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Intercode comparisons for simulating water balance of surficial sediments in semiarid regions

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[1] Near-surface water balance modeling is often used to evaluate land-atmosphere interactions, deep drainage, and groundwater recharge. The purpose of this study was to compare water balance simulation results from seven different codes, HELP, HYDRUS-1D, SHAW, SoilCover, SWIM, UNSAT-H, and VS2DTI, using 1–3 year water balance monitoring data from nonvegetated engineered covers (3 m deep) in warm (Texas) and cold (Idaho) desert regions. Simulation results from most codes were similar and reasonably approximated measured water balance components. Simulation of infiltration-excess runoff was a problem for all codes. Annual drainage was estimated to within ±64% by most codes. Outliers result from the modeling approach (storage routing versus Richards' equation), upper boundary condition during precipitation, lower boundary condition (seepage face versus unit gradient), and water retention function (van Genuchten versus Brooks and Corey). A unique aspect of the code comparison study was the ability to explain the outliers by incorporating the simulation approaches (boundary conditions or hydraulic parameters) used in the outlying codes in a single code and comparing the results of the modified and unmodified code. This approach overcomes the criticism that valid code comparisons are infeasible because of large numbers of differences among codes. The code comparison study identified important factors for simulating the near-surface water balance. *INDEX TERMS:* 1866 Hydrology: Soil moisture; 1818 Hydrology: Evapotranspiration; 1875 Hydrology: Unsaturated zone; 1836 Hydrology: Hydrologic budget (1655); *KEYWORDS:* hydrologic budget, soil moisture, unsaturated zone, water balance modeling

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1. Introduction

[2] The purpose of this study was to compare the performance of seven different codes (HELP, HYDRUS, SoilCover, SHAW, SWIM, UNSAT-H, and VS2DTI) for simulating the near-surface water balance. These codes were chosen because they can simulate flow in response to meteorological forcing, they represent different modeling approaches (storage routing and Richards' equation), they are fairly well documented, they have been widely used and tested, and most are in the public domain. The simulations were applied to nonvegetated, engineered covers in semiarid regions in warm (Chihuahuan Desert of Texas) and cold (Snake River Plain, Idaho) deserts. Although simulation of nonvegetated systems may be considered limiting, the added complexities of simulating vegetation and evapotranspiration, and the lack of field measurements of vegetation parameters and processes (interception, leaf area index, rooting depth, transpiration) would greatly complicate the code comparison analysis. Application of these codes to sites using detailed field-monitored water balance data is valuable for evaluating how well the codes simulate field measurements. A unique aspect of this code comparison study is that it was extended beyond the traditional comparison of code results to attribution of differences to specific processes or parameters by incorporating the different processes or parameters into a single code in order to reproduce the results in other codes. This approach helps to overcome the criticism that valid code comparisons are infeasible as a result of too many differences among codes because it reduces the comparison to single issues. Unique contributions of this study include number of codes being compared, detailed field monitoring of the water balance, length of the monitoring record for simulation (1–3 yr), and different climate settings evaluated (warm and cold desert). Although water balance-monitoring data from engineered covers were used for input and comparison with simulation results, results of this study are not limited to evaluation of the engineered covers but should be applicable to general

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water balance modeling of nonvegetated systems. The approaches used for comparing codes could also be useful in any future code-comparison studies.

1.1. Background

[3] Why are simulations of the water balance of surficial sediments important? Near-surface water balance modeling is used to evaluate land-atmosphere interactions, estimate groundwater recharge and contaminant transport, and evaluate the performance of engineered covers for waste containment. Partitioning of precipitation into the various water balance components is used for evaluating the regional and global water cycle [*Milly*, 1994; *Milly and Dunne*, 1994]. Recharge estimates based on water balance modeling are critical for quantification of water resources and for assessing aquifer vulnerability to contamination. Many previous modeling studies used to estimate groundwater recharge are based on 1-D water balance codes that simulate drainage below the root zone [*Rockhold et al.*, 1995; *Kearns and Hendrickx*, 1998]. Such 1-D models can be applied to areas of different climate, vegetation, and land use to determine the impact of these factors on recharge and to develop recharge maps [*Hatton*, 1998]. The impact of land-use change can also be evaluated using these codes [*Pierce et al.*, 1993]. The 1-D models should be appropriate in areas where lateral flow processes are not important, i.e. no infiltration excess runoff and low topography [*Dawes et al.*, 1997; *Hatton*, 1998].

[4] Numerical water balance models are often used to predict the effectiveness of engineered covers in minimizing infiltration into underlying waste [*Fayer et al.*, 1992; *Khire et al.*, 1997; *Andraski and Jacobson*, 2000]. Sensitivity analyses have been conducted to determine important factors controlling subsurface flow, such as time discretization of precipitation input, vegetation, soil depth and texture, hydraulic parameters, liquid and vapor flow, and hysteresis [*Fayer and Gee*, 1992; *Meyer*, 1993; *Rockhold et al.*, 1995; *Stothoff*, 1997; *Kearns and Hendrickx*, 1998; *Andraski and Jacobson*, 2000]. Recent advances in computer technology, more computationally efficient codes, and availability of input data on climate and hydraulic properties online make long-term simulations of the near-surface water balance much more feasible. Weather generators, such as USCLIMATE and GEM [*Richardson*, 2000] can be used to develop long-term climate records for the simulations. Pedotransfer functions can be used to estimate hydraulic parameters from information on soil texture [*Schaap and Leij*, 1998; *Schaap et al.*, 1998].

