WATER BALANCE MODELING OF EARTHEN FINAL COVERS

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ABSTRACT: Hydrologic data measured from two earthen final cover test sections constructed on actual landfill final covers are presented with predictions made using two water balance models (HELP and UNSAT-H). Both test sections were constructed as traditional resistive barriers comprised of a compacted fine-grained layer overlain by a vegetated surface layer. Hydrologic and meteorological data including precipitation, air temperature, solar radiation, relative humidity, wind speed, and wind direction were collected at each test section for three years. Percolation, overland flow, and soil water content were monitored continuously. Predictions of the water balance were made using the water balance models HELP and UNSAT-H. In general, HELP overpredicted percolation, sometimes significantly, and UNSAT-H slightly underpredicted percolation. However, both models captured the seasonal variations in overland flow, evapotranspiration, soil water storage, and percolation. UNSAT-H captured these variations more accurately than HELP.

INTRODUCTION

Landfill designers are often confronted with the task of estimating the rate at which leachate is produced after closure of a landfill. The most significant factor contributing to leachate production is percolation through the final cover (Farquhar 1989). Thus, if the volume of leachate is to be predicted, percolation through the final cover must be assessed. Geotechnical practitioners often use the U.S. Environmental Protection Agency's water balance model Hydrologic Evaluation of Landfill Performance (HELP) (Schroeder et al. 1994) for predicting percolation through final covers and postclosure leachate generation rates. The water balance model Unsaturated Water and Heat Flow (UNSAT-H) (Fayer and Jones 1990), developed at Pacific Northwest Laboratory, can also be used to make water balance predictions.

HELP and UNSAT-H were selected for evaluation in this study because their formulations are distinctly different. HELP employs simplified schemes to model the routing of water through soil layers and removal of water via overland flow and evapotranspiration and contains databases describing meteorological conditions, vegetation, and saturated and unsaturated soil properties. HELP is operated interactively and a simulation typically requires little processing time on a desktop computer because simplified algorithms are employed. In contrast, UNSAT-H uses a finite-difference implementation of a modified form of Richards' equation that describes unsaturated liquid and vapor flow in soil layers and water removal through plant roots (i.e., transpiration). In addition, UNSAT-H employs rigorous mechanistic methods to compute the surface energy balance and manage water near the soil surface. The boundary conditions employed to solve Richards' equation specify how precipitation is partitioned into overland flow and infiltration and how water is removed by evaporation. Extensive data describing meteorological conditions, unsaturated soil properties, and characteristics of the vegetation are required by UNSAT-H, and no databases are included that provide this information. UNSAT-H is run in a batch mode (noninteractively) and requires extensive processing time even on highspeed workstations (some simulations require several days to finish).

Other programs simulating unsaturated flow could have been used instead of UNSAT-H. However, review of available programs showed that UNSAT-H employed the best procedures for simulating the hydrology of earthen covers, particularly the surface conditions such as overland flow and evaporation. In addition, UNSAT-H is in the public domain.

Because their formulations and input requirements differ significantly, predictions made by HELP and UNSAT-H are likely to differ in accuracy. Some studies conducted by others (Peyton and Schroeder 1988; Barnes and Rodgers 1988; Peters et al. 1986; Gee and Kirkham 1984; Thompson and Tyler 1984; Nichols 1991) have attempted to assess the accuracy of HELP. However, in each of these studies factors exist that preclude making definitive conclusions regarding model accuracy. For example, key input data are not measured (e.g., hydraulic characteristics of the soil layers are not measured), ambiguities exist in the data, or comparisons with field data have not been made (Khire 1995). In addition, an assessment of the accuracy of UNSAT-H has not been made using large-scale field data, particularly for covers designed as resistive barriers [e.g., Fayer et al. (1992)]. The term "resistive barrier" used here, originally coined by Schulz et al. (1988), refers to earthen barriers that employ a layer of compacted fine-grained soil or a geosynthetic (geosynthetic clay liner or geomembrane as the barrier layer) as the primary means to limit flow.

The purpose of this paper is to describe the accuracy of water balance predictions for resistive barriers made using HELP and UNSAT-H. The writers have used HELP and UNSAT-H to simulate the hydrology of two large-scale instrumented earthen covers constructed on landfills. Hydrologic simulations using HELP and UNSAT-H were run for the period from June 1992 to May 1995. The test sections were constructed in different climates (humid and semiarid) so that the effect of climate on accuracy of predictions could be addressed. Input data measured in the laboratory or in the field were used to the greatest extent possible. Data continuity, accuracy, and reliability received special attention (Benson et al. 1993, 1994; Khire et al. 1994) such that a definitive assessment of the accuracy of the models could be made.

TEST SECTIONS

The test sections were constructed as part of final cover activities at Live Oak Landfill, Atlanta, and the Greater Wenatchee Regional Landfill, East Wenatchee, Washington. Each test section is 30 m × 30 m in areal extent, of which a 12.2 m × 18.3 m region is used for monitoring.

Both test sections are designed as traditional earthen resistive barriers. The test section in Atlanta, referred to as the Live Oak test section, has a 90-cm-thick layer of compacted Georgia red clay, and a 15-cm-thick vegetated silty surface layer.

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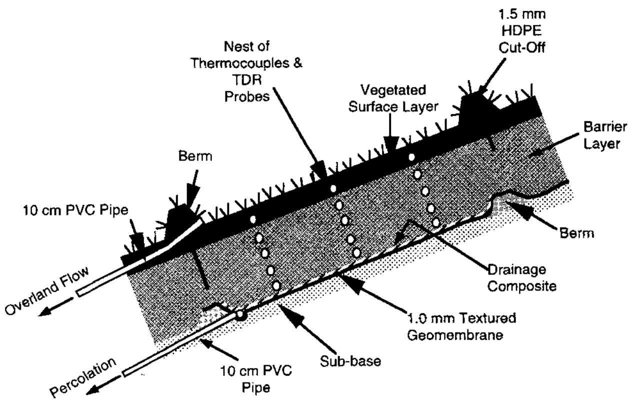

FIG. 1. Schematic of Instrumented Test Section

The test section in East Wenatchee (referred to as the Wenatchee test section) has a 60-cm-thick compacted silty clay barrier layer and a 15-cm-thick silty vegetated surface layer. The barrier layers were compacted in lifts 30 cm thick with a sheepsfoot compactor. The surface layers were not compacted and were seeded to grow vegetation. Benson et al. (1994) and Khire (1995) provide a detailed description of construction of the test sections, soil properties, and data collection and verification procedures.

The test sections are instrumented for continuous monitoring of climatic data, overland flow, soil water content, and percolation. Percolation is collected using a lysimeter 12.2 m wide by 18.3 m long (Fig. 1) constructed using a high density polyethylene (HDPE) geomembrane and a geocomposite drain. The large pores in the geocomposite drain can potentially induce a capillary barrier effect. However, this effect is also likely to occur in actual covers placed over waste because of the larger pores that frequently exist in waste, daily cover, and interim cover.

Overland flow is collected via diversion berms and a collection pipe (Fig. 1). Time domain reflectometry (TDR) is used to measure soil water content. Lateral flow from the surface and the barrier layers is not measured. Because the hydraulic conductivity of all the soil layers is very low and the soils are rarely saturated (Khire et al. 1994), little lateral flow occurs. Benson et al. (1994) indicate that error in the water balance incurred by ignoring the lateral flow is less than 1.5% at Live Oak and much smaller in Wenatchee. Meteorologic and hydrologic data have been obtained continuously since June 1992 for the test section at Live Oak and since November 1992 for the test section at Wenatchee.

Percolation, overland flow, and soil water contents are measured directly. To compute soil water storage, soil water contents are integrated over the depth of a test section. Evapotranspiration E_t is computed by subtracting daily overland flow O_f, percolation P_r, and the change in the soil water storage ΔS_w from daily precipitation P

$$E_t = P - O_f - P_r - \Delta S_w \quad (1)$$

OVERVIEW OF HELP AND UNSAT-H

HELP Model

Schroeder et al. (1994) provide a detailed description of the algorithm HELP (Version 3.01) uses to route water into different components of the water balance. The portion of the methodology relevant to earthen final covers is discussed briefly here. A schematic showing how HELP handles the water balance is shown in Fig. 2(a).

