Comparison of Field Data and Water-Balance Predictions for a Capillary Barrier Cover

A. S. Ogorzalek[1]; G. L. Bohnhoff[2]; C. D. Shackelford[3]; C. H. Benson[4]; and P. Apiwantragoon[5]

Abstract: Predictions of surface runoff (*R*), evapotranspiration (ET), soil–water storage (*S*), and percolation obtained using three numerical codes (LEACHM, HYDRUS, and UNSAT-H) employed to simulate the hydrology of water-balance covers are compared to measured water-balance data from a lysimeter used to monitor a capillary barrier cover profile in a subhumid climate. All of the codes captured the seasonal variations in water-balance quantities observed in the field. LEACHM and HYDRUS predicted total *R* during the monitoring period with reasonable accuracy (within 18 mm using general mean parameters), but the timing of predicted and observed *R* events was different. In contrast, UNSAT-H consistently overpredicted *R* by at least 239 mm. Evapotranspiration was predicted reliably (within 60 mm) with all three codes when data from the first year were excluded. However, all three codes overpredicted ET in late winter and early spring, when snowmelt was occurring and *S* was accumulating in the field. Consequently, *S* generally was underpredicted by all three codes. Predicted and measured percolation were in good agreement (within 1 mm/year), except during the first year. Results of the comparison indicate that cover modelers should scrutinize runoff predictions for reasonableness and carefully account for snow accumulation, snow melt, and ET during snow cover.

DOI: 10.1061/(ASCE)1090-0241(2008)134:4(470)

CE Database subject headings: Unsaturated flow; Water balance; Coverings; Barriers; Containment.

Introduction

Final covers relying on water-balance principles are being used with increasing frequency for closure of waste containment facilities in lieu of more conventional covers that employ resistive barrier layers (e.g., compacted clay layers, geomembranes, and combinations thereof). Covers based on water-balance principles rely on the ability of fine-textured soils to retain infiltrating water with minimal drainage during periods of elevated precipitation and minimal evapotranspiration, as well as the capability of plants and the atmosphere to remove stored water via transpiration and evaporation during drier periods (Albright et al. 2004). Covers functioning on these principles are referred to by a variety of terms, including store-and-release covers, evapotranspirative covers, alternative covers, and water-balance covers. As these covers rely on balancing water storage and evapotranspiration, the "water-balance cover" nomenclature is used herein. In many cases, water-balance covers are designed to transmit very low percolation rates (on the order of 1 mm/yr) (Benson 2001).

Water-balance cover design generally consists of preliminary sizing using hand calculation methods (e.g., Benson and Chen 2003) followed by refinement using numerical codes that simulate the response of the cover to meteorological conditions (Benson et al. 2004, 2005). Although numerical codes have been used in practice for several years (e.g., Zornberg et al. 2003; Kavazanjian et al. 2006; Stockdill et al. 2006; Dwyer et al. 2007; Koragappa et al. 2007), only a limited number of studies comparing model predictions with actual field measurements have been performed for water-balance covers (Fayer et al. 1992; Fayer and Gee 1997; Khire et al. 1997; Roesler et al. 2002; Scanlon et al. 2002, 2005; Benson et al. 2004, 2005). In addition, in many of these studies, critical input parameters, such as soil hydraulic properties and vegetation characteristics have been estimated or selected through calibration exercises. Thus, the accuracy of water-balance predictions made a priori remains poorly understood. Additional studies that compare model predictions based on independently measured input data to field-measured water-balance parameters are needed to assess the accuracy with which the hydrology of water-balance covers can be predicted during design.

The objective of this study was to evaluate the accuracy of water-balance predictions made with three numerical codes based on Richards' equation that are commonly used in practice (HYDRUS, LEACHM, and UNSAT-H). Predictions were made for a capillary barrier cover at a field site in western Montana, and compared to field-measured water-balance quantities obtained

[1]Geoenvironmental Engineer, Vector Engineering, Inc., 1956 SW Forest Ridge Ave., Bend, OR 97702; formerly, Graduate Research Assistant, Dept. of Civil and Environmental Engineering, Colorado State Univ., Fort Collins CO 80523. E-mail: ogorzalek@vectoreng.com

[2]Graduate Teaching Assistant, Dept. of Civil and Environmental Engineering, Colorado State Univ., Fort Collins, CO 80523-1372; formerly, Graduate Research Assistant, Geological Engineering, Univ. of Wisconsin, Madison, WI 53706. E-mail: gbohnhof@engr.colostate.edu

[3]Professor, Dept. of Civil and Environmental Engineering, Colorado State Univ., Fort Collins, CO 80523-1372. E-mail: shackel@engr.colostate.edu

[4]Wisconsin Distinguished Professor and Chairman, Geological Engineering, Univ. of Wisconsin, Madison, WI 53706. E-mail: benson@engr.wisc.edu

[5]Major and Assistant Professor, Dept. of Civil Engineering, Chulachomklao Royal Military Academy, Muang, Nakhon Nayok, 26001, Thailand. E-mail: preecha@nrsc.co.th

Note. Discussion open until September 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on May 1, 2007; approved on September 7, 2007. This paper is part of the ***Journal of Geotechnical and Geoenvironmental Engineering***, Vol. 134, No. 4, April 1, 2008. ©ASCE, ISSN 1090-0241/2008/4-470–486/$25.00.

from an instrumented test section at the field site. Model input consisted of independently measured data obtained using standard methods to the greatest extent possible to provide a direct and unbiased assessment of the predictive capabilities of the codes.

Background

Several studies have compared the ability of hydrologic codes to predict the water balance of landfill final covers. Codes used in previous studies include UNSATH, HYDRUS, SHAW, SoilCover (more recent versions known as Vadose/W), SWIM, VS2DTI, and HELP (Fayer et al. 1992; Fayer and Gee 1997; Khire et al. 1997, 1999; Scanlon et al. 2002, 2005; Benson et al. 2004, 2005). Of these codes, HYDRUS, UNSAT-H, LEACHM, and Vadose/W are used most frequently in practice (Benson 2007).

Fayer et al. (1992) and Fayer and Gee (1997) compared water-balance data from eight nonvegetated lysimeters located in semiarid southeastern Washington state, to predictions made with UNSAT-H. The layering sequence in the cover lysimeters consisted of (top to bottom) 1.5 m of silt, 0.1 m of sand, and 1.33 m of gravel. Soil–water storage generally was underpredicted during winter months and overpredicted during summer months. Differences between measured and predicted soil–water storage were attributed to overprediction of evaporation during the winter and under prediction of evaporation during the summer. Fayer et al. (1992) and Fayer and Gee (1997) indicate that water-balance codes can be calibrated to improve predictions, and that the hydraulic conductivity function, snow cover, hysteresis, and the calculation of potential evaporation can affect the accuracy of water-balance predictions. They also report that heat flow is a minor factor in water-balance predictions, and that model calibration can be improved by focusing on multiple performance variables (i.e., soil–water storage and percolation).

Khire et al. (1997) compared water-balance predictions made using the HELP and UNSAT-H codes with lysimeter data for two resistive barrier covers located in Georgia (humid climate) and Washington state (semiarid climate). The cover profile at both locations consisted of a vegetated surface layer overlying a compacted fine-grained layer. Field- and laboratory-measured input data describing the meteorology, vegetation, and soils were used to the greatest extent practical. Predictions from both codes captured the seasonal trends in surface runoff, evapotranspiration, and soil–water storage, but the predictions from UNSAT-H were in better agreement with the measured water balance than those from HELP. Percolation was found to be grossly overpredicted by HELP and slightly underpredicted by UNSAT-H. Errors in predicting snowmelt and frozen ground were found to affect significantly runoff predictions during the winter months, which affected all other water-balance quantities.

Khire et al. (1999) described a comparison between predictions made with UNSAT-H and field data from a capillary barrier test section consisting of a 150-mm-thick layer of silt overlying a 750-mm-thick layer of sand. The comparison showed that UNSAT-H predicted the water balance of the capillary barrier conservatively, with runoff typically being underpredicted (within 100 mm) and percolation being overpredicted (within 50 mm). Most of the over prediction of percolation was attributed to the under prediction of runoff. Soil–water storage typically was predicted within 30 mm of measured soil–water storage.

Scanlon et al. (2002, 2005) compared predictions made with HELP, HYDRUS, SHAW, SoilCover, SWIM, UNSAT-H, and VS2DTI to water-balance data from covers in semiarid Texas, New Mexico, and Idaho, over a period ranging from one to three years. For the cover in New Mexico, the field data were compared only to predictions from UNSAT-H. The cover profile at the Texas site consisted of (from top to bottom) 0.3 m of sandy clay blended with 15% gravel, 1.7 m of compacted sandy clay, and 1 m of sandy gravel. A 1.07-m-thick monolithic cover of silty sand was evaluated at the New Mexico site and a 3-m-thick monolithic cover of sandy silt was evaluated at the Idaho site. Codes employing Richards' equation predicted the water balance more accurately than the HELP model, which employs a water routing approach. Other factors affecting the water-balance predictions included the method used to simulate evaporation in the upper boundary, the lower boundary condition (seepage face versus unit gradient), the duration of precipitation events and the method used to apply precipitation by the code, and the form of the hydraulic property functions (van Genuchten versus Brooks and Corey). Scanlon et al. (2005) also suggest that the relationship between abundance of vegetation, evapotranspiration, and water availability is an important factor affecting the accuracy of water-balance predictions, and that most codes being used today do not account for this interaction explicitly.

Benson et al. (2004, 2005) compared water-balance data from a monolithic cover at a semiarid site to predictions made with UNSAT-H and Vadose/W. On-site data were used as model input to the greatest extent practical. More accurate predictions were obtained with Vadose/W than UNSAT-H. Surface runoff was overpredicted appreciably by UNSAT-H, which affected all subsurface hydraulic processes. In contrast, Vadose/W accurately predicted surface runoff, evapotranspiration, and the temporal variations in soil–water storage. Neither model predicted percolation accurately, and both codes failed to capture a key change in the transpiration pattern during the last winter–summer period of the monitoring program. Differences in the method used to simulate precipitation intensity were found to be partly responsible for the differences in the accuracy of predicted surface runoff. Simulations conducted to evaluate the importance of the lower boundary condition showed that essentially the same predictions were obtained when the lower boundary was assigned as a unit gradient or seepage face condition.

Site Description

The capillary barrier cover in this study is located approximately 4.8 km southwest of Polson, Mont., which has a cool and seasonal subhumid climate with precipitation in the form of rain and snow. The average annual precipitation is 380 mm/year, and the average annual ratio of precipitation (P) to potential evapotranspiration (PET) is 0.58 (Albright et al. 2004). The cover was evaluated as part of the U.S. Environmental Protection Agency's Alternative Cover Assessment Program (ACAP). Construction of the test section was completed on October 19, 1999, and data collection began on November 19, 1999.