[5] Codes used for simulating the near-surface water balance vary in complexity from bucket codes [*Schroeder et al.*, 1994; *Flint et al.*, 2000] and simple, analytical codes [*Kim et al.*, 1996; *Simmons and Meyer*, 2000] to more complex, numerical codes [*Fayer et al.*, 1992; *Scanlon and Milly*, 1994; *Khire et al.*, 1997; *Stothoff*, 1997]. Bucket codes approximate the storage capacity of the root zone by using a bucket or reservoir. Deep drainage occurs when precipitation exceeds runoff and evapotranspiration. Simple 1-D bucket models have been used to estimate groundwater recharge over large areas [*Hatton*, 1998; *Flint et al.*, 2000] and to evaluate the importance of episodic recharge [*Lewis and Walker*, 2002]. Those interested in global climate change have been developing simplified analytical solutions of Richards' equation in models of near-surface processes to incorporate into global climate models and to assess large-scale water balance and ecohydrologic issues [*Milly*, 2001; *Rodriguez-Iturbe et al.*, 2001]. More complex numerical solutions of Richards' equation are used for water balance modeling where detailed information on hydraulic parameters is available [*Fayer et al.*, 1992; *Flerchinger et al.*, 1996; *Khire et al.*, 1997]. The computational requirements of numerical models are much greater than those of analytical models.

[6] The reliability of model results can be evaluated (1) by comparing results obtained from different codes and (2) by comparing model results with field monitored water balance data. Programs such as nuclear waste disposal have included a wide variety of code comparison studies (e.g., INTRACOIN, 1981–1986; HYDROCOIN; 1984–1989; and INTRAVAL, 1987–1993] for evaluating geosphere transport models for radioactive substances in the subsurface [*Larssen et al.*, 1995]. The Society of Petroleum Engineers conducts an annual study titled Comparative Solution Project that compares the performance of several simulators by using benchmark problems [*Christie and Blunt*, 2001] (http://www.spe.org/csp/). These studies provide valuable insights into important modeling approaches that affect simulations of subsurface flow.

[7] Many code-comparison studies are based on hypothetical input data sets (e.g., Society of Petroleum Engineers, INTRAVAL, Phase 1). Many previous modeling studies have been hypothetical and did not compare model results with field data [*Stothoff*, 1997; *Kearns and Hendrickx*, 1998; *Khire et al.*, 2000]. However, some code-comparison studies include field data for model input and for comparison with simulation results (INTRAVAL, Phase 2). One of the primary sources of field measurements of near-surface water balance is provided by monitoring of engineered covers for waste containment [*Fayer et al.*, 1992; *Khire et al.*, 1997; *Wilson et al.*, 1999]. The Alternative Cover Assessment Program (ACAP) has been set up by the Desert Research Institute (DRI, Nevada), Pacific Northwest National Laboratory (Hanford, Washington), and the Environmental Protection Agency (EPA) to provide detailed water balance monitoring of engineered covers in different types of climate, vegetation, and soils [*Wilson et al.*, 1999]. Limited code-comparison studies have been conducted using water balance-monitoring data from engineered covers [*Nichols*, 1991; *Berger et al.*, 1996; *Khire et al.*, 1997; *Ogan et al.*, 1999; *Wilson et al.*, 1999]. Including field data for model input and comparison with model results should strengthen modeling studies.

1.2. Code Descriptions

[8] The codes evaluated in this study include Hydrologic Evaluation of Landfill Performance (HELP, version 3 [*Schroeder et al.*, 1994]; http://www.wes.army.mil/el/elmodels), HYDRUS-1D (version 3.0 [*Simunek et al.*, 1998]; http://www.ussl.ars.usda.gov/MODELS/HYDR1D1.HTM), SoilCover (version 4.1 [*Wilson*, 1990; *Wilson et al.*, 1994; *GEO2000*, 1997]; http://www.geo2000. com), Simulation of Heat and Water (SHAW, version 2.4 [*Flerchinger and Saxton*, 1989; *Flerchinger et al.*, 1996]; http://www.nwrc.ars.usda.gov/models/shaw/index.html), Soil Water Infiltration and Movement model (SWIM, version 2 [*Verburg et al.*, 1996]; http://www.clw.csiro.au/products/swim),UNSAT-H (version 3.0 [*Fayer*, 2000]; http://hydrology.pnl.gov/resources.asp),

Table 1. Attributes of Various Codes Compared in this Study[a]

Model	PE Input	PE Calc.	Snow	Runoff	Lower b.c.	Water Retention	K(θ,h) Function	I.C.	GUI
UNSAT-H	X	Penman*			UG	VG, BC	Mualem	h	X
HYDRUS-1D	X	PM			UG, S	VG, BC	Mualem	θ or h	X
SHAW		Penman*	X		UG	BC*	Burdine	h	
SoilCover	X				h or θ(c)	Fredlund	Mualem	h	X
SWIM	X				UG, S	VG, BC	Mualem	h	
VS2DTI	X				UG, S	VG, BC	Mualem	h	X
HELP		Penman	X	SCS	UG	BC	Burdine	θ	X

[a]PE, potential evaporation; calc., calculated internally in the code; b.c., boundary condition; GUI, graphical user interface; SCS, Soil Conservation Service curve number; UG, unit gradient; S, seepage face; BC, Brooks and Corey; VG, van Genuchten; BC*, Brooks and Corey with zero residual water content (equivalent to Campbell equation); θ, water content; h, pressure head; PM, Penman Monteith; Penman*, modified Penman equation [*Doorenbos and Pruitt*, 1977]. HYDRUS-1D and VS2DTI were modified to distribute PE daily using a sine function similar to that used in UNSAT-H and described by *Hillel and van Bavel* [1976].

and Variably Saturated 2 Dimensional Transport Interface (VS2DTI, version 1.1 [*Healy*, 1990]; http://water.usgs.gov/software/vs2di.html). Graphical user interfaces are available for most codes (Table 1). SHAW has an interface for data input but does not have a postprocessor. Detailed descriptions of the codes can be found in the user's manuals listed above. It is impossible to describe all the attributes of the various codes in this paper; however, many of the attributes related to water balance modeling of HELP, HYDRUS, SoilCover, and SHAW were described by *Wilson et al.* [1999].

