantial source of water in the spring growing season but that sole reliance on deeper root zone moisture seems unlikely.

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