Covers

HYDROLOGIC MODEL TESTS FOR LANDFILL COVERS USING FIELD DATA

M. J. Fayer[1] and G. W. Gee[1]

ABSTRACT--Landfill covers are used to minimize drainage that could mobilize and transport contaminants to the ground water. The objective of this study was to test two hydrologic simulation models to be used to evaluate cover performance for a minimum of 1000 years. A six-year record of water storage, suction, and drainage data was used to test two models. The data were collected from a non-vegetated weighing lysimeter containing 1.5 m of silt loam over sand and gravel. This capillary-break layering configuration enhances water storage in the upper layer where it can be more easily removed by evapotranspiration. Four simulations were conducted with the Richards-equation-based UNSAT-H: 1) standard parameters, 2) calibrated parameters, 3) heat flow, and 4) hysteresis. Two simulations were conducted with the water-balance-based HELP: 1) standard parameters, and 2) drier than normal initial conditions. The water storage results showed little difference among the four UNSAT-H simulations; the maximum root mean square (RMS) error was 23.7 mm. In contrast, the RMS error from the HELP model was 97.6 mm. The best qualitative match of suction and drainage data was obtained with the UNSAT-H simulation with hysteresis, which predicted cumulative drainage within 52% of the measured amount. HELP predicted drainage in each of the six years; the total was 1800% of the measured amount.

The UNSAT-H results indicated that hysteresis was a significant process in landfill covers and that soil water suction may be a more useful parameter to monitor as an indicator of incipient drainage. The results from the uncalibrated HELP model indicated that the conceptual bases for the model may be inadequate for accurate simulations of drainage through landfill covers using capillary breaks in semiarid environments.

Keywords: Covers, barriers, caps, landfills, drainage, modeling, validation

Radioactive and chemical wastes have been stored in or disposed to the sediments in a variety of locations in the western U.S., including the U.S. Department of Energy's Hanford Site in southcentral Washington State. To protect human health and the environment, multilayer covers (also known as landfill caps or protective barriers) have been proposed as a means of limiting the flow of water through these waste sites (DOE 1987; BHI 1996). Such covers are common to shallow land disposal facilities around the country (as well as the world) and are regulated by numerous Federal, state, and local statutes.

In the semi-arid West, landfill cover designs typically include a capillary break feature, in which coarse sediments underlie a finer-textured surface layer (e.g., Link et al. 1995, Nyhan et al. 1993). The capillary break promotes the storage of water in the upper layer, where the stored water is then subject to removal by evaporation and transpiration. Wing (1994) outlined a comprehensive program at the Hanford Site that was designed to address technical issues associated with the performance of these covers. The computer model UNSAT-H (Fayer and Jones 1990) was used to address one of those issues: water infiltration.

Computer simulation models are used to support the engineering design of landfill covers, interpret the field data collected to verify post-closure performance, and evaluate the effectiveness of the covers at isolating buried wastes well into the future (Sophocleous et al. 1996, Paige et al. 1996, Devaurs and Springer 1988, Nyhan 1990, Peyton and Schroeder 1988, 1989, Johnson et al. 1983, Khire et al. 1997, Magnuson 1993, Fayer et al. 1992). The simulation results are also used to demonstrate compliance with applicable regulatory standards. Meyer et al. (1996) described a 3-step modeling

[1]Pacific Northwest National Laboratory, Box 999, Richland, WA 99352, mj_fayer@pnl.gov

methodology for the hydrologic evaluation of low-level radioactive waste disposal sites: 1) conceptualization, 2) simulation, and 3) interpretation and confidence building (i.e., establishing the credibility of the model).

There are several concerns when using models to predict performance for hundreds to thousands of years. Testing periods are much shorter than the application periods, of necessity, but one concern is that the testing periods are far shorter than they should be. A prototype cover is being evaluated at the Hanford Site for only a 3-year period, while simulation results (Fig. 1) show that durations of 30 years or more may be needed to capture significant hydrologic events. Another concern is whether model calibration significantly improves model performance. Calibration is very model-specific and depends on the model adequately representing the major processes in operation. A third concern is whether models with different conceptual bases can be used to accurately estimate drainage through a landfill cover with a capillary break.

The objective of this effort was compare model simulation results with a 6-year record of data collected from a weighing lysimeter at the Hanford Site. Two models were used: UNSAT-H, a model based on the Richards equation, and HELP (Hydrologic Evaluation of Landfill Performance, Schroeder et al. 1992), a model based on water budgeting. The UNSAT-H is an integral part of the cover program at Hanford. The HELP model was included in this study because of its wide distribution, support by the Environmental Protection Agency and U.S. Army Corp of Engineers, and the potential for its use at the Hanford Site to compare barrier designs.