A cross section of the cover is shown schematically in Fig. 1. The test section was sloped at 3%. The profile consists of (from top to bottom) 150 mm of topsoil (surface layer), 460 mm of sandy silt (water-storage layer), 600 mm of silty sand (capillary break layer), and 460 mm of sandy gravel (interim cover soil) (Roesler et al. 2002). The primary capillary break in the profile forms between the sandy silt storage layer and the silty sand break layer. A secondary capillary break also forms between the silty sand and the sandy gravel. The enhanced storage provided by

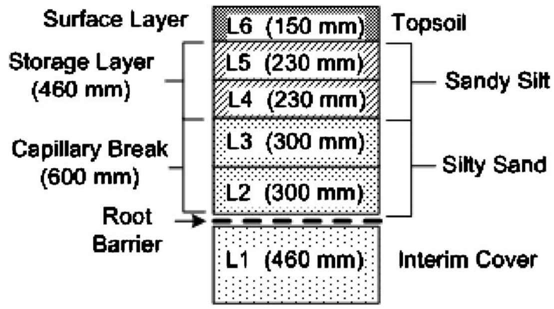

Fig. 1. Profile of the capillary barrier cover at Polson, Mont. Surface and storage layers are sandy silt, capillary break layer is silty sand, and interim cover layer is gravel.

these capillary breaks was not a focus of this study, but has been analyzed by Apiwantragoon (2007).

The test section was seeded with a mixture of local grasses, forbs, and shrubs (thickspike, bluebunch, slender, and crested wheatgrasses, mountain brome, Idaho fescue, Prairie junegrass, needle-and-thread, meadow brome, Canada and Kentucky bluegrasses, yarrow, fringed sagewort, alfalfa, rubber rabbitbrush, prickly rose, arrowleaf, balsamroot, dolted gayfeather, lewis flax, silky lupine, and cicer milkvetch) on March 31, 2000. The coverage ranged from 50 to 80% (Bolen et al. 2001).

Water-Balance Measurements

The water balance was monitored with a 10 m × 20 m ACAP pan lysimeter constructed with linear low-density polyethylene (LLDPE) geomembrane (Benson et al. 2001). A geocomposite drainage layer was placed in the base of the lysimeter to route percolation from the cover to a collection and measurement system. Diversion berms were constructed around the perimeter of each test section to prevent runon and to collect runoff for measurement. All flows were collected in basins monitored with pressure transducers and tipping buckets. Benson et al. (2001) indicate that the collection system measured percolation to within ±0.1 mm/year and runoff to within ±0.5 mm/year.

Water content of the cover soils was measured with three nests of time-domain reflectometry (TDR) probes. Each nest contained probes placed at 75, 350, 450, 700, and 1,100 mm below ground surface. Soil-specific calibrations with temperature compensation were used to determine volumetric water content from the travel time reported by the TDR probes (Kim and Benson 2002). Thermal dissipation sensors for measuring soil suction were colocated with the TDR probes in one nest that was centrally located within the test section. Data from the test sections were recorded on an hourly basis, unless meteorological conditions dictated greater frequency. A detailed description of the lysimeters can be found in Benson et al. (1999, 2001). A description of the monitoring system can be found in Albright et al. (2004).

Surface runoff (R), percolation (P_r), and precipitation (P) were directly measured. Soil–water storage (S) was calculated by integrating volumetric water content measurements over the volume of the lysimeter. Evapotranspiration (ET) was calculated by difference from the water-balance equation:

$$\mathrm{ET} = P - R - P_r - \Delta S \tag{1}$$

This computation of ET assumes that interflow is negligible and water does not collect on the surface of the cover. These assumptions are reasonable given the modest slope of the test section and the small area of the lysimeter (200 m^2). ET computed with Eq. (1) includes actual ET and the net error in the other water-balance quantities. Apiwantragoon (2007) reported good agreement between ET computed with Eq. (1), measurements of ET reported by others, and theoretical estimates of ET.

Hydraulic Properties

Undisturbed block samples for measuring hydraulic properties were collected from each lift of the test section during construction (Gurdal et al. 2003). Each sample was tested in the laboratory to determine the saturated hydraulic conductivity (K_s) and the soil–water characteristic curve (SWCC) for desorption. Flexible-wall permeameters were used to measure K_s per ASTM D 5084 with an average applied effective stress of 21 kPa and a hydraulic gradient of 10. Pressure-plate extractors and a chilled-mirror hygrometer were used to measure the SWCCs per ASTM D 6836. The measured water-retention data were fit using van Genuchten's SWCC function (van Genuchten 1980), and the van Genuchten parameters are used herein to describe the SWCCs. Methods used to sample the soils and conduct the tests are described in detail by Gurdal et al. (2003). All of the test data are compiled in Gurdal et al. (2003), and a summary of the data is included in Albright et al. (2004).

Hydraulic properties of each layer are summarized in Table 1 for four cases: General mean (GM) case, low-storage capacity (LSC) case, high-storage capacity (HSC) case, and a field-fit (FF) case. SWCCs and hydraulic conductivity functions for all four cases are shown in Fig. 2. GM parameters were defined using the geometric mean for log-normally distributed parameters (K_s and van Genuchten's α parameter) and arithmetic means for normally distributed parameters (saturated water content, θ_s; residual water content, θ_r; and van Genuchten's n parameter) (Gurdal et al. 2003). Parameters for the HSC case were defined as two standard deviations above the mean for n and θ_s and two standard deviations below the mean for K_s, α, and θ_r. Parameters for the LSC case were defined in a similar manner, but below the mean for n and θ_s and above the mean for K_s, α, and θ_r.

For the FF case, the SWCC parameters were defined using water contents and matric suctions measured in the field with the colocated TDR probes and thermal dissipation sensors described previously. Field data were not available for the interim cover soil. Thus, parameters for the GM case were used for the interim cover soils for the FF simulations. Most of the FF SWCCs were comparable to those measured in the laboratory. The exception is the capillary break layer, for which the SWCC has higher air-entry suction than the other SWCCs. The reason for this difference is unknown, but the difference probably is due to the difficulty in measuring low suctions that is commonly encountered with thermal dissipation sensors.

Block samples were collected from the surface layer each year after construction to evaluate the effect of weathering and vegetative growth on K_s and the SWCC. No change in the SWCC was observed, which is consistent with the relatively low air-entry suction of the cover soils at the time of construction (Benson et al. 2007). However, K_s increased with time. Similar increases in saturated hydraulic conductivity have been reported by Kelln et al. (2006) and Benson et al. (2008). Four different K_s are reported for the surface layer (one per year since construction) in Table 1 for each of the four different sets of hydraulic properties (i.e., LSC, GM, HSC, and FF).

Table 1. Hydraulic Properties for the Capillary Barrier at Polson, Mont.

Hydraulic properties set	Layer	Thickness (mm)	van Genuchten parameters[a]				Saturated hydraulic conductivity, K_s (cm/s)			
			θ_r	θ_s	α (kPa^{-1})	n	2000	2001	2002	2003
Low storage capacity (LSC)	Surface layer	150	0.00	0.34	0.692	1.43	5.6×10^{-5}	1.6×10^{-4}	1.6×10^{-4}	7.2×10^{-3}
	Storage layer	460	0.03	0.24	0.325	1.35	9.2×10^{-7}			
	Capillary break	600	0.01	0.33	0.749	1.50	2.4×10^{-4}			
	Interim cover	460	0.00	0.32	3.11	3.00	6.1×10^{-3}			
General mean (GM)	Surface layer	150	0.00	0.37	0.610	1.42	3.4×10^{-5}	1.3×10^{-4}	1.3×10^{-4}	4.4×10^{-3}
	Storage layer	460	0.01	0.30	0.182	1.28	4.0×10^{-7}			
	Capillary break	600	0.00	0.36	0.665	1.45	7.9×10^{-5}			
	Interim cover	460	0.00	0.32	3.11	3.00	6.1×10^{-3}			
High storage capacity (HSC)	Surface layer	150	0.00	0.38	0.547	1.40	1.1×10^{-5}	9.9×10^{-5}	9.9×10^{-5}	1.4×10^{-3}
	Storage layer	460	0.00	0.34	0.102	1.22	1.2×10^{-7}			
	Capillary break	600	0.00	0.38	0.580	1.41	4.2×10^{-5}			
	Interim cover	460	0.00	0.32	3.11	3.00	6.1×10^{-3}			
Field fit (FF)	Surface layer	150	0.03	0.38	0.738	1.60	3.4×10^{-5}	1.3×10^{-4}	1.3×10^{-4}	4.4×10^{-3}
	Storage layer	460	0.00	0.31	0.0107	1.36	4.0×10^{-7}			
	Capillary break	600	0.00	0.33	0.0063	2.75	7.9×10^{-5}			
	Interim cover	460	0.00	0.32	3.11	3.00	6.1×10^{-3}			

[a]θ_r=residual volumetric water content; θ_s=saturated volumetric water content; α and n are curve-fitting parameters.

Vegetation Properties

Measurements were made annually at the site to define the peak leaf area index (LAI) and the root density profile. Measurements of LAI were made in the laboratory on clippings using a Li-Cor LI-3100C (Lincoln, NB) area meter and in the field using a Li-Cor LAI-2000 plant canopy analyzer. The peak LAI was determined to be 2.5, on average, and roots were found to extend to the bottom of the storage layer. Root density profiles were measured in the laboratory following the procedure in Liang et al. (1989) on samples collected from the test sections using the Weaver–Darland box method (Benson et al. 2007). The root density data were fit with the exponential model:

$$R_d = ae^{-bz} + c \tag{2}$$

where R_d=normalized root density (m roots/m soil), z=depth (m), and a, b, and c are empirical parameters obtained from a least-squares fit. Average values for these parameters were found to be: a=0.12, b=1.9 m^{-1}, and c=0.0.

Codes

Three water-balance codes were compared in this study: HYDRUS v2.007 (Šimůnek et al. 1999), LEACHM v4.0 (Hutson and Wagenet 1992), and UNSAT-H v3.0 (Fayer 2000). These codes were selected because they rigorously simulate unsaturated flow, root–water uptake, and atmospheric interactions (Benson 2007) and are commonly used for simulating the hydrology of water-balance covers (Fayer et al. 1992; Fayer and Gee 1997; Khire et al. 1997, 1999, 2000; Scanlon et al. 2002, 2005; Benson et al. 2004, 2005; Bohnhoff 2005; Ogorzalek 2005). The water-balance program HELP (Schroeder et al. 1994) was considered, but not used in this study, because the results of several studies have shown that the simple water routing algorithms in HELP are not capable of accurately simulating the complex hydrodynamics associated with unsaturated flow in water-balance covers (Fayer and Gee 1997; Khire et al. 1997; Scanlon et al. 2002; Dwyer et al. 2007).

Aspects of LEACHM, HYDRUS, and UNSAT-H relevant to predicting the hydrology of water-balance covers are summarized in Table 2. More exhaustive information on each code can be found in Hutson (2003), Fayer (2000), and Šimůnek et al. (1999). Briefly, each code simulates unsaturated flow by solving a modified form of Richards' equation, with a flux boundary at the surface representing soil–atmosphere interactions (infiltration, evaporation) and a lower boundary representing the hydrologic condition at the base of the profile. In one-dimensional form, the modified Richards' equation may be written as follows:

$$c_\theta \frac{\partial \psi}{\partial t} = -\frac{\partial}{\partial z}\left[K_c \frac{\partial \psi}{\partial z} + K_\psi + q_{vT}\right] - \Lambda(z,t) \tag{3}$$

where θ=volumetric water content; c_θ=specific water capacity; t=time; z=vertical coordinate (z=0 at the ground surface); ψ=matric suction; K_c=combined liquid and vapor unsaturated hydraulic conductivity; K_ψ=unsaturated liquid hydraulic conductivity; q_{vT}=water vapor flux; and Λ=sink term for extraction of pore water by plant roots. UNSAT-H and LEACHM use the finite-difference method to solve Eq. (3), whereas HYDRUS uses the finite element method. UNSAT-H and HYDRUS also can simulate heat transport and can couple heat and liquid flows. For cover simulations, however, Fayer et al. (1992) and Fayer and Gee (1997) indicate that incorporating heat flow has little effect on water-balance predictions, but causes a considerable increase in computational time. Thus, only isothermal simulations were conducted in this study, primarily for computational convenience.