[9] The code comparison focuses on various components of the water balance equation

$$P + Irr - E - R_0 - D = \Delta S \tag{1}$$

where P is precipitation, Irr is irrigation, E is actual evaporation, R_0 is surface runoff, D is drainage, and ΔS is change in water storage. All codes evaluated in this study simulate subsurface water flow using Richards' equation, with the exception of HELP, which uses a storage-routing or water balance approach. SHAW uses the Green and Ampt approach to simulate infiltration but uses Richards' equation to simulate redistribution. All of the codes simulate liquid flow; however, SoilCover and SWIM also simulate isothermal vapor flow, and HYDRUS-1D, SHAW, and UNSAT-H simulate isothermal and thermal vapor flow. All codes use some type of adaptive time stepping approach that allows the time step size to increase when the code converges readily and decrease when there are convergence problems considering a number of prespecified constraints. Initial time step size is generally a fraction of a second, and time step size can increase to a prespecified maximum (e.g., hr, day).

[10] HELP and SHAW are the only codes that simulate snow accumulation and melt. If air temperature is below 0, precipitation accumulates as snow. Snowmelt is simulated when the temperature rises above freezing. Runoff is simulated explicitly in HELP by using an empirical relationship between precipitation and runoff (curve number) developed by the U.S. Soil Conservation Service [*U.S. Department of Agriculture*, 1985]. In all the other codes, runoff occurs when precipitation intensity exceeds infiltration capacity of the soils. Water that has infiltrated can move up by evaporation or down as a result of gravity or matric-potential gradients. The upper boundary condition can be specified using meteorological data from which the codes can calculate potential evaporation (PE) internally using original or a modified version of the Penman [*Penman*, 1948] equation (Table 1). Alternatively, precipitation and PE can be input directly into many codes (Table 1). PE is not used in SHAW; instead the energy budget equation is solved to simulate actual evaporation.

[11] The codes use a variety of different approaches to simulate evaporation. Potential evaporation is controlled by atmospheric conditions whereas actual evaporation is limited by the rate at which soil can transmit water upward to the land surface. HELP uses a two-stage modified Penman energy balance method [*Ritchie*, 1972]. Stage1 evaporation is equal to potential evaporation (PE) and continues until the flux reaches a value equal to the hydraulic conductivity at a matric potential head of −1 m. Stage 2 evaporation follows and is calculated as a function of the number of days since stage 1 ended and approaches 0 when the wilting point (−153 m) is reached. Evaporation is assumed to occur within the evaporative zone depth specified by the user. HYDRUS-1D and UNSAT-H allow evaporation to occur at the potential rate when the head at the surface node is between 0 and a prespecified lower value. When the head reaches the lower bounding value, the boundary condition changes from a constant flux (PE) to a constant head, and evaporation is controlled by the rate at which water can be transmitted to the soil surface. SWIM and SoilCover calculate evaporation (E) as a sink term using the following equation [*Campbell*, 1985]:

$$E = PE\frac{RH_s - RH_a}{1 - RH_a} \tag{2}$$

where RH is relative humidity and the subscripts represent soil surface (s) and atmosphere (a). The evaporation rate is equal to PE when RH_s is 1 and is equal to 0 when RH_s is equal to RH_a. Simulating evaporation as a sink allows infiltration and evaporation to occur simultaneously, and evaporation can be accounted for at the time discretization used internally in the code rather than that of the precipitation input (generally daily or hourly). The value of RH_s is calculated as a function of matric potential at the surface node. The SWIM user manual [*Verburg et al.*, 1996] indicates that the simulations are not very sensitive to variations in RH_a and suggests a value of 0.5. SoilCover also includes a more complicated approach for calculating evaporation that was not used in this study [*Wilson*, 1990]. Evaporation in VS2DTI is computed as an upward flux driven by the pressure potential gradient between soil and atmosphere:

$$E = K_u\frac{h_a - h}{L} \tag{3}$$

where K_u is the unsaturated hydraulic conductivity of the surface soil, h_a is the pressure potential of the atmosphere, h is the pressure potential of the top node, and L is the distance between the top node and the soil surface. VS2DTI documentation [*Lappala et al.*, 1987] suggests a value of $-1,000$ m for h_a and also states that evaporation is not very sensitive to variations of h_a. The user must also enter a record for PE to serve as the upper limit for evaporation (i.e., if the calculated upward flux is greater than PE, evaporation is set equal to PE).

[12] The lower boundary condition available in most codes includes a unit gradient option, which allows water to drain when it reaches the boundary (Table 1). Many codes also include a seepage face option, which only allows drainage when the boundary becomes saturated (HYDRUS-1D, SWIM, and VS2DTI). This boundary condition is required to simulate lysimeters that do not have wicks to allow drainage under unsaturated conditions. Wickless lysimeters require saturation for drainage to occur. SoilCover only simulates a constant pressure or constant water content lower-boundary condition. Initial conditions for most codes consist of matric potentials, except for the HELP code, which requires water content data.