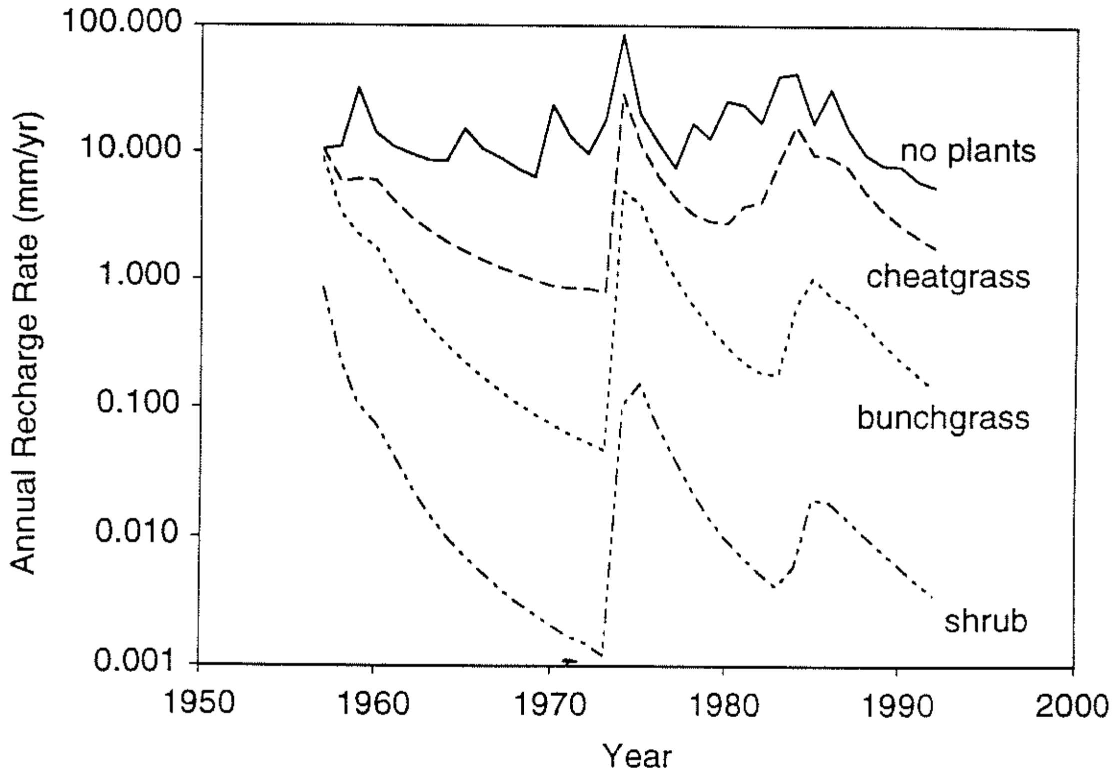

Fig. 1. Simulated annual drainage rates at the 4-m depth of a layered field soil under different vegetation conditions (from Fig. 2 of Fayer et al. 1996).

Comparisons between measured and simulated water storage, suction, and drainage were used to demonstrate multiyear model performance, the value of model calibration, and the relative importance of heat flow and hysteresis to the accurate simulation of landfill cover hydrology.

METHODS

A test facility with 24 lysimeters was constructed at Hanford in 1987 to test various cover designs. One of the lysimeters, known as W4 (Fig. 2), was irrigated and maintained free of vegetation, representing a severe test of the cover. The 6-year record of data used for this model test extended from November 1987 through October 1993. Lysimeter W4 was irrigated to mimic the increased precipitation of a wetter climate. During the first 3 years, enough irrigation water was added monthly, in addition to the natural precipitation, to achieve two times the average monthly precipitation based on records from 1912 to 1980. During the second 3 years, the irrigation rate was increased to achieve three times the average monthly precipitation (Gee et al. 1993). A platform scale enabled measurement of hourly changes in weight. These weight changes were treated as water storage changes, based on the assumption that there was no soil loss or gain. This lysimeter was not vegetated and therefore had no changes in plant dry matter. Matric potential was measured intermittently at two depths, 1.0 and 1.5 m. Drainage was monitored biweekly for the first five years. Once drainage commenced in February 1993, the monitoring rate was increased to almost daily until the drainage rate subsided and eventually stopped (late March 1993).

Four simulations were conducted using the UNSAT-H version 2.0 code: standard,

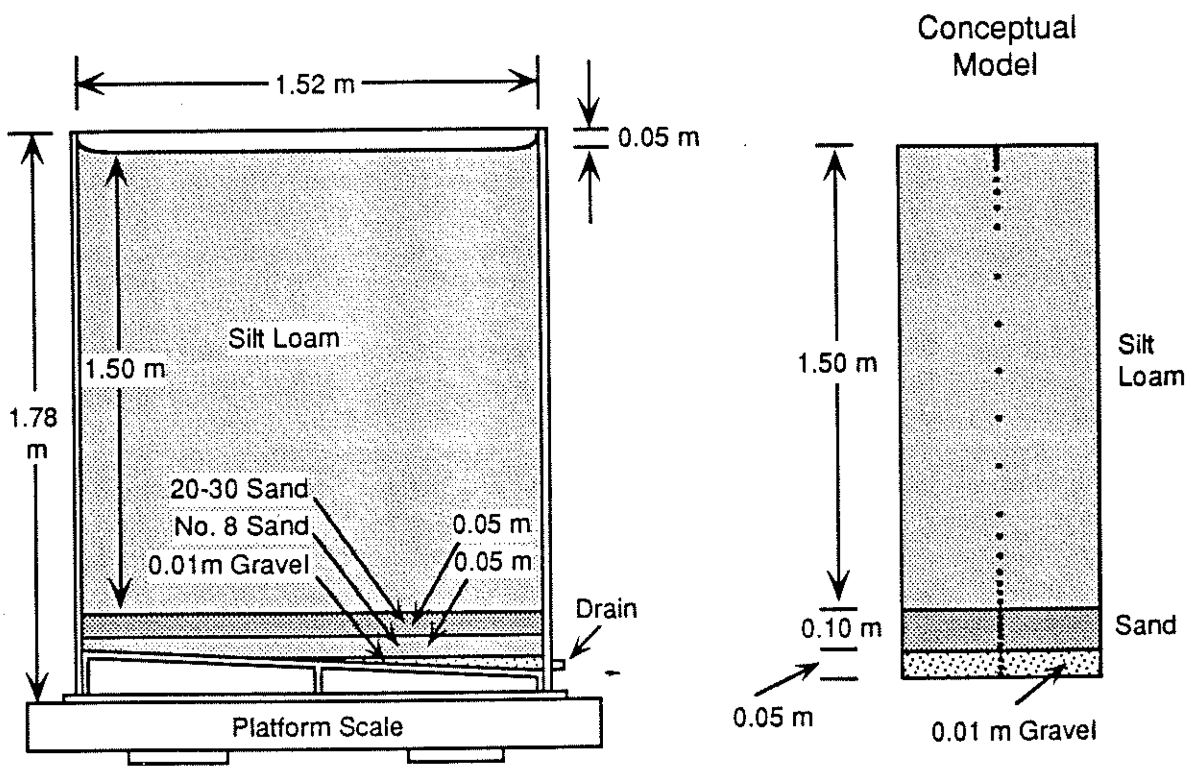

Fig. 2. Dimensions and material content of lysimeter W4 and its associated conceptual model.

calibrated, heat, and hysteresis. The standard simulation was conducted with lab-measured properties, isothermally, and without hysteresis; it served as the baseline. For the calibrated simulation, four parameters were adjusted in a calibration process that used data from the first 1.5 years of the experiment (Fayer et al. 1992). This simulation was designed to gain experience with the calibration process and to determine its limitations. The third simulation included heat flow. This heat simulation was designed to demonstrate the effect of thermal flow on evaporation and soil water redistribution via vapor flow. The fourth simulation included hysteresis in the water content-pressure head relationship and was designed to demonstrate whether inclusion of this phenomenon improved the simulation results. For this simulation, UNSAT-H version 2.0 was modified to include hysteresis (Fayer 1993).