Each model employs an atmospheric boundary condition consisting of evaporation or infiltration, with the difference between applied precipitation and infiltration assumed to be runoff (i.e., canopy storage and ponding on the surface are ignored). Infiltration rate is controlled by the rate at which precipitation is applied and by the infiltration capacity of the profile, the latter defined by the hydrologic conditions in the cover profile during infiltration. Total precipitation is applied in LEACHM and UNSAT-H, whereas net precipitation (total precipitation—potential evaporation) is applied in HYDRUS. Evaporation is computed as the liquid flux at the surface boundary using Darcy's Law in

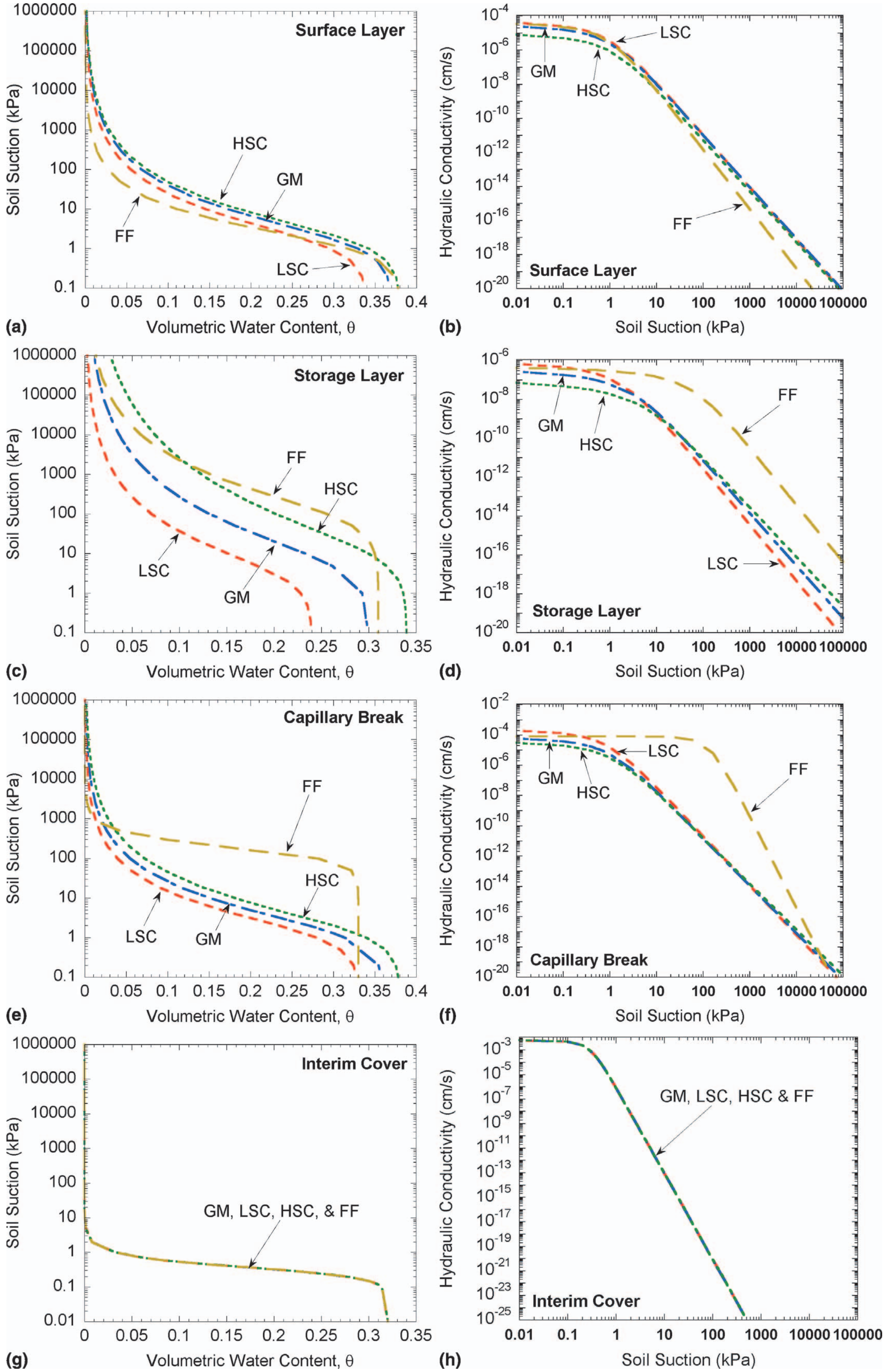

Fig. 2. (Color) Soil–water characteristic curves and hydraulic conductivity functions for each layer in the cover profile (GM=general mean, LSC=low storage capacity, HSC=high storage capacity, and FF=field fit)

Table 2. Comparison of Elements of LEACHM, HYDRUS, and UNSAT-H

Component	Variable/process	LEACHM	HYDRUS	UNSAT-H
Initial conditions and boundary conditions	Initial condition	Initial water content or initial matric suction	Initial water content or initial matric suction	Initial matric suction
	Atmospheric upper boundary condition	Infiltration at rate defined by hydraulic properties at surface when precipitation >0; otherwise evaporation at rate defined by hydraulic properties at surface (limited by PE)	Infiltration at rate defined by hydraulic properties at surface when net precipitation >0; otherwise evaporation at rate defined by hydraulic properties at surface (limited by PE) or constant head when user-defined upper or lower bounds on suction are exceeded.	Infiltration during precipitation at rate defined by hydraulic properties at surface; evaporation at PE until suction at surface reaches air-dry condition. For higher suctions, a constant head boundary is applied corresponding to the suction for air-dry soil.
	Relevant lower boundary conditions	Unit gradient or seepage face with specified suction at drainage	Constant head, unit gradient, seepage face	Constant head or unit gradient.
Climate data	Meteorological input	Daily precipitation, mean weekly temperature and mean weekly amplitude (°C), weekly total PET	Precipitation and PE. Input discretization selected by user.	Precipitation, minimum and maximum air temperature, solar radiation, dew point, wind speed, elevation, cloud cover. Daily or hourly input.
	Precipitation distribution and application	Uniformly distributed over user-defined period	Net precipitation (precipitation-PE) distributed uniformly during time step.	10 mm/h (default) or user defined rate when daily data are input; uniformly distributed with hourly input.
Vegetative water uptake	Potential transpiration	Computed from PET with user input crop cover fraction	User inputs PT	User inputs PT or partitioned from PET based on LAI with user-defined model.
	Water use and availability	Nimah and Hanks method; min. surface root water potential, max ratio actual to PT, and root resistance factor input by user	Feddes or van Genuchten functions; anaerobiosis, limiting, and wilting points or end points and shape parameters input by user. PT distributed through root zone in proportion to root density.	Feddes function; anaerobiosis, limiting, and wilting points input by user. PT distributed through root zone in proportion to root density.
	Root density	Estimated using the Davidson method (Davidson et al. 1978) and root growth period	User defined versus depth or exponential model with user-defined parameters.	Exponential root density distribution and daily root depth. Function parameters and root depth input by user.
Soil properties	SWCC	Hybrid of Hutson and Campbell equations	Brooks–Corey, van Genuchten (VG), Modified VG, Kosugi log-normal	Brooks–Corey, van Genuchten, Rossi–Nimmo, Haverkamp, or polynomial.
	Hydraulic conductivity (K_ψ)	Campbell; parameterized from SWCC and requires K_s, pore interaction parameter	Brooks–Corey, van Genuchten–Mualem, Kosugi–Mualem, or dual-porosity formulations; parameterized from SWCC and requires K_s and pore interaction parameter. Temperature dependence optional.	van Genuchten–Mualem, Brooks–Corey, polynomial. van Genuchten–Mualem and Brooks–Corey models require K_s and pore interaction parameter. Shape parameters from SWCC or independent.
	Hysteresis	No	Yes (SWCC and K_ψ)	Yes (SWCC and K_ψ)
Numerics	Solution method	Finite difference	Finite element	Finite difference
	Iteration tolerance	Matric suction	Matric suction and water content; tolerances and iteration limit input by user	Matric suction and water content; tolerances and iteration limit input by user
	Temporal discretization	User inputs time step interval (<0.1 day)	Adaptive time stepping with iteration limits and scaling factors input by user	Adaptive time stepping with iteration limits and scaling factors input by user

Table 3. Initial Conditions for the Capillary Barrier at Polson, Mont.

Layer	Thickness (mm)	Initial volumetric water content	Matric suction (m)			
			Low storage capacity	Geometric mean storage capacity	High storage capacity	Field fit
Surface layer	150	0.065	6.8	10.4	15.1	2.4
Storage layer	460	0.143	1.6	8.5	49.9	75.6
Capillary break	600	0.086	2.3	3.7	6.4	32.6
Interim cover	460	0.063	0.07	0.07	0.07	0.07

LEACHM and HYDRUS, and is bounded by the potential evaporation (PE) rate. In UNSAT-H, evaporation is set at PE until the vapor pressure at the soil surface equals that in the atmosphere. Once this condition is reached, the evaporative flux is computed using a constant head boundary, with the suction at the surface corresponding to the vapor pressure in the atmosphere (Fayer 2000). The lower boundary in all three codes can be set as constant head or unit gradient. A seepage face boundary (i.e., flux $=0$ when the boundary is unsaturated; flux$=K_s$ when the boundary is saturated) also can be simulated with LEACHM and HYDRUS.

Vegetative water uptake is simulated using a mechanistic approach based on the Nimah and Hanks (1973) model (LEACHM) or a semiempirical approach where potential transpiration (PT) is distributed throughout the root zone in proportion to the relative root density (HYDRUS and UNSAT-H). In the latter approach, the effects of water availability are simulated using an empirical plant limiting function (e.g., Feddes and Zaradny 1978 or van Genuchten 1987). For all three codes, water uptake at a given depth ceases when the suction exceeds the wilting point. The wilting point is input to LEACHM, HYDRUS, and UNSAT-H.

Soil hydraulic properties are described parametrically in all three codes. LEACHM uses a two-part function for the SWCC consisting of Campbell‘s function (1974) for the dry end and the Hutson-Cass function for the wet end (Hutson and Cass 1987). Unsaturated hydraulic conductivity is computed in LEACHM using Campbell’s (1974) equation with the shape parameters from the SWCC. HYDRUS and UNSAT-H have multiple functions available for describing the hydraulic properties. In this study, the van Genuchten model was used as the basis for describing the SWCC in HYDRUS and UNSAT-H, although one simulation was conducted with UNSAT-H using the Brooks–Corey function to describe the SWCC. The van Genuchten-Mualem model was used for the hydraulic conductivity function in HYDRUS and UNSAT-H to define the unsaturated hydraulic conductivity, except in one case where the Brooks-Corey hydraulic conductivity function was used in UNSAT-H.