[13] Many codes (HYDRUS-1D, SWIM, UNSAT-H, and VS2DTI) include multiple analytical functions for water retention and unsaturated hydraulic conductivity. Most codes include the van Genuchten water retention function [*van Genuchten*, 1980] and the Mualem hydraulic conductivity function [*Mualem*, 1976]. SHAW uses Campbell's water retention function [*Campbell*, 1974, 1985], which is similar to the Brooks and Corey function [*Brooks and Corey*, 1966] except that the residual water content is zero, and the Burdine hydraulic conductivity function [*Burdine*, 1953]. HELP uses porosity, wilting point, field capacity, and saturated hydraulic conductivity data to calculate the Brooks and Corey water retention and Burdine hydraulic conductivity functions. SoilCover requires tabulated water retention data and saturated hydraulic conductivity, which are fitted to water retention and unsaturated hydraulic conductivity functions developed by *Fredlund et al.* [1994] and *Fredlund and Xing* [1994].

1.3. Site Descriptions

[14] The Texas site is located near Sierra Blanca, which is about 120 km southeast of El Paso, Texas. The site is within the Chihuahuan Desert of Texas. Long-term (30-yr) mean annual precipitation at Sierra Blanca is 320 mm. The site consists of heavily instrumented engineered covers that were installed in the summer of 1997. The surface dimensions of the engineered cover are 34 $\times$ 17 m. Subsurface water movement was restricted primarily to the upper 2 m of the profile, which consists of 0.3 m of topsoil (sandy clay loam with 15% gravel), underlain by 1.7 m of compacted native material (sandy clay loam) (Figure 1). This material is in turn underlain by a capillary barrier that consists of sand and gravel. The various components of the water balance equation are monitored, except evaporation, which is calculated by difference. The monitoring system consists of an onsite meteorologic station that monitors precipitation, wind speed, relative humidity, temperature, and solar and net radiation; a surface-runoff system that includes interception drains, underground storage tanks and pressure transducers; water content monitoring using time domain reflectometry (TDR) in the topsoil, 10 vertical neutron probe access tubes to 2 m depth, vertical profiles of heat dissipation sensors (depths: 0.15, 0.3, 0.6, 0.9, 1.2, 1.5, and 2 m) to monitor matric potentials; and a 3-m-deep, wickless lysimeter to monitor drainage. TDR signals below the topsoil were generally attenuated because of high salinity and high clay content. Water storage of the engineered cover was calculated by integrating the water content data averaged from all 10 neutron probe access tubes with depth. The site was irrigated in August and September 1998 to establish vegetation by using a 0.3-m grid drip-irrigation system. Seedlings of five perennial bunchgrass species were transplanted on a nominal 0.8-m grid. The vegetation is expected to have a negligible effect on the water balance in September and October 1998 because time was insufficient for roots to be established. The application rate was approximately 17 mm/hr. Irrigation water was applied between 2:00 and 5:00 a.m. and resulted in an average of 5.7 mm per application. Daily irrigations from 5–31 August resulted in 150.9 mm of water applied, and alternate day irrigations from 3–27 September resulted in 74.8 mm of water applied.

[15] The Idaho site is located at the Idaho National Engineering and Environmental Laboratory in southeastern Idaho [*Porro*, 2001] on the Snake River Plain. Long-term (40-yr) mean annual precipitation is 221 mm. The site consists of a concrete structure containing 10 cells, each of which is 3 m $\times$ 3 m $\times$ 3 m (four walls and a floor). Replicates of a monolithic soil cover and a capillary barrier cover were constructed in the cells. Data from only one of the monolithic soil cover cells are used in this study. The texture of the soil is silt loam, and the upper 0.15 m of the profile has 25% gravel by volume mixed with the silt loam soil to reduce wind erosion (Figure 1). Daily climate data were recorded at a NOAA station 11 km northeast of the test facility and include daily precipitation, solar radiation, temperature, wind speed, and relative humidity. Various components of the water balance were monitored, including soil water storage, using TDR probes at approximately 0.2-m depth intervals, and drainage from the bottom of the cell. Matric potential was monitored by tensiometers at 0.2-m intervals from 0.4 to 1.4 m depth and at 1.8, 2.6, and 3 m depths. Sidewalls on the test cells prevent run-on and runoff. Actual ET was calculated from the water balance equation (1) for both sites.

2. Model Input

[16] Parameters for the various models were chosen so that the simulations were approximately equivalent. All codes were set up to simulate liquid flow only, except SoilCover, which has no option for deselecting isothermal vapor flow.

2.1. Texas Site

[17] Simulations were conducted for the 1998 water year (October 1997 through September 1998) when the site was unvegetated. PE was calculated externally using net radiation in a Penman-Monteith equation [*Monteith and Unsworth*, 1990] and was used in the HYDRUS-1D, SoilCover, SWIM, UNSAT-H, and VS2DTI input (Table 1). Basic meteorological data (precipitation, wind speed, relative humidity, temperature, and solar radiation) were used in the HELP and SHAW input. An SCS curve number of 94 was specified by HELP (sandy clay loam soil, 2% slope, 17-m slope length)

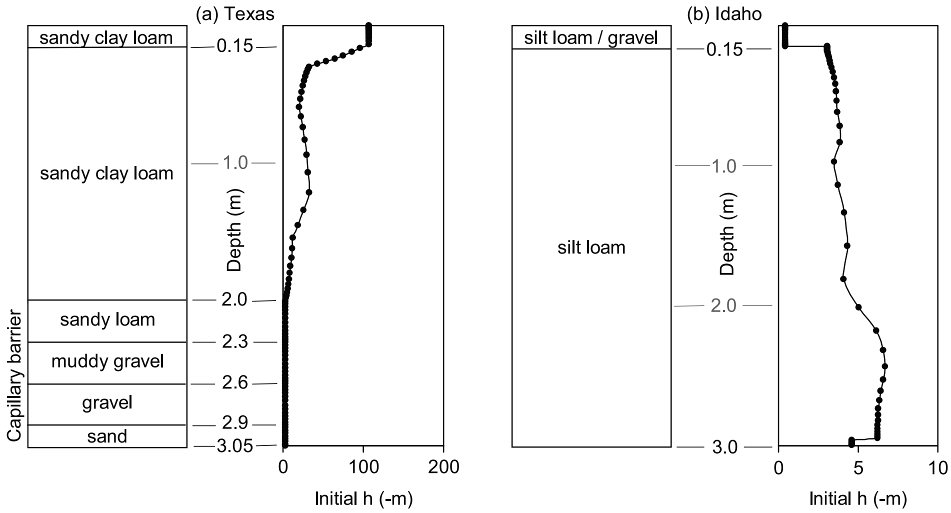

Figure 1. Texture profiles and initial matric potentials (ψ) for the (a) Texas and (b) Idaho sites.

