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A Report to the Westinghouse Hanford Company

Comparative Simulations of a Two-Layer Landfill Barrier Using the Help Version 2.0 and UNSAT-H Version 2.0 Computer Codes

W. E. Nichols

January 1991

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
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COMPARATIVE SIMULATIONS OF A TWO-LAYER LANDFILL BARRIER USING THE HELP VERSION 2.0 AND UNSAT-H VERSION 2.0 COMPUTER CODES

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Richland, Washington 99352

EXECUTIVE SUMMARY

This report documents the results of a simulation of the performance of a two-layer infiltration barrier for a nonradioactive dangerous waste landfill (NRDWL) at the U.S. Department of Energy's Hanford Site in semi-arid southeast Washington State. The performance of the barrier was simulated for a period of 10 years using the UNSAT-H version 2.0 groundwater flow computer code. Pacific Northwest Laboratory performed this simulation to compare results using UNSAT-H 2.0 with those of the U.S. Environmental Protection Agency's Hydrologic Evaluation of Landfill Performance (HELP) version 2.0 code.

A conceptualization of the actual landfill barrier design was modeled using both codes. The two layers consisted of 76.2 cm (30.0 in.) of silt loam underlain by 15.2 cm (6.0 in.) of fine sand. This model was simulated using 10 years of daily meteorological data collected at the Hanford Meteorological Station from 1979 through 1988. The intent of the comparison was to demonstrate that HELP conservatively predicts deep percolation of meteoric water at the Hanford Site. This demonstration required that the two codes be used to simulate the same conceptual model using identical, or at least essentially equivalent, input data.

HELP and UNSAT-H represent distinct approaches to unsaturated-zone modeling. UNSAT-H uses a one-dimensional, fully implicit finite-difference scheme to solve the Richard's equation. HELP, in contrast, uses a quasi-two-dimensional moisture routing model. The fundamental consequence of this difference is that the HELP code does not account for capillary flow, while UNSAT-H does. Therefore, with all other factors equal the HELP code should predict more percolation than the UNSAT-H code. Because UNSAT-H is physically based, whereas HELP is more empirical, the two models necessarily differ in the kinds and numbers of input parameters required. These differences were identified to operate the codes equivalently. For each identified difference, input values were chosen to achieve comparable representations of the physical system. A question regarding the appropriate selection of a root-density function for the vegetation model in UNSAT-H was addressed by selecting a likely case (exponential root-density function) and then "bracketing" the possible range with two additional sets of simulations that maximized (constant root-density function) and minimized transpiration (no transpiration).

For the 10-year period the worst-case UNSAT-H simulation (no-transpiration case) predicted a total of 0.0005 cm (0.000197 in.) of net water flux across the interface between the top layer of silt loam and the underlying sand layer of the conceptual design. No percolation was predicted at the base of the sand layer in any UNSAT-H simulation. Hence, the UNSAT-H 2.0 code predicted that the two-layer barrier was 100% effective in preventing drainage for the 10-year period simulated for the soil properties used.

The total mass-balance error for the three UNSAT-H simulations ranged from 0.551 cm (0.217 in.) to 0.570 cm (0.224 in.). These values indicate the precision of UNSAT-H predictions for water-balance components and is equal to the net amount of water unaccounted for in the simulation. In contrast, the HELP simulation mass-balance error for the same 10-year period was -0.001 cm (0.0004 in.). Because it is based on mass conservation (as a moisture-routing model) HELP should have essentially perfect mass balance. UNSAT-H uses the mass-balance error to achieve a balance between the size of the time steps used in the simulation and the precision in the mass balance. In this simulation, the maximum permitted daily mass-balance error was 1.0 x 10^{-4} cm (3.94 x 10^{-5} in.) and the maximum time step was 60 min.

Comparing the results of the 10-year simulations showed that for the meteorological data and soil properties modeled the HELP 2.0 code was more conservative than the UNSAT-H code. HELP predicted a net drainage or deep percolation of 0.3592 cm (0.1556 in.) from the barrier for the 10-year period simulated. None of the UNSAT-H simulations predicted any deep percolation. HELP also predicted a greater proportion of precipitation returned to the atmosphere through evapotranspiration than did the UNSAT-H simulations in spite of the larger precipitation values being provided to HELP through an apparent data-entry error.

ACKNOWLEDGMENTS

This report was partially funded by the Protective Barriers Program (ADS 8176). Research was conducted in support of the Westinghouse Hanford Company's nonradioactive dangerous waste landfill closure and postclosure plan preparation. The author thanks M. J. Fayer and M. L. Rockhold for their scientific insight and technical assistance with the UNSAT-H 2.0 code.

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INTRODUCTION

The nonradioactive dangerous waste landfill (NRDWL) located at the U.S. Department of Energy's (DOE's) Hanford Site in semi-arid southeast Washington State is undergoing closure. A final landfill barrier cover will be installed when the landfill is closed. The primary objective of the work described in this report was to simulate the hydrologic performance of a landfill barrier concept for NRDWL using the UNSAT-H version 2.0 code and compare the results with those of another code, Hydrologic Evaluation of Landfill Performance (HELP) version 2.0 developed by the U.S. Environmental Protection Agency (EPA). Westinghouse Hanford Company personnel simulated the NRDWL conceptual model using the HELP in conjunction with the UNSAT-H simulation performed by Pacific Northwest Laboratory[(a)] (PNL). Pacific Northwest Laboratory and Westinghouse Hanford staff cooperated to develop essentially equivalent input data sets within the constraints of the codes. The goal of the work was to provide evidence of the presumed "conservative" nature of the HELP code in predicting vertical percolation of meteoric water through the barrier. Conservative in this case means overestimation of deep percolation, a conservative code predicting a less effective barrier than would actually be the case. The basis for the presumption of HELP's conservative nature is that is does not account for capillary flow, which is present in the physical system and is modeled by UNSAT-H. By not taking upward capillary flow into account, HELP is expected to overpredict percolation. The UNSAT-H version 2.0 code was recently verified and benchmarked by an independent organization (Baca and Magnuson 1990). The testing documented the capability of the UNSAT-H code to provide a physically realistic and accurate simulation of the processes controlling the movement of water in the unsaturated zone.

The codes were applied independently to simulate the performance of a conceptual model of the landfill barrier. The design to which HELP was applied consisted of a topsoil and subsoil (vertical percolation layers), a geonet for lateral drainage, and a composite barrier consisting of a flexible membrane liner over 0.61 m (2.0 ft) of compacted soil. Figure 1 illustrates this conceptual design. UNSAT-H cannot evaluate lateral drainage or address geosynthetic materials. Because an initial HELP simulation predicted that no drainage flux would occur past the second soil layer, the conceptual model was reduced to the first two layers for this comparison. The first layer consisted of silt loam extending from the surface to a depth of 76.2 cm (30.0 in.), and the second consisted of a fine sand with a thickness of 15.2 cm (6.0 in.), giving a barrier depth of 91.4 cm (36.0 in.). The first layer is unofficially referred to as McGee Ranch silt loam and is tentatively classified as Warden silt loam, a Xerollic Camborthid (Gee et al. 1989a).

The UNSAT-H code was used to simulate 10 years of hydrologic activity in the two-layer conceptual barrier. Daily meteorological data recorded at the Hanford Meteorological Station (HMS) from 1979

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through 1988 were used to describe the boundary condition at the top of the model domain. Soil hydraulic properties were selected based on reported values for Hanford Site soils (Rockhold et al. 1988, Gee et al. 1989a, Gee et al. 1989b). The heat-flow modeling capability of UNSAT-H was not invoked. Initial conditions were computed to match the initial soil moisture conditions specified for the HELP code simulation.