Two simulations were conducted with the HELP Version 2.05 code. The first simulation used standard parameters that were derived from the parameters used in the standard UNSAT-H simulation. A second simulation was conducted in which the initial conditions were set to the driest value possible to highlight the impact of initial conditions on the HELP simulations.

Two methods were used to compare model results with measurements. In the first method, time series of water storage, suction, and drainage were plotted to illustrate qualitatively any differences. In the second method, water storage differences were quantified using the root mean square (RMS) error, calculated as:

$$RMS_{\varepsilon} = \left[\frac{1}{k}\sum_{i=1}^{k}\left(m_i - p_i\right)^2\right]^{0.5} \qquad (1)$$

where m and p and are the measured and predicted values of storage and k is the number of values. The mean, median, and maximum differences were also calculated.

UNSAT-H Parameters

UNSAT-H is a one-dimensional model that simulates the dynamic processes of infiltration, drainage, redistribution, surface evaporation, and the uptake of water from soil by plants. The mathematical bases of the model are Richards' equation for water flow, Fick's law for vapor diffusion, and Fourier's law for heat flow. UNSAT-H uses a fully implicit, finite difference method for solving the water and heat flow equations. Plant water uptake is introduced as a sink term at each node and is calculated as a function of root density, water content, and potential evapotranspiration. The simulated profile can be homogeneous or layered. The boundary conditions can be controlled as either constant (potential or temperature) or flux conditions to reflect actual conditions at a given site. Hydraulic properties for the lysimeter materials (Fig. 3) are identical to those used by Fayer et al. (1992). For the simulation with calibrated parameters, the saturated conductivity value was increased by a factor of 1.43, the pore interaction term was reduced from 0.5 to 0, the potential evaporation (PE) values were reduced by 30%, and periods of snow cover greater than 6 days were mimicked by reducing PE to zero during that time. These calibrated parameters were determined on lysimeter W4 for the period from 4 November 1987 through 30 April 1989. The simulations reported below include this period plus the subsequent 4.5 years.

The simulation that included heat flow required additional parameters. Thermal conductivity and vapor enhancement data were obtained from Cass et al. (1984). For the silt loam, the parameters for Portneuf silt loam at 32°C were used. For the sand and gravel, the parameters for Lysimeter sand at 22.5°C were used. The volumetric heat capacity of all three materials was specified as 2.39 MJ m^{-3} K^{-1}, which was the nominal value for clay minerals reported by Campbell (1985). The initial temperature at all depths was specified as 289.1 K, which was the maximum air

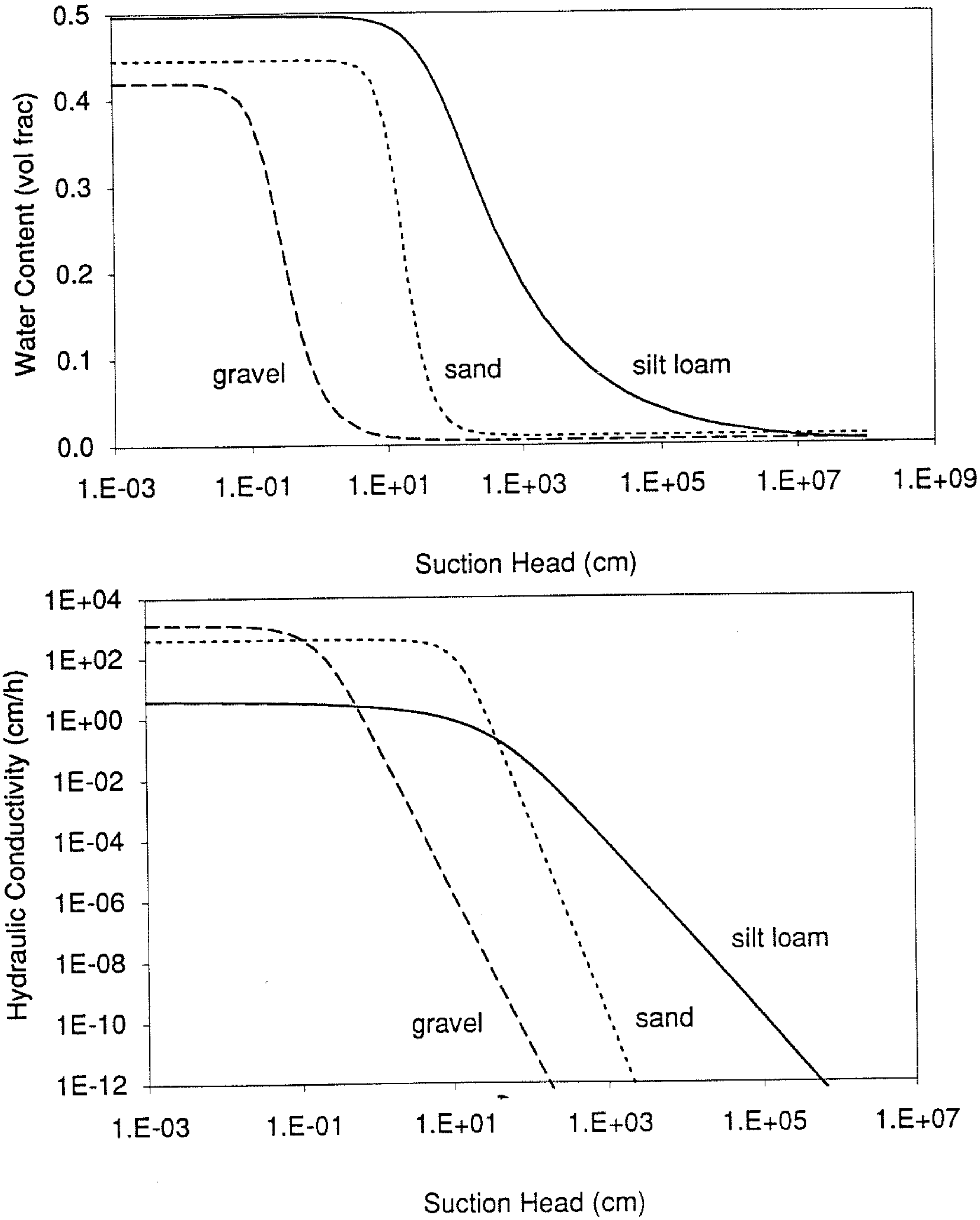

Fig. 3. Hydraulic properties of the lysimeter materials for the UNSAT-H simulations.

temperature on 5 November 1987, the starting date. The roughness lengths were specified as 0.49 mm as determined for silt loam by Ligotke (1988). The zero plane displacement height was specified as zero because there was no vegetation. The measurement heights for air temperature and wind speed were 0.914 and 2.13 m, respectively.

