

# Field Data and Water-Balance Predictions for a Monolithic Cover in a Semiarid Climate

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**Abstract:** Water-balance predictions made using four codes (UNSAT-H, VADOSE/W, HYDRUS, and LEACHM) are compared with water-balance data from a test section located in a semiarid climate simulating a monolithic water-balance cover. The accuracy of the runoff prediction (underprediction or overprediction) was found to affect the accuracy of all other water-balance quantities. Runoff was predicted more accurately when precipitation was applied uniformly throughout the day, the surface layer was assigned higher saturated hydraulic conductivity, or when Brooks-Corey functions were used to describe the hydraulic properties of the cover soils. However, no definitive or universal recommendation could be identified that would provide reasonable assurance that runoff mechanisms are properly simulated and runoff predictions are accurate. Evapotranspiration and soil-water storage were predicted reasonably well (within  $\approx 25$  mm/yr) when runoff was predicted accurately, general mean hydraulic properties were used as input, and the vegetation followed a consistent seasonal transpiration cycle. However, percolation was consistently underpredicted ( $>3$  mm total) even when evapotranspiration and soil-water storage were predicted reliably. Better agreement between measured and predicted percolation (or a more conservative prediction) was obtained using mean properties for the soil-water characteristic curve and increasing the saturated hydraulic conductivity of the cover soils by a factor between 5 and 10. Evapotranspiration and soil-water storage were predicted poorly at the end of the monitoring period by all of the codes due to a change in the evapotranspiration pattern that was not captured by the models. The inability to capture such changes is a weakness in current modeling approaches that needs further study.

**DOI:** 10.1061/(ASCE)1090-0241(2009)135:3(333)

**CE Database subject headings:** Evapotranspiration; Landfill; Numerical model; Unsaturated flow; Waste management; Water balance; Unsaturated soils; Arid lands; Field tests.

## Introduction

Final covers for waste containment facilities that rely on water-balance principles are being considered as substitutes in drier environments for conventional covers that rely on hydraulic barriers (e.g., compacted clay layers, geomembranes, geosynthetic clay liners). These covers are known by a variety of names, including

alternative covers, store-and-release covers, evapotranspirative covers, and water-balance covers, but the principle of limiting percolation into the underlying waste by balancing soil-water storages and evapotranspiration (ET) is common regardless of the nomenclature used. Finer-grained soil is used to store infiltration from precipitation and snowmelt with minimal drainage during wetter conditions, and ET is used to return the stored water to the atmosphere during drier conditions (Khire et al. 1997; Hauser et al. 2001). Because water-balance principles are intrinsic to the function of these covers, they are referred to herein as “water-balance covers.”

A key aspect of the design of water-balance covers is ensuring that the cover has adequate water-storage capacity for wetter periods, and that plants and the atmosphere are capable of removing the stored water during drier periods (Dwyer 1998; Zornberg et al. 2003; Albright et al. 2004). These issues are normally addressed during preliminary design through hand calculations (Morris and Stormont 1997; Khire et al. 2000; Benson and Chen 2003). Hydrologic modeling is then conducted using water-balance codes that simulate cover hydrology. Although a variety of codes have been used for cover design, only a limited number of studies have compared code predictions with direct measurements of field water-balance quantities from vegetated covers (Khire et al. 1997, 1999; Benson et al. 2004, 2005; Scanlon et al. 2002, 2005; Ogorzalek et al. 2008). Additional studies comparing code results with field-measured water-balance data are needed to improve the confidence in codes and to identify shortcomings. Code accuracy can be particularly important where a cover must be designed to meet a stringent percolation criterion, such as the 0.5 mm/yr criterion used for designing the Hanford barrier (Fayer

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Note. Discussion open until August 1, 2009. Separate discussions must be submitted for individual papers. The manuscript for this paper was submitted for review and possible publication on September 13, 2007; approved on April 23, 2008. This paper is part of the *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 135, No. 3, March 1, 2009. ©ASCE, ISSN 1090-0241/2009/3-333–348/\$25.00.

et al. 1992). Comparisons are also needed for covers located in different climates, constructed with different soils and/or layering, and vegetated with different plants.

The objective of this study was to compare water-balance predictions from four codes, viz. UNSAT-H (Fayer 2000), HYDRUS (Šimůnek et al. 2005), VADOSE/W (Krahn 2004), and LEACHM (Hutson and Wagenet 1992), to field-measured water-balance data from an instrumented test section simulating a monolithic water-balance cover in a semiarid climate. The test section was constructed, characterized, and monitored as a part of the U.S. Environmental Protection Agency's (USEPA) alternative cover assessment program (ACAP) (Albright et al. 2004). Measured quantities were used as input to the codes to the greatest extent practical so that ambiguity in the code evaluation as it pertains to practice would be minimized. This study is unique relative to code validation studies conducted previously in terms of the location and climate of the site, the use of finer-grained soils relative to past studies, the presence of vegetation and simulation of transpiration, and the duration of the field data record.

## Previous Studies Comparing Code Predictions and Field Data

Fayer et al. (1992) and Fayer and Gee (1997) simulated the water balance of eight unvegetated lysimeters at the Hanford site (Richland, Washington) using UNSAT-H. They found that UNSAT-H underpredicted soil-water storage ( $S$ ) up to 30 mm during the winter and overpredicted  $S$  by 25 mm during the summer months. The deviations in  $S$  were attributed primarily to ET being overestimated in the winter and underestimated the rest of the year. Snowmelt and frozen ground also contributed to the differences between measured and predicted ET and  $S$ . Setting potential evaporation (PE) to zero on days when there was snow cover, reduced ET, and increased  $S$  during the winter months. Accounting for heat flow improved the prediction of  $S$ , but did not alter the predicted evaporation. Inclusion of hysteresis in the hydraulic properties improved predictions of  $S$  in the summer, but not in the winter. Percolation was underpredicted in all cases, and was non-zero for the simulations where hysteresis was included. Using calibrated parameters resulted in more precise predictions during the first 2 years, but the improvement diminished after the second year.

Khire et al. (1997) compared predictions from UNSAT-H to 3 years of field data from test sections simulating earthen covers in Atlanta, Georgia and East Wenatchee, Washington. Percolation was underpredicted by UNSAT-H at both sites over the monitoring period (underpredicted by 60 mm for the Atlanta site, 13 mm for the Wenatchee site). Percolation was underpredicted for the Wenatchee site because preferential flow occurred in the field, but was not accounted for in the code. Percolation for the Atlanta site was underpredicted because runoff was overpredicted, and, therefore, less water was available for percolation.

Khire et al. (1999) compared 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 overprediction of percolation was attributed to the underprediction 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 1–3 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 (from top to bottom) of 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, the lower boundary condition (seepage face versus unit gradient), the duration of precipitation events, 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 interrelationship 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 code 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. Both codes underpredicted percolation. 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 condition was assigned as a unit gradient or seepage face.

Ogorzalek et al. (2008) compared predictions made with UNSAT-H, HYDRUS, and LEACHM to water-balance data from a capillary barrier located in subhumid western Montana. Each code captured the seasonal variations in the water balance observed in the field. LEACHM and HYDRUS predicted total runoff with reasonable accuracy, but the timing of predicted and observed runoff events was different. In contrast, UNSAT-H consistently overpredicted runoff. Annual evapotranspiration was predicted reliably with all three codes when data from the first year were excluded. However, all three codes overpredicted evapotranspiration in late winter and early spring, when snowmelt was occurring and water was accumulating in the cover. Consequently, soil-water storage generally was underpredicted by all three codes. Predicted and measured percolation were in good agreement, 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, snowmelt, and evapotranspiration during snow cover.

## Description of Field Site

The test section in this study was located in Altamont, California, which is 80 km east of San Francisco. Altamont has a semiarid

climate with cool wet winters and warm dry summers. The average annual precipitation ( $P_a$ ) is 358 mm/yr and the ratio of  $P_a$  to average annual potential evapotranspiration ( $PET_a$ ) is 0.31. Snowfall in Altamont is rare. Other characteristics of the climate are summarized in Albright et al. (2004).

The test section simulated a monolithic cover consisting of a 150-mm-thick surface layer underlain by a water-storage layer that is 910 mm thick constructed on top of a 300-mm-thick layer of soil simulating interim cover (i.e., the existing cover over the waste on which a full-scale cover would be constructed). The interim cover layer was constructed with the same soil used for the storage layer. Construction of the test section was completed in Aug. 2000, and was seeded with a mixture of local grasses immediately after construction (soft chess, slender oats, foxtail chess, Italian ryegrass, red-stemmed filaree, black mustard, yellow star-thistle, prickly lettuce, bull thistle, prickly sow-thistle, blue dicks, California poppy, purple owl's-clover, and miniature lupine) (Roesler et al. 2002). The percent cover was in excess of 75% within 1 year of construction.

The test section, which was constructed following ACAP guidelines (Benson et al. 1999), was 30 m  $\times$  30 m in areal extent on the top deck and contained a 10 m  $\times$  20 m pan lysimeter in the center. The lysimeter was constructed with polyethylene geomembrane and included vertical walls that extended from the base to the surface. A geocomposite drainage layer was placed on the base to route water to a collection system. Berms were constructed on the surface around the perimeter of the lysimeter to collect runoff and prevent run on, and the collection pipe was designed to conduct runoff rapidly so that ponding would not occur. Percolation (drainage from the base of the test section) and runoff were collected in basins monitored with pressure transducers and tipping buckets. A detailed description of the ACAP test section and the pan lysimeter can be found in Benson et al. (1999, 2001) and Albright et al. (2004). Benson et al. (2001) indicate that the flow monitoring system used for ACAP lysimeters can resolve percolation to  $<0.1$  mm/yr and runoff to  $<0.4$  mm/yr.

A weather station was installed on the test section to collect meteorological data on site. Water content reflectometers (WCRs) were used to measure soil water content and thermal dissipation (TD) sensors were used to monitor matric suction. Three nests of colocated WCRs and TD sensors were installed at the quarter points along the centerline of each test section. Each nest contained four to six WCRs and TDs. Water contents measured with the WCRs were integrated spatially with depth to determine  $S$ . Soil-specific calibrations with temperature compensation were developed for the WCR and TD sensors (Kim and Benson 2002).

A lightweight nonwoven geotextile with the root inhibitor tri-fluralin (a geosynthetic root barrier) was placed between the storage layer and the interim cover to prevent roots from growing beneath the cover profile and within the collection systems. Field observations have shown that the root barrier is effective in preventing roots from entering the drainage system, but does not inhibit root growth within the cover soils (Albright et al. 2005; Benson et al. 2006). The root barrier is also very thin and the pores readily fill with adjacent soils. Consequently, the root barrier has a negligible effect on water movement in the cover profile.