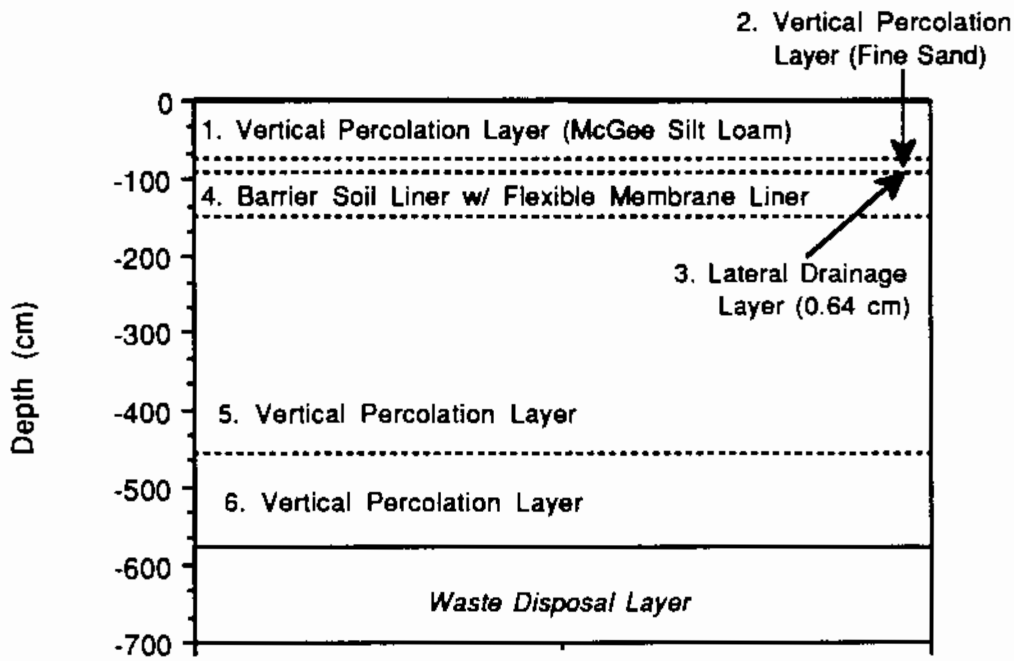

FIGURE 1. Conceptual Design of the NRDWL Barrier

DIFFERENCES IN PHYSICAL INTERPRETATION

The two HELP and UNSAT-H codes interpret the hydrologic processes of the unsaturated zone in different ways; hence, some variation between the predictions obtained using these codes was expected. An important fundamental difference is that while UNSAT-H models both gravitational and capillary flow, HELP only models gravitational flow. Examination of the two codes revealed that the other areas of difference related to this work include the manner in which the soil continuum was discretized, the description of transpiration, and the manner in which the nonlinear relationships between soil moisture, pressure head, and partially saturated hydraulic conductivity were quantified.

The performance of the barrier conceptual model was judged with respect to its ability to limit or prevent drainage. Drainage (also referred to as deep percolation) is a component of the water balance, which for the UNSAT-H code is expressed as

$$P + I - E - T - R - D = \Delta S \qquad (1)$$

where
- P = precipitation
- I = irrigation
- E = evaporation
- T = transpiration
- R = surface runoff
- D = drainage (or deep percolation)
- ΔS = change in storage during the period considered.

This balance is computed with respect to time. The irrigation component is not applicable to this simulation. Precipitation is entered from meteorological records. The remaining variables are simulated by UNSAT-H. The water balance is similar for the HELP code, except that the evaporation and transpiration components are lumped into a single evapotranspiration (ET) component.

The ability of a code to account for capillary flow significantly affects the magnitudes predicted for water-balance components. Capillary flow results in upward movement of water toward the surface and consequently causes more water to be made available for evaporation and transpiration and proportionately less available for drainage. In arid regimes this is particularly important, because infrequent precipitation events result in longer soil-water residence times and consequently more evapotranspiration per unit of water. Because the HELP code does not account for capillary flow, it should predict more percolation than should the UNSAT-H code when all other factors are equal. This was demonstrated by Thompson and Tyler (1984) when they compared HELP version 1.0 and UNSAT1D (a predecessor to UNSAT-H version 2.0 code) simulations for two landfill barrier designs and three climatic regimes. They concluded that under semi-humid and arid climates, more representative results may be obtained using the UNSAT1D code, because the algorithms used in that code account for both gravity and capillary forces.

The discretization of the soil continuum was distinctly different for the two codes. A moisture-routing model, HELP treats hydrologically similar soils as a single layer and reports one representative value for parameters (e.g., soil moisture) describing the properties of that layer. UNSAT-H reports values at increments equal to the discrete division of the soil used in its finite-difference formulation. This permits the variation of a quantity (such as soil moisture) to be analyzed within each layer. Thus, although both codes were used to determine average soil moisture content by layer at a specified time, UNSAT-H was also able to describe the soil moisture profile (variation with depth) of the multiple layers. Using the UNSAT-H code required discretization of the soil continuum into a one-dimensional node network. Figure 2 shows the specific node network used for this simulation, superimposed on a portion of the conceptual model of the landfill barrier illustrated in Figure 1.

Each code accounted for transpiration differently. HELP 2.0 modeled transpiration using a general vegetative growth model requiring estimates of the maximum leaf area index (LAI) and growing-season length. UNSAT-H 2.0 contained an untested general vegetation model and an empirical cheatgrass relationship suited to the Hanford Site (Fayer and Jones 1990). The cheatgrass relationship was chosen for these simulations. The vegetative cover specified by the landfill design was a mixture of Siberian and thickspike wheatgrasses. The cheatgrass relationship had to be forced to mimic wheatgrass with respect to root-zone development (wheatgrass is a perennial; cheatgrass is an annual). Therefore, the root zone was explicitly defined to be the entire model domain (0 to 91.4 cm) commencing the first day of the growing season.

The UNSAT-H 2.0 code models transpiration as a sink term at each node, with the fraction of the transpiration calculated as the root-length density of the node divided by the total root length within the soil profile (Fayer and Jones 1990). An exponential model of root distribution based on root mass data from the end of the 1974 growing season at the Hanford Site (Fayer and Jones 1990) was used for a 10-year simulation. However, the investigators thought the exponential root density placed too much emphasis on water at the top of the profile, ignoring the ability of vegetation to adapt to water distributions in the soil profile and thus underpredicting transpiration. To bracket the uncertainty caused by the selection of a root-zone distribution, two additional 10-year simulations were performed. The first of these was designed to maximize transpiration by means of a constant root-zone distribution. The second was designed to minimize transpiration by explicitly setting it to zero.

The most significant discrepancy between the transpiration models was in the length of the growing season. For both simulations, the first day of the growing season was taken as day-of-year 90 (March 30 or April 1). The end of the growing season used in the HELP simulation was day 292 (October 18 or 19).