The simulation that included hysteresis required specification of the number of scanning loops allowed, the alpha parameter for imbibition, the maximum entrapped air content, and the starting scanning loop. The silt loam and sand materials were allowed up to 7 scanning loops. Hysteresis was not simulated in the gravel. Based on Kool and Parker (1987), the alpha parameter for imbibition was estimated to be equal to twice the value of the alpha parameter for drainage, which was the alpha value reported by Fayer et al. (1992). The maximum entrapped air content was set at 0.127 $m^3 m^{-3}$ (field-measured) for the silt loam and 0.05 $m^3 m^{-3}$ (lab measured) for the sand (Fayer 1993). Both materials were started on the main drainage branch rather than the primary drainage branch. The surface boundary was represented with hourly precipitation (snow treated as rain) and irrigation data, and daily estimates of PE derived using the Penman equation. The bottom boundary was described with a unit gradient condition in the gravel. For the heat flow simulation, daily maximum and minimum temperatures, average dewpoint temperature, wind speed, solar radiation, and cloud cover were provided for the upper boundary. The lower boundary was described with a no heat flux condition. HELP Parameters.

The HELP model is a quasi-two-dimensional hydrologic model of daily water movement into, through, and out of landfill systems, including covers, liners, and leachate collection systems. HELP uses daily climate data to calculate daily runoff, evapotranspiration, barrier-layer percolation, and lateral drainage from the landfill. The HELP model employs a number of simplifying assumptions that reduce the number of required parameters and enable a quick solution on a personal computer. The HELP version 2.05 code was used to simulate the W4 lysimeter using the soil parameters in Table 1. Additional parameters included the slope (2%), drainage length (14 m), Soil Conservation Service (SCS) runoff curve number (85), evaporative zone depth (constant at 1.6 m), and initial snow water content (0). Daily air temperature, solar radiation, and

Table 1. Parameters for the HELP Version 2.05 computer code. dZ is the layer thickness, s is the saturated water content, FC is the field capacity, WP is the wilting point, i is the initial water content, and K_s is the saturated conductivity.

Layer Type	Equivalent Soil	dZ (cm)	s ($m^3 m^{-3}$)	FC ($m^3 m^{-3}$)	WP ($m^3 m^{-3}$)	i ($m^3 m^{-3}$)	K_s ($cm\ s^{-1}$)
Vertical percolation	silt	150.0	0.496	0.265	0.0737	0.2127	0.00112
Vertical percolation	sand	10.0	0.445	0.021	0.020	0.020	0.1094
Lateral drainage	gravel	5.1	0.419	0.021	0.020	0.021	$1x10^{-6}$
Barrier soil liner	asphalt	15.2	0.03	0.021	0.020	0.021	$1x10^{-10}$

rainfall data were used, supplemented with rirrigation data.

Results

Water Storage

The UNSAT-H simulation using standard parameters did not match the measured values of low storage in summer and high storage in winter (Fig. 4a). In the summer, the model overpredicted storage by 30 to 35 mm during the first 3 years, and 12 to 30 mm during the second 3 years (Fig. 4b). During the winter, the model underpredicted storage by 15 to 35 mm during the first 3 years and by 45 to 75 mm during the second 3 years. These result are consistent with earlier work (Fayer et al. 1992; Fayer 1993). Underprediction of the high values of storage in the winter is particularly important because it is during these times that drainage through the barrier is most likely to occur. The UNSAT-H simulation with the calibrated parameters improved the match to the measured values during the first 2 years, but less so in the following 4 years (Fig. 5a). For the 6-year period, summer storage values were underpredicted by 10 to 15 mm (Fig. 5b). In the winter, storage was underpredicted by 0 to 35 mm during the first 3 years, and 15 to 60 mm during the second 3 years.

The simulation with heat flow produced results that were similar to the simulation with standard parameters. Apparently, the inclusion of heat flow did not significantly alter the simulation of evaporation. The predicted storage values were always within 10 mm of the simulation with standard parameters.

The simulation with hysteresis also produced water storage results that were similar to the results from the simulations with standard parameters and heat flow. At no time were the differences more than 15 mm. Generally, water storage values predicted using hysteresis were slightly closer to the measured values in mid-summer and slightly further from the measured values in mid-winter, although these relationships did not hold for every year. The HELP simulation did not match the measured storage values well throughout the entire 6 years (Fig. 6). In the summers, predicted storage values were 30 to 50 mm less than those measured during the first 3 years, and 30 to 90 mm less during the second 3 years. In the winters, predicted water storage values were 95 to 145 mm less than those measured during the first 3 years, and 100 to 265 mm less during the second 3 years. The RMS error of the four UNSAT-H simulations were almost identical, which was somewhat surprising. The calibration, using the first 1.5 years of data, reduced the RMS error by half (relative to the simulation with standard parameters). For the entire 6-year period, however, the advantage appears to have disappeared.

With respect to the other three storage metrics (Table 2), the calibrated simulation results differed the most. It produced the lowest maximum storage difference (always in mid-winter), which was not unexpected because the goal of the calibration was to match the peak storage in winter (Fayer et al. 1992). For the other two metrics (the mean and median differences), the calibrated simulation yielded values that were much higher than those from the other UNSAT-H simulations, indicating that it produced positive differences more consistently. The metrics for the HELP simulation indicated a much poorer prediction of storage. The RMS error was four times larger than for any of the UNSAT-H simulations and the maximum difference was three times larger. The mean and median differences, which should approach zero given a sufficiently large time of comparison, were also much larger than those for any of the UNSAT-H simulations.