HELP requires that each layer of a landfill cover be specified as a vertical percolation layer, barrier soil liner, lateral drainage layer, or geomembrane liner depending on the function and hydraulic properties of the layer. In a vertical percolation layer, unsaturated flow of water occurs in the vertically downward direction. A barrier layer (soil liner) has low saturated hydraulic conductivity and is assumed to always be saturated. Percolation from the barrier layer is assumed to occur whenever water ponds on its surface. A lateral drainage layer has moderate to high hydraulic conductivity and is underlain by a liner.

HELP divides precipitation into overland flow and infiltration based on a modified version of the SCS runoff curve number method. The SCS runoff curve number used by HELP is based on the hydraulic conductivity of the surface layer, condition of vegetation (i.e., bare, poor, good, etc.), and the

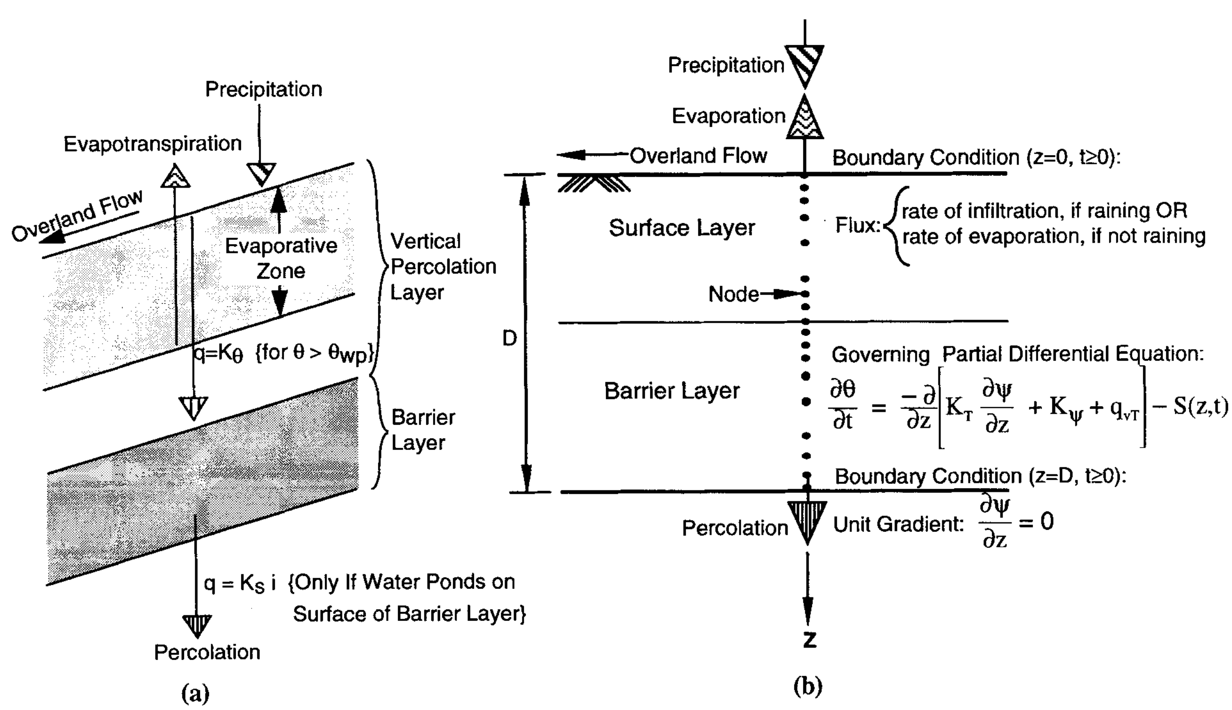

FIG. 2. Schematic Representation of Water Balance Computations by: (a) HELP; (b) UNSAT-H

slope and slope length of the cover. If the air temperature is ≤0°C, precipitation is stored as a snowpack. The snowpack is allowed to melt only when the air temperature rises above 0°C and, if the soil is deemed frozen, essentially all melt water is shed as overland flow. Water that infiltrates remains in storage or is subjected to evapotranspiration, lateral drainage, and percolation.

Water is removed by evapotranspiration only from the evaporative depth of the cover, which is defined as the maximum depth from which water may be removed by evapotranspiration. HELP provides default values for the evaporative depth based on the location of the site and the condition of the vegetation. The quantity of water removed by evapotranspiration is computed using an approach recommended by Ritchie (1972) and is a function of potential evapotranspiration (maximum possible evapotranspiration) and the availability of water from soil water storage. Potential evapotranspiration is calculated using a modified form of Penman's (1963) equation.

If the layer is a vertical percolation layer, water from soil water storage is routed based on a unit hydraulic gradient in the vertically downward direction [Fig. 2(a)] using Darcy's law and unsaturated hydraulic conductivity (K_θ) computed using Campbell's (1974) equation. Water from the vertical percolation layer is removed by percolation or evapotranspiration if the water content is above the wilting point (θ_{wp}).

If the layer is a barrier soil liner, the saturated hydraulic conductivity and the depth of ponding of water on the surface of the barrier soil liner are used with Darcy's law to compute percolation [Fig. 2(a)]. The saturated hydraulic conductivity is used because the barrier soil liner is always assumed to be saturated.

UNSAT-H Model

UNSAT-H (Version 2.0) is a one-dimensional, finite-difference computer program developed at Pacific Northwest Laboratory by Fayer and Jones (1990). UNSAT-H can simulate the water balance of landfill covers as well as soil heat flow (Fayer and Jones 1990; Fayer et al. 1992), but is used only for water balance simulations in this study. UNSAT-H simulates water flow through soils by solving Richards' partial differential equation and simulates heat flow by solving Fourier's heat conduction equation. This approach for analyzing water flow in earthen covers is distinctly different from the approach used by HELP. The form of Richards' equation solved by UNSAT-H is

$$\frac{\partial\theta}{\partial\Psi}\frac{\partial\Psi}{\partial t} = \frac{-\partial}{\partial z}\left[K_T\frac{\partial\Psi}{\partial z} + K_\Psi + q_{vT}\right] - S(z, t) \qquad (2)$$

where Ψ = matric suction; t = time; z = vertical coordinate; θ = volumetric water content; K_Ψ = unsaturated hydraulic conductivity; $K_T = K_\Psi + K_{v\Psi}$, where $K_{v\Psi}$ = isothermal vapor conductivity; q_{vT} = thermal vapor flux density; and $S(z, t)$ = sink term representing water uptake by vegetation. Thermal vapor flux density q_{vT} is computed by applying Fick's law to vapor diffusion. Hysteresis of the soil water characteristic curve is not considered.

A schematic showing how UNSAT-H computes the water balance is shown in Fig. 2(b). UNSAT-H separates precipitation falling on a landfill cover into infiltration and overland flow. Overland flow occurs when water applied to the soil surface exceeds the infiltration capacity of the soil profile immediately prior to or during rainfall. Thus, the fraction of precipitation shed as overland flow depends on the saturated and unsaturated hydraulic conductivities of the soils constituting the final cover. UNSAT-H does not consider absorption and interception of water by the plant canopy and the effect of slope and slope length when computing overland flow.

Water that infiltrates moves upward due to evaporation or downward as a consequence of gravity and matric potential [Fig. 2(b)]. When the upper boundary is selected as a flux boundary, infiltration and evaporation from the surface are the specified fluxes. Evaporation is computed using Fick's law. Water removal by transpiration of plants is treated as a sink term in Richards' equation (2). Potential evapotranspiration (the upper limit on actual evapotranspiration) is computed from the daily relative humidity, net solar radiation, wind speed, and daily minimum and maximum air temperatures using a modified form of Penman's equation given by Doorenbos and Pruitt (1977). Soil water storage is computed by integrating the water content profile. Flux from the lower boundary is percolation [Fig. 2(b)]. UNSAT-H, being a one-dimensional model, does not compute lateral drainage.