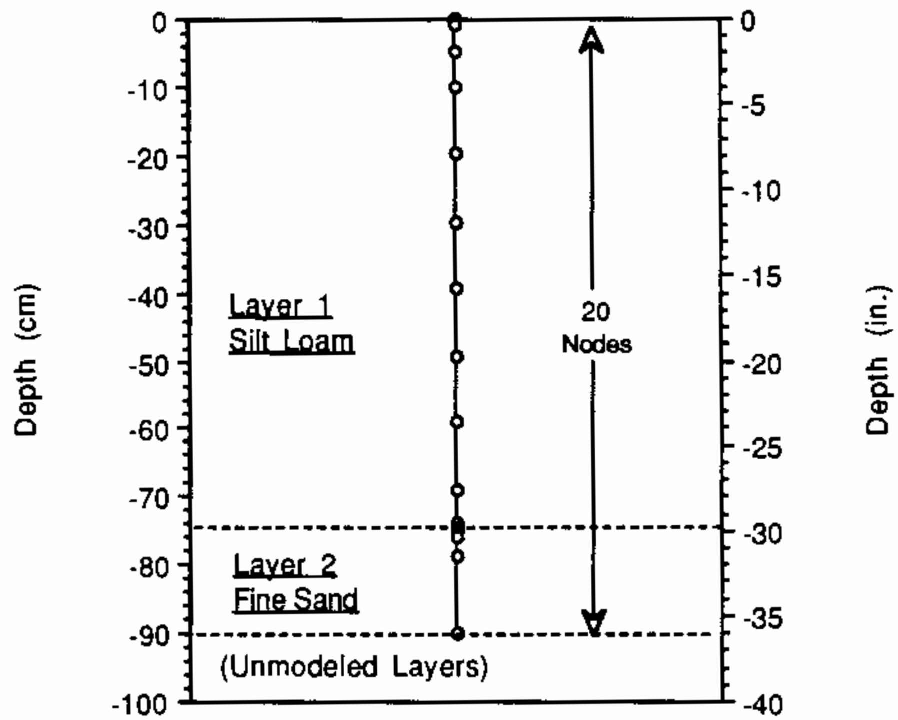

FIGURE 2. Illustration of the Node Network Used for UNSAT-H Simulations

The cheatgrass algorithm encoded in UNSAT-H restricted the last possible date for this period to day 242 (August 30 or 31). Hence, the HELP code can predict transpiration for 50 days more each year than UNSAT-H, given appropriate meteorological and water-availability conditions.

The net effect of using the different vegetation models and different growing-season lengths could not be determined, because HELP reports only the sum of evaporation and transpiration (evapotranspiration). Fortunately, in this simulation great precision was not required of the transpiration prediction, because transpiration is a small portion of the water balance at a semi-arid site. For example, UNSAT-H predicted an average annual transpiration of 1.94 cm (0.76 in.) during the 10 years simulated, which represents 11% of average annual meteoric water. For the limited moisture conditions it is likely that any increase or reduction in transpiration is reflected in the evaporation component, rather than in percolation. Because percolation is the variable of interest, trade-offs between evaporation and transpiration are not important to the water balance so long as the total evapotranspiration does not change significantly. For these reasons the error introduced to the water balance by use of the cheatgrass relations was deemed negligible.

The two models account differently for the nonlinear relationships between soil moisture content, pressure head, and unsaturated hydraulic conductivity. HELP applies the Brooks and Corey relations implicitly (Schroeder et al. 1984), and its input consists of variables such as field capacity, wilting point, and porosity. Field capacity is the soil-moisture content attained in an originally thoroughly wet field- that is, at or near saturation, after the rate of drainage by gravity has markedly decreased (Cuenca, 1989). In agricultural application, field capacity is often identified as existing when water in a soil matrix is under a tension of1.0 m (0.1 bar) to 3.4 m (0.33 bar). The wilting point is defined as the point as which plants cannot recover overnight from excessive drying during the day. Both field capacity and wilting point are fairly subjective inputs, and this reflects the empirical and approximate nature of the HELP code. Values for the field capacity, wilting point, and porosity are related to the function-fitting parameters (air entry head, a fitting exponent, etc.) through some internal, empirically-based method that is invisible to the code operator. In contrast, the UNSAT-H code can use several functional relationships, including the Brooks and Corey and the van Genuchten (van Genuchten 1978, van Genuchten 1980) relationships. UNSAT-H requires the actual fitting parameters for these relations to quantify the nonlinear relations in question. The investigators carefully considered this difference between the HELP and UNSAT-H codes in selecting hydrologic parameters to achieve essentially equivalent treatment of the soil physics.

DIFFERENCES IN REQUIREMENTS FOR CODE INPUT

For both codes, specific input parameters were identified and values chosen to maximize similarity in treatment of the physical processes occurring in the model domain. The chief concern was the hydrologic properties for the soils specified in the conceptual model. The van Genuchten functional relations were chosen for the UNSAT-H code simulations because these curve-fitting parameters (α and n) were available for the soils of interest. To obtain the corresponding inputs for the HELP code [i.e., wilting point (θ_w) and field capacity (θ_{fc})], values of soil moisture were computed using the van Genuchten relations for tension heads of 15 bars (wilting point) and 0.33 bars (field capacity).

Table 1 summarizes the input parameters for both codes for the top layer, consisting of silt loam. The hydraulic properties were those reported for the McGee Ranch silt loam used in the Field Lysimeter Test Facility (Gee et al. 1989a). Lysimeter values for a disturbed soil were chosen in preference to field-scale in situ values because construction of a landfill cover presumably would result in disturbance of the soil structure for the period simulated. Both codes required values for the saturated hydraulic conductivity (K_S). Other input requirements differed. HELP required values for the effective porosity (n_E), the soil moisture at wilting point, the soil moisture at field capacity, while UNSAT-H required values for the residual moisture content (θ_R) and the saturated moisture content (θ_S) as well as the van Genuchten parameters (α and n).

TABLE 1. Summary of Hydrologic Input Parameters Used for Layer 1 (silt loam)

Parameter	Units	HELP	UNSAT-H
K_S	cm h^{-1}	3.564	3.564
	cm s^{-1}	9.90×10^{-4}	9.90×10^{-4}
	in. h^{-1}	1.403	1.403
θ_R	(vol vol^{-1})		0.005
θ_S	(vol vol^{-1})		0.496
n_E	(vol vol^{-1})	0.496	
n	-		1.372
α	cm^{-1}		0.016
	in^{-1}		0.041
θ_w	(vol vol^{-1})	0.06806	
θ_{fc}	(vol vol^{-1})	0.25848	

A specific sand lithology (e.g., Warden silt loam) was not used for the conceptual model's subsoil underlying the silt loam layer; rather, this material was loosely described as a "fine sand." The saturated hydraulic conductivity was computed as the average of values reported in Fruland et al. (1989) for the Hanford Site Solid Waste Landfill, from samples taken to a depth of 7.62 m (25 ft) in wells SW-1 and SW-5. The van Genuchten curve-fitting parameters, the saturated moisture content, and the residual moisture content that were used in the UNSAT-H simulation are those of the Hanford AP-1g sand (Smoot and Sagar 1990). Again, the wilting-point and field-capacity values were calculated using the van Genuchten relations at 15 bars and 0.33 bars tension head, respectively, and these values were provided to the operators of the HELP code. The values for hydrologic properties for the sand layer are listed in Table 2. Results of the UNSAT-H simulation, discussed later in this report, indicated that very little flux, [0.12 cm (0.05 in.)], occurred between the silt loam layer and the underlying sand layer. Hence, the actual values used for the sand layer were inconsequential with respect to their effect on simulation results. If a large amount of percolation though this layer had been predicted, however, more precise information for the sand layer would have been required.

Computation of the soil moisture value for the wilting point provided an additional UNSAT-H code input for the transpiration submodel. This parameter was used to quantify a lower limit below which transpiration would not occur (Fayer and Jones 1990). The field capacity value was not an input parameter for the UNSAT-H.

TABLE 2. Summary of Hydrologic Input Parameters Used for Layer 2 (fine sand)

Parameter	Units	HELP	UNSAT-H
K_S	cm h^{-1}	17.1	17.1
	cm s^{-1}	0.00475	0.00475
	in. h^{-1}	6.732	6.732
θ_R	(vol vol^{-1})		0.010
θ_S	(vol vol^{-1})		0.445
n_E	(vol vol^{-1})	0.445	
n	-		2.8036
α	cm^{-1}		0.07255
	$in.^{-1}$		0.18428
θ_w	(vol vol^{-1})	0.0326	
θ_{fc}	(vol vol^{-1})	0.0831	

The initial conditions the WHC staff selected for the HELP model in terms of water content (volume basis) for each soil layer. The corresponding tension head was back-calculated using the van Genuchten relations to obtain an equivalent set of initial conditions for use with UNSAT-H. For the top layer of silt loam, the initial soil moisture was 0.071 (vol vol^{-1}), for which the computed tension head was 13,600 cm. The initial soil moisture content for the underlying layer of fine sand was 0.033 (vol vol^{-1}), for which the computed tension head was 15,300 cm.