Model Setup

Initial Conditions

Initial conditions input to each code are summarized in Table 3. Nodes in each soil layer were assigned a matric suction (UNSAT-H) or water content (HYDRUS and LEACHM) corresponding to the average water content in the layer measured in the field on the first day of the simulation (January 1, 2000). Suctions input to UNSAT-H were obtained from the field-measured water contents and the SWCC for each layer.

Upper Boundary Condition

An atmospheric boundary was applied at the surface. Daily precipitation was applied using default conditions in each code (10 mm/h in UNSAT-H; uniformly throughout the time steps in LEACHM and HYDRUS), as is convention in practice. For LEACHM, precipitation was assumed to occur throughout the entire day to ensure consistency with the other codes. Potential evapotranspiration (PET) was computed by UNSAT-H using the modified Penman equation in Doorenbos and Pruitt (1977). The same PET was used for the LEACHM and HYDRUS simulations for consistency. For all three codes, PET was partitioned into PE and PT using the Ritchie–Burnett–Ankeny equation (Chadwick et al. 1999):

$$\mathrm{PT} = 0.52\mathrm{PET}\sqrt{\mathrm{LAI}} \tag{4}$$

Daily meteorological properties were input to each code as needed to define the atmospheric boundary. On-site measurements were used for wind speed and direction, air temperature, relative humidity, and solar radiation. Daily precipitation data were obtained from the weather station operated by the U.S. National Oceanic and Atmospheric Administration (NOAA) in Polson (Station No. 246635). On-site precipitation data were not used because the on-site precipitation gage was not shielded, which resulted in downward bias. A discussion of this bias, which is common in micrometeorological stations, can be found in Albright et al. (2004). The maximum suction at the surface used in HYDRUS was set at 100 MPa, which is more than 10 times greater than the highest suction observed in the field at a depth of 75 mm. Sensitivity analysis also showed that increasing the maximum suction above 100 MPa had no effect on the predictions made with HYDRUS.

None of the codes used in this study included an algorithm for snow hydrology. Thus, the data were preprocessed to account for accumulation of frozen precipitation and melt. Precipitation received when the air temperature was $<0°C$ was assumed to be frozen and was accumulated. Melting was assumed to occur when the air temperature was $>0°C$ and was computed using the degree-day approach in Kustas et al. (1994). This approach ignores sublimation, and thus may overestimate the amount of frozen precipitation applied to the surface as water (Dwyer et al. 2007).

Lower Boundary Condition

Simulations were conducted using a unit gradient (UG) lower boundary condition for all three codes, as is conventionally done in practice (Benson 2007). Comparative simulations also were conducted with HYDRUS and LEACHM using a seepage face

(SF) lower boundary condition. Scanlon et al. (2002) recommend a SF boundary to simulate the capillary break at the base of a pan lysimeter more accurately.

Soil Properties

Input hydraulic properties are summarized in Table 1. Four sets of parameters were used corresponding to the GM, HSC, LSC, and FF cases mentioned previously. The SWCCs were defined using van Genuchten's function for HYDRUS and UNSAT-H. For LEACHM, SWCC parameters were obtained by fitting the Campbell-Hutson-Cass SWCC function to the SWCC defined by the van Genuchten parameters using a least-squares optimization procedure (Ogorzalek 2005). Both functions provide a similar SWCC (Fig. 3), except near the air-entry suction, where the Campbell–Hutson–Cass function predicts higher water contents for a given suction. Only drying SWCCs were available. Thus, all simulations were conducted without hysteresis, as is common in practice.

The van Genuchten-Mualem function was used for the unsaturated hydraulic conductivity function in UNSAT-H and HYDRUS (Fig. 2). In LEACHM, the unsaturated hydraulic conductivity function is defined by Campbell's (1974) equation. The pore interaction term was set at 0.5 in the van Genuchten–Mualem function and 2.0 in the Campbell function, which is typical in practice (Benson 2007). Unsaturated hydraulic conductivities predicted by the Campbell function typically were higher than those predicted by the van Genuchten–Mualem function, particularly near the air-entry suction (Fig. 3).

The root barrier layer was not included in the model and therefore was not assigned hydraulic properties. The root barrier was excluded because the geotextile is very thin and soil readily embeds in pores, providing direct hydraulic connectivity between the adjacent soils. Consequently, the root barrier has negligible impact on water movement within the profile.

Vegetation

The LAI function was defined using the peak LAI measured in the field and end points of the growing season recommended by the Soil Conservation Service for the vegetation at the field site. The LAI was assumed to increase from 0 to 2.5 during the first 30 days of the growing season, decrease from 2.5 to 0 over the last 30 days of the growing season, and remain constant in between. For the first growing season, the peak LAI was set to 0.82 to account for the immaturity of the vegetation.

For HYDRUS and UNSAT-H, the root depth was assumed to increase 3 mm/day during the growing season until the root barrier was reached, as recommended in Roesler et al. (2002). Root density was modeled with Eq. (2) using the average field-measured root density parameters mentioned previously. For LEACHM, the date of root maturity was defined as the end of the growing season for the first year of simulation, and 30 days after the first day of the growing season for subsequent years.

Water uptake was defined in HYDRUS and UNSAT-H using the Feddes plant limiting function (Feddes and Zaradny 1978). The wilting point was defined by the highest matric suctions measured in the deeper portion of the root zone (i.e., >300 mm) during the monitoring period (3.6 MPa). This condition was achieved in late summer, when the water contents were at their lowest and the vegetation appeared dormant and water stressed. The limiting point (280 kPa) was computed using the method in Doorenbos and Kassam (1979). The anaerobiosis point was set at 10 kPa, which corresponds to 85% saturation in the storage layer for the GM case (Bohnhoff 2005). In LEACHM, the minimum root water potential was set at 3,000 kPa, as recommended in Hutson (2003). Default conditions were used for the maximum ratio of actual transpiration (AT) to PT (=1.1) and the root resistance factor (1.0) in LEACHM.

Spatial and Temporal Domain and Discretization

The spatial and temporal discretization used in each code was adjusted so that the mass balance error was <1 mm/year. In HYDRUS and UNSAT-H, a nodal spacing or element thickness as small as 1 mm was used at the ground surface and at soil interfaces. In LEACHM, the nodal spacing was uniform (as required by the code) and ranged from 20 to 30 mm depending on the simulation.

The maximum time step used in UNSAT-H was 0.25 h and the minimum time step required for convergence was 1.0×10^{-5} h. The maximum time step was set at 0.1 day (2.4 h) for all LEACHM simulations. For HYDRUS, the maximum time step was set at 24 h and the minimum time step was 6.6×10^{-5} h. All simulations were conducted for a record period between January 1, 2000 and September 30, 2003 (four growing seasons).

Some of the simulations conducted with HYDRUS considered one-dimensional (1D) and two-dimensional (2D) domains. Water-balance quantities predicted from the 2D simulations were nearly identical to those obtained from the 1D simulations (Benson 2007). Thus, only 1D (i.e., vertical) simulations are reported herein.

Comparison of Model Predictions and Field Data

Simulations were conducted with LEACHM, HYDRUS, and UNSAT-H using hydraulic properties corresponding to the LSC, GM, HSC, and FF cases. The predicted and measured water-balance quantities are shown in Figs. 4–7. Figs. 4–7 contains four graphs corresponding to the four sets of hydraulic properties. Unless noted otherwise, a unit gradient boundary was applied at the base of the cover profile for all of the simulations. Annual water-balance quantities predicted by the codes and measured in the field are summarized in Table 4 and shown graphically in Fig. 8.

Runoff (*R*)

Measured and predicted cumulative runoff (R) are shown in Fig. 4 along with cumulative precipitation. Runoff is shown on the right ordinate axis and precipitation on the left ordinate axis. Only 17.8 mm of runoff occurred during the monitoring period (1.5% of precipitation). This small amount of runoff is characteristic of water-balance covers, for which annual runoff is typically less than 5% of precipitation (Albright et al. 2004). Runoff predicted by HYDRUS and LEACHM also was relatively small, and the total runoff predicted by both codes agreed reasonably well with the total field-measured runoff (except for the HSC case predicted by HYDRUS). For example, with the GM parameters, HYDRUS predicted 22.9 mm of runoff during the monitoring period whereas LEACHM predicted 0.4 mm of runoff. In contrast, UNSAT-H overpredicted runoff significantly for all three parameters sets, with total runoff during the record period ranging from 257 mm (FF case) to 355 mm (HSC case) (Table 4).

For all four parameter sets, LEACHM predicted the least amount of runoff, UNSAT-H predicted the most runoff, and HY-

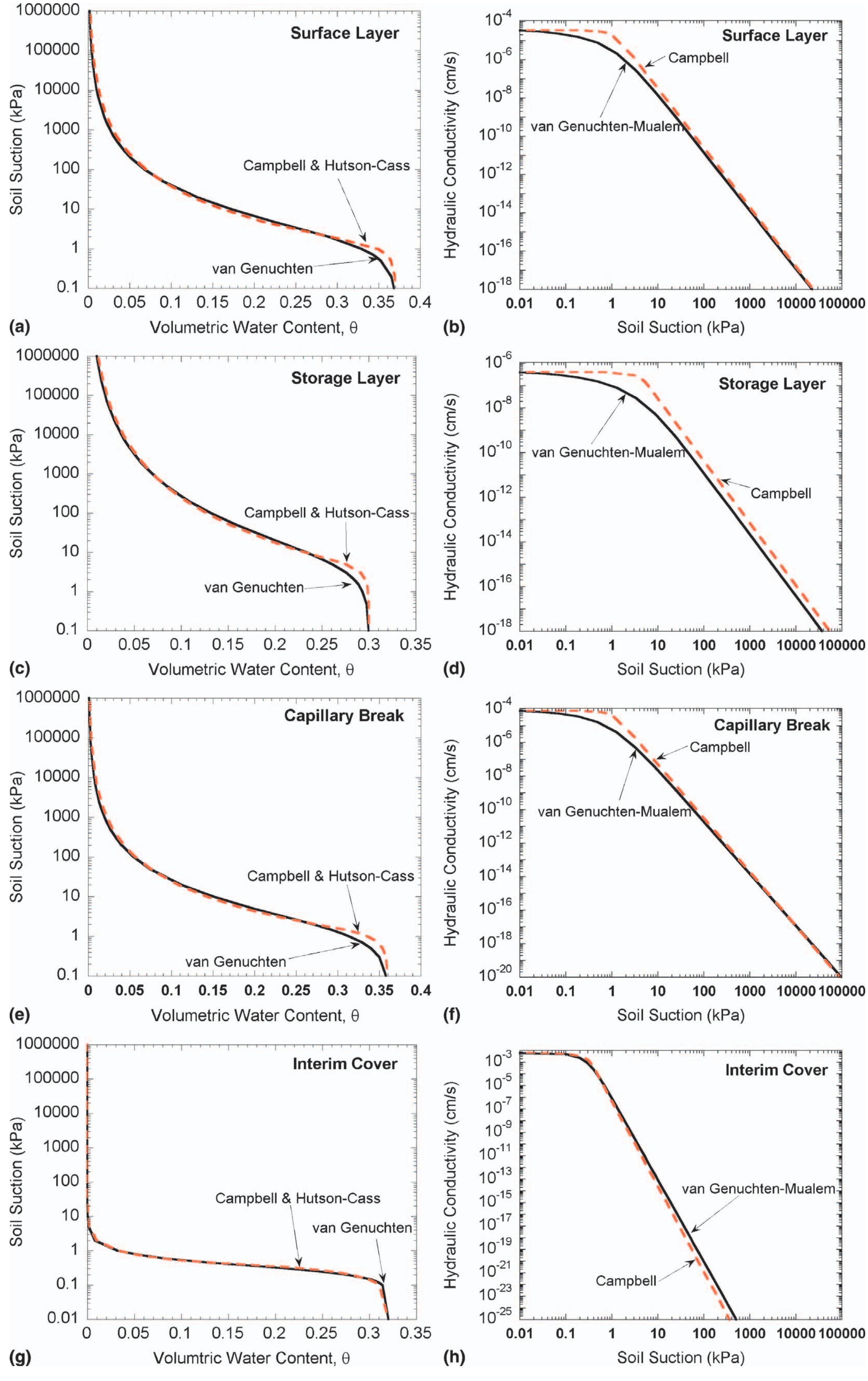

Fig. 3. (Color) van Genuchten and Campbell–Hutson–Cass soil–water characteristic curves and hydraulic conductivity functions for GM parameters