for runoff. The lower boundary condition was specified as a seepage face in codes that include this option (HYDRUS-1D, SWIM, VS2DTI) and as a unit gradient (HELP, SHAW and UNSAT-H) or a constant matric-potential maintained at the initial value (−260 cm) (SoilCover) in codes that do not.

[18] The soil profile (3.05 m) was divided into six layers representing the different materials (Figure 1). A total of 103 nodes were used to represent the profile, with nodal spacing ranging from 0.2 cm at the soil surface and 2 cm at material interfaces, to a maximum of 15 cm within materials. The original SHAW code allowed only 50 nodes and was modified to increase the number of nodes. SoilCover allows a maximum of 100 nodes, and the grid for this code differs slightly from that used in other codes. All soil layers in the profile were specified as vertical percolation layers in HELP. HELP internally divided the Texas profile into 14 segments, with the upper 7 located in the 45-cm-thick evaporative zone (default evaporative zone thickness for the code). Initial conditions for the simulations were based on linear interpolation of matric potentials measured by the heat dissipation sensors on 1 October 1997. The corresponding water contents were estimated for HELP using the water retention function.

[19] Water retention data for soils in the upper three soil layers were based on laboratory measurements using a hanging water column (0 to −0.02 MPa [−2 m]) and a pressure-plate apparatus (−0.01 to −0.5 MPa [−1 to −50 m]). The measurements of layer 1 (the topsoil) were made on the fine soil fraction and the saturated water content of this layer was modified to account for the 15% gravel mixed with the sandy clay loam assuming that the gravel holds negligible water (Table 2). Water retention data and saturated hydraulic conductivity (K_s) for the underlying soil layers were obtained from various sources (layer 4 [UNSODA 2642]; layer 5 [*Rockhold et al.*, 1993]; layer 6 [UNSODA 4650]). The UNSODA database was described by *Leij et al.* [1996]. Residual water contents were set to zero for the van Genuchten water retention functions (Table 2). To determine van Genuchten shape parameters (α and n), van Genuchten water retention functions were fitted to the measured θ and h data using Solver in Microsoft Excel (Table 2). Detailed water retention data generated from the van Genuchten function were used to fit Brooks and Corey water retention parameters using Solver (Table 2, BC h_b and BC λ) for the SHAW code (Figure 2).

[20] Initial simulations were conducted using representative K_s values from existing databases for layers 1 and 2 (sandy clay loam [*Schaap and Leij*, 1998]). Field measurements of K_s in the topsoil gravelly sandy clay loam (layer 1) using a Guelph permeameter were similar to the database values, and the field measurements were used in the final simulations (Table 2). In contrast, K_s of the subsoil com-

Table 2. Model Input Parameter Values: Layer Thickness, Particle Size Distribution, Saturated Hydraulic Conductivity (K_s) and Saturated Water Content (θ_s) for All Codes; Water Content at Field Capacity (θ_{fc}) and at Wilting Point (θ_{wp}) for the HELP code; Residual Water Content (θ_r) and van Genuchten Shape Parameters (α, n) for HYDRUS-1D, SWIM, UNSAT-H, and VS2DTI; and Brooks and Corey Air Entry Pressure Head (h_b) and λ Parameters for SHAW[a]

Site	Layer	Thickness, m	Percent Gravel, Sand Silt, Clay	K_s	θ_s	θ_{fc}	θ_{wp}	θ_r	VG α, cm^{-1}	VG n	BC h_b, cm	BC λ
Texas	1	0.30	15, 48, 19, 18	41	0.45	0.230	0.090	0.000	0.027	1.276	24.946	0.240
Texas	2	1.70	0, 55,18, 27	20	0.35	0.280	0.150	0.000	0.010	1.167	52.072	0.138
Texas	3	0.30	0, 89, 3, 8	639	0.40	0.160	0.030	0.000	0.020	1.464	26.620	0.368
Texas	4	0.30	63, 28, 4, 5	10	0.14	0.110	0.060	0.000	0.007	1.188	73.836	0.191
Texas	5	0.30	gravel	159840	0.51	0.0014	0.0001	0.000	10.95	1.722	0.085	0.706
Texas	6	0.15	0, 92, 7, 1	587	0.38	0.040	0.002	0.000	0.050	1.774	12.280	0.605
Idaho	1	0.15	25, 16, 40, 19	94	0.36	0.115	0.043	0.035	0.036	1.601	11.200	0.321
Idaho	2	2.85	0, 22, 53, 25	43	0.47	0.237	0.019	0.015	0.005	2.090	109.70	0.685
Idaho	3	0.10	gravel	30240	0.42	0.032	0.013	0.005	4.930	2.190	0.900	0.706

[a]Layer 3 in the Idaho profile is not real but was used in SHAW and UNSAT-H simulations to approximate a seepage face.