UNSAT-H SIMULATION RESULTS

The parameters of interest for evaluating barrier performance for both UNSAT-H version 2.0 and HELP version 2.0 were the components of the water balance for the two simulated layers of the barrier. These parameters included precipitation (an input parameter that should be identical for each code), evapotranspiration, profile moisture storage, and percolation through the base of the second layer. To provide a set of variables common to both simulations for the comparison, it was necessary to sum the water-balance values for both layers. An annual period of summation based on the calendar year (January 1 to December 31) was selected for conformity with the output reported by HELP.

Tables 3, 4, and 5 list the water-balance components on a calendar-year basis predicted by the UNSAT-H code for the 10-year simulations for the exponential-root-density condition, the constant-root-density condition, and the zero-transpiration condition, respectively. The components apply to the total barrier, i.e., to both layers. These values, except for the input precipitation values, were generated by the UNSAT-H code as daily output, from hourly or shorter computations within mass-balance error constraints. Although evaporation and transpiration were accounted for and reported separately by UNSAT-H, these values can be summed for comparison with the evapotranspiration values predicted by the HELP code. The change in moisture storage is computed as the difference in total soil moisture storage on December 31 of the current and previous years. Figure 3 illustrates the relative magnitudes of the non-zero water-balance components annually for the constant-root-density simulations (Table 4).

For reference, two other parameters are included in Tables 3, 4, and 5. The absolute moisture storage on December 31 of the year is provided for comparison with the HELP code simulation predictions of total water storage. The annual mass-balance error is included to quantify the confidence in UNSAT-H predictions of the water-balance components. The maximum mass-balance error for any day of a simulation was explicitly specified to be 1.0×10^{-4} cm (3.94×10^{-5} in.). UNSAT-H reduces time steps from the maximum 1-h increment as needed during simulations to achieve the necessary precision to constrain this error to the specified limit. The maximum mass-balance error for any single year of any simulation was 0.0772 cm (0.0304 in.). For the 10-year constant-root-zone simulation the total mass-balance error was 0.5697 cm (0.2243 in.).

No surface runoff was predicted by UNSAT-H in any simulation. Although surface runoff is a multi-dimensional phenomenon, it is used as a water-balance component by UNSAT-H to account for the infiltration capacity of the soil. The rate of infiltration may be less than the rate of precipitation when the infiltration capacity of the soil is exceeded (Linsley et al. 1982, Freeze and Cherry 1979). If this occurs, excess

TABLE 3. Annual Water-Balance Components Predicted by UNSAT-H 2.0 for the Exponential-Root-Density Condition

Year	P (cm)	E (cm)	T (cm)	R (cm)	D (cm)	ΔS (cm)	S (cm)	error (cm)
1978							6.2641	
1979	14.0460	9.1524	0.6500	0.0000	0.0000	4.1829	10.4470	0.0609
1980	24.5870	19.5650	2.0594	0.0000	0.0000	2.8950	13.3420	0.0676
1981	17.8820	15.7580	1.9234	0.0000	0.0000	0.1490	13.4910	0.0516
1982	20.2690	17.4520	2.1998	0.0000	0.0000	0.5570	14.0480	0.0602
1983	28.1180	23.3240	2.3411	0.0000	0.0000	2.3760	16.4240	0.0772
1984	18.4400	19.9400	2.3297	0.0000	0.0000	-3.8880	12.5360	0.0588
1985	12.9540	10.4130	1.6794	0.0000	0.0000	0.8130	13.3490	0.0491
1986	18.0090	16.7970	1.9764	0.0000	0.0000	-0.8170	12.5320	0.0524
1987	12.9030	12.0400	1.8912	0.0000	0.0000	-1.0690	11.4630	0.0406
1988	10.5920	10.9790	1.6025	0.0000	0.0000	-2.0316	9.4314	0.0422
Mean	17.7800	15.5420	1.8653	0.0000	0.0000	0.3167	12.7063	0.0561
Total	177.800	155.420	18.653	0.000	0.000	3.167	-	0.561

TABLE 4. Annual Water-Balance Components Predicted by UNSAT-H 2.0 for the Constant-Root-Density Condition

Year	P (cm)	E (cm)	T (cm)	R (cm)	D (cm)	ΔS (cm)	S (cm)	error (cm)
1978							6.2641	
1979	14.0460	9.2933	0.6626	0.0000	0.0000	4.0309	10.2950	0.0593
1980	24.5870	19.6760	3.2549	0.0000	0.0000	1.5860	11.8810	0.0702
1981	17.8820	15.1560	2.8617	0.0000	0.0000	-0.1880	11.6930	0.0525
1982	20.2690	17.0070	2.6935	0.0000	0.0000	0.5070	12.2000	0.0619
1983	28.1180	22.4420	3.2312	0.0000	0.0000	2.3690	14.5690	0.0752
1984	18.4400	18.8420	3.3836	0.0000	0.0000	-3.8440	10.7250	0.0596
1985	12.9540	9.7279	2.6331	0.0000	0.0000	0.5450	11.2700	0.0478
1986	18.0090	15.5350	3.0123	0.0000	0.0000	-0.5940	10.6760	0.0547
1987	12.9030	11.4710	2.3913	0.0000	0.0000	-1.0035	9.6725	0.0449
1988	10.5920	10.4220	2.0722	0.0000	0.0000	-1.9459	7.7266	0.0435
Mean	17.7800	14.9572	2.6196	0.0000	0.0000	0.1463	11.0708	0.0570
Total	177.800	149.572	26.196	0.000	0.000	1.463	-	0.570

TABLE 5. Annual Water-Balance Components Predicted by UNSAT-H 2.0 for the Zero-Transpiration Condition

Year	P (cm)	E (cm)	T (cm)	R (cm)	D (cm)	ΔS (cm)	S (cm)	error (cm)
1978							6.2641	
1979	14.0460	9.4936	0.0000	0.0000	0.0000	4.4929	10.7570	0.0595
1980	24.5870	21.1880	0.0000	0.0000	0.0000	3.3280	14.0850	0.0719
1981	17.8820	17.6570	0.0000	0.0000	0.0000	0.1740	14.2590	0.0501
1982	20.2690	19.5610	0.0000	0.0000	0.0000	0.6480	14.9070	0.0602
1983	28.1180	25.7520	0.0000	0.0000	0.0000	2.2920	17.1990	0.0734
1984	18.4400	22.2980	0.0000	0.0000	0.0000	-3.9120	13.2870	0.0546
1985	12.9540	11.8540	0.0000	0.0000	0.0000	1.0540	14.3410	0.0464
1986	18.0090	19.0470	0.0000	0.0000	0.0000	-1.0880	13.2530	0.0498
1987	12.9030	13.7720	0.0000	0.0000	0.0000	-0.9120	12.3410	0.0424
1988	10.5920	12.5390	0.0000	0.0000	0.0000	-1.9890	10.3520	0.0424
Mean	17.7800	17.3162	0.0000	0.0000	0.0000	0.4088	13.4781	0.0551
Total	177.800	173.162	0.000	0.000	0.000	4.088	-	0.551