Soil Water Suction

There was significant variability in predicting suctions using the UNSAT-H model (Fig. 7). The simulation with standard

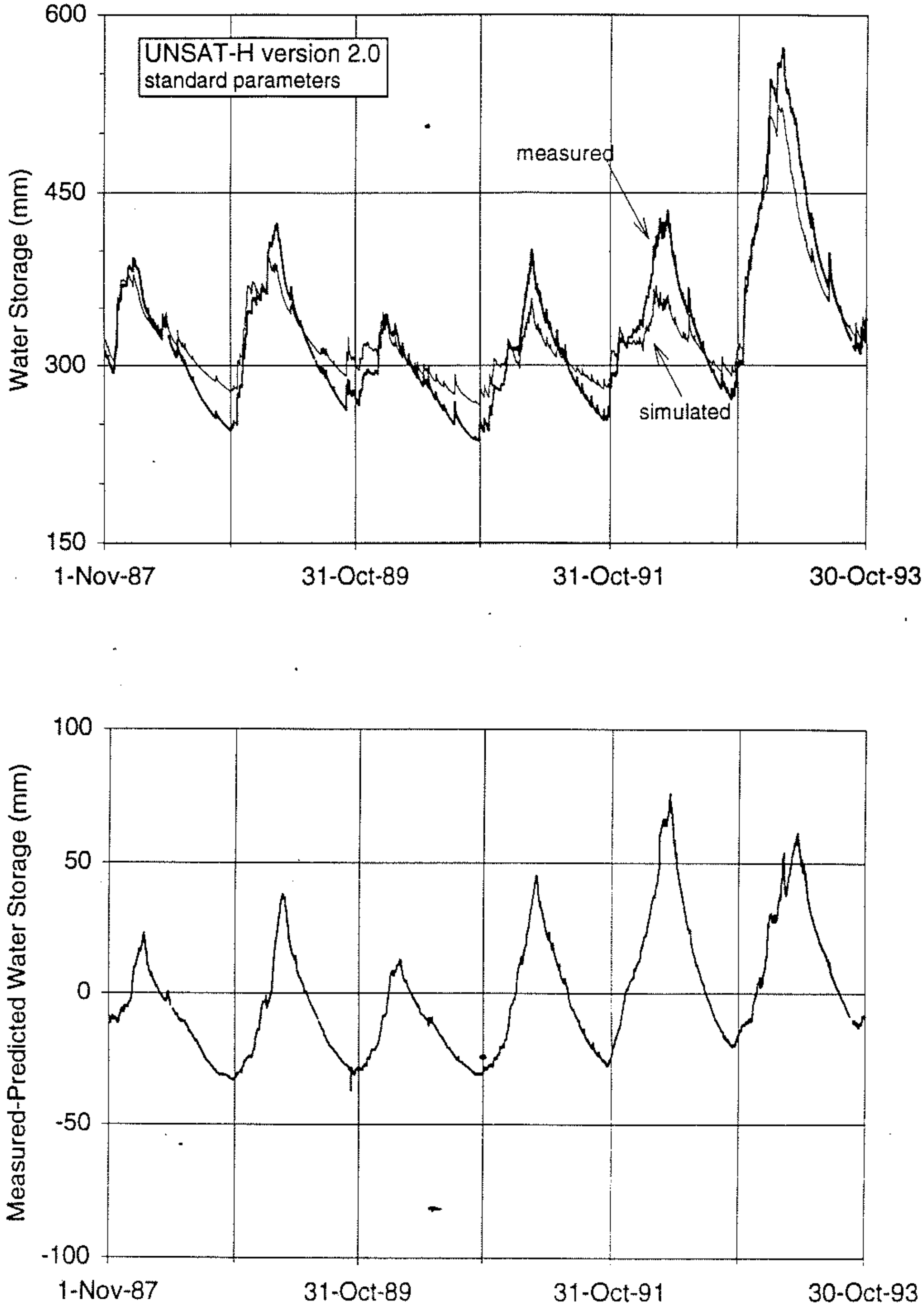

Fig. 4. Measured and simulated storage using UNSAT-H version 2.0 with standard parameters.