INPUT FOR HELP AND UNSAT-H

Input for HELP and UNSAT-H can be categorized into soil data, hydrologic data, vegetative data, meteorological data, and initial and boundary conditions. HELP requires that the layer types (vertical percolation layer, barrier soil liner, or lateral drainage layer) be specified. The input data used to simulate the water balance of the test sections are summarized in Table 1.

Soil Data

Saturated Hydraulic Conductivity

Saturated hydraulic conductivities of the barrier soils were measured on specimens collected using thin-walled sampling tubes (Benson et al. 1994), whereas the saturated hydraulic conductivities of the surface layers were obtained from measurements on large undisturbed block specimens (Benson et al. 1993; Khire et al. 1994). Table 1 lists the saturated hydraulic conductivities of the soils from the test sections at Live Oak and Wenatchee. Benson et al. (1993) confirmed that the saturated hydraulic conductivities measured on the tube specimens are representative of the field-scale saturated hydraulic conductivity by calculating the field-scale saturated hydraulic conductivity using steady-state percolation rates measured when the barrier layers were field saturated in February 1993. Saturated hydraulic conductivities determined using both methods were essentially the same.

Soil Water Characteristic Curves

Water contents corresponding to field capacity and wilting point used in HELP were obtained from soil water characteristic curves developed using pressure-plate extractors. Benson et al. (1993) describe the procedure in detail. Khire et al. (1994) present the soil water characteristic curves for the soils used in this study. The Haverkamp function for the soil water characteristic curve (Haverkamp et al. 1977) was fit to the soil water characteristic data for each soil using a computer program described by Khire et al. (1994). The Haverkamp function is

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{\alpha}{\alpha + \Psi^\beta} \qquad (3)$$

where θ = volumetric water content; subscripts s and r = saturated and residual conditions, respectively; and α and β = fitting parameters. The Haverkamp function was used because it provided a good fit to the data and can be directly input to UNSAT-H. Haverkamp parameters for the cover soils from Live Oak and Wenatchee are listed in Table 1.

Unsaturated Hydraulic Conductivity Function

Unsaturated hydraulic conductivity functions were measured in the laboratory by Meerdink et al. (1996) and in the

TABLE 1. Input Parameters for Model Simulations

Parameter (1)	Site/layer (2)	Input value (3)	Reference (4)	Model applicable (5)
		(*a*) Soil properties		
Porosity (cm/cm)	Live Oak: surface layer; barrier layer Wenatchee: surface layer; barrier layer	0.40; 0.52 0.40; 0.36	Field density test (Lane et al. 1992)	HELP; UNSAT-H
Field capacity (cm/cm)	Live Oak: surface layer; barrier layer Wenatchee: surface layer; barrier layer	0.35; 0.33 0.29; 0.25	Pressure plate test (Khire et al. 1994)	HELP
Wilting point (cm/cm)	Live oak: surface layer; barrier layer Wenatchee: surface layer; barrier layer	0.15; 0.17 0.06; 0.07	On-site TDR measurements (Khire et al. 1994)	HELP
Saturated hydraulic conductivity (cm/s)	Live Oak: surface layer Live Oak: barrier layer Wenatchee: surface layer Wenatchee: barrier layer	1.0×10^{-4} 3.2×10^{-6} 4.5×10^{-5} 2.2×10^{-7}	Laboratory hydraulic conductivity tests (Benson et al. 1993)	HELP; UNSAT-H
Haverkamp fitting parameters for soil water characteristic curve	Live Oak: surface layer Live Oak: barrier layer Wenatchee: surface layer Wenatchee: barrier layer	$\alpha = 200$; β (1/cm) = 0.65 $\alpha = 17$; β (1/cm) = 0.40 $\alpha = 80$; β (1/cm) = 0.60 $\alpha = 72$; β (1/cm) = 0.60	Khire et al. (1994)	UNSAT-H
Haverkamp fitting parameters for unsaturated hydraulic conductivity function	Live Oak: surface layer Live Oak: barrier layer Wenatchee: surface layer Wenatchee: barrier layer	$A = 1$; B (1/cm) = 1.45 $A = 8$; B (1/cm) = 1.15 $A = 300$; B (1/cm) = 2.2 $A = 400$; B (1/cm) = 1.3	Khire et al. (1994) Khire et al. (1995)	UNSAT-H
		(*b*) Plant data		
Evaporative depth (cm)	Live Oak Wenatchee	56 75	Schroeder et al. (1994)	HELP
Root zone depth (cm)	Live Oak Wenatchee	24 23	Benson et al. (1993)	HELP; UNSAT-H
Percent bare area	Live Oak Wenatchee	59 40	Grid pictures (Benson et al. 1993)	UNSAT-H
Leaf area index	Live Oak Wenatchee	2.0 1.0	Expert opinion	HELP; UNSAT-H
Growing season (Julian Day)	Live Oak Wenatchee	75–320 105–225	Expert opinion	HELP; UNSAT-H
Fitting parameters for root density function	Live Oak Wenatchee	$a = 0.315$; b_1 (1/cm) = 0.0773; b_2 = 0.0755 $a = 1.16$; b_1 (1/cm) = 0.129; b_2 = 0.02	Fayer and Jones (1990) Fayer and Walters (1995)	UNSAT-H
		(*c*) Hydrologic data		
Soil surface albedo	Live Oak Wenatchee	0.2	Chudnovskii (1966)	UNSAT-H
SCS surface runoff curve number (CN)	Live Oak Wenatchee	87.7 89.5	Schroeder et al. (1994)	HELP
		(*d*) Climatological and cover data		
Precipitation, air temperature, solar radiation, and wind speed	Live Oak Wenatchee	— —	On-site measurement (Khire et al. 1994)	HELP; UNSAT-H
Dew point	Live Oak Wenatchee	— —	On-site measurement (Khire et al. 1994)	UNSAT-H
Quarterly relative humidity (%)	Live Oak Wenatchee	68; 74; 86; 79 73; 47; 52; 80	On-site measurement (Khire et al. 1994)	HELP
Latitude	Live Oak Wenatchee	33.7°N 47.4°N	National Weather Service	UNSAT-H
Altitude (m)	Live Oak Wenatchee	315 379	National Weather Service	UNSAT-H
Layer thickness (cm)	Live Oak: surface layer; barrier layer Wenatchee: surface layer; barrier layer	15; 91.5 15; 61	Design values (Lane et al. 1992)	HELP; UNSAT-H
Cover slope	Live Oak Wenatchee	4:1 2.8:1	Measured (Khire et al. 1994)	HELP
		(*e*) Initial and boundary conditions		
Boundary conditions (upper boundary)	Live Oak Wenatchee	Specified flux	Measured precipitation (on-site)	UNSAT-H
Boundary conditions (lower boundary)	Live Oak Wenatchee	Unit gradient	Fayer et al. (1992)	UNSAT-H
Initial conditions (cm)	Live Oak Wenatchee	Matric suction	Pressure plate test (Benson et al. 1993) and on-site measurements	UNSAT-H
Initial conditions (cm/cm)	Live Oak Wenatchee	Water content	On-site TDR measurements	HELP

field by Khire et al. (1994). These hydraulic conductivity functions, which were both determined using the instantaneous profile method, are essentially identical (Meerdink et al. 1996; Khire et al. 1995). The Haverkamp unsaturated hydraulic conductivity function was fit to the unsaturated hydraulic conductivity data for the surface and barrier layers using the program described by Khire et al. (1994). The Haverkamp function has the form

$$\frac{K_\Psi}{K_s} = \frac{A}{A + \Psi^B} \tag{4}$$

where K_Ψ and K_s = unsaturated and saturated hydraulic conductivities; and A and B = fitting parameters. Parameters in (4) for the surface and barrier layer soils are listed in Table 1.

Vegetative Data

Vegetative input for HELP includes evaporative depth, leaf area index (LAI), and growing season. Vegetative input for UNSAT-H includes rooting depth, LAI, growing season, percent bare area (PBA), and parameters describing the root length density function (Fayer and Jones 1990). The vegetative input data are listed in Table 1. The writers note that vegetation was established on the test sections by the time hydrologic data collection began (Benson et al. 1993).