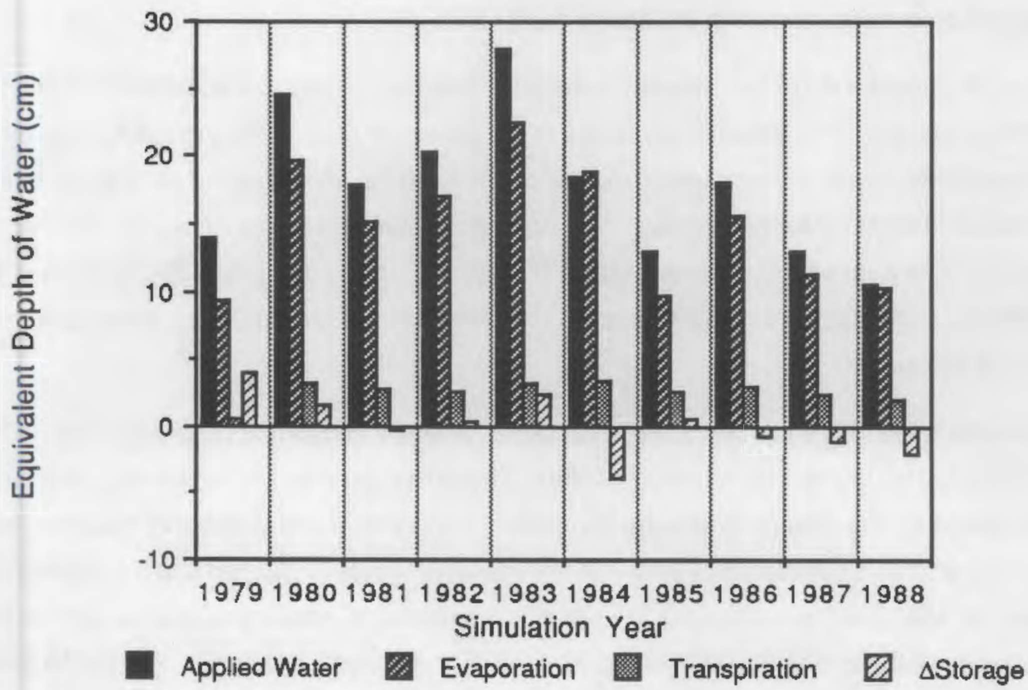

FIGURE 3. Non-Zero Water-Balance Components for Constant-Root-Density Simulations

water which cannot infiltrate the soil is present at the surface. UNSAT-H assigns this excess to the surface-runoff term. In reality, the ultimate fate of this water depends on the topography of the surrounding area. In assigning the water to surface runoff, the underlying assumption of the UNSAT-H algorithm is that the excess water is removed through overland flow.

The affect of the root-zone-density choice in the UNSAT-H model is reflected in Figures 4, 5, and 6, which show the different annual magnitudes of evaporation, transpiration, and change in water storage, respectively, resulting from the three conditions applied. Because the exponential root density was considered too constraining compared with actual transpiration, two other conditions were simulated to bracket the transpiration term: a zero-transpiration condition and a constant-root-zone condition (maximizing transpiration).

One of the strengths of using a discrete-based approach such as the one embodied in the UNSAT-H code is the ability to examine the variation of a parameter with depth. Figures 7 through 10 depict the soil moisture profile predicted by UNSAT-H at four specific dates of each year, March 30, June 30, September 30, and December 31, respectively. For each figure, 10 lines represent the predicted soil moisture profile on that date for each of the 10 simulated years. These figures do not indicate the absolute maximum or minimum of soil moisture predicted by UNSAT-H, but rather are meant to illustrate the nature of water movement and storage in the barrier model soils.

The apparent discontinuity of soil moisture across the interface of layers 1 and 2 in Figures 7 though 10 merits some explanation. The discontinuity is due to the presence of a capillary break formed by the placement of a relatively coarse material, sand, directly underneath the finer-textured silt loam soil. In this arrangement, the silt loam close to the interface must approach saturation before water will flow into the sand layer, which is at or near atmospheric pressure. The hydraulic head, the actual driving force of soil water movement, is continuous across the interface. This effect is largely responsible for the effectiveness of the simulated barrier.

The years simulated, 1979 through 1988, included a generally wet period (approximately 1979 through 1983) followed by drying (1984 through 1988). These two periods are reflected by the tendency toward positive values for the change in storage component during the first 5 years and toward negative values for the last 5 years. Examination of year-end soil moisture profiles indicated that the highest moisture storage was for 1983, but the capacity of the soil to store the water was not exceeded, and no percolation was predicted by UNSAT-H at the base of the model (i.e., the bottom of layer 2). The model predicted a small amount of interfacial flux, ranging from zero for the constant-root density simulation to 0.0005 cm (0.00020 in.) for the zero-transpiration simulation. This flux represented the net water movement across the interface between the two layers during the 10 years simulated, and resulted in a small increase in the