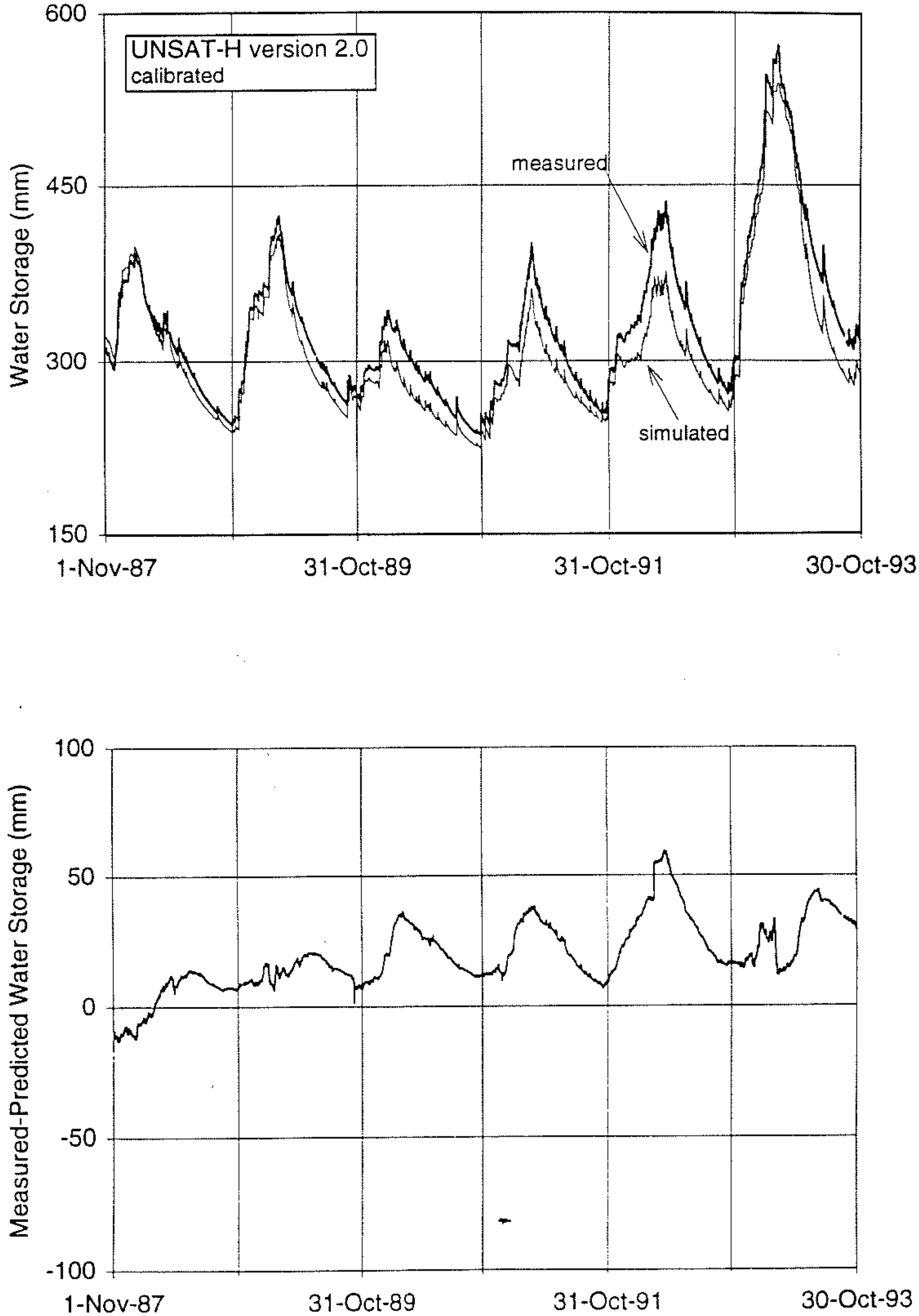

Fig. 5. Measured and simulated storage using UNSAT-H version 2.0 with calibrated parameters.

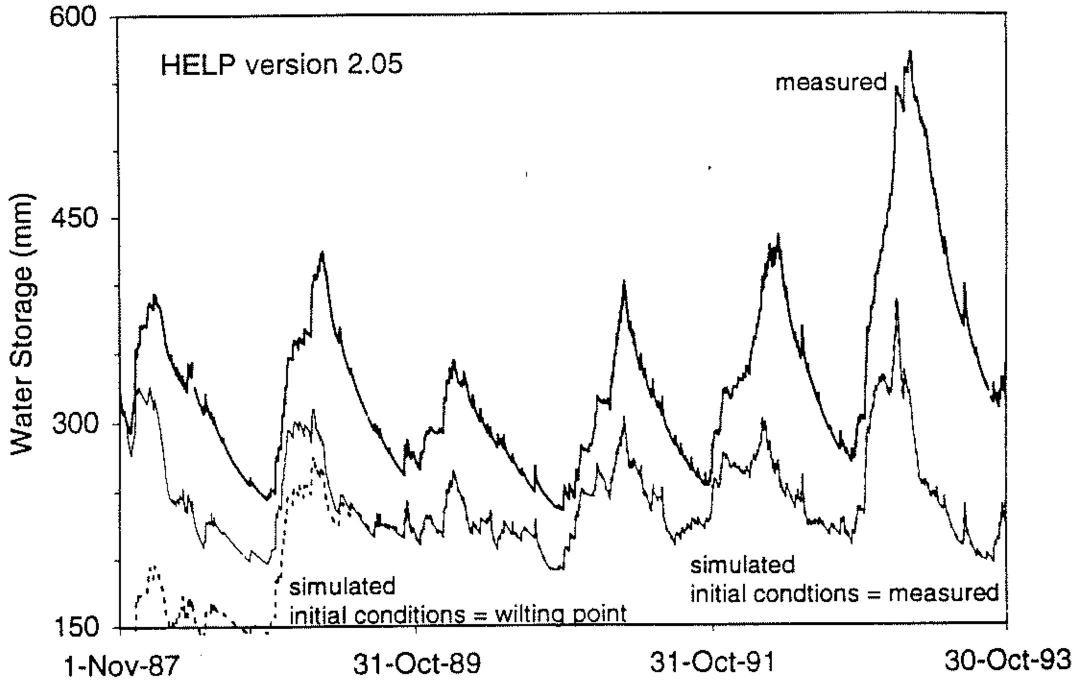

Fig. 6. Measured and simulated storage using HELP 2.05.

Table 2. Summary statistics (mm) of model comparisons. Daily differences were calculated by subtracting predicted storage from measured storage. Measured drainage was 29.6 mm.

Storage Model Description	RMS Error	Maximum Difference	Mean Difference	Median Difference	Cumulative Drainage
UNSAT-H Version 2.0					
Standard	23.6	75.8	-0.9	-6.0	0.0
Calibrated	23.6	59.3	19.6	16.5	0.0
Heat	23.4	80.2	1.6	-3.4	0.0
Hysteresis	23.7	74.8	3.0	-2.0	15.3
HELP Version 2.05	97.6	264.4	84.9	73.1	537.0