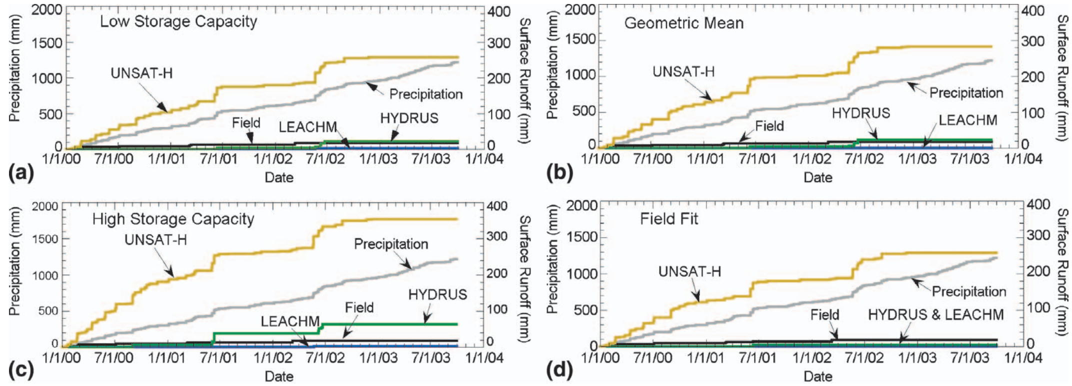

Fig. 4. (Color) Measured precipitation, measured runoff, and runoff predicted by LEACHM, HYDRUS, and UNSAT-H for different sets of hydraulic properties

DRUS predicted an intermediate amount of runoff. This hierarchy is illustrated in Fig. 8(a) for predictions made with GM parameters. Differences in the predictions can be attributed to how the codes apply precipitation (temporally and total versus net precipitation) and the functions used to simulate the hydraulic properties. Both factors influence the infiltration capacity of the profile and, therefore, the amount of precipitation shed as runoff during precipitation.

For example, the large over prediction of runoff by UNSAT-H is due in part to the default precipitation rate (10 mm/h), which is nearly 20 times higher than the average hourly precipitation rate recorded during the monitoring period (0.51 mm/h). As shown in Fig. 9(a), a simulation conducted with UNSAT-H using an average precipitation rate of 0.51 mm/h predicted considerably lower total runoff (114 mm). UNSAT-H also applies total precipitation to the surface, whereas HYDRUS applies net precipitation (total

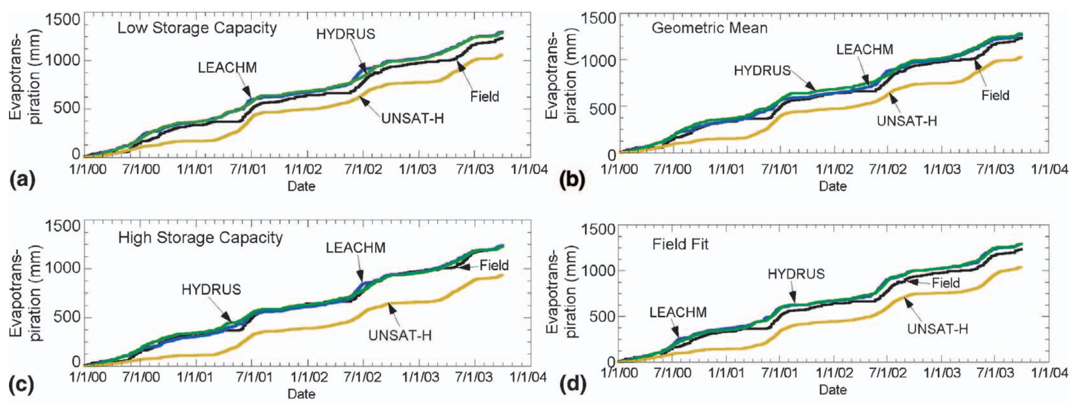

Fig. 5. (Color) Measured evapotranspiration and evapotranspiration predicted by LEACHM, HYDRUS, and UNSAT-H for different sets of hydraulic properties

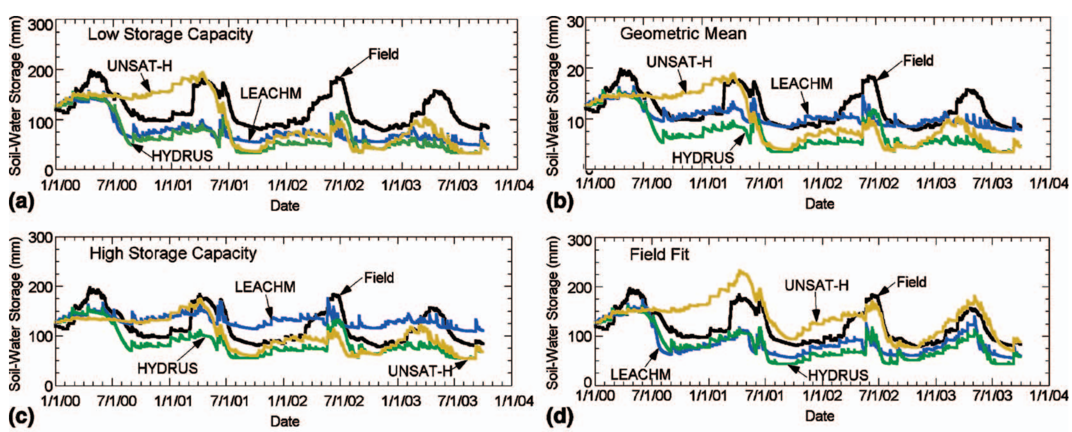

Fig. 6. (Color) Measured soil–water storage and soil-water storage predicted soil by LEACHM, HYDRUS, and UNSAT-H for different sets of hydraulic properties

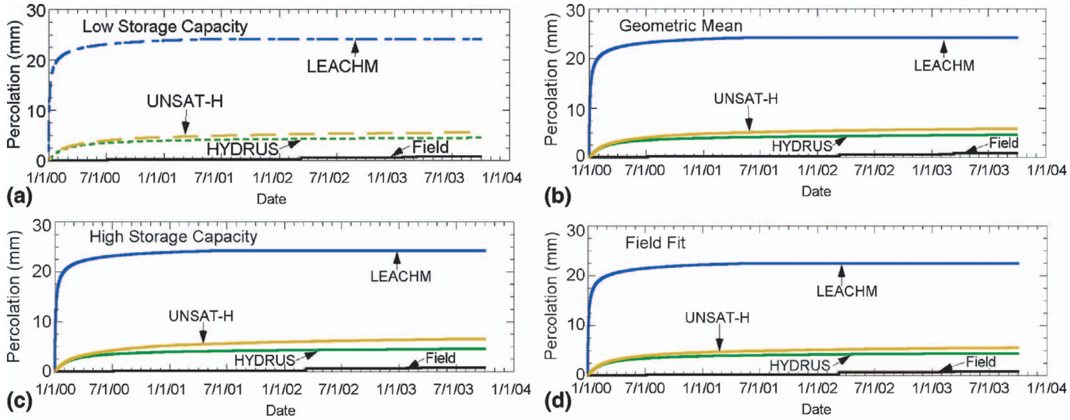

Fig. 7. (Color) Measured percolation and percolation predicted soil by LEACHM, HYDRUS, and UNSAT-H for different sets of hydraulic properties

precipitation—PE). Therefore, when all other factors are equal, UNSAT-H will apply more water to the surface than HYDRUS for a given precipitation record (Scanlon et al. 2002) and, therefore, will predict more runoff.

The hydraulic conductivity from the van Genuchten–Mualem function used in UNSAT-H and HYDRUS generally is lower than the hydraulic conductivity from the Campbell function used in LEACHM (Fig. 3). This is particularly important near the air-entry suction, where the hydraulic conductivities can differ by approximately a factor of 10 for the surface layer. This difference near the air-entry suction has a significant effect on runoff, as the infiltration capacity is reached when the soil surface approaches saturation. To illustrate how hydraulic conductivity near the air-entry suction affects runoff, a simulation was conducted with UNSAT-H using the Brooks–Corey function (Brooks and Corey 1964) instead of the van Genuchten–Mualem function (the Campbell function was not used because it is not available in UNSAT-H; see Table 2). The Brooks–Corey function closely resembles the Campbell–Huston–Cass function near the air-entry suction (Ogorzalek 2005), and yields hydraulic conductivities higher than those predicted by the van Genuchten–Mualem function near the air entry suction. Brooks–Corey parameters were obtained by fitting the Brooks–Corey function for the SWCC using the same least-squares technique used to obtain the Campbell–Huston–Cass parameters. As shown in Fig. 9(a), much less runoff is predicted with the Brooks–Corey function (75.2 mm total) than with the van Genuchten–Mualem function (282 mm total), when all other variables are maintained constant. The influence of the hydraulic conductivity of the surface also is evident when the annual predictions of runoff made with UNSAT-H [Fig. 8(a)] are compared. The error in runoff is smaller in 2001–2003 than in 2000 because a higher saturated hydraulic conductivity was used in 2001–2003 than in 2000.

Inspection of the runoff record in Fig. 4 indicates that nearly all of the runoff occurred in one event each year. Moreover, except for the first year, most runoff occurred in early spring (Feburary–March) each year in response to snowmelt (2000–7.8 mm, 2001–3.8 mm, 2002–3.6 mm, 2003–0.0 mm). The codes also predicted runoff to occur in annual cycles (except for UNSAT-H, which predicted runoff more regularly). However, the codes predicted runoff approximately 3 months later than actually occurred in the field, and this runoff was predicted in response to heavy precipitation events rather than snowmelt. Thus, the relatively good agreement between total runoff occurring in the field and predicted by HYDRUS or LEACHM is partly coincidental.

The absence of predicted runoff from snowmelt also suggests that improved methods to simulate snow hydrology are needed for codes used to evaluate water-balance covers in cooler climates. Khire et al. (1997, 1999) also found that snowmelt predictions can have a significant effect on the accuracy of runoff predictions for conventional covers. Codes based on Richards' equation that include snow hydrology algorithms include VADOSE/W (Krahn 2004) and SHAW (Flerchinger and Saxton 1989).