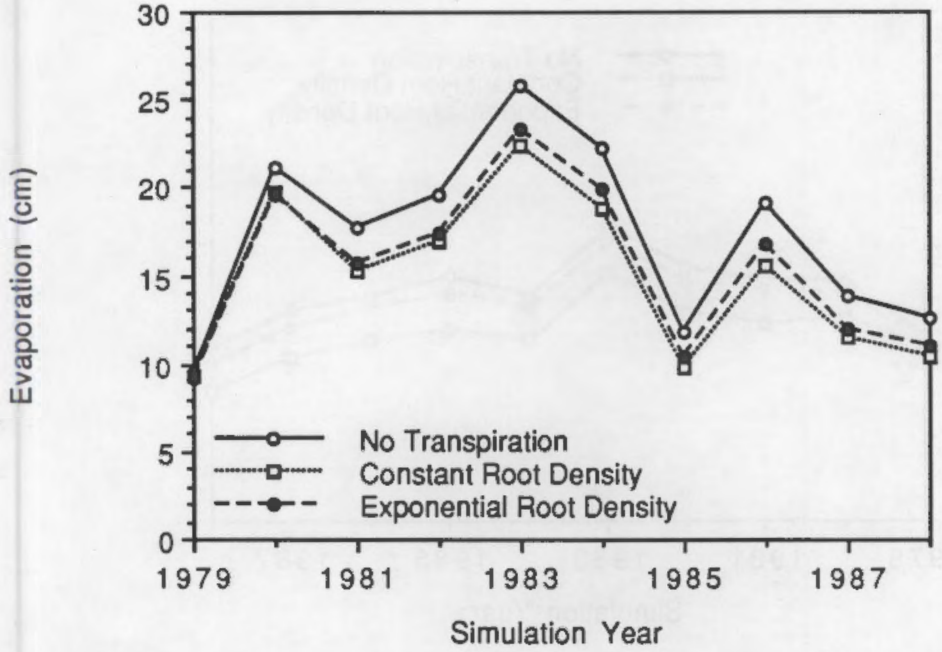

FIGURE 4. Comparison of Total Calendar-Year Evaporation Predictions

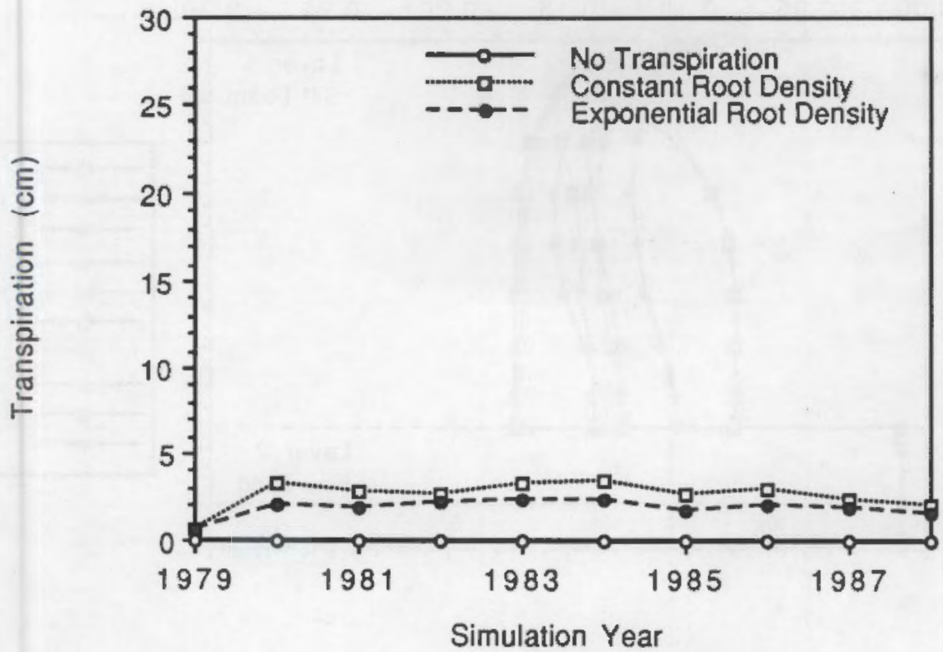

FIGURE 5. Comparison of Total Calendar-Year Transpiration Predictions

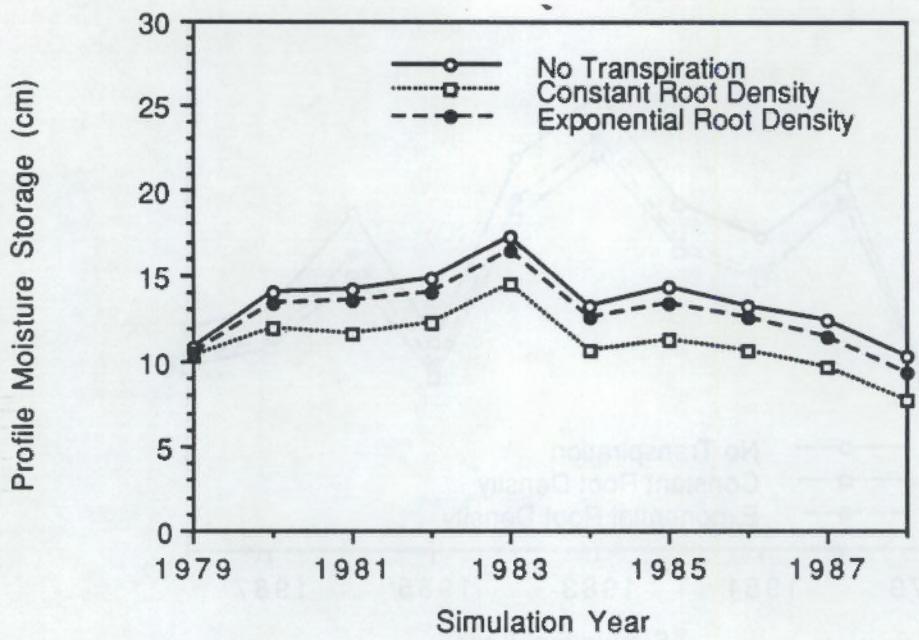

FIGURE 6. Comparison of Soil Moisture Storage Predictions at December 31

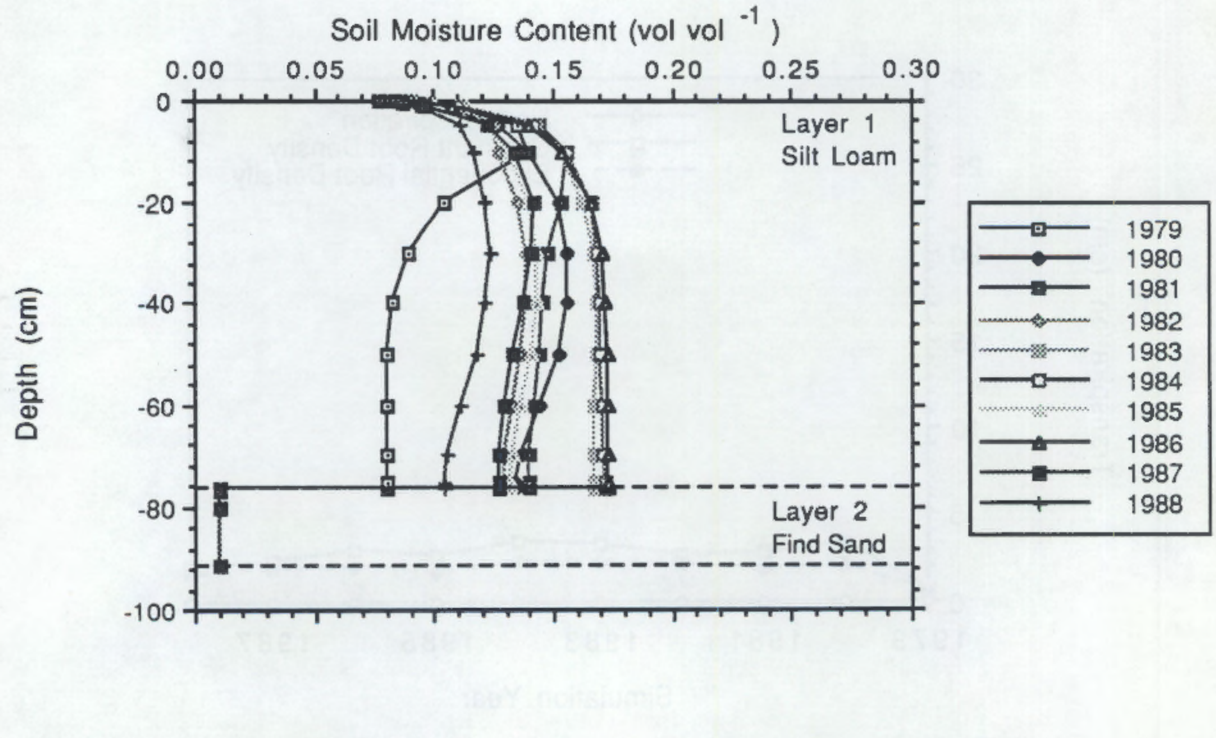

FIGURE 7. Soil Moisture Profile on March 31 of Each Simulated Year

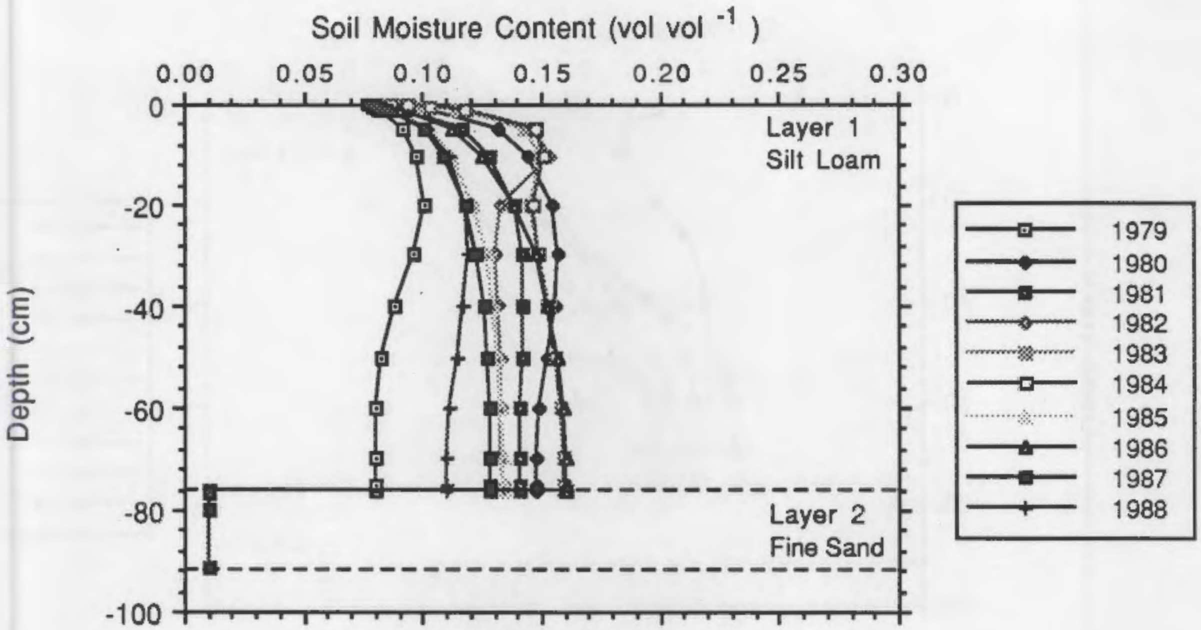

FIGURE 8. Soil Moisture Profile on June 30 of Each Simulated Year

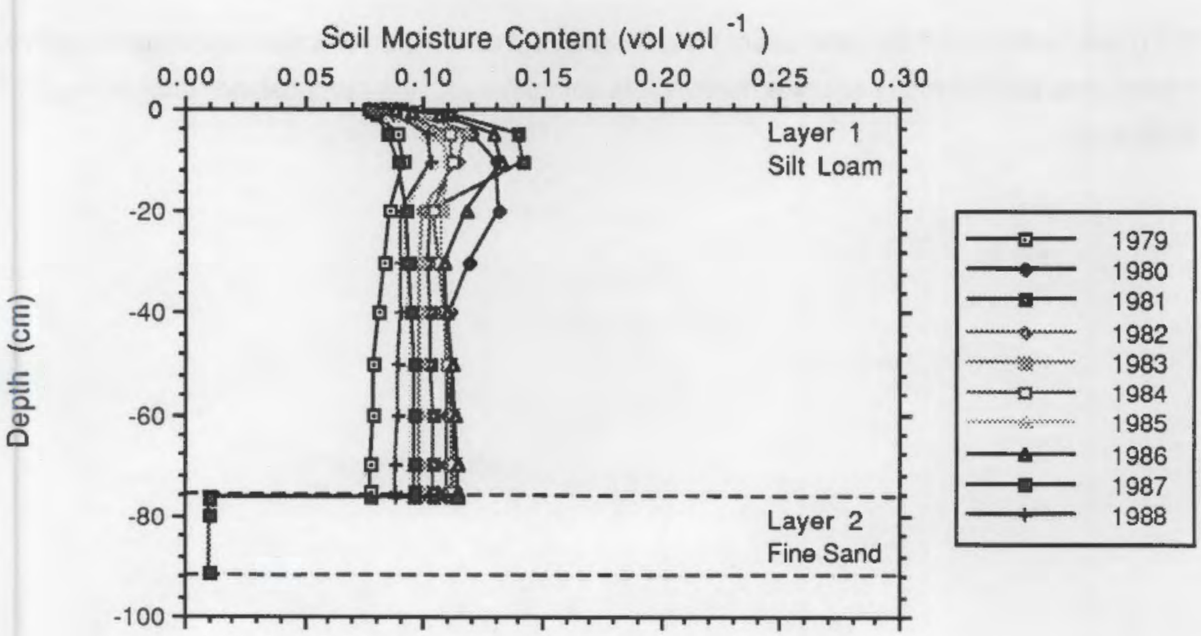

FIGURE 9. Soil Moisture Profiles on September 30 of Each Simulated Year

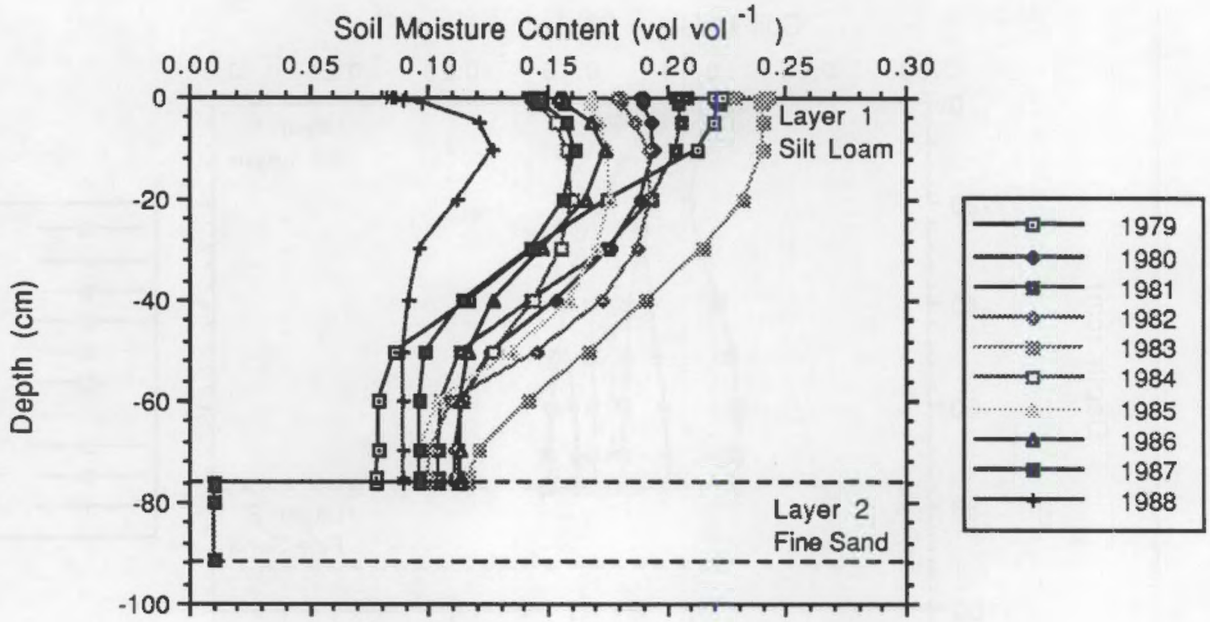

FIGURE 10. Soil Moisture Profile on December 31 of Each Simulated Year

soil moisture content of the sand layer. In reality such a small amount of water movement would not be measurable, and the total amount is meaningless compared with the mass-balance error of these simulations.

COMPARISON OF SIMULATION RESULTS

Westinghouse Hanford staff generated HELP 2.0 results by independently modeling the NRDWL conceptual design shown in Figure 1. Results are summarized on an annual basis in Table 6. Table 6 is similar to Tables 3, 4, and 5, which list water-balance components predicted by UNSAT-H 2.0 for the NRDWL simulations. As these tables show, HELP 2.0 reports only evapotranspiration, while UNSAT-H 2.0 distinguishes between evaporation (E) and transpiration (T). Evapotranspiration values predicted by HELP 2.0 are shown in Table 6 under the heading "E + T."

Table 7 provides an initial basis for comparison. The table lists the cumulative water-balance components for each of the 10-year simulations (three UNSAT-H 2.0 simulations and one HELP 2.0 simulation). The UNSAT-H 2.0 and the HELP 2.0 simulations both used HMS data collected from 1979 through 1988 as the source of precipitation input values. Therefore, the difference in these values (Table 7) should be zero. However, this was not the case. Because these values were not in agreement, the original HMS climatological-data reports were checked. Table 8 contrasts annual total precipitation recorded in those reports with the total precipitation values entered for the UNSAT-H 2.0 and HELP 2.0 simulations. The UNSAT-H 2.0 input values and the HMS record differed only by 0.04 in. (0.10 cm). The values applied in the HELP 2.0 simulations may, therefore, have been subject to data-entry errors. This was unfortunate because it obscures interpretation of the differences in code outputs for these simulations. The 2.13-cm (0.84-in.) difference in precipitation values is far larger than the mass-balance errors in any of the simulations (see Tables 3, 4, 5, and 6).