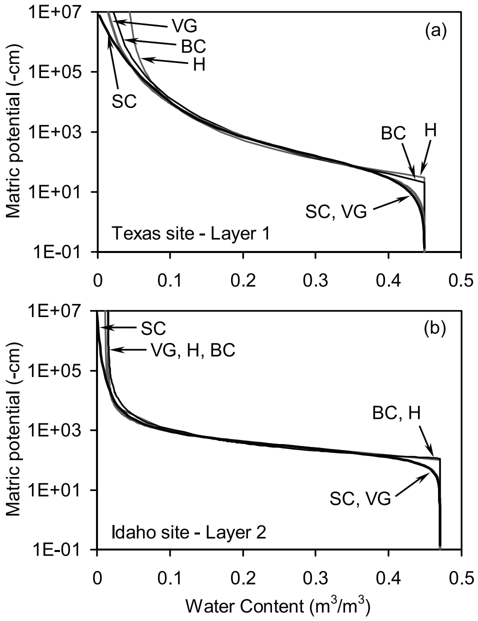

Figure 2. Example water retention functions for (a) layer 1 at the Texas site and (b) layer 2 at the Idaho site. Curves represent HELP (H), Brooks and Corey with zero residual water content (BC) (used in SHAW), van Genuchten (VG), and SoilCover (SC) water retention curves.

pacted sandy clay loam (layer 2) measured in the laboratory using a constant head permeameter [*ASTM D2434*, 1994] and a flexible wall permeameter [*ASTM D5084*, 1990] and in the field using a Guelph permeameter (Soilmoisture Equipment Corp., Santa Barbara, CA) were much lower than the database value of 9.6 cm/d. Simulations using these measured K_s values did not match the measured water balance as well as the database values for layer 2. These differences may be related to scaling issues as suggested by the order of magnitude increase in hydraulic conductivity between laboratory core measurements and field measurements using a Guelph permeameter. Therefore, in the code-comparison analysis we used the original database K_s values for layer 2.

2.2. Idaho Site

[21] Simulations were conducted for the period 21 July 1997 through 31 October 1999. PE calculated by UNSAT-H was used as input to the other codes that had a PE input option (Table 1). Meteorologic data were input into HELP and SHAW. The precipitation data were manipulated to account for snow accumulation and melting in all codes except SHAW, which calculates these processes internally. Therefore, in all simulations, precipitation assumed to be snow accumulated on days with an average temperature below 32°F (0°C), and was released as snowmelt on warmer days using the degree-day method [*Mockus*, 1972; *Magnuson*, 1993]. PE was set equal to zero when the soil was consistently frozen below 20 cm depth on the basis of temperature-monitoring data because soil moisture in frozen soil reduces hydraulic conductivity and inhibits evaporation, and snow on the surface acts as a sealant between the soil and the atmosphere. A similar approach was used by *Fayer et al.* [1992] to approximate a snow cover. The lower boundary condition was specified as a seepage face in codes that include this option (HYDRUS-1D, SWIM, VS2DTI). A unit-gradient lower boundary condition and a 10-cm-thick gravel layer at the base (Table 2, layer 3) were used in SHAW and UNSAT-H to approximate a seepage face although the engineered cover did not include a gravel layer at the base, unlike the Texas site. HELP simulates downward flow using a unit gradient, which also applies to the lower boundary. A constant matric potential (−5 cm) lower boundary was specified for SoilCover simulations. Initial conditions for the simulations were based on linear interpolation of matric potentials measured using tensiometers. The corresponding water contents were calculated for HELP using the water retention function.

[22] The soil profile (3.00 m) was divided into two layers (Figure 1b). An additional 10 cm of gravel was included at the base for codes that did not include a seepage face. A total of 120 nodes were used to represent the profile in all codes except SoilCover, which has a maximum of 100 nodes. Nodal spacing was 0.2 cm at the soil surface, 2 cm at material interfaces, and a maximum of 24 cm within materials. HELP internally divided the Idaho profile into 11 segments, with the upper 7 located in the 30-cm-thick evaporative zone (default evaporative zone thickness for code).

[23] Previous modeling studies using laboratory-measured water retention and K_s data in UNSAT-H simulations did not adequately reproduce the measured water balance components at the site [*Porro and Martian*, 1999; *Porro*, 2001]. The water application rate in the initial wetting phase (16.4–19.2 cm/d) generally exceeded the laboratory-measured K_s values (layer 1, 5.9 cm/d; layer 2, 8.9 cm/d). *Porro and Martian* [1999] used trial-and-error calibration with UNSAT-H to estimate the hydraulic parameters. In this study we used van Genuchten water retention and K_s values generated by the UNSAT-H calibration as input to other codes that used van Genuchten parameters or to generate other water retention functions for other codes (Table 2 and Figure 1). Because UNSAT-H was used for calibration, the performance of this code could not be evaluated for the Idaho site.

3. Results and Discussion

[24] Various simulation results are shown in Tables 3 and 4 and in Figures 3 through 5. For ease of comparison, the different simulations have been numbered in Tables 3 and 4, and these numbers are included in parentheses when necessary for clarification.

3.1. Texas Site

[25] Measured and simulated water balances for the Texas site were compared for 1 October 1997 through 30 September 1998.