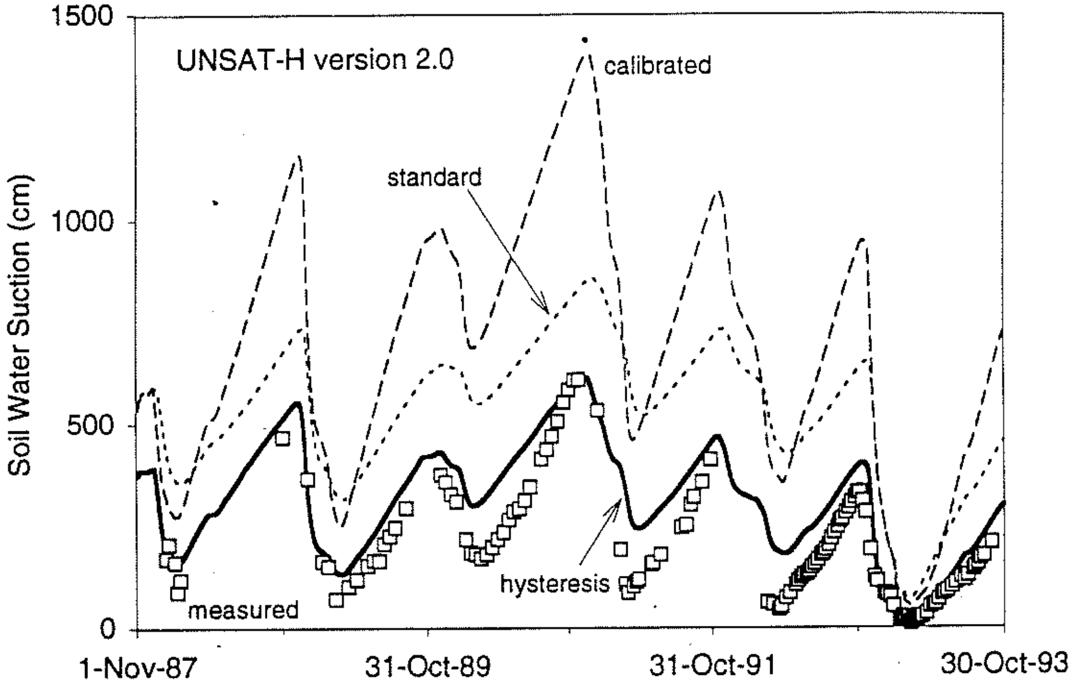

Fig. 7. Measured and simulated suction using UNSAT-H version 2.0, 1987 to 1993. The hysteresis simulation was conducted with the modified version 2.0.

parameters estimated much higher soil water suctions than the measured values throughout the 6 years; the heat flow simulation results were very similar. The calibrated simulation estimated much higher suctions than the measurements in the summer, but closer to the measurements in winter relative to the simulations with standard parameters. The hysteresis simulation estimated suctions that were in closest agreement with the measured values.

Figure 8 shows a subset of the suction data in Fig. 7 using a magnified scale for the period of drainage in 1993. Relative to the simulation with standard parameters, the calibrated simulation provided only slightly better estimates of suction during the limited time when suctions were lowest (i.e., storage was greatest). Compared to the other simulations, the hysteresis simulation predicted suctions that were in much better agreement with the measurements during this drainage period.

Drainage

Of the four UNSAT-H simulations, only the simulation with hysteresis predicted any drainage (Table 2). This was likely because this simulation was more successful at predicting soil water suctions. The total

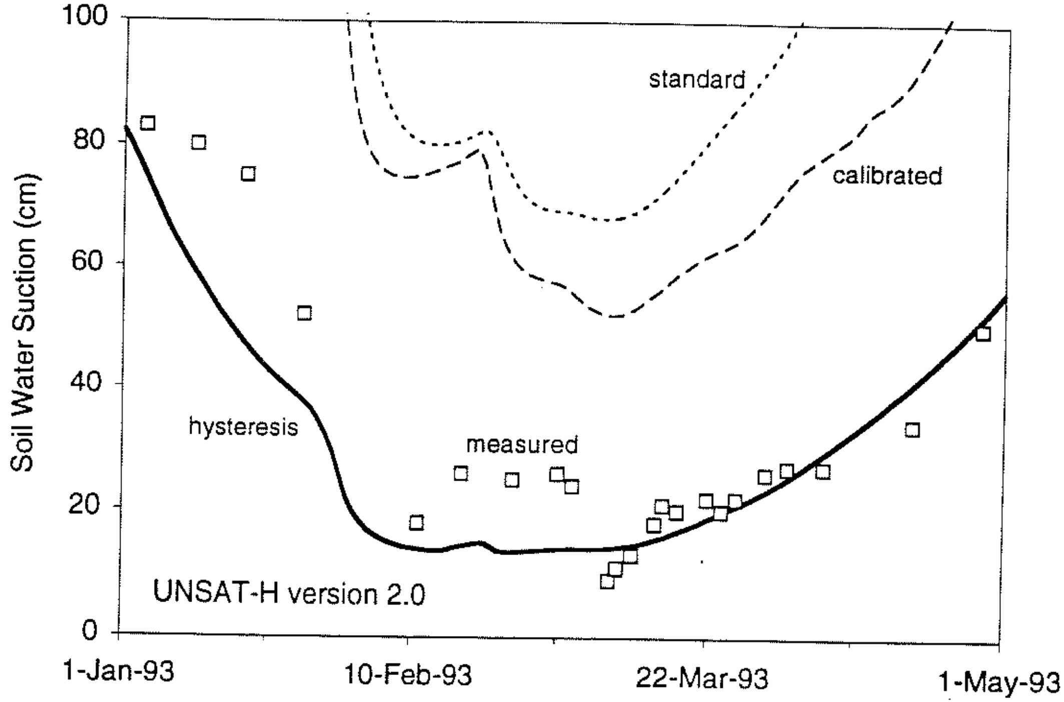

Fig. 8. Measured and simulated suction using UNSAT-H version 2.0, Jan to May 1993. The hysteresis simulation was conducted with the modified version 2.0.

drainage predicted by the hysteresis simulation was 52% of the measured value of 29.6 cm.

When suctions decreased below approximately 20 cm (February 10 and March 7, 1993), drainage occurred (Fig. 9). This result demonstrates the sensitivity of drainage to suction values at the interface. Previous modeling studies have made this point (Frind et al. 1977, Johnson et al. 1983, Fayer 1993)

The HELP model predicted drainage in all 6 years, whereas the measurements showed drainage in only the last year. The total drainage predicted by HELP, 537 cm, exceeded the measured value by 1800%.