Barrier effectiveness is sometimes judged in terms of the proportion of precipitation that is returned to the atmosphere as evaporation and transpiration. Under this criterion, the efficiency (e) of a barrier is defined as

$$e = (E + T)/P \qquad (2)$$

where E is evaporation, T is transpiration, and P is precipitation. Figure 11 illustrates the 10-year efficiency predicted from HELP 2.0 simulation results and from the three UNSAT-H 2.0 simulations of the NRDWL conceptual design.

TABLE 6. Annual Water-Balance Components Predicted by HELP 2.0

Year	P (cm)	E+T (cm)	R (cm)	D (cm)	ΔS (cm)	S (cm)	error (cm)
1978						34.0614	
1979	14.3002	10.7010	0.0000	0.0000	3.6068	37.6682	-0.0076
1980	24.6380	24.4272	0.0000	0.0000	0.2032	37.8714	0.0076
1981	17.8816	18.2194	0.0000	0.0000	-0.3302	37.5412	-0.0076
1982	20.4978	19.5199	0.0000	0.0000	0.9652	38.5064	0.0127
1983	28.1178	25.0114	0.0000	0.0922	3.0226	41.5290	-0.0084
1984	18.4658	23.7617	0.0000	0.2670	-5.5626	35.9664	-0.0003
1985	13.0048	12.2530	0.0000	0.0000	0.7620	36.7284	-0.0102
1986	17.6022	17.8537	0.0000	0.0000	-0.2540	36.4744	0.0025
1987	14.2748	14.2951	0.0000	0.0000	-0.0254	36.4490	0.0051
1988	11.1506	13.5331	0.0000	0.0000	-2.3876	34.0614	0.0051
Mean	17.9934	17.9575	0.0000	0.0359	0.0000	37.2796	-0.0001
Total	179.934	179.576	0.000	0.359	0.000	-	-0.001

TABLE 7. Comparison of 10-Year Simulation Water-Balance-Component Totals

Components	HELP	UNSAT-H Exponential	UNSAT-H Constant	UNSAT-H No Transpiration
P, cm	179.93	177.80	177.80	177. 80
R, cm	0.00	0.00	0.00	0.00
E + T, cm	179.58	174.07	175.77	173.16
D, cm	0.36	0.00	0.00	0.00
ΔS, cm	0.00	0.32	0.15	0.41
(E+T)/P	99.8%	97.9%	98.9%	97.4%

TABLE 8. Comparison of HELP 2.0 and UNSAT-H 2.0 Annual Precipitation Input Values

Year	HMS Records (in.)	UNSAT-H Input (in.)	HELP Input (in.)
1979	5.56	5.53	5.63
1980	9.68	9.68	9.70
1981	7.04	7.04	7.04
1982	7.98	7.98	8.07
1983	11.07	11.07	11.07
1984	7.27	7.26	7.27
1985	5.10	5.10	5.12
1986	7.09	7.09	6.93
1987	5.07	5.08	5.62
1988	4.18	4.17	4.39
Total	70.04	70.00	70.84

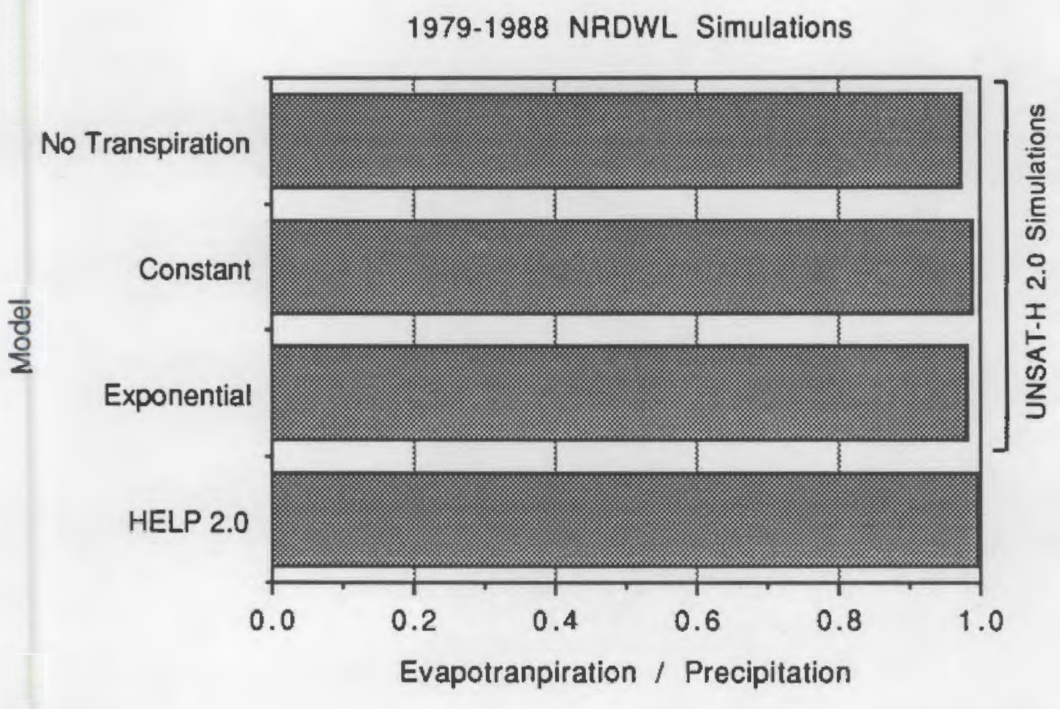

FIGURE 11. Comparison of Barrier Efficiency Predicted by HELP and UNSAT-H Models

CONCLUSIONS

UNSAT-H version 2.0 was used to simulate the performance of a two-layer landfill barrier for a period of 10 years, using actual meteorological data for 1979 through 1988 and appropriate soil-property values. In this simulation, UNSAT-H predicted 0.125 cm (0.0491 in.) of percolation from the base of the top layer of silt loam. The model predicted no percolation past the base of the underlying sand layer. The computed mass-balance error, representing the total mass unaccounted for in the 10-year simulation, ranged from 0.55 cm (0.217 in.) to 0.57 cm (0.224 in.) for the three conditions simulated (exponential-root-density, constant-root-density, and zero-transpiration).

Three UNSAT-H version 2.0 simulations representing different treatments of the root-density term were compared with a HELP 2.0 simulation performed by WHC personnel. Discrepancies in precipitation values derived from HMS records were inspected and compared with original HMS reports. This comparison demonstrated that the HELP 2.0 simulation input contained a total error of 2.03 cm (0.80 in.) precipitation for the 10-year period, while the UNSAT-H 2.0 simulation input records were only in error by 0.10 cm (0.04 in.) for the same period. Data-entry errors were suspected to be at least partially responsible for the discrepancies in the HELP precipitation input. Because the input precipitation values were not precisely equal, caution was exercised in comparing results of these simulations. Yet in spite of the larger amount of applied water in the HELP 2.0 simulation, that code still predicted a greater portion of precipitation returned to the atmosphere through evapotranspiration than did any of the UNSAT-H 2.0 simulations. HELP 2.0 also predicted percolation past the base of the barrier (0.36 cm [0.142 in.] in 10 years), while UNSAT-H 2.0 predicted no percolation in any simulation conducted. These results confirm that the HELP 2.0 code is conservative for the semi-arid climate of the Hanford Site for the conditions simulated.

The comparative simulations reported here were sufficient to demonstrate the conservative nature of the HELP 2.0 code for the NRDWL barrier conceptual design under recent Hanford Site meteorological conditions. However, these results cannot be extrapolated to more stressful conditions involving larger amounts of barrier percolation. It is possible that if precipitation had been greater, the HELP code might have predicted more percolation while UNSAT-H continued to predict none. For a better assessment of code capabilities, the models should be applied to conditions involving sizable percolation and should be compared with actual soil-moisture data.

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