3.1.1. Runoff

[26] A total of 6 cm of runoff was measured at the site. Runoff occurred primarily in October 1997 following an intense precipitation event (2.1 cm of precipitation in ~15 min; 1.7 cm runoff) and in August and September 1998, when the soil cover was irrigated to establish vegetation (22.3 cm irrigation; 3.5 cm runoff). Runoff was underpredicted by all codes when daily precipitation was input. HELP and SoilCover predicted 1.5 and 0.9 cm of runoff, respectively, whereas all other codes predicted zero runoff when using

Table 3. Measured and Simulated Water Balance Components for the Texas Site (October 1997 Through September 1998)[a]

	Code	Time	R_0	E	RMSE (E)	ΔS	RMSE (ΔS)	D
	Measured		**0.0**	**32.6**		**4.1**		**0.0**
(1)	UNSAT-H (UG)	d	0.0	29.7	2.0	6.7	1.7	0.3
(1)	UNSAT-H (UG)	h	0.0	29.9	2.0	6.6	1.7	0.3
(2)	HYDRUS-1D (S)	d	0.0	35.0	1.6	1.6	1.7	0.0
(2)	HYDRUS-1D (S)	h	0.0	33.4	1.2	3.3	1.1	0.0
(3)	SHAW (UG)	d	0.1	31.5	0.8	4.8	0.7	0.3
(3)	SHAW (UG)	h	0.0	33.1	0.7	3.5	1.0	0.2
(4)	SoilCover	d	0.0	34.6	1.4	2.1	1.4	0.0
(4)	SoilCover	h	4.4	25.7	3.5	6.6	1.0	0.0
(5)	SWIM (S)	d	0.0	34.1	1.4	2.6	1.5	0.0
(5)	SWIM (S)	h	0.0	33.6	1.4	3.0	1.5	0.0
(6)	VS2DTI (S)	d	0.0	**17.9**	7.1	**18.8**	7.1	0.0
(6)	VS2DTI (S)	h	0.0	29.9	2.0	6.8	1.9	0.0
(7)	HELP (UG)	d	0.0	**21.5**	5.2	**14.2**	4.5	0.9
(8)	HYDRUS-1D (UG)	d	0.0	35.0		1.2		0.4
(9)	HYDRUS-1D (S, hyst.)	h	0.0	33.4		3.0		0.4
(10)	UNSAT-H (VS2DTI)	d	0.0	18.0		18.4		0.3
(11)	UNSAT-H (HYDRUS-1D)	d	0.0	34.4		2.0		0.3
(12)	UNSAT-H (vapor)	h	0.0	30.1		6.4		0.3
(13)	UNSAT-H (hysteresis)	h	0.0	30.7		5.8		0.3

[a]R_0, surface runoff; E, evaporation; RMSE, root mean square error; ΔS, change in water storage, D, drainage; d, daily, h, hourly precipitation input; S, seepage face and UG, unit gradient lower boundary conditions, and UNSAT-H (vapor) simulates isothermal vapor flow. The water balance components (E, ΔS, and D) represent results from applying net precipitation (42.7 cm precipitation minus 6 cm of runoff = 36.7 cm net precipitation). Potential evaporation = 164 cm. Significant outliers are shown in bold. Code 1 (code 2): simulation using code 1 adjusted to represent code 2.

daily precipitation input. The effect of precipitation intensity on simulated runoff was tested by using daily and hourly precipitation in all codes that include this option (all codes except HELP) and 15-min precipitation in HYDRUS-1D, SWIM, and VS2DTI, which are the only codes that allow input on any time interval. SoilCover simulated 6.2 cm of runoff using hourly precipitation input, which is similar to the measured runoff (6.0 cm); however, there was little difference (<0.1 cm) in simulated runoff between daily and hourly precipitation input for all other codes. Using 15-min precipitation input, SWIM simulated 0 runoff and HYDRUS-1D and VS2DTI simulated ~1 cm runoff (October 1997) but did not simulate the runoff during irrigation, which was even more intense than represented by the 15-min precipitation input. The temporal resolution of the precipitation measurements was 15 min from October 1997 through June 1998. Measurements were made at much higher resolution (10 to 15 s) from June through October 1998. Additional simulations with actual intensities for this time period resulted in negligible (0 to 0.1 cm) increases in runoff. The inability to simulate runoff may result from spatial focusing of irrigation at the drip centers (0.3 m grid) and uncertainty in the hydraulic conductivity of the surficial sediments. The simulation results generally demonstrate the difficulties of simulating infiltration-excess runoff. Similar results were found in a study by *Meyer* [1993], who showed that use of daily versus hourly precipitation underpredicted runoff by a factor of 5 at a humid site in South Carolina characterized by high-intensity, short-duration rainfall. One option to overcome this problem may be to calibrate the models to runoff by decreasing the hydraulic conductivity of the surficial sediments. The hydraulic conductivity of the topsoil had to be decreased by an order of magnitude to simulate ~6 cm of runoff at the site using UNSAT-H.

[27] Underprediction of runoff in most codes results in more infiltration into the system, which in turn affects the remaining terms in the water balance equation. To better compare the simulated water balance of all codes, runoff (6 cm) was subtracted from precipitation (42.7 cm), and net precipitation (36.7 cm) was input to the simulations. On days when runoff was measured, the precipitation applied at the soil surface was reduced by the amount of the measured runoff. Using net precipitation, all codes simulated zero runoff, except SHAW (0.2 cm; daily precipitation input) and SoilCover (4.4 cm, hourly precipitation input) (Table 3). Simulation of runoff using SoilCover with daily precipitation input does not suggest that this code is more reliable than the others because SoilCover also simulated runoff when net precipitation was input.

3.1.2. Drainage, Evaporation, and Water Storage Change

[28] No drainage was measured at the site and most codes simulated zero drainage (Table 3). Small amounts of drainage (≤0.9 cm) were simulated using HELP, SHAW, and UNSAT-H at the start of the simulation. These drainage amounts may reflect the wet initial conditions and nonequilibrium of the initialization of the simulated system (profile matric potentials and boundary conditions), the simulation technique (storage routing versus Richards' equation), and/or the use of unit gradient rather than seepage face lower boundary conditions. HELP uses a storage routing approach and only considers gravitational gradients and ignores matric potential gradients, which are often upward in semiarid regions. Therefore water flows vertically downward under unit-gradient conditions, provided that the water content in the evaporative zone is above the wilting point. The representation of the lower boundary as a unit gradient rather than a seepage face may also contribute to the excess drainage simulated by all three codes. The effect of the lower boundary condition was evaluated by rerunning the HYDRUS-1D simulation with a unit gradient rather than a seepage face lower boundary condition, which resulted in 0.4 cm of drainage (simulation 8; Table 3), similar to the values simulated by SHAW and UNSAT-H.