The drainage layer used to collect water at the base of the lysimeter is known to form a capillary break at the base of the cover profile. At municipal solid waste (MSW) landfills, a similar capillary break usually exists at the interface between interim cover soils and waste because the hydraulic properties of MSW mimic those characteristic of coarse-grained soils (i.e., low air

entry suction and rapidly diminishing water content for suctions above the air entry suction) (Benson and Wang 1998). Thus, the profile in the lysimeters used in this study (cover soils, interim cover layer, and drainage layer) is believed to replicate the field condition at a MSW landfill reasonably well. However, the capillary break existing in a field condition probably is not as sharp as the break present in an ACAP lysimeter.

All components of the water balance were monitored with the lysimeters except for ET, which could not be directly measured at canopy scale on a continuous basis given the geometric properties of the test section. Thus, ET was computed as the residual of the water balance

$$ET = P - R - P_r - \Delta S \quad (1)$$

where  $P$ =precipitation;  $R$ =runoff;  $P_r$ =percolation; and  $\Delta S$ =change in soil-water storage ( $S$ ). ET was computed on a daily basis using Eq. (1). Interflow was assumed to be zero because the test sections were on a shallow slope ( $<5\%$ ), no internal drainage layers were included in the cover design, and no sharp capillary contrasts were present in the cover profile. ET computed with Eq. (1) includes actual ET and the net error in the other water-balance quantities. Evaporation of precipitation by the plant canopy is also included in ET computed with Eq. (1). Apiwantragoon (2007) reports good agreement between ET computed with Eq. (1), measurements of ET reported by others, and theoretical estimates of ET.

## Codes

Four codes were evaluated in this study: UNSAT-H v3.0 (Fayer 2000), VADOSE/W v6.02 (Krahn 2004), HYDRUS v2.007 (Šimůnek et al. 2005), and LEACHM v4.0 (Hutson and Wagenet 1992). These are the most commonly used codes in engineering practice for simulating the hydrology of water-balance covers. 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 simulating the complex hydrodynamics associated with unsaturated flow in water-balance covers (Fayer and Gee 1997; Khire et al. 1997; Scanlon et al. 2002, 2005).

A detailed comparison of UNSAT-H, HYDRUS, VADOSE/W, and LEACHM can be found in Benson (2007) and Ogorzalek et al. (2008). A summary is provided in the following. Each code solves a modified form of Richards' equation similar to the 1D expression

$$\frac{\partial \theta}{\partial t} = - \frac{\partial}{\partial z} \left[ K_c \frac{\partial \psi}{\partial z} + K_\psi \right] - \Lambda(z, t) \quad (2)$$

where  $\psi$ =matric suction;  $t$ =time;  $z$ =vertical coordinate ( $z=0$  at the ground surface);  $\theta$ =volumetric water content;  $K_\psi$ =unsaturated hydraulic conductivity;  $K_c$ =combined=hydraulic conductivity accounting for liquid and vapor flows; and  $\Lambda(z, t)$ =sink term for root water uptake. Each of these codes can simulate other processes as well (e.g., solute transport, gas diffusion, heat transfer, volume change, etc.), but only water flow was simulated in this study. The exception was VADOSE/W, which must be run with simultaneous coupled heat and water flow. UNSAT-H and LEACHM are one-dimensional (1D) codes that employ the finite-difference method to solve Eq. (2). HYDRUS and VADOSE/W are finite-element codes that can be run in 1D or

two-dimensional (2D) modes, but only 1D simulations are presented in this study. Two-dimensional simulations were found to be unnecessary because of the shallow slope (<5%) of the test section. Test simulations with HYDRUS and VADOSE/W showed that 1D and 2D predictions obtained from both codes were essentially identical (Bohnhoff 2005; Ogorzalek 2005).

Each code 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). The infiltration rate is controlled by the rate at which precipitation is applied and by the infiltration capacity of the surficial soil, 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—evaporation) is applied in HYDRUS and VADOSE/W. Evaporation is computed as the liquid flux at the surface boundary using Darcy's Law in LEACHM, HYDRUS, and VADOSE/W, 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). Several boundary conditions can be applied at the lower boundary in all four codes. In this study, unit gradient and seepage face boundaries (i.e., flux=0 when the boundary is unsaturated; flux=saturated hydraulic conductivity when the boundary is saturated) were used. Additional details on how boundary fluxes are computed by the codes can be found in Bohnhoff (2005), Ogorzalek (2005), and Ogorzalek et al. (2008).

Vegetative water uptake is simulated using a mechanistic approach based on the Nimah and Hanks (1973) formulation (LEACHM) or a semiempirical approach where potential transpiration (PT) is distributed throughout the root zone in proportion to the relative root density (HYDRUS, UNSAT-H, and VADOSE/W). In the latter approach, the effects of water availability are simulated using an empirical plant limiting function (Feddes and Zaradny 1978; van Genuchten 1987). For all four codes, water uptake at a given depth ceases when the suction exceeds the wilting point. The wilting point is input to HYDRUS, UNSAT-H, and VADOSE/W. LEACHM fixes the wilting point at 1,500 kPa.

## Code Input

### Meteorological Data

The water-balance simulations were conducted using meteorological data beginning on Jan. 1, 2001. Daily quantities were used as meteorological input for all of the codes. Precipitation was applied at the default rate (10 mm/h) in UNSAT-H and at a constant uniform daily rate in VADOSE/W and HYDRUS. Sinusoidal and linearly varying daily precipitation patterns are also available in VADOSE/W. Comparative simulations showed that nearly identical predictions were obtained using all three options (Ogorzalek 2005). The average hourly precipitation rate (0.68 mm/h at Altamont) was used as the application rate in LEACHM. For days when the total precipitation exceeded that possible using the average hourly precipitation rate, the application rate was increased to allow all of the precipitation to be applied in 24 h.

## Hydraulic Properties

Hydraulic properties input to all of the codes include parameters describing the soil water characteristic curve (SWCC) and the saturated hydraulic conductivity ( $K_s$ ). Drying SWCCs were used as input for most of the simulations, as most applications in practice normally employ drying SWCCs and ignore hysteresis due to the difficulty in determining wetting SWCCs for fine-textured soils. However, a limited number of simulations were conducted with hysteresis in the hydraulic properties.

The hydraulic properties used as input were based on SWCCs and saturated hydraulic conductivities measured in the laboratory by Gurdal et al. (2003) on hand-carved block samples collected from each layer at the end of construction and from the surface layer each year after construction. The SWCCs were defined using van Genuchten's function (van Genuchten 1980)

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left\{ \frac{1}{1 + (\alpha\psi)^n} \right\}^m \quad (3)$$

where  $\theta_s$ =volumetric water content at saturation;  $\theta_r$ =residual volumetric water content; and  $\alpha$ ,  $n$ , and  $m$  ( $=1-n^{-1}$ )=fitting parameters. The unsaturated hydraulic conductivity ( $K_\psi$ ) was assumed to follow the van Genuchten-Mualem function (van Genuchten 1980) using  $\alpha$  and  $n$  from the SWCC

$$\frac{K_\psi}{K_s} = \frac{\{1 - (\alpha\psi)^{n-1} [1 + (\alpha\psi)^n]^{-m}\}^2}{[1 + (\alpha\psi)^n]^{m/2}} \quad (4)$$

Evaluation of the hydraulic properties suggested that the profile could be divided into three layers (Gurdal et al. 2003): the surface layer and the upper 110 mm of the storage layer, the lower 600 mm of the storage layer, and the interim cover layer. Four cases were used to describe the range of hydraulic properties of each layer: general mean (GM), low-storage capacity (LSC), high-storage capacity (HSC), and field fit (FF). A summary of the hydraulic properties for these cases is given in Table 1. The LSC and HSC hydraulic properties bracket the range of hydraulic properties observed in the field. The GM properties represent average conditions based on laboratory tests, whereas the FF case is intended to represent average field conditions.

The general mean case corresponds to the geometric mean  $K_s$  and  $\alpha$  (both of which are log normally distributed) and arithmetic means for  $\theta_r$ ,  $\theta_s$ , and  $n$  (each of which is normally distributed) (Gurdal et al. 2003). For the LSC and HSC cases, the hydraulic properties were chosen to be  $\pm 2$  standard deviations from the mean (arithmetic or geometric) of each variable to represent practical upper and lower bounds on the properties. The LSC properties correspond to low storage (i.e., high  $\alpha$ , high  $n$ ) and high transmission capacity (high  $K_s$ ), whereas HSC properties correspond to high storage (i.e., low  $\alpha$ , low  $n$ ) and low transmission capacity (low  $K_s$ ). Field-fit (FF) hydraulic properties consisted of the geometric mean  $K_s$  and parameters obtained by fitting Eq. (3) to water contents ( $\theta$ ) and suctions ( $\psi$ ) measured in the field using colocated WCR and TD sensors. A typical set of SWCCs is shown Fig. 1. In most cases, the "field-fit" SWCCs fell within the range defined by SWCCs for the HSC and LSC cases.

The van Genuchten (VG) parameters in Table 1 were used as input to UNSAT-H and HYDRUS. However, van Genuchten parameters cannot be directly input to the versions of VADOSE/W or LEACHM that were used in this study. For VADOSE/W, the spline function was used to describe the SWCC and the van Genuchten option was used to describe the unsaturated hydraulic conductivity. For LEACHM, a hybrid Campbell-Hutson-Cass (CHC) (Hutson and Cass 1987) function is used for the SWCC

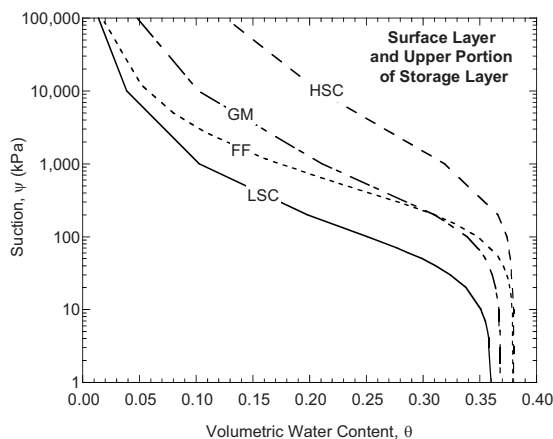
**Table 1.** van Genuchten Parameters and Saturated Hydraulic Conductivities Corresponding to LSC, GM, HSC, and FF Parameter Sets