Evapotranspiration (ET)

Field and predicted ET are shown in Fig. 5 for each set of hydraulic properties. All four codes replicate the seasonal variation in ET, although the codes predict the onset of ET earlier than occurs in the field and predict a lesser rate of ET during the spring and summer months. ET predicted by UNSAT-H is consistently lower than field ET for all four data sets, whereas LEACHM and HYDRUS generally over predict ET (except for simulations conducted with the HSC hydraulic properties).

The under prediction of ET using UNSAT-H is due in part to the over prediction of runoff during 2000, which reduced the amount of water available for ET. For example, much better agreement between field and predicted ET was obtained when simulations with UNSAT-H were conducted with the average precipitation measured in the field or using the Brooks–Corey functions for the hydraulic properties [Fig. 9(b)], both of which reduce the predicted runoff [Fig. 9(a)]. In subsequent years, ET predicted by UNSAT-H was in closer agreement with ET from the field, as shown by the annual quantities in Fig. 8. The agreement was better because the over prediction of runoff by UNSAT-H was smaller (Fig. 8), and soil–water storage was depleted each summer (Fig. 6).

Both HYDRUS and LEACHM provide similar and relatively accurate predictions of ET for all four sets of hydraulic properties, with predicted-to-field ET ranging from 99 to 105% for HYDRUS and from 100 to 105% for LEACHM. The slight over predictions of ET are attributed to over predictions during March–May (Fig. 5), when water was accumulating in the cover in response to snow melt and spring rain (Fig. 6) and little ET was occurring in the field. UNSAT-H also over predicted ET during

Table 4. Measured and Predicted Runoff, Evapotranspiration, and Percolation for Hydraulic Properties Corresponding to the LSC, GM, HSC, and FF Cases

Cumulative water-balance quantity	Field or model	Water-balance quantity (mm)					
		Parameter set	2000	2001	2002	2003[a]	Total
Precipitation	Field	—	298	307	358	255	1218
Runoff	Field	—	8.8	4.3	4.7	0.0	17.8
	LEACHM	LSC	0.0	0.0	3.1	0.0	3.1
		GM	0.0	0.0	0.4	0.0	0.4
		HSC	0.4	0.0	1.7	0.0	2.1
		FF	0.0	0.0	0.0	0.0	0.0
	HYDRUS	LSC	0.0	4.0	18.5	0.0	22.5
		GM	0.0	4.9	18.0	0.0	22.9
		HSC	5.2	32.1	26.0	0.0	63.3
		FF	0.0	3.8	0.0	0.0	3.8
	UNSAT-H	LSC	103	77	77	0.0	257
		GM	122	79	81	0.0	282
		HSC	180	84	90	1.0	355
		FF	122	61	74	0.0	257
Evapotranspiration	Field	—	332	309	334	257	1,232
	LEACHM	LSC	364	307	352	271	1,294
		GM	333	308	355	273	1,269
		HSC	304	305	353	272	1,234
		FF	365	301	354	270	1,290
	HYDRUS	LSC	364	318	334	271	1,287
		GM	361	319	334	268	1,282
		HSC	341	288	326	267	1,222
		FF	347	324	353	264	1,288
	UNSAT-H	LSC	166	329	278	283	1,056
		GM	149	321	276	281	1,027
		HSC	111	276	270	275	932
		FF	142	301	312	282	1,037
Percolation	Field	—	0.2	0.0	0.4	0.2	0.8
	LEACHM	LSC	23.8	0.3	0.0	0.0	24.1
		GM	23.9	0.3	0.0	0.0	24.2
		HSC	23.9	0.3	0.0	0.0	24.2
		FF	22.2	0.2	0.0	0.0	22.4
	HYDRUS	LSC	3.9	0.3	0.2	0.1	4.5
		GM	3.9	0.3	0.2	0.2	4.6
		HSC	3.9	0.3	0.2	0.1	4.5
		FF	3.8	0.4	0.1	0.1	4.4
	UNSAT-H	LSC	4.6	0.5	0.3	0.2	5.6
		GM	4.8	0.5	0.3	0.2	5.8
		HSC	5.2	0.7	0.4	0.2	6.5
		FF	4.6	0.5	0.3	0.1	5.5

[a]Partial year ending October 1, 2003.

these months, but this over prediction was masked by the overall under prediction of ET by UNSAT-H in 2000. The algorithm used by HYDRUS to compute net precipitation also over predicts evaporation during precipitation (Scanlon et al. 2002), which contributes to the over prediction of ET. The over prediction of ET using LEACHM also can be attributed to the under prediction of runoff, which makes more water available for ET.

The over predictions of ET during March–May may be due to inadequate parameterization of the plant parameters controlling transpiration, such as the onset of the growing season and the temporal distribution of LAI during the spring (i.e., if the start of growing season had been delayed, more accumulation of water would have occurred). Plant behavior is difficult to predict using the algorithms in these codes, which decouple phenology from meteorological conditions (Scanlon et al. 2005). Additionally, the

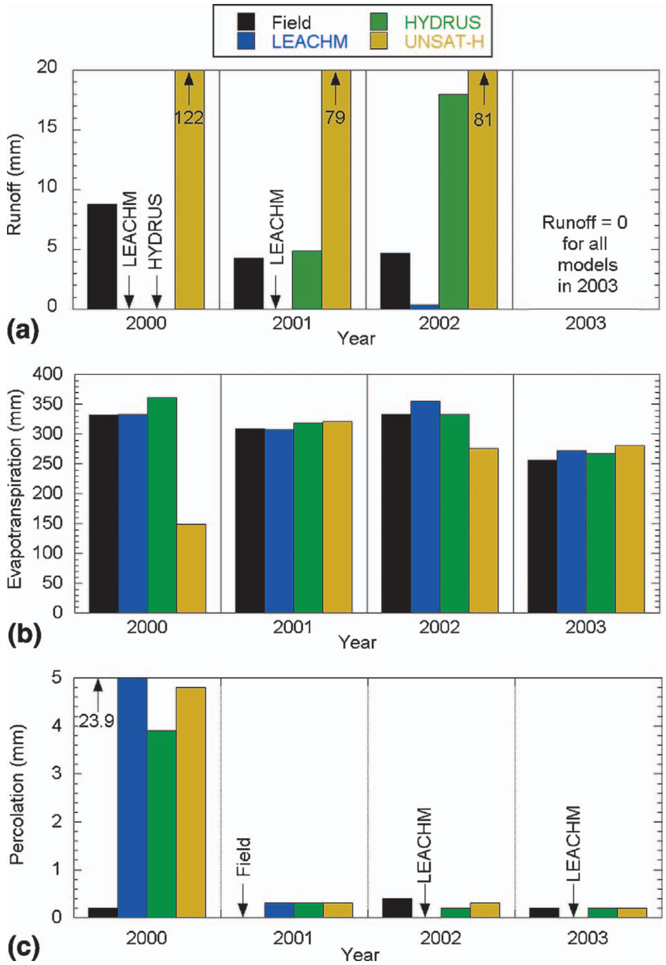

Fig. 8. (Color) Annual measured and predicted (a) runoff; (b) evapotranspiration; and (c) percolation using geometric mean hydraulic properties

plant parameters used in the codes, which are difficult to quantify a priori, can have an important effect on model predictions (Ogorzalek 2005, Benson 2007).

Soil-Water Storage

Predicted and measured soil-water storage are shown in Fig. 6. Even though an exact match existed for the initial condition for all parameter sets, none of the codes predicts soil-water storage accurately. In general, predicted soil-water storage typically is lower than measured soil-water storage. UNSAT-H provided the closest agreement between predicted and measured soil-water storage using field-fit parameters for input (except for 2000). Soil–water storage predicted by LEACHM using GM parameters is also in reasonable overall agreement with measured soil–water storage, although the peaks in soil–water storage are under predicted each year. In contrast, HYDRUS under predicted soil–water storage in all cases.

All of the codes under predict the accumulation of soil–water storage that occurred in early spring each year because ET was over predicted during this period. Consequently, the peak soil–water storage and the overall annual change in soil–water storage were under predicted (the prediction with UNSAT-H using FF parameters is an exception). UNSAT-H also failed to capture the drop in soil–water storage in Spring 2000 for all parameter sets. This error may be an artifact of the lower LAI and the longer duration for root penetration used during the first growing season in UNSAT-H to account for immaturity of the vegetation.

The prediction of soil–water storage by UNSAT-H also was affected by the overprediction of runoff, as illustrated in Fig. 9. Using the average precipitation intensity or the Brooks–Corey hydraulic functions as input results in less runoff [Fig. 9(a)], higher peak soil-water storage [Fig. 9(c)], and larger seasonal variations in soil-water storage [Fig. 9(c)].

Percolation (P_r)

Predicted and measured percolation are shown in Fig. 7. Percolation is over predicted by all three codes using all four sets of

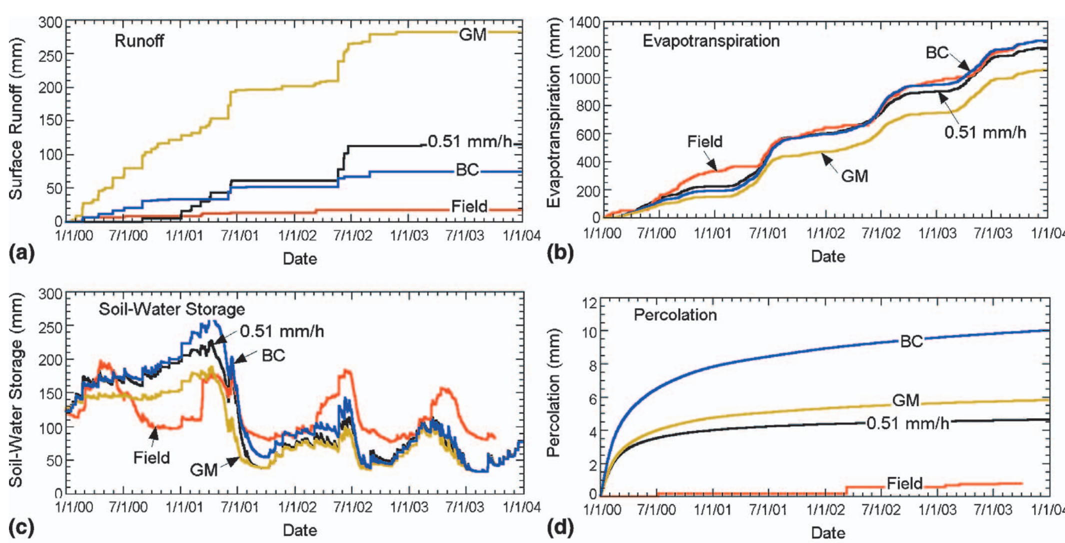

Fig. 9. (Color) Field data and water-balance predictions obtained with UNSAT-H using default geometric mean (GM) hydraulic properties and default precipitation rate (GM case), average precipitation rate in the field (0.51 mm/h), and GM hydraulic properties using Brooks–Corey constitutive functions (BC)