The LAI for the test sections at Live Oak and Wenatchee were recommended as 2.0 and 1.0, respectively, by the Soil Conservation Service's (SCS) offices in Atlanta and Wenatchee. Rooting depth was determined using data obtained from specimens collected with sampling tubes. PBA measured in the field was used as input. Benson et al. (1993) describe the methods used to measure rooting depth and PBA. Growing seasons for vegetation on the test sections at Live Oak and Wenatchee were supplied by the respective SCS offices, after visiting the sites.

The root length density function, which is used in UNSAT-H, has the following form:

$$R = ae^{-zb_1} + b_2 \tag{5}$$

where R = normalized root length density; a, b_1, and b_2 = coefficients that optimize the fit to the root length density data; and z = depth from the surface of the cover. Normalized root length density is the root mass per unit area at depth z divided by the total root mass (integrated over the entire depth) per unit area.

Root length densities at Live Oak and Wenatchee were not measured. Instead, the root length density functions of Fayer and Jones (1990) and Fayer and Walters (1995) were used by modifying the functions for the rooting depths measured at Live Oak and Wenatchee. For Live Oak, parameters for Bunchgrass (Fayer and Walters 1995) were used. For Wenatchee, parameters for Cheatgrass at the Hanford site (Fayer and Jones 1990) were used. Table 1 lists fitted parameters for the root length density function. Khire (1995) reports that water balance predictions made by UNSAT-H are not particularly sensitive to the shape of the root density function. Nichols (1991) reports similar findings.

Hydrologic and Meteorological Data

Energy refection by the ground surface is described by the surface albedo. HELP has a "built-in" albedo of 0.23 (Schroeder et al. 1994). For UNSAT-H, a soil surface albedo of 0.2 was used for both test sections, which is consistent with albedos recommended by Chudnovskii (1966) and Benson et al. (1996).

SCS runoff curve numbers recommended in the HELP model manual were used for both test sections. The curve numbers recommended by HELP depend on the saturated hydraulic conductivity, condition of vegetation, slope, and slope length. HELP recommended curve numbers of 87.7 and 89.5 for Live Oak and Wenatchee, respectively. An alternative approach to select curve numbers would have been to use calibrated curve numbers (e.g., back-calculated using data from a large storm). However, calibration was not the objective of the study. Rather, the objective was to evaluate models using the best available data that could be directly measured without prior knowledge of the hydrologic behavior of the test sections.

Meteorological input for HELP includes daily precipitation, average daily air temperature, daily solar radiation, quarterly relative humidity, and average yearly wind speed. Climatic input for UNSAT-H includes daily and hourly precipitation, daily maximum and minimum air temperatures, daily solar radiation, average daily dew point, and average daily wind speed. The data collected on site (Khire et al. 1994) were used as input to HELP and UNSAT-H.

Unlike HELP, UNSAT-H does not have a snow-melt algorithm. Hence, precipitation in the form of snow has to be "melted" before it is input to UNSAT-H. For calculating daily snow melt, the restricted degree-day radiation balance approach (Kustas et al. 1994) was used. In this method, daily snow melt M is computed using the following equation (Kustas et al. 1994):

$$M = a_r T_d + m_Q R_n \tag{6}$$

where a_r = restricted degree-day factor ranging between 0.20 and 0.25 cm/°C; T_d = average daily air temperature above the base temperature (base temperature assumed 0°C in this study); m_Q = conversion constant equal to 0.026 W/m^2; and R_n = net solar radiation. To calculate net solar radiation from global solar radiation, a snow surface albedo of 0.74 was used for the snow. Kustas et al. (1994) report that the snow surface albedo is 0.85 for fresh dry snow, whereas it decreases to 0.59 as the snow becomes saturated and contaminated near the end of the ablation (i.e., melting) period. Benson et al. (1996) report similar albedos for snow. Snow melt computed using (6) was input to UNSAT-H as rainfall between hours 10:00 A.M. and 5:00 P.M., which typically corresponds to the period of highest solar radiation (Khire et al. 1994). Snow-melt data were not collected.

Initial and Boundary Conditions

Initial conditions for HELP were specified by assigning the initial water content to each layer of the final cover test section. Initial conditions for UNSAT-H were specified by assigning the initial head to each node in the finite-difference nodal grid [Fig. 2(b)]. Matric suctions corresponding to water contents observed in the field were used to determine the initial heads.

HELP has "built-in" boundary conditions. A flux condition is used at the surface. At the base, a unit gradient is used if the bottom layer is a vertical percolation layer (simulations in this study) or a calculated hydraulic gradient is used if the bottom layer is a barrier layer. Simulations with UNSAT-H were conducted using the lower boundary as a unit gradient and the upper boundary as a specified infiltration or evaporation flux boundary. Similar boundary conditions were used by Fayer et al. (1992) for simulating the hydrology of drainage lysimeters constructed at the Hanford site.

Layer Types

The surface layers and underlying compacted fine-grained layers were input to HELP as vertical percolation layers. The surface layers were input as vertical percolation layers because

they are vegetated (Schroeder et al. 1994). Schroeder et al. (1994) recommend that low hydraulic conductivity layers be input as barrier layers. However, the compacted fine-grained barrier layers in this study were input as vertical percolation layers because the field water contents show that changes in water content occur throughout the entire depth of the compacted clay layers each year (Khire et al. 1994; Meerdink et al. 1996). In addition, plant roots were found in the compacted fine-grained layers (Benson et al. 1993), indicating that water is removed from these layers by transpiration.

Nodal Spacing and Mass Balance Criterion for UNSAT-H

Discretization of the covers in UNSAT-H included 64 nodes along the depth of the test sections [Fig 2(b)]. A small nodal spacing (<0.1 cm) was used near the upper and lower boundaries and the interfaces between layers. The spacing became progressively larger away from the boundaries (3–4 cm). This spacing was selected to minimize numerical errors while maintaining reasonable execution times.

The maximum tolerable mass balance error for UNSAT-H was input as 10^{-5} cm per time step. This mass balance criterion resulted in cumulative mass balance errors that were less than 0.05%.

MODEL PREDICTIONS AND FIELD DATA: LIVE OAK

Overland Flow

Accurate predictions of overland flow are important because they affect the volume of water that infiltrates. If the volume of water infiltrating the soil is incorrect, all subsequent flow processes may be incorrect. Overland flow at Live Oak is shown in Fig. 3 with predictions made with HELP and UNSAT-H. Overland flow at Live Oak is generally higher in fall and winter and lower in spring and summer. HELP and UNSAT-H predicted similar seasonal trends (Fig. 3).

HELP underestimated overland flow by 74.4 cm during the monitoring period, with the largest deviations occurring between winter 1993 and spring 1994. The primary factors contributing to the underestimation are: (1) overestimation of initial abstraction (i.e., amount of precipitation that occurs before overland flow begins) and interception by the plant canopy; and (2) the use of a fixed SCS runoff curve number (CN) for the entire year.

HELP began overestimating abstraction when it underestimated soil water storage in the evaporative zone during drier periods (spring to fall 1993, and spring 1994) (Fig. 4). When