Hydraulic parameter set	Layer	Thickness (mm)	van Genuchten parameters				Saturated hydraulic conductivity, $K_s$ (cm/s)		
			$\theta_r$	$\theta_s$	$\alpha$ ( $m^{-1}$ )	$n$	2001	2002	2003
Low storage capacity (LSC)	Surface layer and upper portion of storage layer	460	0.00	0.36	0.177	1.43	$5.8 \times 10^{-6}$	$2.4 \times 10^{-5}$	$1.1 \times 10^{-4}$
	Lower portion of storage layer	600	0.02	0.32	0.095	2.23		$2.8 \times 10^{-4}$	
	Interim cover	300	0.00	0.32	0.179	1.53		$8.2 \times 10^{-5}$	
General mean (GM)	Surface layer and upper portion of storage layer	460	0.00	0.37	0.050	1.33	$5.3 \times 10^{-7}$	$2.2 \times 10^{-6}$	$1.1 \times 10^{-4}$
	Lower portion of storage layer	600	0.00	0.35	0.025	1.54		$4.5 \times 10^{-7}$	
	Interim cover	300	0.00	0.35	0.057	1.36		$3.0 \times 10^{-6}$	
High storage capacity (HSC)	Surface layer and upper portion of storage layer	460	0.00	0.38	0.015	1.22	$9.2 \times 10^{-8}$	$3.8 \times 10^{-7}$	$1.1 \times 10^{-4}$
	Lower portion of storage layer	600	0.00	0.37	0.008	1.30		$5.5 \times 10^{-8}$	
	Interim cover	300	0.00	0.38	0.022	1.25		$2.2 \times 10^{-7}$	
Field fit (FF)	Surface layer and upper portion of storage layer	460	0.00	0.38	0.044	1.50	$5.3 \times 10^{-7}$	$2.2 \times 10^{-6}$	$1.1 \times 10^{-4}$
	Lower portion of storage layer	600	0.00	0.30	0.006	2.07		$4.5 \times 10^{-7}$	
	Interim cover	300	0.00	0.35	0.057	1.36		$3.0 \times 10^{-6}$	

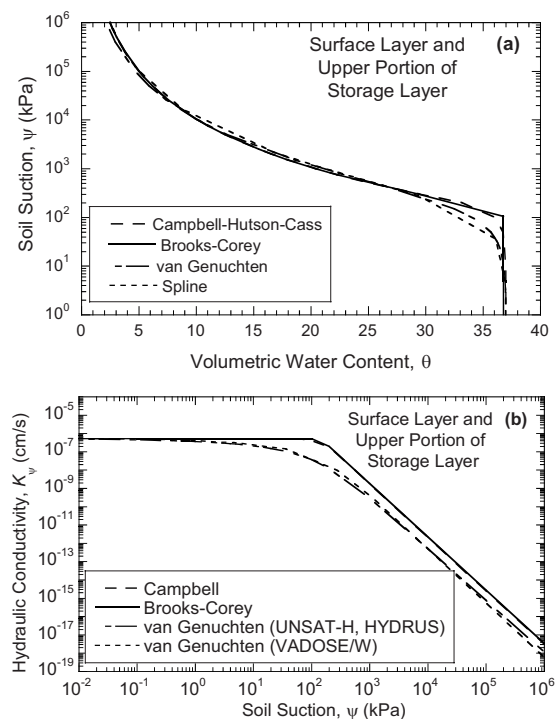
and the Campbell (1974) equation is used for the unsaturated hydraulic conductivity. To ensure consistency, the spline function in VADOSE/W and the CHC function in LEACHM were fit to the VG function defined by the parameters in Table 1 using a least-squares optimization method. The fitted CHC parameters were used in Campbell's equation to describe the unsaturated hydraulic conductivity with the pore interaction term set at 2. The Brooks-Corey (BC) (Brooks and Corey 1964) function also was used in UNSAT-H for some comparative simulations. Parameters for the Brooks-Corey function were matched to those from the VG function using the same method employed for the spline and CHC functions.

A typical example of the four SWCC and hydraulic conductivity functions is shown in Fig. 2. The SWCCs defined by all four functions are similar, except near the air entry suction, where the CHC and BC functions have higher water contents. The VG hydraulic conductivity functions used in UNSAT-H and HYDRUS (based on the VG SWCC function) are nearly identical to the VG hydraulic conductivity function used in VADOSE/W. In contrast, the Campbell hydraulic conductivity function (LEACHM) and the BC hydraulic conductivity function have

higher hydraulic conductivities than the VG function for suctions greater than 1 kPa. Near the air entry suction, the hydraulic conductivity from the VG function is an order of magnitude lower than the hydraulic conductivity predicted by the Campbell and BC functions. At higher suctions, all of the functions predict a similar rate of decrease in hydraulic conductivity with increasing suction, but the hydraulic conductivities predicted with the VG function are approximately four times lower than those for the BC and Campbell functions.



**Fig. 1.** Example of SWCCs corresponding to the HSC, GM, LSC, and FF parameter sets; van Genuchten's function was used to parameterize the SWCC; parameters are for the uppermost layer in the model (surface layer and upper portion of the storage layer)



**Fig. 2.** Example of SWCCs (a); hydraulic conductivity functions (b) for the GM input to the four codes; example corresponds to GM parameter set for uppermost layer in the model (surface layer and upper portion of the storage layer)

**Table 2.** LAIs and  $R_d$  Parameters Measured from 2001–2003

Year	LAI	Parameters for the root length density function		
		$a$	$b$	$c$ ( $\text{m}^{-1}$ )
2001	2.85	0.44	0.08	1.0
2002	2.25	3.64	0.08	2.9
2003	2.31	0.68	0.05	0.0

### Vegetation

The growing season was defined by Julian day 245 (germination) and 183 (plants cease transpiring) based on Roesler et al. (2002). Peak leaf area index (LAI) was measured annually using a Li-Cor (Lincoln, Nebraska) LAI-2000 plant canopy analyzer and measurements made in the laboratory on clippings using a Li-Cor LI-3100C area meter (Table 2). The LAI was assumed to increase linearly from 0 to the peak LAI during the first 30 d after germination, diminish to zero linearly during the final 30 d of the growing season, and remain constant between these periods. For the first year of simulation, the LAI was reduced to simulate the immaturity of the vegetation. The LAI was assumed to follow a triangular distribution, with the peak at 30 d from the end of the growing season. Coverage was set at 50% for the first year and 75% for subsequent years.

The maximum root depth was set at the depth of the root barrier (1,060 mm) and the root growth rate in UNSAT-H, HYDRUS, and VADOSE/W was set at 3 mm/d (Roesler et al. 2002). Root length densities ( $R_d$ ) were measured annually with the Weaver-Darland box method (Bohm 1979) and were characterized by the exponential function

$$R_d = ae^{-bz} + c \quad (5)$$

where  $z$ =depth (m); and  $a$ ,  $b$ ,  $c$ =empirical parameters (Table 2). VADOSE/W assumes that  $R_d$  is triangular. Thus, for VADOSE/W, the peak  $R_d$  measured in the field was used as the maximum density at the ground surface. For LEACHM, the root growth is defined using the method in Davidson et al. (1978) and Tillotson et al. (1980). The root maturity in LEACHM was defined as the end of the growing season for the first year of simulation, and 30 d after the first day of the growing season for subsequent years.

The lowest average water content in the lower portion of the root zone (i.e., at a depth where the influence of evaporation was minimal) was used to define the wilting point at 6,250 kPa (Roesler et al. 2002). This condition was achieved in late summer, when the vegetation appeared dormant and water stressed, and temporal changes in water content were small. The wilting point defined in this manner is higher than the conventional wilting point of 1,500 kPa, but is characteristic of wilting points commonly found in semiarid regions (Gee et al. 1999). The limiting

point (502 kPa) was computed using the method described by Doorenbos and Kassam (1979), and the anaerobiosis point was set at 79 kPa. In LEACHM, the minimum root water potential was set at 3,000 kPa, the maximum ratio of actual-to-potential transpiration was set at 1.1, and the root resistance factor was set at 1.0, as recommended in Hutson (2003).

Potential evapotranspiration (PET) was computed by UNSAT-H using the modified Penman equation in Doorenbos and Pruitt (1977). The same PET was input to LEACHM and HYDRUS for consistency. For all three codes, PET was partitioned into PE and PT using the Ritchie-Burnett-Ankeny equation (Chadwick et al. 1999). PET was computed and partitioned into PT and PE by VADOSE/W using algorithms intrinsic to the code, which are similar to those in UNSAT-H.

Simulations were conducted with LAIs and  $R_d$ s that varied annually and with average properties over the entire simulation period. Differences between the predictions were negligible (Bohnhoff 2005). Thus, only predictions using average vegetative properties are presented herein.

### Initial Conditions

Initial conditions were assigned based on the average water content (LEACHM), average suction (UNSAT-H, VADOSE/W, and HYDRUS), and average temperature (VADOSE/W) measured in the field in each layer on Jan. 1, 2001 (start date of the simulation). A summary of the initial conditions is provided in Table 3.

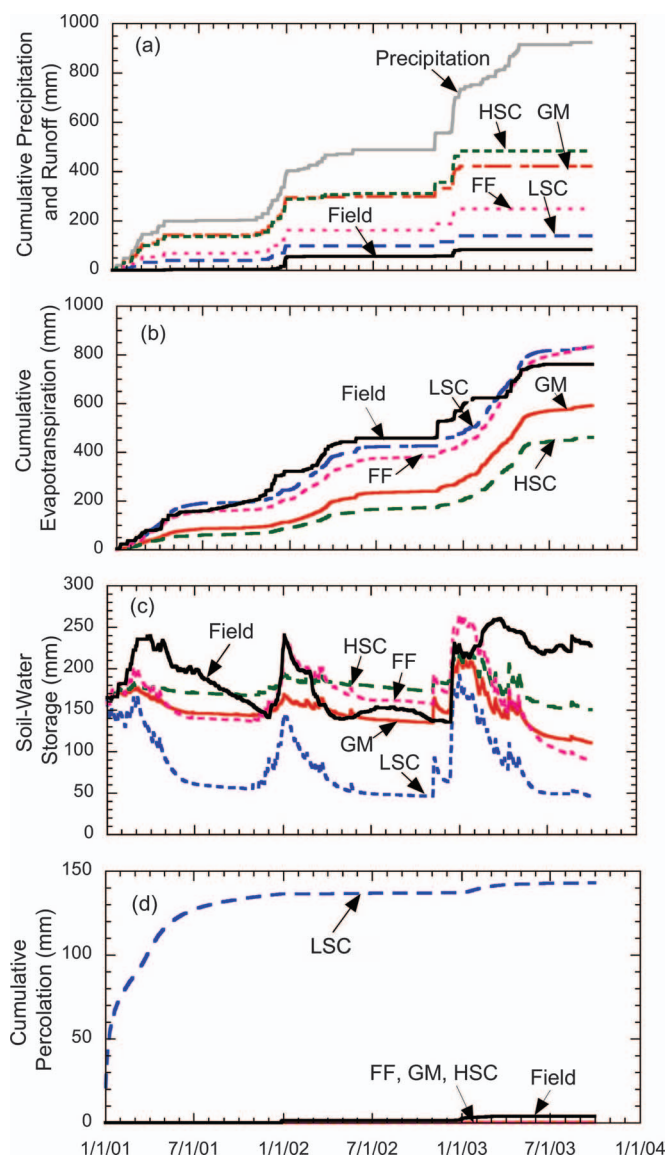
### Numerical Control Parameters

The spatial and temporal discretization were adjusted to achieve a mass balance error <1 mm/yr. The nodal spacing or element thickness was 1 mm near the boundaries and as large as 60 mm away from the boundaries for UNSAT-H, HYDRUS, and VADOSE/W. LEACHM uses a uniform nodal spacing, which was set at 20 mm. For UNSAT-H, the maximum time step was 0.25 h and the minimum time step was  $1 \times 10^{-5}$  h. For VADOSE/W and HYDRUS, the maximum time step was 24 h with a minimum time step of 0.024 h (VADOSE/W) or  $10^{-11}$  h (HYDRUS). The LEACHM simulations used the default maximum water flux per time step (0.01, dimensionless) and a maximum time step of 0.1 d.