Because of the excessive drainage, a second HELP simulation was conducted in which the initial conditions were set to the wilting point, a much drier initial condition. Even with a dry initial condition, simulated storage achieved the same storage levels as in the original HELP simulation within about 1.5 years (Fig. 6). For the rest of that simulation, drainage rates were identical to the original HELP simulation, thus demonstrating that the higher drainage rates predicted by HELP were not a function of the initial conditions. Changing a fitting parameter, such as evaporative depth, can make significant differences in the predicted drainage, but selection of these parameters is somewhat arbitrary. Martian (1994) found that matching Hanford lysimeter data required temporal adjustment of the

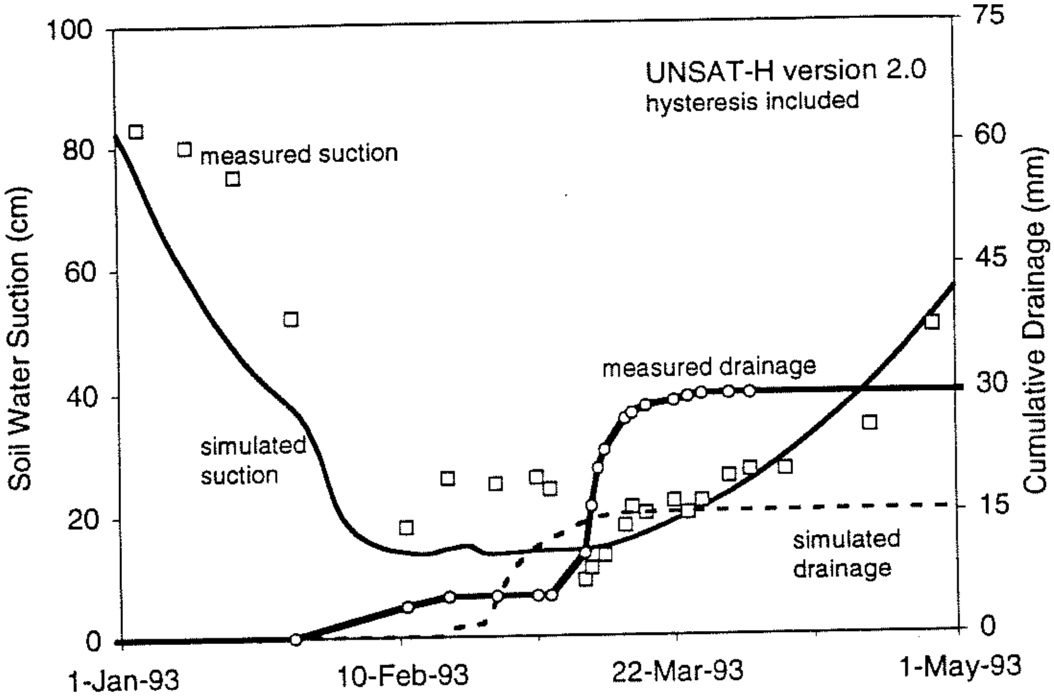

Fig. 9. Measured and simulated suction and drainage using UNSAT-H version 2.0 with hysteresis, Jan to May 1993.

evaporative depth, but no physical basis for this adjust was provided. Because HELP 2.05 assumes a unit gradient drainage condition, the processes involved in water storage in layered (capillary barrier) soils are not properly modeled and drainage can be significantly overestimated.

DISCUSSION

Although water storage comparisons are valuable because of their emphasis on total water and water balance, soil water suction is a better indicator of conditions at the silt loam-sand interface that control drainage. A higher frequency of measurement between January and May 1993 would have allowed for a better estimate of the suction values at the onset and termination of drainage. The briefness of this drainage event indicates that more resources should go into higher frequency observations of suction and drainage rates during such potential drainage periods as mid-to-late winter or irrigation testing. Monitoring efforts designed to evaluate the long-term performance of waste sites should consider hysteresis. This phenomenon has been observed in the field (Royer and Vachaud 1975, Watson et al. 1975) and modeling studies (Dane and Wierenga 1975) have shown its influence on water redistribution and drainage. The nature of a landfill cover with a

capillary break is such that its layering sequence promotes increased water storage above the interface, thus increasing the manifestation of hysteresis.

Short-duration observations may not capture the range of possible values of water balance components such as drainage. For example, the drainage observed in lysimeter W4 did not occur until the sixth year following the melting of a major snow pack. Monitoring programs should be continued until such events occur or until conditions are created to reproduce such events (e.g., artificially adding snow).

Calibration of the UNSAT-H model improved predictions within the calibration period, but not as much beyond the calibration period. This observation should concern landfill operators and regulators: a calibrated model is not necessarily a correct or superior predictive model. The somewhat lackluster performance of the calibrated model in this study may have occurred because the calibration focused on improving the match to a single variable (i.e., water storage) rather than multiple variables. Another possible reason is that the calibrated model lacked important phenomena, such as hysteresis. The next step should be to calibrate the model with hysteresis using multiple measurement variables for an adequate period of time. It appears that calibration periods less than 6 years may not be adequate to demonstrate model performance for the expected range of conditions.

Only two simulations were conducted with HELP 2.05 for this project, so it is possible that the model was not ideally parameterized. But, given that reasonable parameters were used and yielded the results shown in Fig. 6 and Table 2, the HELP model may not be appropriate for quantifying hydrologic variables such as drainage for landfill covers that utilize the capillary break feature in a semiarid environment. Previous studies (Nichols 1991, Martian 1994) that have shown similar drainage results when comparing UNSAT-H and HELP have included plants. The simulation results reported here are for non-vegetated covers and the results imply that HELP may not represent the evaporation-storage-drainage processes adequately. Peyton and Schroeder (1989) noted "that the most appropriate use for models such as (HELP) is for comparison of designs rather than for prediction of quantities that one expects to be exactly reproduced in the field." Without further study, it is unknown whether the HELP model can even be used for comparative studies of capillary barrier designs for locales such as the Hanford Site or other arid sites.

Modifications and corrections of the HELP model appeared after this work was completed. HELP version 3.01 was obtained and the analyses repeated to determine if the results would change. HELP version 3.01 predicted total amounts of evaporation and drainage that were 1.9% higher and 2.7% lower, respectively, than the amounts predicted by HELP version 2.05. These differences were not sufficient to alter the conclusions drawn about the efficacy of using HELP for simulating capillary barriers in arid environments. In summary, this model-testing exercise showed the value of using a Richards-equation- based model to make quantitative predictions of drainage through landfill covers that use capillary breaks. For these types of covers, hysteresis is an important phenomenon that should be considered in the analyses. In contrast, heat flow appeared to be a minor factor, although this test did not address the impacts of heat flow and snow accumulation and melt nor did it evaluate the ability of the model to simulate soil temperatures. The limited calibration process improved model predictions within but not outside of the calibration period. Steps were proposed to improve the calibration process. These include consideration of hysteresis, calibration using multiple performance measures over several years, and testing for periods long enough to include the range of conditions envisioned for the site during the design life of the cover.

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