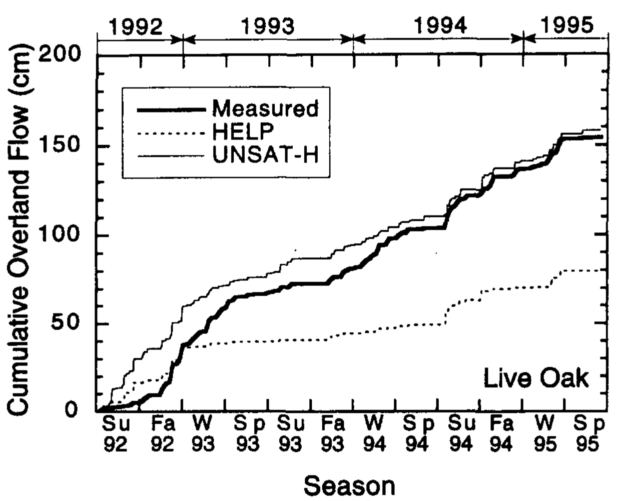

FIG. 3. Measured and Predicted Overland Flow at Live Oak

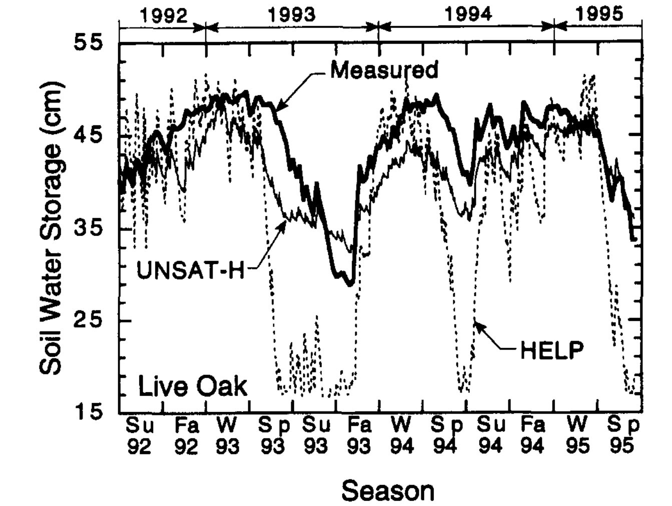

FIG. 4. Measured and Predicted Soil Water Storage at Live Oak

TABLE 2. Initial Abstraction and SCS Runoff Curve Number for Live Oak

Season (1)	Measured abstraction (cm) (2)	HELP abstraction (cm) (3)	HELP CN (4)	CN for better prediction of overland flow (5)	Average increase in overland flow[a] (cm) (6)
Spring 1993	0.7			95	1.5
Summer 1993	0.7	1.8	87.7	91	1.0
Fall 1993	0.1			96	1.6
Spring 1994	0.9			89.5	0.8

[a]Average increase in overland flow is per storm event.

the water content in the evaporative zone decreases, the initial abstraction calculated by HELP increases. For example, in spring to fall 1993 and late spring 1994, HELP subtracted an abstraction of 1.8 cm and an average interception of 0.06 cm each day when precipitation occurred. Thus, overland flow did not occur during these periods unless the daily precipitation exceeded 1.8 cm. In contrast, during the same period, the actual abstraction ranged from 0.1 to 0.9 cm (Table 2).

Had the abstraction predicted by HELP been correct, the predicted overland flow still would have been less than the measured overland flow because overland flow is larger for storms of higher intensity, which is not considered in the SCS method. One way to reduce this error is to use a seasonally adjusted CN. For Live Oak, using a higher CN in fall and spring resulted in more overland flow (Table 2).

Predictions of overland flow by UNSAT-H (Fig. 3) are surprisingly accurate given the simple infiltration capacity method employed by the model. UNSAT-H underpredicted overland flow by only 3.9 cm (error = 2.7%) between fall 1992 and spring 1995. The writers note, however, that significant potential for error exists when using the infiltration capacity approach, because the method does not account for absorption and interception of precipitation by the plant canopy.

Soil Water Storage

Measured and predicted soil water storage for the test section at Live Oak are shown in Fig. 4. The field data show that soil water storage increases in fall and winter and decreases during spring and summer. Similar trends are evident in predictions of soil water storage made using HELP and UNSAT-H. However, HELP drastically underpredicted soil water stor-

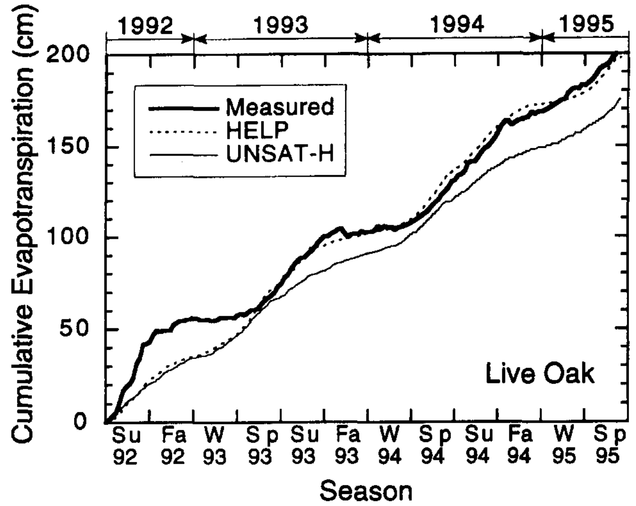

FIG. 5. Measured and Predicted Evapotranspiration at Live Oak

age during the period between spring 1993 and fall 1993, during spring 1994, and during spring 1995 (Fig. 5). The primary reason why HELP underpredicted soil water storage during spring 1993 through fall 1993, spring 1994, and spring 1995 is that it overpredicted percolation (see subsequent section on percolation).

The large seasonal fluctuations in soil water storage occurring in the field are captured fairly accurately by UNSAT-H (Fig. 4). Nevertheless, UNSAT-H underpredicted soil water storage during winter 1993, winter 1994, and winter 1995 and overpredicted soil water storage during summer 1993 and summer 1994 (Fig. 5). Fayer et al. (1992) found similar under- and overpredictions when they simulated the hydrology of lysimeters at the Hanford site. Fayer (1993) attribute this discrepancy to the influence of hysteresis in the soil water characteristic curve, which is not incorporated in the model. Fayer (1993) reports that incorporating hysteresis, at the expense of additional computational effort, results in better predictions of soil water storage.

Evapotranspiration

Evapotranspiration at Live Oak back-calculated using (1) is shown in Fig. 5. The field data show a higher rate of evapotranspiration during spring and summer and a lower rate in fall and winter, which is consistent with changes in temperature, solar radiation, and growing season of the vegetation. Predictions from HELP and UNSAT-H show similar trends.

HELP predicted evapotranspiration very accurately. Evapotranspiration predicted by HELP was 7.1 cm less than the measured evapotranspiration, and the only significant deviation between measured and predicted evaporation occurred within the first year of monitoring. The accurate prediction of evapotranspiration was not expected given that HELP underestimated overland flow by 74.4 cm. When overland flow is underestimated, more water infiltrates into the cover and thus more water is available for evapotranspiration. However, actual evapotranspiration cannot exceed potential evapotranspiration (PET) and the evaporation rate is generally close to PET or equals the PET rate for soils having high water content (Hillel 1980). The test section at Live Oak had relatively high water contents during the portions of the monitoring period when evapotranspiration is significant (e.g., spring) and therefore evapotranspiration should have occurred near the potential evapotranspiration rate. Furthermore, Wilson et al. (1994) have shown that the Penman equation used by HELP accurately predicts PET.

UNSAT-H underpredicted evapotranspiration by 30 cm (Fig. 5). Overpredictions of evapotranspiration occurred during the fall and winter seasons, and underpredictions occurred during spring and summer (Fig. 5). Fayer et al. (1992) report similar findings for their simulations of the field lysimeters at the Hanford site and Fayer (1993) found that this error is caused primarily by ignoring hysteresis. Another reason why UNSAT-H may have underpredicted evapotranspiration is that the root length density function for Bunchgrass from Fayer and Walters (1995) was used, even though the vegetation at Live Oak is not Bunchgrass. Khire (1995) reports that the root length density function has a very small impact on the water balance. Similar findings have been reported by Nichols (1991). In the absence of transpiration data, however, the importance of the root density function cannot be definitively determined.

Percolation

Measured and predicted percolation for Live Oak are shown in Fig. 6. Percolation at Live Oak normally occurs during the late fall, winter, and early spring, or during very heavy precipitation in summer (e.g., percolation occurred throughout summer 1994 during the record 1994 Georgia flood). HELP and UNSAT-H capture the trends in percolation fairly well; however, HELP grossly overpredicted percolation by 77.3 cm, whereas UNSAT-H underpredicted it slightly (by 5.7 cm).