The simulations were performed on desktop PCs running Windows XP (SP1 or SP2) on Pentium processors (2.0–2.6 GHz) with at least 512 MB of RAM. These relatively stringent control parameters resulted in relatively long simulation times in some cases. Simulations with UNSAT-H ran about 4–6 h/yr of simulation, whereas simulation times for VADOSE/W and HYDRUS varied from 0.5–24 h/yr of simulation. Simulation times for LEACHM were much quicker, ranging from 0.003–0.008 h/yr of simulation.

**Table 3.** Initial Conditions for the Simulations

Layer	Thickness (mm)	Temperature (°C)	Initial volumetric water content	Soil suction (kPa)			
				Low storage capacity	General mean	High storage capacity	Field fit
Surface layer and upper portion of storage layer	460	10.4	0.171	295	1,990	24,870	5,220
Lower portion of storage layer	600	13.3	0.144	187	1,930	27,950	11,600
Interim cover	300	14.1	0.175	150	1,130	9,890	4,690



**Fig. 3.** (Color) (a) Runoff; (b) evapotranspiration; (c) soil-water storage; and (d) percolation measured in the field and predicted by UNSAT-H using (LSC: blue), (GM: red), (HSC: green), and (FF: fuchsia) parameter sets. Field data in black.

## Comparison of Measured and Predicted Water Balance

### UNSAT-H

Predictions obtained with UNSAT-H are shown in Fig. 3 along with the field data. Annual water balance quantities are summarized in Table 4. The precipitation data [Fig. 3(a)] indicate that two distinct hydrologic periods exist at Altamont: (1) a wet season from November through April and (2) a dry season from May through October. At least half of the annual precipitation normally occurs during the first two months (Nov. and Dec.) of the wet season [Fig. 3(a)].

Predicted and measured surface runoff are shown in Fig. 3(a) along with the precipitation record. Nearly all of the runoff in the field occurs during Nov. and Dec. The runoff predicted by UNSAT-H also occurs during Nov. and Dec., but UNSAT-H overpredicts runoff for all four hydraulic parameter sets. The overpre-

dictions are very large in some cases, with the largest errors coincident with the largest precipitation events. For example, UNSAT-H predicted 30–40 mm of runoff for a large precipitation event in Nov. 2002 (68 mm over 4 d) depending on the hydraulic properties that were used. In contrast, only 1.5 mm of runoff was recorded in the field during this event. Errors in the runoff prediction are sensitive to the hydraulic properties used for input, with the smallest errors associated with the LSC parameters and the largest errors associated with the HSC parameters. Most of this effect is related to the  $K_s$  used in the simulations, which affects the maximum infiltration capacity. However, the SWCC is also important, as SWCC affects the amount of water retained and the unsaturated hydraulic conductivity near the surface. For example, the FF simulation resulted in 1.7 times less runoff than the GM simulation, even though both parameter sets have the same  $K_s$  (Table 4).

Predicted and measured ET are compared in Fig. 3(b). UNSAT-H underpredicts ET for most of the monitoring period, particularly during the wet months of Nov. and Dec. The exceptions are the early part of the record, which was soon after seeding, and the end of the record, when little ET occurred in the field despite an abundance of water (see subsequent discussion). The underpredictions of ET are closely tied to overpredictions of runoff. For example, the HSC simulation results in the greatest overprediction of runoff [Fig. 3(a)] and greatest underprediction of ET, whereas the LSC and FF simulations have the lowest underpredictions of runoff and the smallest errors in ET. When less water enters the cover via infiltration, less water is available for ET.

Predicted and measured  $S$  are shown in Fig. 3(c). Predicted and measured water content records can be found in Bohnhoff (2005). In general,  $S$  undergoes an annual net change of approximately 100 mm, with increases in  $S$  occurring in late winter and early spring due to infiltration of wet season precipitation, and decreases in late spring through fall when precipitation is infrequent. UNSAT-H predicts a similar seasonality in  $S$ , but the annual net change in  $S$  is considerably smaller (GM, HSC, and FF) or the total  $S$  is considerably lower than the  $S$  in the field (LSC case). Overall, the simulated  $S$  for the FF case most closely resembles the field  $S$ , with reasonable agreement (within  $\approx 25$  mm) from Jan. 2002 through Mar. 2003.

As with ET, the error in  $S$  is closely tied to the error in runoff and the hydraulic properties. Conditions that result in a greater overprediction of runoff (HSC and GM cases) result in less water entering the cover, a smaller increase in  $S$ , less ET, and a greater deviation between the predicted and measured  $S$ .

Both field ET and  $S$  exhibit unusual behavior in spring and summer 2003. The plants appear to have ceased transpiring in response to the very wet winter, resulting in a lower ratio of ET to precipitation ( $ET/P=0.89$ ) through Sept. 30, 2003 than in previous years ( $ET/P=0.96$  through Sept. 30 in 2001 and 2002), and elevated  $S$  through the spring, summer, and fall. The reason for this anomalous behavior is unclear, and the LAI and  $R_d$  in 2003 were not significantly different from previous years (Table 2). One potential cause is a transition in vegetative species, which resulted in similar behavior in two monolithic water-balance covers in the same region (Sacramento, California) over the same time period (Benson et al. 2006). The important observation, however, is that the vegetation transpired differently in 2003 and this change was not captured in the predictions.

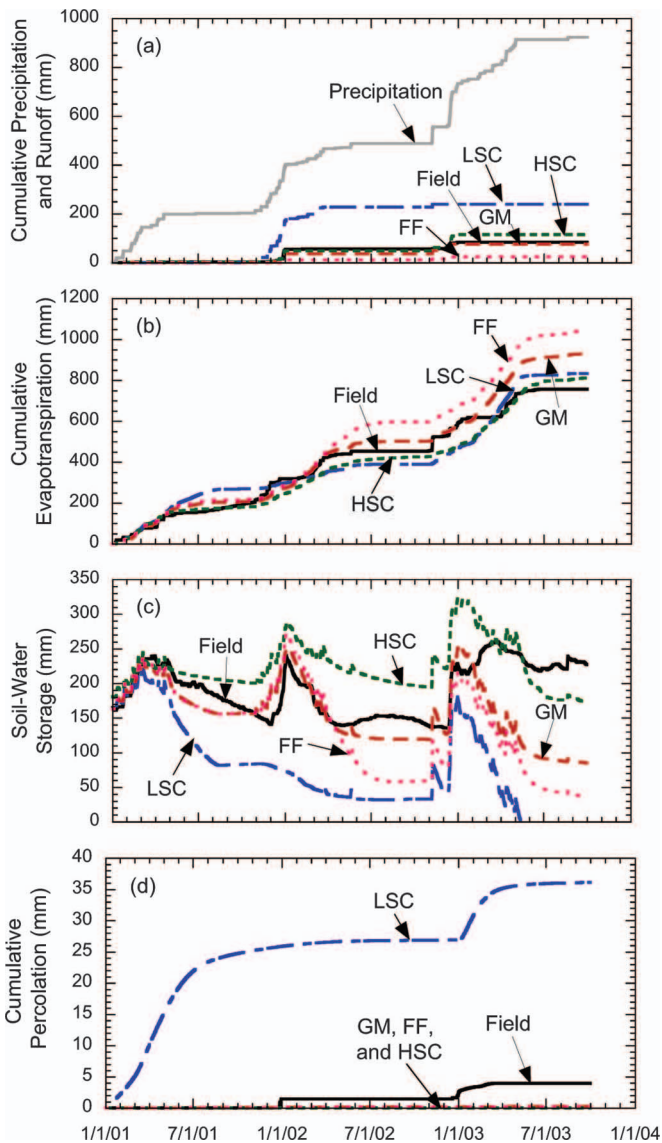
Predicted and measured percolation are shown in Fig. 3(d). Percolation was underpredicted for three of the simulations (GM, HSC, and FF), and overpredicted for one simulation (LSC). The

**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	Parameter set	Water-balance quantity (mm)			
			2001	2002	2003 <sup>a</sup>	Total
Precipitation	Field	—	392	342	189	923
Runoff	Field	—	55	29	0	84
	UNSAT-H	LSC	99	40	0	139
		GM	292	130	0	422
		HSC	282	202	0	484
		FF	163	86	0	249
	VADOSE/W	LSC	171	69	0	240
		GM	36	40	0	76
		HSC	49	67	0	115
		FF	13	11	0	24
	HYDRUS	LSC	0	0	0	0
		GM	37	34	0	71
		HSC	115	35	0	151
		FF	13	8	0	21
	LEACHM	LSC	0	0	0	0
		GM	9	3	0	12
		HSC	55	67	0	123
		FF	10	3	0	13
Evapotranspiration <sup>b</sup>	Field	—	322	275	164	761
	UNSAT-H	LSC	245	236	352	833
		GM	114	174	304	591
		HSC	87	118	257	462
		FF	205	231	397	834
	VADOSE/W	LSC	299	171	363	834
		GM	274	305	351	930
		HSC	246	235	330	811
		FF	286	389	368	1043
	HYDRUS	LSC	399	304	349	1051
		GM	326	268	330	923
		HSC	217	207	326	749
		FF	339	288	377	1004
	LEACHM	LSC	363	308	347	1018
		GM	288	302	360	950
		HSC	168	207	301	676
		FF	289	302	362	952
Percolation	Field	—	1.5	1.0	1.5	4.0
	UNSAT-H	LSC	137	0.64	5.84	143
		GM	0.13	0.09	0.01	0.22
		HSC	0.00	0.00	0.00	0.00
		FF	0.06	0.08	0.01	0.15
	VADOSE/W	LSC	26	1.03	9.22	36
		GM	0.10	0.09	0.08	0.26
		HSC	0.00	0.00	0.00	0.00
		FF	0.10	0.09	0.03	0.22
	HYDRUS	LSC	15	3.27	7.13	26
		GM	0.93	0.28	0.43	1.63
		HSC	0.00	0.00	0.00	0.00
		FF	0.06	0.03	0.07	0.16
	LEACHM	LSC	39	10.09	16.00	65
		GM	0.67	0.65	1.99	3.31
		HSC	0.02	0.36	1.10	1.48
		FF	0.00	0.00	0.00	0.00

<sup>a</sup>Partial year ending Oct. 2003.