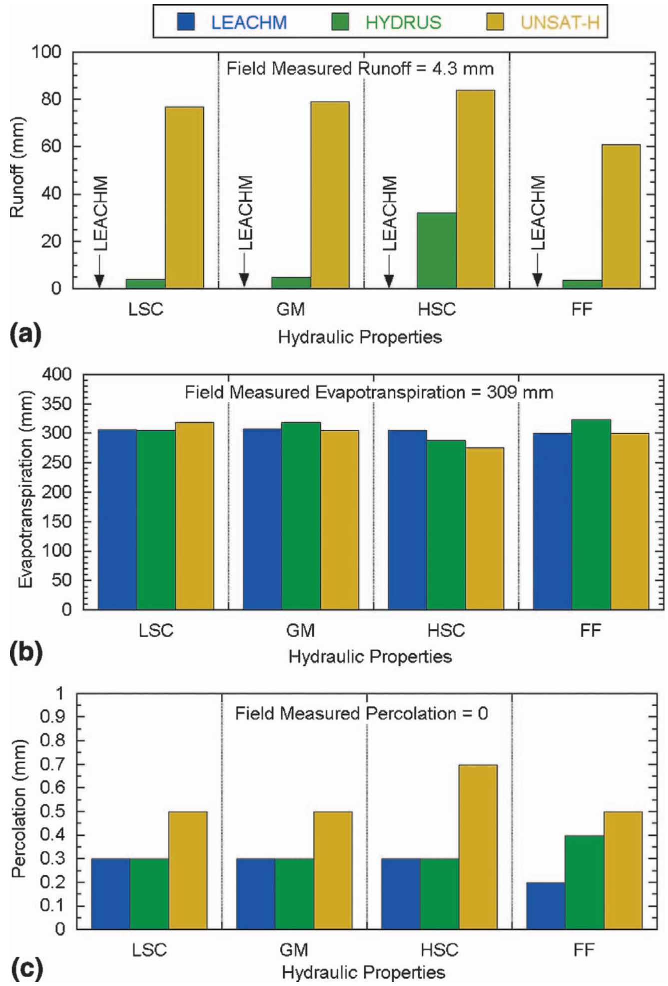

Fig. 10. (Color) Measured and predicted (a) runoff; (b) evapotranspiration; and (c) percolation for 2001 using different sets of hydraulic properties: LSC=low storage capacity; GM=geometric mean; HSC=high storage capacity; and FF=field fit

hydraulic properties, with the over prediction ranging from approximately 4 to 23 mm. For example, using GM parameters, LEACHM predicted 24.2 mm of percolation, HYDRUS predicted 4.6 mm of percolation, and UNSAT-H predicted 5.8 mm of percolation, whereas only 0.8 mm of percolation occurred in the field (Table 4). However, the majority of the over prediction occurred during the first six months of the simulation period; thereafter, the annual percolation predicted with all three codes was in reasonably close agreement with the field-measured percolation [Fig. 8(c)].

The over prediction of percolation during the first six months of the simulation is due to drainage from the gravelly interim cover (Fig. 1) that occurs with the UG boundary condition. The initial volumetric water content for the gravelly interim cover was set at 0.063, which is above field capacity ($\theta \approx 0$ at $\psi = 33$ kPa, Fig. 3). Thus, the water in this gravel is expected to drain under unit gradient conditions. In the lysimeter, however, this water would be retained in the gravel due to the capillary break imposed by the geocomposite drainage layer used in the bottom of the lysimeter.

To validate the capillary break hypothesis, computations of storage afforded by the capillary break were made using the procedure in Khire et al. (2000) with SWCCs for nonwoven geotextiles from Stormont et al. (1997). These computations showed that the capillary break could result in 10–45 mm of water stored in the gravelly interim cover layer depending on the SWCC used to describe the nonwoven geotextile at the surface of the geocomposite drainage layer.

Simulations also were conducted with a seepage face (SF) boundary condition using HYDRUS and LEACHM (UNSAT-H does not have this option), which simulates the capillary break by only permitting flow when the boundary is saturated. With a SF boundary and GM hydraulic properties, HYDRUS predicted 0.8 mm of percolation and LEACHM predicted 8.3 mm of percolation during the first year, and no percolation for the remainder of the monitoring period. Thus, the over prediction of percolation during the first year is most likely due to the UG boundary condition applied at the bottom of the cover. In contrast, changing the lower boundary condition had virtually no effect on any of the other water-balance quantities (Bohnhoff 2005; Ogorzalek 2005).

Table 5. Hydraulic Parameter Set for Each Model Yielding the Lowest Mean Square between Predicted Runoff, ET, and Percolation

Model	Runoff	Evapotranspiration	Percolation
LEACHM	HSC	GM	LSC
HYDRUS	GM	HSC	GM
UNSAT-H	LSC	LSC	LSC

Effect of Hydraulic Parameter Sets

The predictions made by all three codes are affected by the hydraulic parameter set used for input (HSC, GM, LSC, or FF; see Table 4). Predictions using HSC parameters typically have the largest runoff, lowest evapotranspiration, and smallest seasonal variation in soil–water storage (see Figs. 4–6, Table 4). Conversely, predictions with LSC parameters typically have the least runoff, most evapotranspiration, and the largest variations in soil–water storage. Predictions made with GM or FF parameters typically fall between predictions obtained with HSC and LSC parameters. Selection of the hydraulic parameter set had much less effect on percolation than the other water-balance variables. Annual percolation varies no more than 1.8 mm between parameter sets, and generally varies less than 1.0 mm between parameter sets.

The variations in predictions of runoff and ET are consistent with the differences in the hydraulic properties in the parameter sets. HSC parameters include the lowest saturated hydraulic conductivities and SWCCs corresponding to the greatest retention of water, whereas LSC parameters correspond to the highest saturated hydraulic conductivities and the least retention of water. Therefore, simulations with HSC parameters are the most restrictive of upper boundary fluxes (infiltration, ET), whereas simulations with LSC parameters are the least restrictive of upper boundary fluxes. The saturated hydraulic conductivity and water-retention characteristics of the GM and FF parameter sets typically fall between those for the HSC and LSC parameter sets.

An analysis was conducted to determine which parameter set yielded the least mean square error between the annual predicted and measured runoff, ET, and percolation for each model. Results of the analysis are summarized in Table 5. None of the parameter sets consistently provided better agreement between predicted and measured water-balance quantities in terms of minimum mean square error. GM parameters provided the best agreement be-

tween runoff and percolation for HYDRUS. For UNSAT-H, LSC parameters provided the best agreement because the runoff error was lowest when LSC parameters were input. For percolation alone, only subtle differences between the predictions and the field data can be attributed to the parameters sets. All four parameter sets provided predictions that were in comparable agreement with measured percolation (Table 4).

Predicted and measured runoff, ET, and percolation for 2001 are summarized in Fig. 10 to illustrate the relative differences between the predictions that can be attributed to the parameter sets relative to differences that can be attributed to variations between codes. Quantities from 2001 were selected because 2001 resulted in the lowest overall mean square error. Comparison of the water-balance quantities in Fig. 10 shows that the variations between predictions obtained from different codes using a particular parameter set are as large as, or larger than, the variations in predictions obtained with different parameter sets using a particular code. This finding suggests that model selection and formulation can be as important as defining the range of parameters to be used for simulation.

Summary and Recommendations

Predictions of surface runoff, evapotranspiration (ET), soil–water storage, and percolation obtained using three numerical codes used to simulate the hydrology of water-balance covers (LEACHM, HYDRUS, and UNSAT-H) were compared to measured water-balance data from a lysimeter used to monitor a capillary barrier cover profile in a subhumid climate. Data collected from field and laboratory tests were used as input to the codes to the greatest extent possible so that the accuracy of the codes could be addressed in the context of predictions made for engineering design (i.e., without a priori calibration).

Comparison of the predictions and the field data showed that all of the codes captured the seasonal variations in water-balance quantities that were observed in the field. LEACHM and HYDRUS predicted total runoff during the monitoring period with reasonable accuracy. However, the runoff predicted by both codes occurred in response to heavy summer precipitation, whereas runoff occurred in the field only during spring snowmelt events. In contrast, UNSAT-H consistently over predicted runoff due to the high rate at which precipitation is applied under default conditions. Evapotranspiration over the entire monitoring period generally was over predicted modestly by LEACHM and HYDRUS and under predicted significantly by UNSAT-H. All three codes over predicted ET in late winter and early spring when snowmelt was occurring and soil–water storage was accumulating. Soil–water storage generally was under predicted by all three codes throughout the monitoring period. Seasonal fluctuations in soil–water storage also were under predicted by all three codes due to the over prediction of ET during the late winter and early spring. Some of these errors in ET are probably due to difficulty in defining parameters in functions describing the vegetation. Research on ET algorithms for water-balance covers and better definition of vegetation parameters is recommended.

All three codes over predicted percolation. Most of the over prediction occurred during the first year of the simulation as water initially in the gravel layer at the bottom of the profile drained under unit gradient conditions. In subsequent years, the predicted and measured percolation were in good agreement (within 1 mm/year). Using a seepage face boundary condition to simulate the capillary break caused by the lysimeter resulted in a significant reduction in the over estimate of percolation during the first year. However, in subsequent years, percolation predicted with the seepage face boundary was less than percolation measured in the field.

An analysis of the importance of the hydraulic parameter sets showed that no single parameter set provided more accurate predictions for all three codes. Mean parameters provided predictions with the least overall mean square error for HYDRUS, whereas parameters corresponding to low-storage capacity conditions provided the least overall mean square error for UNSAT-H. No definitive conclusion could be drawn regarding which parameter set provided the least mean square error for LEACHM. Overall, however, the variations in predictions attributed to differences in the parameter sets were comparable to, or smaller than, the variations between predictions obtained with different codes using the same parameter set.

Based on these findings, the following recommendations are made for those involved in modeling the hydrology of water-balance covers:

1. Runoff predictions should be scrutinized to determine whether they are reasonable and consistent with field data, such as the data reported here and by others. Care should be used when selecting the rate at which precipitation is applied in the model and the hydraulic properties of the surface layer. These inputs should reflect field conditions as accurately as practical.
2. Care should be used when modeling the hydrology of water-balance covers in regions where snow accumulates. Designers should compare model predictions of snow melt and runoff to local observations to ensure that the model reasonably represents the timing and magnitude of snow-melt events. Evapotranspiration while snow is present and/or melting can be over estimated with these codes. One approach to resolve this problem is to reduce the PET used as input during these periods, as suggested by Fayer and Gee (1997).
3. Caution should be used when making inferences regarding field conditions based on model predictions. Although all three codes captured the seasonality in the water balance, absolute differences between the measured and predicted water-balance quantities generally were larger than target percolation rates for water-balance covers intended to be equivalent to conventional covers. Thus, predictions obtained with the codes are more appropriate for understanding parameter sensitivity or comparative analyses rather than for direct prediction during design.

Acknowledgments

Financial support for this project was provided by the United States Environmental Protection Agency's (USEPA's) Science to Achieve Results (STAR) program (Grant No. R-82951501-0) as part of the USEPA's Rocky Mountain Hazardous Substance Research Center (HSRC) and by USEPA's Alternative Cover Assessment Program (ACAP). Dr. Mitch Lasat is the USEPA program manager for the HSRC and Mr. Steven Rock is the USEPA program manager for ACAP. The results and opinions expressed in this paper are solely those of the writers, and endorsement by the USEPA is not implied and should not be assumed.

References

Albright, W. H., Benson, C. H., Gee, G. W., Roesler, A. C., Abichou, T., Apiwantragoon, P., Lyles, B. F., and Rock, S. A. (2004). "Field water balance of landfill final covers." *J. Environ. Qual.*, 33(6), 2317–2332.