Two factors contributed to HELP's overprediction of percolation: (1) the underprediction of overland flow; and (2) the unit vertical gradient method used to route water in unsaturated soil. Had HELP predicted overland flow correctly, the predicted percolation would have been much closer because less water would have been available to percolate. Nevertheless, because HELP uses the unit gradient method, percolation probably still would have been overpredicted. HELP directs flow vertically downward under unit gradient provided that the water content in the evaporative zone is above the wilting point θ_{wp}. In the field, however, the hydraulic gradient varies seasonally. The hydraulic gradient at a depth of 27 cm (Fig. 7) was computed using average daily water contents measured in the field and the soil water characteristic curves measured in the laboratory. Because the soil water characteristic curves are for desorption and daily average water contents were used, the calculated hydraulic gradients are only an approximation (e.g., the gradient at 27 cm must be positive during some of the wet period because percolation did occur). Nevertheless, Fig. 8 illustrates that large changes in hydraulic gradient occur in the field, and that for a significant portion of a year the gradient is upward. Because a downward unit gradient is assumed, HELP continually drained water from the soil until the

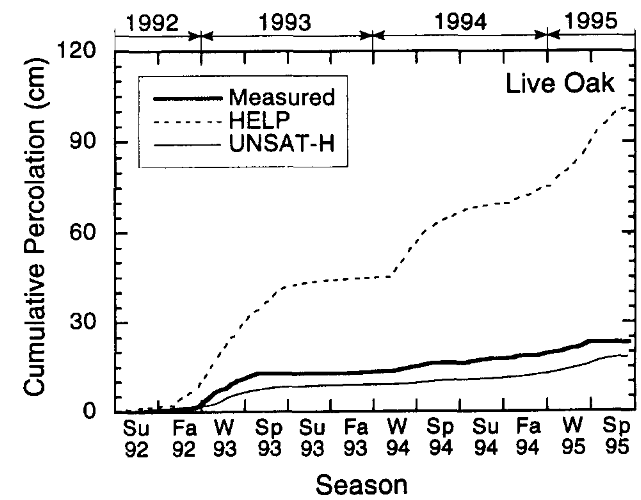

FIG. 6. Measured and Predicted Percolation at Live Oak

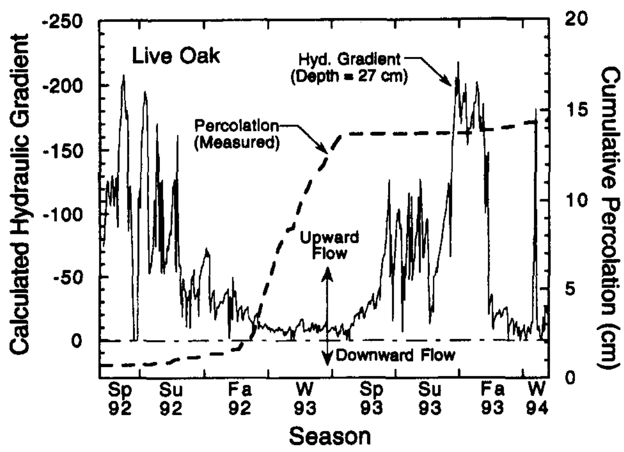

FIG. 7. Measured Percolation and Calculated Hydraulic Gradient at 27 cm at Live Oak

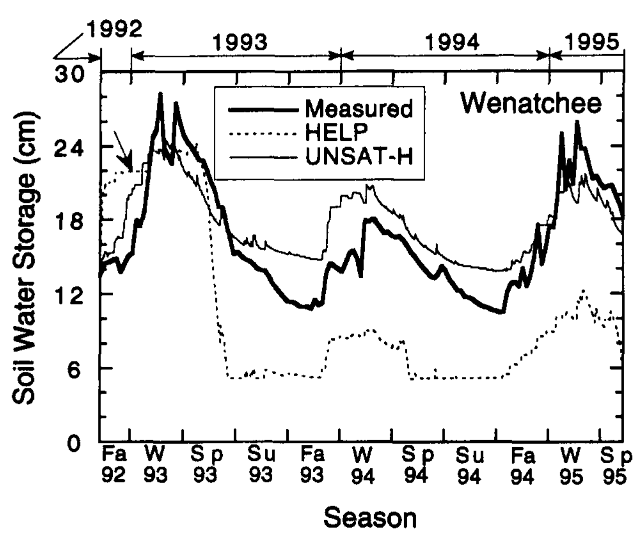

FIG. 8. Measured and Predicted Soil Water Storage at Wenatchee

wilting point (θ_{wp}) was reached (see Fig. 4, where θ_{wp} corresponds to soil water storage = 17 cm). In the field, however, percolation ceased at an average water content = 0.38, because the gradient within most of the test section was upward, not downward.

MODEL PREDICTIONS AND FIELD DATA: WENATCHEE

Overland Flow

Measured overland flow and overland flow predicted by HELP and UNSAT-H for the test section at Wenatchee are shown in Fig. 9. The field data show that overland flow at Wenatchee does not have a well-defined seasonal trend. Furthermore, most of the cumulative overland occurred during winter 1995.

HELP overpredicted overland flow by 2.7 cm. Most of the error in the predicted overland flow occurred during winters 1993 and 1995. Overland flow was overpredicted during winter 1993 and underpredicted during winter 1995. The measured overland flow was very small during winter 1993 and large during winter 1995 (Fig. 9).

The primary reason why HELP over- or underpredicted overland flow was an inability to accurately predict whether snow melt occurred and, when melt did occur, whether the melt water infiltrated or was shed as overland flow. The fate of melt water depends on whether the soil surface is frozen.

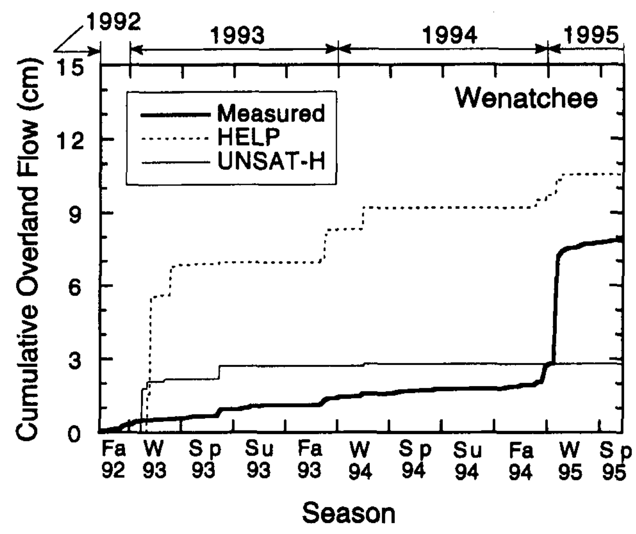

FIG. 9. Measured and Predicted Overland Flow at Wenatchee

HELP assumes that the soil surface freezes when the 30-day average air temperature drops below 0°C (Schroeder et al. 1994). When the soil is assumed frozen, HELP increases the SCS runoff curve number (CN) to 98 if the curve number is originally above 80 to shed melt water as overland flow. If the air temperature is below 0°C, precipitation is assumed to be snow and is stored as snow pack at the surface. When the average daily air temperature rises above 0°C, HELP computes potential daily snow melt using

$$M = F_m T_d \tag{7}$$

where F_m = function of month (e.g., for February, F_m = 0.24 cm/day/°C); and T_d = average daily air temperature.

During early winter 1993, the average daily air temperature and the 30-day average air temperature were below 0°C for more than 30 days [Fig. 10(a)]. Hence, HELP assumed that the soil surface was frozen. Consequently, precipitation in the form of snow was stored on the surface as snow pack. When the average daily air temperature later rose above 0°C [early part of February 1993, see Fig. 10(a)], the snow was melted and overland flow was computed using CN = 98. Consequently, nearly all of the melted snow was shed as overland flow.

In contrast, the data show that overland flow during winter 1993 was minimal (Fig. 9). Overland flow was minimal because the soil was not frozen [see Fig. 10(a)] and water from snow melt gradually infiltrated into the test section, as is evident by the gradual increase in water content that occurred at all depths in the test section during winter 1993 [Fig. 10(b)]. As a result, little overland flow occurred in the field (Fig. 9).

During winter 1995, HELP underpredicted overland flow primarily because evapotranspiration was overpredicted (Fig. 11). During the early part of winter 1995, a large pulse of overland flow occurred when the air temperature rose above 0°C while the soil surface remained frozen. For this period, HELP accurately predicted that the soil was frozen and that most of the melting snow should be shed as overland flow (Khire 1995). However, HELP also predicted that 3 cm of the melting snow evapotranspired, whereas evapotranspiration was nil in the field (Fig. 11).