<sup>b</sup>Computed using Eq. (1).



**Fig. 4.** (Color) (a) Runoff; (b) evapotranspiration; (c) soil-water storage; and (d) percolation measured in the field and predicted by VADOSE/W using (LSC: blue), (GM: red), (HSC: green), and (FF: fuchsia) parameter sets. Field data in black.

total percolation recorded during the monitoring period was 4.0 mm, with 1.5 mm occurring in Jan. 2002 and 2.5 mm occurring between Jan. and Mar. 2003. UNSAT-H predicted total percolation of 0.002 mm (HSC), 0.22 mm (GM), 0.15 mm (FF), or 143.0 mm (LSC). The large overprediction for the LSC case is mainly due to drainage during the first year of the simulation (137 mm). In subsequent years, annual percolation predicted with the LSC parameter set was less than 6 mm (Table 4).

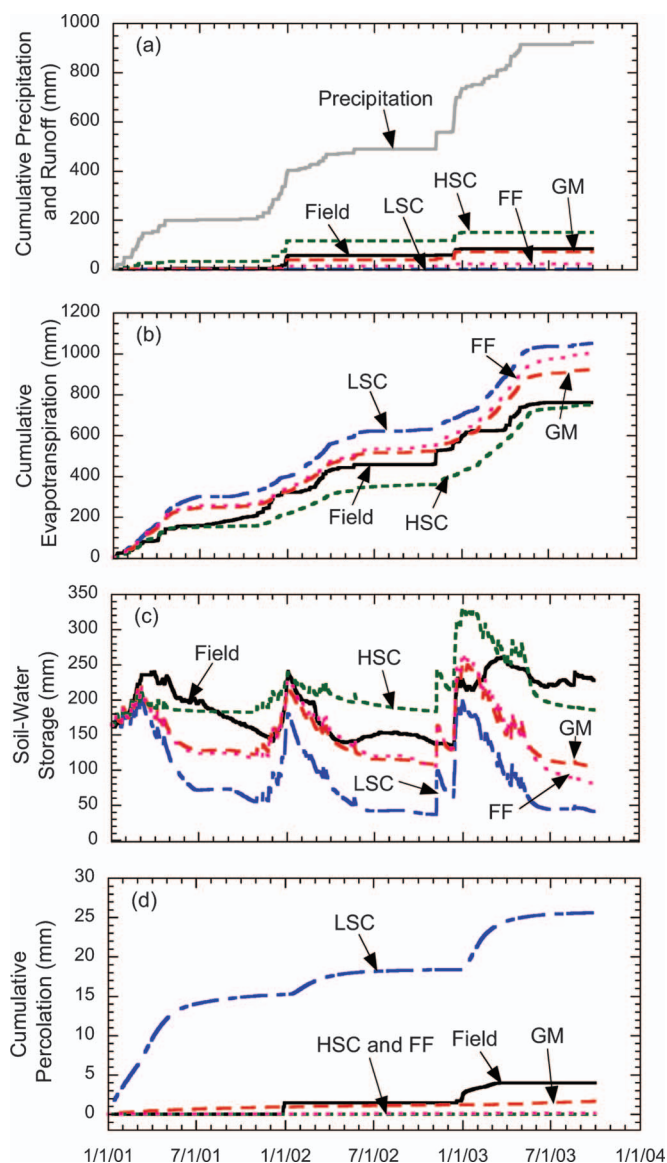
Underprediction of  $S$  due to the overprediction of runoff is one factor contributing to the underprediction of percolation for GM, HSC, and FF simulation. However, other factors must contribute to the error too. For example, the peak  $S$  was overpredicted by 30 mm in Jan. 2003 using the FF properties, and yet UNSAT-H still predicted only 0.15 mm of total percolation, and 0.01 mm of percolation for 2003 (Table 4).

Water-balance quantities predicted with VADOSE/W are compared with those measured in the field in Fig. 4. Annual water balance quantities are summarized in Table 4. Surface runoff was predicted more accurately with VADOSE/W than UNSAT-H, with the predictions made using GM parameters being very close (within 20 mm/yr) to the field data (Table 4). Predictions made with the HSC parameters also closely followed the field predicted runoff, even though this parameter set had the lowest  $K_s$ . The FF simulation underestimated runoff by approximately 60 mm. VADOSE/W also correctly predicts that most of the runoff occurs during Nov. and Dec.

In contrast to the UNSAT-H simulations, the LSC simulation using VADOSE/W overpredicts runoff even though this parameter set has the highest  $K_s$ . For example, almost 200 mm of runoff was predicted in Nov. and Dec. of 2001 using the LSC parameters. The LSC simulation yielded more runoff because the profile drained appreciably from Jan. to June 2001 [Figs. 4(c and d)], and ET was overpredicted in spring 2001 [Fig. 4(b)]. Both factors contributed to underprediction of the water content at the surface, and an extremely low unsaturated hydraulic conductivity of the surface layer ( $K_{\psi}=1 \times 10^{-19}$  cm/s at  $\theta=0.01$ ) when the wet season began in Nov. 2001. As a result, the infiltration capacity was too low and runoff was grossly overpredicted during the wet season that began in Nov. 2001. In contrast, the unsaturated hydraulic conductivity of the surface layer was 12 orders of magnitude higher ( $K_{\psi}=1 \times 10^{-7}$  cm/s at  $\theta=0.20$ ) in Nov. 2002, resulting in much higher infiltration capacity and less runoff, even though more precipitation occurred. These findings indicate that a parameter set with higher  $K_s$  does not necessarily yield more infiltration or a more accurate prediction of runoff.

Predicted and measured ET are shown in Fig. 4(b). The accuracy of the ET prediction is largely affected by the accuracy of the runoff prediction and, therefore, is sensitive to the hydraulic properties used as input. The closest agreement for ET and runoff was obtained with the GM parameter set (<50 mm difference for ET, Table 4), and the poorest agreement was obtained with the LSC and FF parameter sets. Besides affecting runoff, the hydraulic properties directly affect ET by controlling the rate at which water can migrate within the root zone. For example, even though runoff was only slightly underpredicted for the HSC parameter set, ET was underpredicted because the lower  $K_s$  and greater water retention associated with the HSC SWCC made movement and release of water more difficult. This is evinced by the overprediction of  $S$  throughout the simulation period using the HSC parameter set [Fig. 4(c)]. Similarly, the high  $K_s$  and low water retention associated with the LSC parameter permits too much ET and drainage during the first year, resulting in too little water being stored within the root zone and, therefore, unavailable for ET later in the simulation period [Fig. 4(c)]. Like UNSAT-H, VADOSE/W overpredicts ET during spring and summer 2003, when the field ET was much less than expected.

The  $S$  predicted by VADOSE/W mimics the ET record. Soil-water storage was predicted very well (within  $\approx 25$  mm) with the GM parameter set [Fig. 4(c)], and nearly as well with the FF parameter set. The exceptions are in summer and fall 2002, when  $S$  is underpredicted slightly for the GM parameter set and appreciably for the FF parameters set, and in summer 2003 when ET was overpredicted [Fig. 4(c)]. The predictions of  $S$  for the LSC and HSC cases are consistent with the propensity for transmission and retention of water for these parameter sets. Soil-water storage was underpredicted for the LSC case because the profile permits



**Fig. 5.** (Color) (a) Runoff; (b) evapotranspiration; (c) soil-water storage; and (d) percolation measured in the field and predicted by HYDRUS using (LSC: blue), (GM: red), (HSC: green), and (FF: fuchsia) parameter sets. Field data in black.

water to be released readily, resulting in an overestimate of ET [Fig. 4(b), 2001] and percolation [Fig. 4(d)]. Similarly,  $S$  is overpredicted for the HSC simulation because water that infiltrated was strongly retained within the cover and transmitted slowly, resulting in underestimates of ET and percolation.

As with UNSAT-H, VADOSE/W underpredicted percolation for all cases except the LSC case [Fig. 4(d)]. VADOSE/W overpredicts percolation by 25 mm with LSC parameters, with 20 mm predicted in the first year due to gravity drainage (Table 4). Less than 1 mm of percolation was predicted for the entire record using the mean, HSC, and FF parameters, even though  $S$  was predicted relatively accurately (Table 4).

## HYDRUS

Water-balance predictions from HYDRUS are shown in Fig. 5 along with the field data. Annual water balance quantities are

summarized in Table 4. The predictions from HYDRUS are more similar to those obtained from VADOSE/W (Fig. 4) than those from UNSAT-H (Fig. 3).

Runoff was predicted accurately with the GM parameter set ( $<20$  mm/yr difference, Table 4), underpredicted for the FF parameter set, and overpredicted for the HSC parameter set [Fig. 5(a)]. This hierarchy in the runoff predictions is consistent with the hierarchy in  $K_s$  assigned to the parameter sets, as was observed with UNSAT-H. Moreover, the difference between the runoff predictions obtained using the GM and FF parameters illustrates again that both saturated and unsaturated hydraulic properties affect runoff.

The hierarchy in the ET predictions is consistent with the hierarchy in the runoff predictions (e.g., lowest ET and highest runoff with HSC parameters, highest ET and lowest runoff with LSC parameters, closest agreement for GM and FF parameters), as was observed for UNSAT-H and VADOSE/W [Fig. 5(b)]. The errors in the predicted ET are also similar to those for the predictions obtained with VADOSE/W [Fig. 4(b)], because both codes predicted runoff with similar accuracy (the LSC case being an exception). The predictions for  $S$  [Fig. 5(c)] also follow a similar hierarchy as observed with VADOSE/W [Fig. 4(c)]. Soil-water storage predictions [Fig. 5(c)] obtained using GM and FF parameters are in closest agreement with the field  $S$  (typically within 25 mm),  $S$  predicted with HSC parameters is greater than  $S$  in the field because ET is underpredicted, and  $S$  predicted with LSC parameter is less than  $S$  in the field because ET and percolation [Fig. 5(d)] are overpredicted. Moreover, none of the simulations with HYDRUS captured the anomalous  $S$  in 2003, as was also observed for UNSAT-H and VADOSE/W.