Apiwantragoon, P. (2007). "Field hydrologic evaluation of final covers for waste containment." Ph.D. dissertation, Univ. of Wisconsin, Madison, Wis.

Benson, C. H. (2001). "Waste containment: strategies and performance." *Austral. Geomech. J.*, 36(4), 1–25.

Benson, C. H. (2007). "Modeling unsaturated flow and atmospheric interactions." *Theoretical and numerical unsaturated soil mechanics*, T. Schanz, ed., Springer, Berlin, 187–202.

Benson, C., Abichou, T., Albright, W., Gee, G., and Roesler, A. (2001). "Field evaluation of alternative earthen final covers." *International J. Phytoremediation*, 3(1), 1–21.

Benson, C., and Chen, C. (2003). "Selecting the thickness of monolithic earthen covers for waste containment." *Soil and Rock America 2003*, P. J. Culligan, H. H. Einstein, and A. J. Whittle, eds., Verlag Gluck auf GMBH, Essen, Germany, 1397–1404.

Benson, C. H., Abichou, T., Wang, X., Gee, G. W., and Albright, W. H. (1999). "Test section installation instructions, assessment program." *Geoengineering Rep. No. 99-3*, Geo Engineering, University of Wisconsin, Madison, Wis.

Benson, C. H., Bohnhoff, G. L., Apiwantragoon, P., Ogorzalek, A. S., Shackelford, C. D., and Albright, W. H. (2004). "Comparison of model predictions and field data for an ET cover." *Tailings and Mine Waste '04*, Balkema, Leiden, The Netherlands, 137–142.

Benson, C. H., Bohnhoff, G. L., Ogorzalek, A. S., Shackelford, C. D., Apiwantragoon, P., and Albright, W. H. (2005). "Field data and model predictions for an alternative cover." *Waste containment and remediation* (CD-ROM), ASCE Geotechnical Special Publication No. 47, A. Alshawabkeh et al., eds., ASCE, Reston, Va.

Benson, C., Sawangsuriya, A., Trzebiatowski, B., and Albright, W. (2007). "Postconstruction changes in the hydraulic properties of water balance cover soils." *J. Geotech. Geoenviron. Eng.*, 133(4), 349–359.

Benson, C. H., Thorstad, P. A., Jo, H. Y., and Rock, S. A. (2007). "Hydraulic performance of geosynthetic clay liners in a landfill final cover." *J. Geotech. Geoenviron. Eng.*, 133(7), 814–827.

Bohnhoff, G. L. (2005). "Water balance and field data for water-balance covers in semi-arid regions." MS thesis, Univ. of Wisconsin, Madison, Wis.

Bolen, M., Roesler, A., Benson, C., and Albright, W. (2001). "Alternative cover assessment program: Phase II report." *Geoengineering Rep. No. 01-10*, University of Wisconsin, Madison, Wis.

Brooks, R. H., and Corey, A. T. (1964). "Hydraulic properties of porous media." *Hydrology Papers, No. 3*, Colorado State Univ., Fort Collins, Colo.

Campbell, G. S. (1974). "A simple method for determining unsaturated conductivity from moisture retention data." *Soil Sci.*, 117(6), 311–314.

Chadwick, D., Ankeny, M., Greer, L., Mackey, C., and McClain, M. (1999). "Field test of potential RCRA-equivalent covers at the Rocky Mountain Arsenal." *Proc., SWANA 4th Annual Landfill Symp.*, SWANA Publication No. GR-LM-0004, Silver Spring, Md., 12–33.

Davidson, J. M., Graetz, D. A., Rao, C., and Selim, H. M. (1978). "Simulations of nitrogen movement, transformation, and uptake in plant root zone." *EPA-600/3-78-029*, Environmental Protection Agency, Cincinnati.

Doorenbos, J., and Kassam, A. (1979). "Yield response to water." *FAO Irrigation and Drainage, Paper No. 33*, Food and Agricultural Organization of the United Nations Rome.

Doorenbos, J., and Pruitt, W. (1977). "Guidelines for predicting crop agriculture requirements." *FAO Irrigation Paper No. 24*, 2nd Ed., Food and Agricultural Organization of the United Nations, Rome.

Dwyer, S. F., Bull, L., Johnson, T., and Obereiner, J. (2007). "Evaluating the Vadose/W model for deployment of evapotranspiration covers in cold and wet climates." *Proc., WasteTech 2007*, Penton Media, Inc., New York.

Fayer, M. (2000). "UNSAT-H version 3.0: Unsaturated soil water and heat flow model-theory, user manual, and examples." *Rep. No. PNNL-13249*, Pacific Northwest National Laboratory, Richland, Wash.

Fayer, M. J., and Gee, G. W. (1997). "Hydraulic model tests for landfill covers using field data." *Landfill capping in the semiarid west: Problems, perspectives, and solutions*, Environmental Science and Research Foundation, Idaho Falls, Idaho, 53–68.

Fayer, M. J., Rockhold, M. L., and Campbell, M. D. (1992). "Hydrologic modeling of protective barriers: comparison of field data and simulation results." *Soil Sci. Soc. Am. J.*, 56(3), 690–700.

Feddes, R., and Zaradny, H. (1978). "Model for simulating soil water content considering evapotranspiration—Comments." *J. Hydrol.*, 37(3–4), 393–397.

Flerchinger, G. N., and Saxton, K. E. (1989). "Simultaneous heat and water model of a freezing snow-residue-soil system. I: Theory and development." *Trans. ASAE*, 32(2), 565–571.

Gurdal, T., Benson, C., and Albright, W. (2003). "Hydrologic properties of final cover soils from the alternative cover assessment program." *Geoengineering Rep. 03-02*, Geoengineering Program, University of Wisconsin-Madison, Madison, Wis.

Hutson, J. L. (2003). *Leaching estimation and chemistry model, LEACHM, model description and user's guide*, School of Chemistry, Physics and Earth Sciences, The Flinders University of South Australia, Adelaide, Australia.

Hutson, J. L., and Cass, A. (1987). "A retention function for use in soil-water simulation models." *J. Soil Sci.*, 38(1), 105–113.

Hutson, J. L., and Wagenet, R. J. (1992). *LEACHM: Leaching estimation and chemistry model: A process based model of water and solute movement transformations, plant uptake, and chemical reactions in the unsaturated zone*, Continuum Vol. 2, Version 3, Water Resources Institute, Cornell University, Ithaca, N.Y.

Kavazanjian, E., Gross, B., and Hadj-Hamou, T. (2006). "Unsaturated flow flux assessment for evapotranspirative cover compliance." *Unsaturated soils 2006, geotechnical special publication No. 147*, G. Miller et al., eds., ASCE, Reston, Va., 634–645.

Kelln, C., Barbour, S., Elshorbagy, A., and Qualizza, C. (2006). "Long-term performance of reclamation cover: The evolution of hydraulic properties and hydrologic response." *Unsaturated soils 2006, geotechnical special publication No. 147*, G. Miller et al., eds., ASCE, Reston, Va., 813–824.

Khire, M. V., Benson, C. H., and Bosscher, P. J. (1997). "Water balance modeling of earthen final covers." *J. Geotech. Geoenviron. Eng.*, 123(8), 744–754.

Khire, M. V., Benson, C. H., and Bosscher, P. J. (1999). "Field data from a capillary barrier and model predictions with UNSAT-H." *J. Geotech. Geoenviron. Eng.*, 125(6), 518–527.

Khire, M. V., Benson, C. H., and Bosscher, P. J. (2000). "Capillary barriers: design variables and water balance." *J. Geotech. Geoenviron. Eng.*, 126(8), 695–708.

Kim, K., and Benson, C. (2002). "Water content calibrations for final cover soils." *Geoengineering Rep. No. 02-12*, Geo Engineering Program, Univ. of Wisconsin-Madison, Madison, Wis.

Koragappa, N., Wall, R. V., and Benson, C. H. (2007). "Evapotranspirative final cover–Case study of a southern California landfill." *Proc., WasteTech 2007*, Penton Media, Inc., New York.

Krahn, J. (2004). *Vadose zone modeling with VADOSE/W*, GEO-SLOPE International, Ltd., Calgary, Alta., Canada.

Kustas, W., Rango, A., and Uijlenhoet, R. (1994). "A simple energy budget algorithm for the snow melt runoff model." *Water Resour. Res.*, 30(5), 1515–1527.

Liang, Y., Hazlett, D., and Lauenroth, W. (1989). "Biomass dynamics and water use efficiencies of five plant communities in the Shortgrass Steppe." *Oecologia*, 80(2), 148–153.

Nimah, M. N., and Hanks, R. J. (1973). "Model for estimation of soil water, plant, and atmospheric interrelations: I. Description and sensitivity." *Soil Sci. Soc. Am. Proc.*, 37(4), 522–527.

Ogorzalek, A. S. (2005). “Evaluation of hydrologic models for alternative covers.” MS thesis, Colorado State University, Fort Collins, Colo.

Roesler, A., Benson, C., and Albright, W. (2002). “Field hydrology and model predictions for final covers in the alternative cover assessment program 2002.” *Geoengineering Rep. No. 02-08*, Dept. of Civil and Environmental Engineering, Univ. of Wisconsin-Madison, Madison, Wis.

Scanlon, B. R., Christman, M., Reedy, R. C., Porro, I., Šimůnek, J., and Flerchinger, G. N. (2002). “Intercode comparisons for simulating water balance of surficial sediments in semiarid regions.” *Water Resour. Res.*, 38(12), 1323–1339.

Scanlon, B. R., Reedy, R. C., Keese, K. E., and Dwyer, S. F. (2005). “Evaluation of evapotranspirative covers for waste containment in arid and semiarid regions of the Southwestern USA.” *Vadose Zone J.*, 4(1), 55–71.

Schroeder, P., Lloyd, C., and Zappi, P. (1994). *The hydrologic evaluation of landfill performance (HELP) model, user’s guide for version 3.0*, Environmental Protection Agency, Cincinnati.

Šimůnek, J., Sejna, M., and van Genuchten, M. T. (1999). *HYDRUS: Simulating water flow, heat, and solute transport in two-dimensional variably-saturated media*, IGWMC—TPS 53, International Groundwater Modeling Center, Colorado School of Mines, Golden, Colo.

Stockdill, D., Jorgenson, R., and Obermeyer, J. (2006). “Case history and regulatory aspects of a final cover performance evaluation involving conventional and evapotranspirative cover designs.” *Unsaturated soils 2006, geotechnical special publication No. 147*, G. Miller et al., eds., ASCE, Reston, Va., 789–800.

Stormont, J. C., Henry, K. S., and Evans, T. M. (1997). “Water retention functions of four nonwoven polypropylene geotextiles.” *Geosynthet. Int.*, 4(6), 661–672.

van Genuchten, M. T. (1980). “A closed-form equation for predicting the hydraulic conductivity of unsaturated soils.” *Soil Sci. Soc. Am. J.*, 44(5), 892–898.

van Genuchten, M. T. (1987). “A numerical model for water and solute movement in and below the root zone.” *Research Rep. No. 121*, U.S. Salinity Laboratory, USDA, ARS, Riverside, Calif.

Zornberg, J., LaFountain, L., and Caldwell, J. (2003). “Analysis and design of evapotranspirative cover for hazardous waste landfill.” *J. Geotech. Geoenviron. Eng.*, ASCE, 129(6), 427–436.