UNSAT-H underpredicted overland flow by 5.1 cm (Fig. 9). Furthermore, like HELP, UNSAT-H predicted most of the overland flow during winter 1993. One possible reason why UNSAT-H overpredicted overland flow is that the melt water applied as precipitation was too rapid. If rate of application of snow melt was reduced by stretching the input period (e.g., 7:00 A.M. to 8:00 P.M. instead of 10:00 A.M. to 5:00 P.M.), the

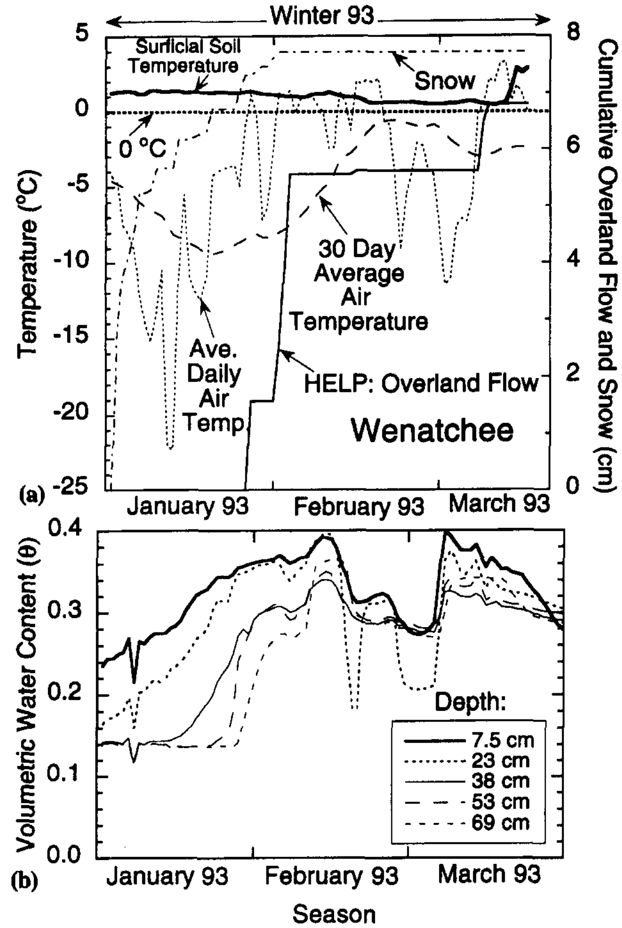

FIG. 10. (a) Air Temperatures, 30-Day Average Air Temperature, Surficial Soil Temperature, Cumulative Snowfall, and Overland Flow Predicted by HELP; (b) Water Contents at Wenatchee during Winter 1995

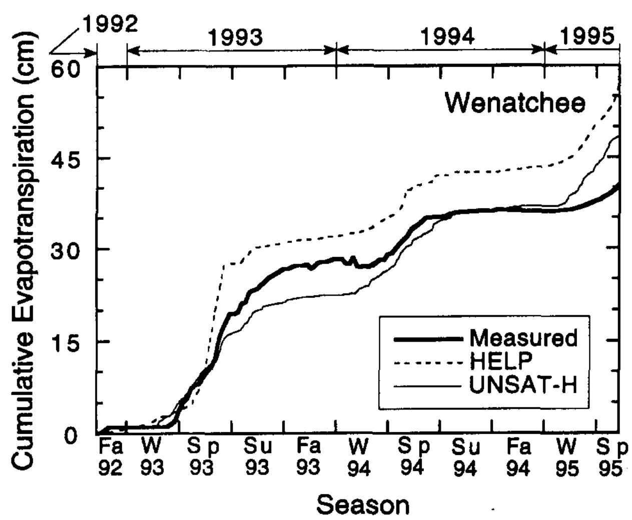

FIG. 11. Measured and Predicted Evapotranspiration at Wenatchee

predicted infiltration would have increased and overland flow would have been less.

In winter 1995, overland flow predicted by UNSAT-H was zero whereas 5.5 cm of overland flow occurred in the field. The primary reason for this discrepancy is UNSAT-H does not have an algorithm to predict freezing of ground. In the field, most of the snow melt was shed as overland flow because the ground was frozen, whereas UNSAT-H allowed the water to infiltrate during late fall 1994 and early winter 1995. Later, the infiltrated water was removed by UNSAT-H via evapotranspiration, which was overpredicted by 4 cm (Fig. 11).

Soil Water Storage

Measured and predicted soil water storage for Wenatchee are shown in Fig. 8. The field data show that soil water storage increases in fall and winter and decreases during spring and summer. These changes in storage are similar to those measured at Live Oak in 1993 (a dry summer), but larger than those measured at Live Oak in 1994 and 1995 (wetter summers). Similar trends exist in the predictions by HELP and UNSAT-H.

Throughout fall 1992 and partly during winter 1993, the field soil water storage increased until the test section was nearly saturated (~27 cm). HELP also predicted an increase in soil water storage (beginning of fall 1992), but more rapidly and earlier than in the field. The period of rapidly increasing soil water storage predicted by HELP was followed by a period when virtually no change in soil water storage was predicted (shown by arrow near upper left corner of Fig. 8). No change in soil water storage was predicted because HELP assumed the ground was frozen during late fall 1992 and early winter 1993 and shed melt water as overland flow (Fig. 9). Furthermore, under these conditions, HELP predicted that infiltration and evapotranspiration did not occur and, because the ground was assumed frozen, percolation was zero.

At the end of spring 1993, HELP significantly underpredicted soil water storage (Fig. 8) primarily because evapotranspiration and percolation were both overpredicted (Figs. 11 and 12). HELP overpredicted percolation because a unit gradient was assumed, which is not consistent with conditions existing in the field.

UNSAT-H predicted an increase in soil water storage in fall 1992 four weeks earlier than occurred in the field (Fig. 8). Similarly, UNSAT-H predicted a decrease in soil water storage at the end of spring 1993 that was 3 to 4 weeks earlier than the measured decrease in soil water storage (Fig. 8). This shift in predicted soil water storage relative to soil water storage in field is primarily due to the premature snow melt predicted by (2) (Kustas et al. 1994). When simulations were conducted using a delayed snow melt, the increase and decrease in predicted soil water storage matched the field soil water storage fairly accurately. Also, when the snow was assumed to melt instantaneously (i.e., no accumulation of snowpack, the increase in soil water storage (and subsequent decrease) occurred even earlier (Khire 1995).

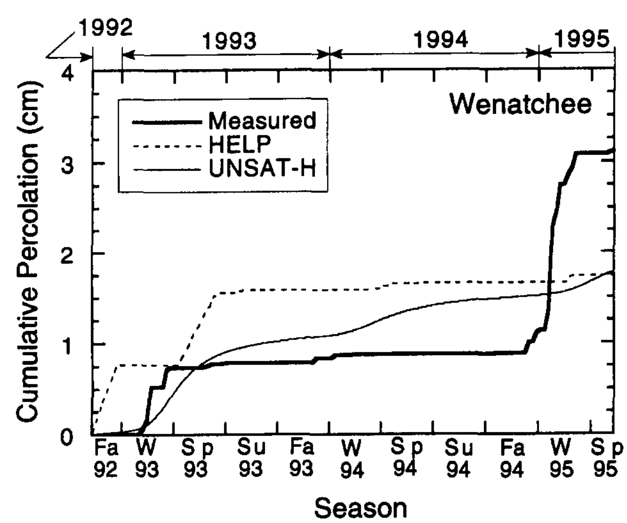

FIG. 12. Measured and Predicted Percolation at Wenatchee

Subsequent predictions of soil water storage from winter 1994 onwards by UNSAT-H are in close agreement with the measured soil water storage, except UNSAT-H tends to overpredict soil water storage in summer, and underpredict it in winter. The under- and overpredictions are probably caused by ignoring hysteresis.

Evapotranspiration

Evapotranspiration observed at Wenatchee and predictions by HELP and UNSAT-H are shown in Fig. 11. The field data show that evapotranspiration occurs at the highest rate during spring and early summer, whereas it is at its lowest rate during fall and winter, which is consistent with changing seasons. The predictions from HELP and UNSAT-H are similar.