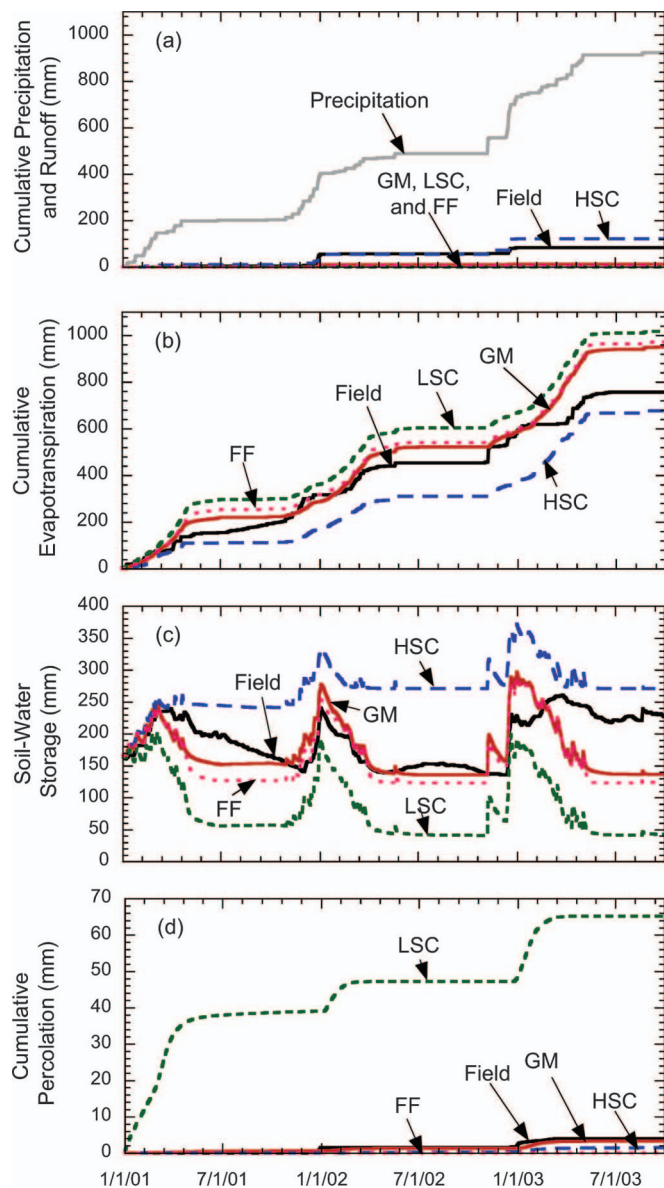
Percolation predicted with HYDRUS [Fig. 5(d)] was similar to percolation predicted with VADOSE/W [Fig. 4(d)] for all four parameter sets. Percolation was underpredicted slightly using the HSC, GM, and FF parameters ( $\approx 3.0$  mm total), and overpredicted significantly using LSC parameters (22 mm total, Table 4).

## LEACHM

Water-balance predictions from LEACHM are shown in Fig. 6 along with the field data. In contrast to the other codes, LEACHM underpredicted runoff for all but the HSC case, for which runoff was overpredicted. Runoff predicted by the HSC simulation was consistent with the field runoff until late 2002, when LEACHM overpredicted runoff by 38 mm (Table 4).

As observed with the other codes, the ET predictions complement the runoff predictions [Fig. 6(b)]. LEACHM overpredicted ET during most of each year when the GM and FF parameters were used as input, and throughout the monitoring period when the LSC parameters were used as input. In contrast, LEACHM underpredicted ET when the HSC parameters were used as input. LEACHM predicted total ET accurately (within 34 mm/yr) during each of the first two years when the GM and FF parameters were used as input (Table 4). However, ET was overpredicted in the spring and early summer, and underpredicted in the late summer and fall during the first year. This may reflect the immaturity of the vegetation during the first year of the study, as  $S$  depleted more slowly in the field during the first year compared to the second year [Fig. 6(c)]. Like the other codes, LEACHM overpredicted ET during the final year of the study, when ET measured in the field was lower than in other years.

Soil-water storage predicted by LEACHM using the LSC and HSC properties brackets the measured  $S$  [Fig. 6(c)], as was also observed with VADOSE/W and HYDRUS. Soil-water storage



**Fig. 6.** (Color) (a) Runoff; (b) evapotranspiration; (c) soil-water storage; and (d) percolation measured in the field and predicted by LEACHM using (LSC: green), (GM: red), (HSC: blue), and (FF: fuchsia) parameter sets. Field data in black.

was predicted accurately using the GM and FF parameters (typically within 20 mm), although the rate of depletion of  $S$  in 2001 was overpredicted and the peak  $S$  was overpredicted in 2002. The nearly invariant change in  $S$  that occurred in 2003 was not captured for any of the parameter sets.

In contrast to the other codes, LEACHM predicted percolation for all four parameter sets [Fig. 6(d)], although percolation predicted with the FF parameters was less than 0.005 mm/yr. The timing of percolation and the total amount of percolation were predicted with remarkable accuracy (within 16%, or 0.7 mm) when the GM parameters were used as input (Table 4). Percolation was underpredicted slightly when the HSC and FF parameters were used as input, and was overpredicted significantly when the LSC parameters were used as input (as observed with VADOSE/W and HYDRUS). The differences in percolation pre-

dicted with the GM and FF parameters illustrate that both the saturated and unsaturated hydraulic properties control the timing and magnitude of the percolation rate.

## Parametric Analysis

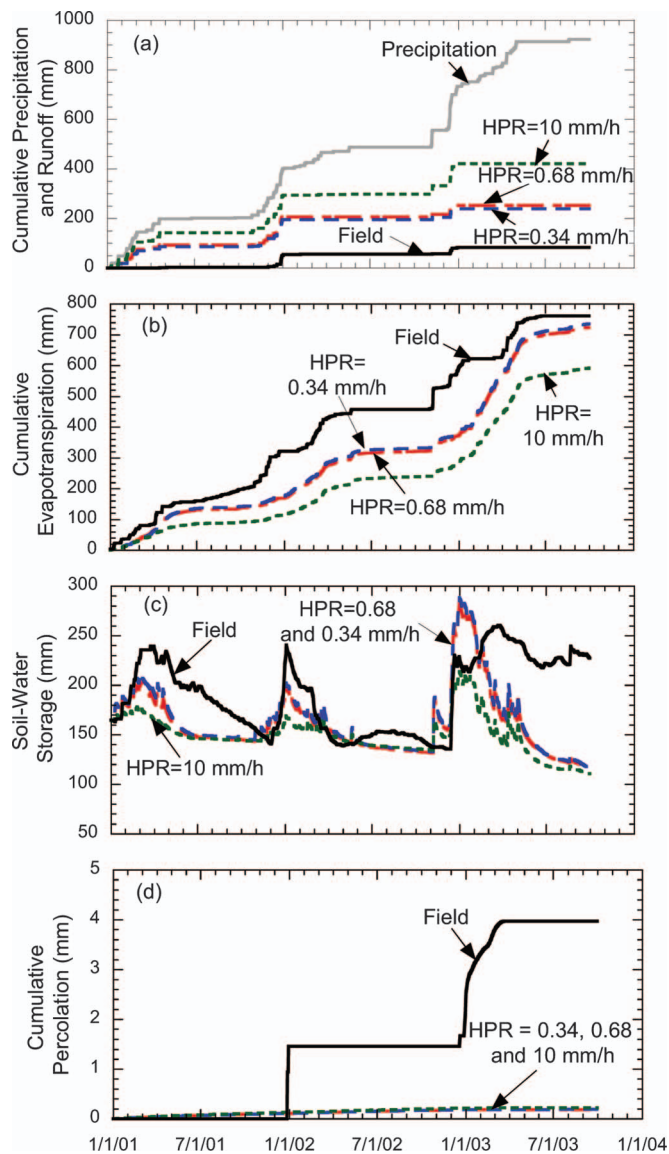
### Runoff, Precipitation Rate, and Hydraulic Properties

UNSAT-H predicted much more runoff than occurred in the field, and much more than any of the other codes. One factor that may have contributed to these overpredictions is the relatively high rate at which precipitation is applied by UNSAT-H relative to the other codes (Benson 2007; Ogorzalek et al. 2008). UNSAT-H applies precipitation at 10 mm/h under default conditions, which is much higher than the average hourly precipitation rate at Altamont (0.68 mm/h). In contrast, the other codes apply precipitation uniformly throughout each day, which results in an application rate that is lower than the average precipitation rate in the field on most days.

Ogorzalek et al. (2008) report similar overpredictions of runoff when UNSAT-H was used to predict the water balance of a capillary barrier in Montana. Using the average hourly precipitation rate (HPR) measured at the site instead of the default precipitation rate reduced (but did not eliminate) the over prediction. Similar findings were obtained in this study when the HPR was set to 0.68 mm/h (average field precipitation rate) or 0.34 mm/h (one-half the average field precipitation rate) (Fig. 7). Using the field-measured HPR reduces the overprediction of runoff over the entire monitoring period by approximately a factor of 2, whereas decreasing the precipitation rate to 0.34 mm/h has very little additional effect on predicted runoff. The reduction in runoff resulted in greater accumulation of soil-water storage during wet periods of the year (i.e., due to greater infiltration) and more ET, but peak soil-water storage and ET were still underpredicted during the first 2 years of the monitoring period.

More detailed examination of Fig. 7(a) indicates that much closer agreement between predicted and measured runoff was achieved during the second wet season using the field-measured HPR compared to previous periods. This difference in accuracy is due in part to the different  $K_s$  assigned to the surface layer, which was largest in the third year ( $1.1 \times 10^{-4}$  cm/s, Table 1). To assess the effect of  $K_s$  of the surface layer independent of HPR, an additional simulation was conducted using the default HPR and  $K_s$  of the surface layer set at  $1.1 \times 10^{-4}$  cm/s for the entire simulation period. Predictions obtained from this simulation are shown in Fig. 8 along with the field data. Very good agreement was obtained between predicted and measured runoff using higher  $K_s$  and the default HPR. Additionally, ET and soil-water storage were predicted more accurately, but percolation was still underpredicted.

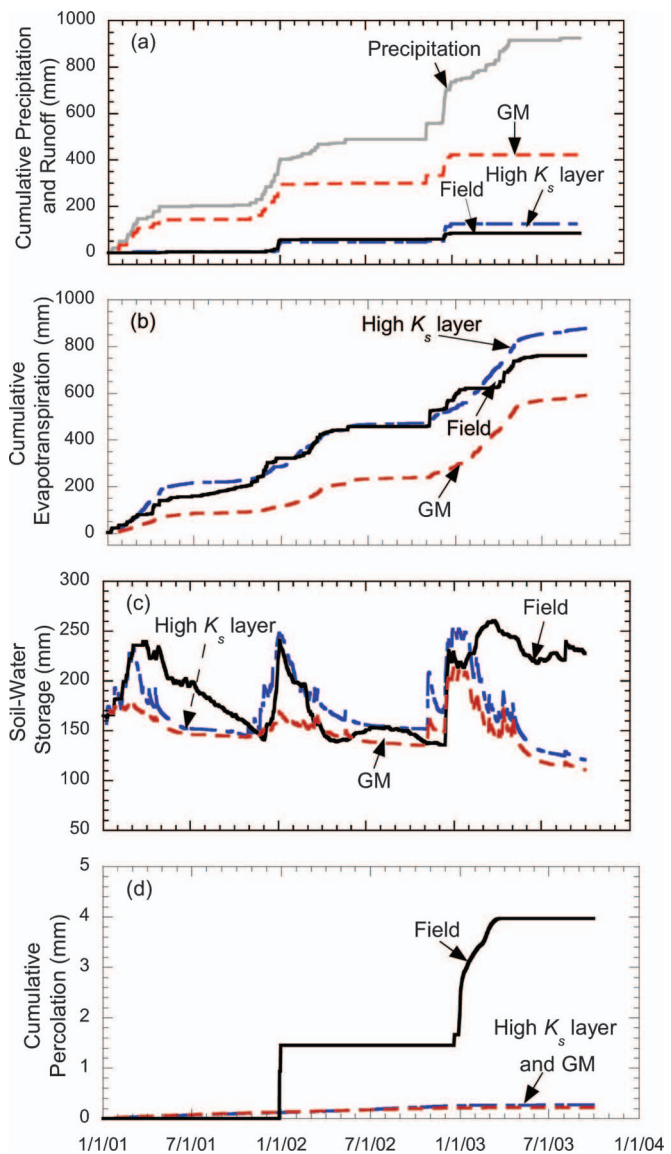
An additional simulation was conducted with UNSAT-H to assess whether hysteresis affected the water-balance predictions, particularly runoff. This analysis was conducted because infiltration and runoff are wetting processes, whereas drying SWCCs were used in the simulations. Additionally, Fayer and Gee (1997) report closer agreement between water-balance predictions and field data when hysteresis was included, and Khire et al. (1997) attributed overpredictions in runoff to ignoring hysteresis in their modeling study of earthen covers. The simulations were conducted using data from the FF parameter set, since this was the only parameter set where SWCCs were available for wetting and drying conditions. Water-balance predictions obtained from these



**Fig. 7.** (Color) (a) Runoff; (b) evapotranspiration; (c) soil-water storage; and (d) percolation measured in the field and predicted by UNSAT-H using the GM parameter set and HPR of 10 (default, green), 0.68 (field rate, red), or 0.34 mm/h (blue); field water-balance quantities in black

simulations are shown with the field data in Fig. 9. Including hysteresis resulted in less runoff, less ET, smaller seasonal fluctuations in soil-water storage, and slightly more percolation. Overall, however, hysteresis had a small effect on the water-balance predictions compared to precipitation rate and  $K_s$  of the surface layer.

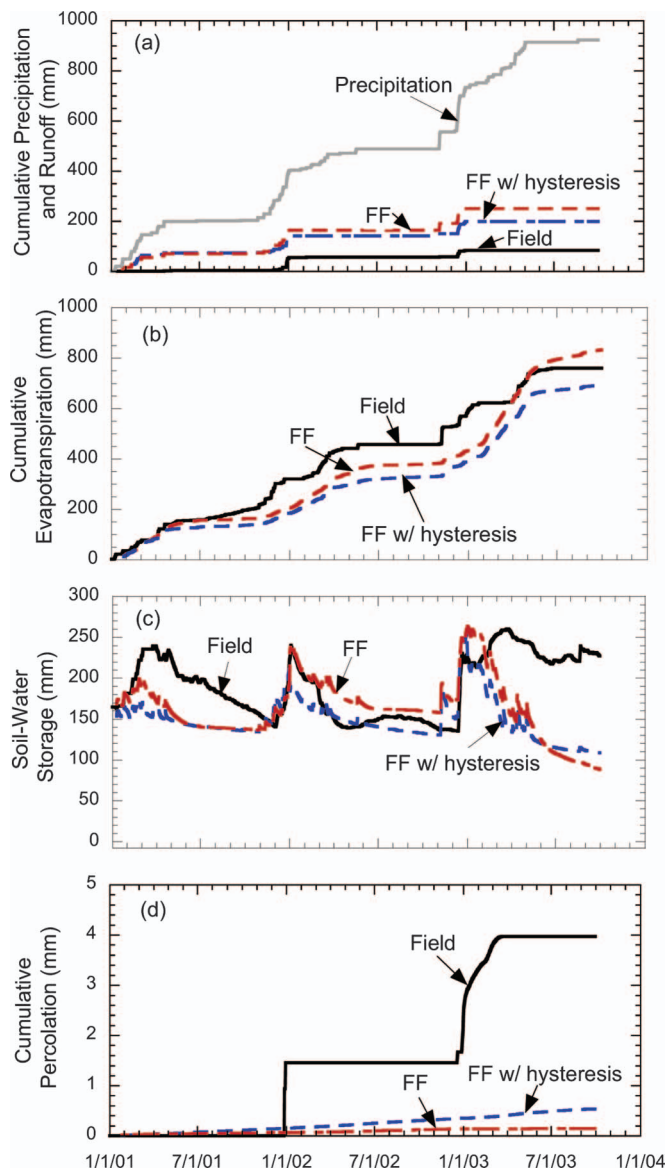
These simulations indicate that runoff predictions are sensitive to both the precipitation rate assigned in the code and the hydraulic properties assigned at the surface of the profile, and that adjusting either can result in a more accurate prediction of runoff. Thus, good agreement between measured and predicted runoff is a necessary, but not sufficient condition to confirm that mechanisms controlling infiltration and runoff are properly represented. For example, precipitation intensity is known to vary considerably. Thus, the reasonable agreement between measured and predicted runoff obtained when precipitation is applied at a uniform rate (e.g., as with HYDRUS or VADOSE/W, Figs. 4 and 5) may



**Fig. 8.** (Color) (a) Runoff; (b) evapotranspiration; (c) soil-water storage; and (d) percolation measured in the field and predicted by UNSAT-H using the GM parameter set with a surface layer having high  $K_s$  ( $1 \times 10^{-4}$  cm/s, blue) or  $K_s$  from the GM parameter set (red); field water balance shown in black

be coincidental. Similarly,  $K_s$  of the surface layer is known to evolve over time (Benson et al. 2007), making good agreement using a single  $K_s$  of the surface layer potentially coincidental.

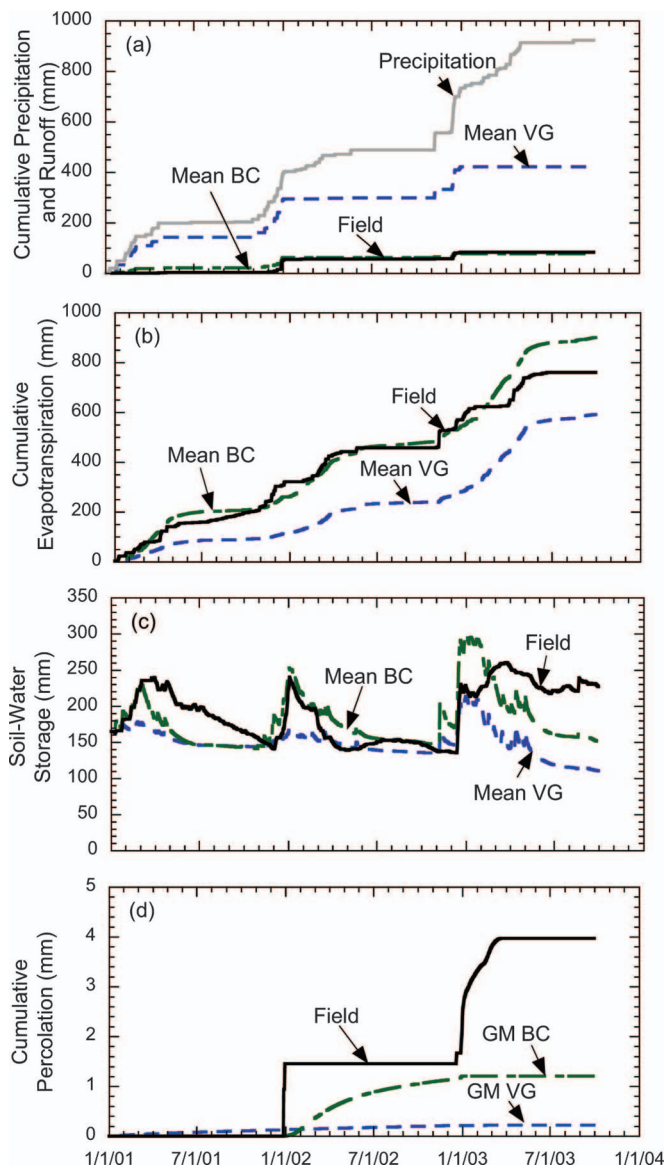
No definitive recommendation can be drawn from these findings regarding the most appropriate modeling procedures to ensure that runoff is predicted accurately. However, the findings show definitively that reasonable predictions of runoff are needed to ensure that other water-balance quantities are predicted reliably. Consequently, runoff predictions should be reviewed critically to ensure reasonableness and consistency with field data reported elsewhere. Albright et al. (2004) and Apiwantragoon (2007) indicate that runoff from water-balance covers rarely exceeds 10% of the annual water balance, and usually is less than 5% of the water balance.



**Fig. 9.** (Color) (a) Runoff; (b) evapotranspiration; (c) soil-water storage; and (d) percolation measured in the field and predicted by UNSAT-H using the FF parameter set with hysteresis (blue) and without hysteresis (red); field water balance shown in black

### Hydraulic Property Functions

Differences between the predictions made with LEACHM (Fig. 6) and those from the other codes (Figs. 3–5) are due in part to differences in the SWCC and hydraulic conductivity functions (Campbell versus van Genuchten). For example, at low suctions characteristic of conditions during infiltration and runoff, the Campbell hydraulic conductivity function yields a hydraulic conductivity approximately 10 times higher than the hydraulic conductivity from the VG function (Fig. 2, HYDRUS, VADOSE/W), which resulted in less runoff and more infiltration. Similarly, at high suctions, the Campbell function yields a hydraulic conductivity approximately four times higher than the VG function, which can result in more percolation. Andraski and Jacobson (2000), Scanlon et al. (2002), and Ogorzalek et al. (2008) also report that water-balance predictions are sensitive to the hydraulic



**Fig. 10.** (Color) (a) Runoff; (b) evapotranspiration; (c) soil-water storage; and (d) percolation measured in the field and predicted by UNSAT-H using the GM parameter set with the hydraulic properties described by the van Genuchten-Mualem model (VG, blue) or the Brooks-Corey model (BC, green). Field data in black.

conductivity function that is employed, even when the function used to predict hydraulic conductivity is parametrized using the same data describing the SWCC.