HELP overpredicted evapotranspiration by 16.5 cm, with the primary overprediction occurring in spring 1993. The overprediction of evapotranspiration is closely linked to the high water contents that were attained as a result of the large quantity of precipitation received during the previous winter. Nichols (1991) also reports that HELP tends to overpredict evapotranspiration in semiarid climates.

UNSAT-H overpredicted evapotranspiration by 8.1 cm. Evapotranspiration was primarily overpredicted during winter (Fig. 11), which may be caused by the inability of the model to limit evaporation when the soil is frozen or covered with snow. Unlike Live Oak, however, the overprediction in winter is compensated by an equivalent underprediction in spring and summer (Fig. 9). Consequently, the evapotranspiration predicted by UNSAT-H for Wenatchee is accurate, on average.

Percolation

Measured percolation and percolation predicted by HELP and UNSAT-H for Wenatchee are shown in Fig. 12. Two major pulses of percolation occurred in the field, one during winter 1993 and another during fall 1994 to winter 1995.

HELP also predicted two major pulses of percolation. However, the onset and magnitude of the predicted percolation do not match that occurring in the field. HELP predicted percolation throughout fall 1992 and spring 1993, whereas little or no percolation occurred in the field during these periods.

The pulse of percolation predicted by HELP in spring 1993 corresponded with the sharp decrease in simulated soil water storage (24–5.1 cm, Fig. 8) that occurred as HELP drained water from soil water storage under a unit gradient. In contrast, the field data suggest that water was removed from the test section more slowly than predicted by HELP (Fig. 8) and primarily by evapotranspiration rather than percolation (Figs. 11 and 12).

The large pulse of percolation during fall 1994 and winter 1995 is believed to be due to flow through cracks and animal burrows. A crack in the barrier layer was observed in a test pit outside the monitoring area during an investigation in March 1994 (Benson and Khire 1995). The crack was moist and covered with a thin layer of mold, suggesting that it had been conducting flow. In addition, snow filled animal burrows were found in spring 1995 (Benson et al. 1996a). When the pulse of percolation was observed in early winter 1995 [see January, Fig. 13(a)], the water content near the deepest TDR probes (depth = 69 cm) remained at 0.13 [Fig. 13(b)], indicating that the water from snow melt and rain was seeping through preferential flow paths. HELP does not account for flow of water through preferential flow paths in soil and hence did not capture these pulses of percolation. In contrast, the pulses of percolation observed later in winter 1995 (late February and March) correlate well with precipitation received and changes in water content (Fig. 13).

The onset and magnitude of percolation predicted by UNSAT-H agree with measured percolation during the period between winter 1993 and spring 1993 (Fig. 12). However, UNSAT-H predicted very little percolation during fall 1994 and winter 1995, when a 2-cm pulse of percolation was observed. The pulse of percolation observed in the field during winter 1995 was much sharper than predicted by UNSAT-H (Fig. 12), which also suggests that flow was occurring through preferential pathways that UNSAT-H, like HELP, does not consider.

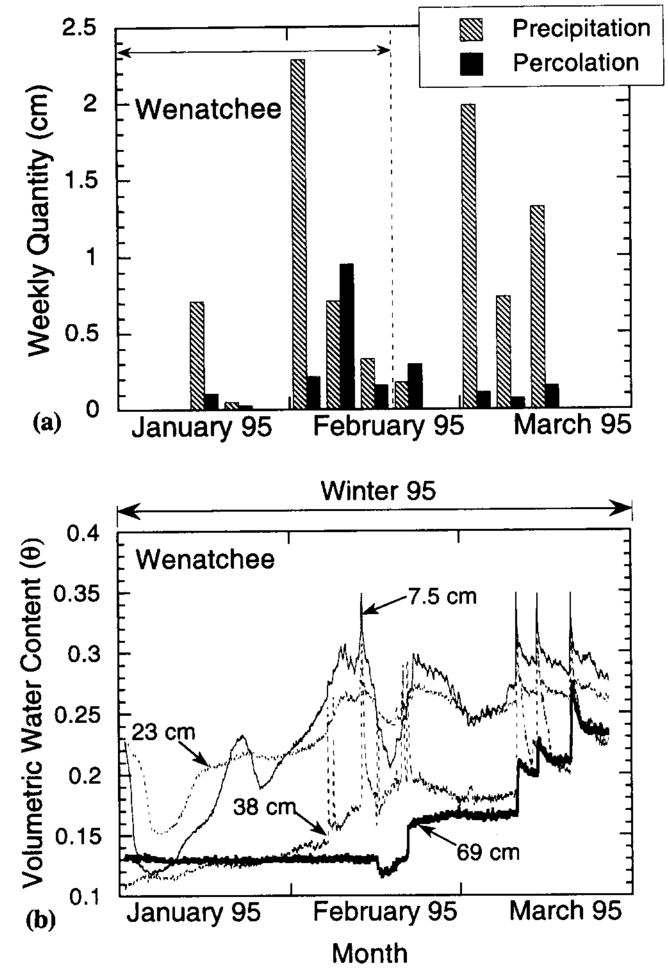

FIG. 13. Winter 1995 at Wenatchee: (a) Precipitation and Percolation; (b) Water Contents

PRACTICAL IMPLICATIONS AND CONCLUSIONS

The comparison of measured and predicted components of the water balance has shown that both HELP and UNSAT-H capture the seasonal trends in the water balance. Given the complexity of hydrologic systems, both models simulated the hydrology of the covers well. The predictions from UNSAT-H are more accurate than those obtained with HELP, which is expected given the more sophisticated and rigorous algorithms UNSAT-H employs. Nevertheless, the errors HELP makes predicting percolation tend to be conservative, except in the case where the barrier layer sustains damage that results in preferential flow. Furthermore, these errors can probably be reduced if HELP is modified to more accurately simulate overland flow and unsaturated flow.

For the semiarid site (East Wenatchee), snow cover, snow melt, and the thermal conditions of the ground surface had significant impacts on the water balance that were not properly captured by HELP or UNSAT-H. Improving these models to properly capture these conditions will be difficult because of the complex interactions between meteorological conditions, thermal conditions in the snow cover, and thermal conditions

in the cover and underlying waste. Consequently, caution should be employed when interpreting predictions made with these models for sites where snow cover is significant, particularly in arid regions where snow constitutes a significant fraction of annual precipitation.

The writers also caution that less accurate predictions should be expected in general practice because the input data in this study were defined with much greater detail and accuracy than is generally practical. For example, when using different methods to estimate the unsaturated hydraulic conductivity functions, dramatically different water balance predictions can be obtained (Khire et al. 1995). A lack of detailed data may have greater impact on predictions made with more sophisticated models. Also, in any design the impacts of deterioration of the cover need to be considered when making water balance predictions. Neither of the models examined in this study include algorithms that simulate the formation of macrodefects that influence the water balance, particularly percolation.

Finally, in practice the designer must choose between simpler, easier to use, less accurate, yet conservative models (e.g., HELP) and more accurate, more complex models (e.g., UNSAT-H) requiring extensive input. A logical choice is to use the simpler model (HELP) to investigate alternatives during an iterative design phase and then to make final checks and predictions using the more complex model (e.g., UNSAT-H). This approach exploits the advantages of both models, and should minimize costs during final cover design and after closure of the landfill. Nevertheless, the differences between measured and predicted behavior that have been presented illustrate that any water balance model is subject to error. The user should always be cognizant of potential errors, and their impact on engineering and financial decisions.

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APPENDIX I. SIMULATIONS WITH RECENT VERSIONS OF HELP

When this study was conducted the most recent version of HELP was version 3.01. Since then several updates to the program have been released. When the last revision of this manuscript was prepared, HELP v.3.05 was available. Runs made with version 3.05 yielded results similar to those described in this paper. The following predictions were made with HELP v.3.05 for the test section at Live Oak: overland flow = 94 cm, evapotranspiration = 211 cm, and percolation = 96.7 cm. For the test section at Wenatchee the following predictions were made: surface overland flow = 10.2 cm, evapotranspiration = 55.3 cm, and percolation = 2.9 cm.

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