The hydraulic properties functions used in LEACHM are not available in the other codes, and LEACHM does not have an option to use other hydraulic properties functions. Thus, to assess the effect of the hydraulic conductivity function, a simulation was conducted with UNSAT-H using the BC function, which is very similar to the Campbell function (Fig. 2). Results of these UNSAT-H simulations are shown in Fig. 10 along with the field data and predictions made with UNSAT-H using van Genuchten hydraulic properties. In both cases, the GM parameter set was input. Excellent agreement was obtained between measured and predicted runoff and ET with the BC function, and good agreement was obtained between predicted and measured soil-water

storage. Percolation was still underpredicted with the BC function, but to a lesser extent than with the VG function.

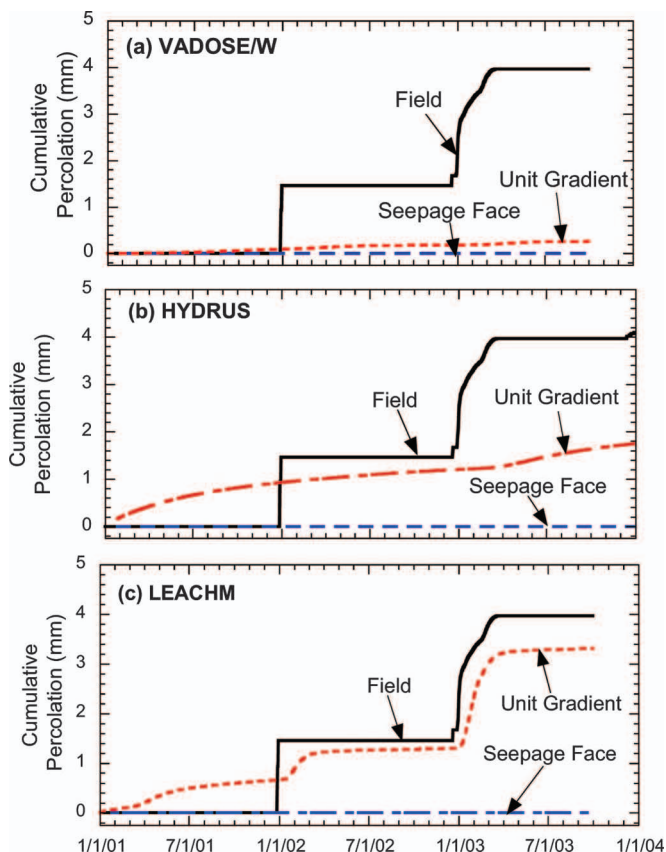
The sensitivity to the form of the hydraulic conductivity function illustrates the important influence that the unsaturated hydraulic conductivity has on water balance predictions made with the codes used in this study. Another issue not evaluated in this study, but of practical importance, is the accuracy with which hydraulic conductivity functions represent the actual unsaturated hydraulic conductivity of cover soils. For example, Meerdink et al. (1995) show that the unsaturated hydraulic conductivity predicted with models such as the VG and BC functions can deviate appreciably from the unsaturated hydraulic conductivity measured in the field in some cases. Thus, when practical, the unsaturated hydraulic conductivity of the cover soils should be measured, and the accuracy of the hydraulic conductivity functions evaluated as part of a modeling and design effort.

### Percolation, Lower Boundary Condition, and Saturated Hydraulic Conductivity

Simulations were conducted with VADOSE/W, HYDRUS, and LEACHM using unit gradient and seepage face boundary conditions to evaluate how selection of the lower boundary condition affects water-balance predictions. GM hydraulic parameters were used in each case. UNSAT-H was not used for this analysis because the code does not include a seepage face boundary condition.

For all three codes, changing the lower boundary condition had no effect on runoff, soil-water storage, or evapotranspiration (Bohnhoff 2005; Ogorzalek 2005). The effect of the lower boundary condition on percolation is shown in Fig. 11. The lower boundary condition had little effect on percolation predicted by VADOSE/W [Fig. 11(a)], a modest effect on percolation predicted by HYDRUS [Fig. 11(b)], and a significant effect on percolation predicted by LEACHM. In all cases, more percolation was predicted using a unit gradient boundary condition than a seepage face boundary condition, which is expected given that the seepage face boundary condition transmits percolation only when the boundary becomes saturated. Based on this comparison, and the inherent uncertainty in the actual boundary condition existing in the field, design simulations that consider only the cover profile (e.g., waste and other underlying layers excluded) should employ a unit gradient lower boundary. Alternatively, a more complete profile could be simulated that incorporates other layers (e.g., waste, leachate collection system, liner, etc.) and an appropriate boundary condition.

The underprediction of percolation observed in this study (Figs. 3–5 and 11) has also been reported by others simulating the water balance of covers with fine-textured soil layers (Fayer et al. 1992; Fayer and Gee 1997; Khire et al. 1997; Benson et al. 2004; 2005; Ogorzalek et al. 2008). Thus, simulations were conducted with UNSAT-H, VADOSE/W, and HYDRUS where  $K_s$  in each layer for the GM parameter set was scaled by a factor of 5, 10, or 20 to assess whether a more accurate prediction of percolation could be obtained. LEACHM was not used for this analysis because the code predicted percolation accurately using the GM parameter set. Percolation predicted for these simulations is shown in Fig. 12 along with predictions made with the GM parameter set and the field data. A five-fold increase in  $K_s$  was required to achieve a slightly conservative prediction of percolation with HYDRUS, a 10-fold increase in  $K_s$  was required for VADOSE/W, and an increase between 10- and 20-fold was re-



**Fig. 11.** (Color) Percolation measured in the field and predicted by (a) VADOSE/W; (b) HYDRUS; and (c) LEACHM using unit gradient and seepage face boundary conditions with the GM parameter set. Field data in black.

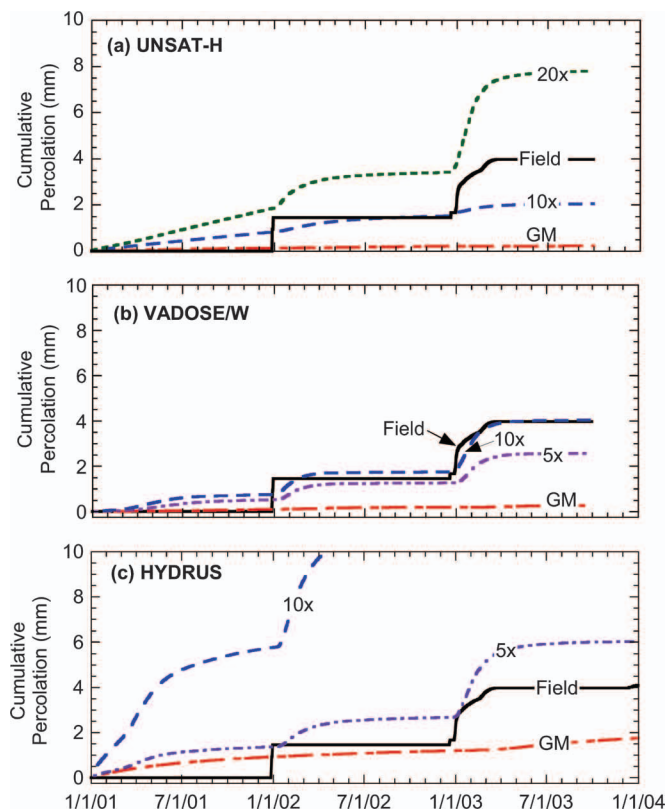
quired for UNSAT-H. However, a scaling factor of 10 probably would have resulted in closer agreement between measured and predicted percolation with UNSAT-H if runoff had been predicted more accurately.

Underpredictions of percolation may also be caused by preferential flow, which is not accounted for in any of the models evaluated in this study. For example, Khire et al. (1997) demonstrate that preferential flow was a key factor contributing to underprediction of percolation for an earthen cover in central Washington state. In this study, however, preferential flow was not a significant factor affecting the percolation rate measured in the field.

### Summary and Conclusions

Water-balance predictions made using four codes (UNSAT-H, VADOSE/W, HYDRUS, and LEACHM) have been compared with water-balance data from a test section located in a semiarid climate simulating a monolithic water-balance cover. The hydraulic, meteorological, and vegetative input into the codes was based on field and laboratory measured properties to the greatest extent practical so that an independent assessment of the predictive capabilities of the codes could be made that would be relevant to practice. Parametric simulations were also conducted to assess the sensitivity of each code to precipitation rate, saturated hydraulic conductivity, form of the hydraulic conductivity function, and the lower boundary condition.

Accuracy of the runoff prediction was found to affect the ac-



**Fig. 12.** (Color) Percolation measured in the field and predicted by: (a) UNSAT-H; (b) VADOSE/W; and (c) HYDRUS (c) using unit gradient and seepage face boundary conditions with the GM parameter set. Field data in black.

curacy of all other water-balance quantities. Runoff was predicted more accurately when precipitation was applied uniformly throughout the day, the surface layer was assigned higher saturated hydraulic conductivity ( $10^{-4}$  cm/s), or when Brooks-Corey functions were used to describe the hydraulic properties of the cover soils. However, no definitive recommendation could be identified that will provide reasonable assurance that runoff mechanisms are properly simulated and runoff predictions are accurate. Thus, modelers should examine runoff predictions for reasonableness and consistency with other field data. Existing field data from water-balance covers suggest that runoff should not constitute more than 10% of the annual water balance.

Evapotranspiration and soil-water storage were predicted reasonably well when runoff was predicted accurately (both within  $\approx 25$  mm annually), general mean hydraulic properties were used as input, and the vegetation followed a consistent seasonal transpiration cycle. However, percolation was consistently underpredicted even when evapotranspiration and soil-water storage were predicted reliably. Better agreement between measured and predicted percolation was obtained by increasing the saturated hydraulic conductivity of the cover soils by a factor between 5 and 10 while using general mean parameters for the soil-water characteristic curve.

Evapotranspiration and soil-water storage were predicted poorly at the end of the monitoring period by all of the codes because of a change in the evapotranspiration pattern that occurred in the field. The reason for this change in field behavior remains unknown, but similar changes at another cover in the region were attributed to a transition in vegetation species. The

inability to account for such changes is a weakness in the current models, and is a topic recommended for future study.

## Acknowledgments

Financial support for this project was provided by the USEPA Science to Achieve Results (STAR) Program (Grant No. R-82951501-0) as part of the USEPA's Rocky Mountain Hazardous Substance Research Center (HSRC), USEPA's Alternative Cover Assessment Program (ACAP), and the National Science Foundation (Grant No. CMS-0625850). Dr. Mitch Laset is the USEPA program manager for the HSRC and Mr. Steven Rock is the USEPA program manager for ACAP. The software programs used in this study were supplied as in-kind support by Geo-Slope International Ltd. and the University of Wisconsin-Madison Geotechnics Laboratory. The results and opinions expressed in this paper are solely those of the writers. Endorsement by USEPA, NSF, or GeoSlope is not implied and should not be assumed.

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