Table 4. Measured and Simulated Annual Water Balance Components for the Idaho Site[a]

	Code	Time	Pre-WY 98 P 75.9 PE 45.8			WY 98 P 24.2 PE 118.0			WY99 P 19.8 PE 129.3		
			E	ΔS	D	E	ΔS	D	E	ΔS	D
	Measured		**5.2**	**48.0**	**22.7**	**15.4**	**0.5**	**8.3**	**11.7**	**−0.8**	**8.9**
(1)	UNSAT-H (UG, G), VG, Mualem	d	5.2	48.7	22.1	13.1	0.8	10.3	10.1	−2.6	12.3
(2)	HYDRUS-1D (S), VG, Mualem	d	**10.2**	**48.0**	**17.7**	18.7	−0.8	6.3	13.5	−1.3	7.7
(3)	SHAW (UG, G), BC, $\theta_r = 0$, Burdine	d	9.3	48.5	18.1	19.9	−0.7	5.0	**22.8**	**−3.6**	**0.6**
(4)	SoilCover (const. h), (Fredlund)	d	9.9	49.7	16.2	16.8	−1.2	8.7	11.2	−1.3	10.0
(5)	SWIM (S), VG, Mualem	d	9.5	51.1	15.3	16.1	0.2	7.9	10.4	−1.3	10.8
(6)	VS2DTI (S), VG, Mualem	d	3.5	51.3	21.2	**10.0**	**0.7**	**13.6**	9.0	−2.8	13.7
(7)	HELP (UG), BC	d	**10.0**	**7.3**	**58.7**	15.4	1.9	7.0	13.6	−2.6	8.8
(8)	HYDRUS-1D (UG, G)	d	10.3	47.9	17.7	19.0	−1.0	6.3	13.7	−1.2	7.3
(9)	HYDRUS-1D (UG)	d	9.3	−11.7	78.3	14.3	−13.4	23.4	8.9	−1.3	12.3
(10)	HYDRUS-1D (hysteresis)	d	10.2	46.6	19.1	18.5	−0.7	6.5	13.3	−3.2	9.7
(11)	UNSAT-H (UG)	d	4.3	−10.4	82.0	9.8	−11.1	25.6	6.7	−5.3	18.5
(12)	UNSAT-H (BC, Burdine, $\theta_r = 0$)	d	6.8	48.5	20.6	19.8	−1.4	5.9	**16.4**	**−5.1**	**8.5**
(13)	UNSAT-H (BC, Burdine, $\theta_r \neq 0$)	d	6.6	46.9	22.4	19.4	−1.3	6.1	16.2	−5.1	8.8
(14)	UNSAT-H (BC, Mualem, $\theta_r \neq 0$)	d	9.2	44.5	22.3	26.7	−4.7	2.3	23.7	−7.1	3.2
(15)	UNSAT-H (VS2DTI)	d	3.4	48.9	23.6	**8.3**	**0.9**	**15.0**	7.9	−2.8	14.7
(16)	UNSAT-H (HYDRUS-1D)	d	**9.8**	**48.5**	**17.7**	16.9	−0.5	7.8	11.7	−2.3	10.5
(17)	UNSAT-H (1) (vapor)	d	5.2	48.7	22.1	13.4	0.7	10.1	10.4	−2.7	12.1
(18)	UNSAT-H (1) (hysteresis)	d	5.0	40.8	30.1	12.0	−0.2	12.5	9.7	−3.0	13.2

[a]Pre-WY98 (12 July to 30 September 1998); WY, water year; P, precipitation; PE, potential evaporation; d, daily precipitation input; E, evaporation; ΔS change in soil-water storage; and D, drainage; UG, unit gradient lower boundary condition; G, gravel to approximate a seepage face; S, seepage face lower boundary condition; θ_r, residual water content, BC, Brooks and Corey water retention function; Burdine and Mualem are hydraulic conductivity functions. Simulation 1 (UNSAT-H) was the calibration run used to generate hydraulic parameters for all the other codes. Simulation 8 was conducted to determine whether a seepage face could be approximated by a unit gradient lower boundary condition with a gravel layer at the base of the profile. Simulations 9 and 11 evaluate the use of a UG lower boundary condition. Simulations 10 and 18 examine the impact of hysteresis. Simulation 12 was conducted to replicate the SHAW simulation (3). Simulation 13 evaluates the impact of the residual water content (by comparing with 12); simulation 14 examines the effect of the hydraulic conductivity function. Simulation 15 was set up to replicate the upper boundary conditions from VS2DTI in UNSAT-H and simulation 16 replicates that of HYDRUS-1D. Simulation 17 examines isothermal vapor flow. All units in cm. Noteworthy simulation results are shown in bold. Code 1(code 2): simulation using code 1 adjusted to represent code 2.

[29] The main process in the water balance at this site is partitioning of water between evaporation and water storage change. These two components are inversely related; i.e., if evaporation is overpredicted, then water storage change is underpredicted, and vice versa. The accuracy of the simulations was evaluated by calculating the root mean square error (RMSE) between simulated and measured storage and evaporation change. The time periods over which the changes were evaluated correspond with the neutron probe water content measurement intervals (~monthly) (Figure 3):

$$RMSE = \left(\frac{1}{n} \sum_{i=1}^{n} (X_m - X_s)_i^2 \right)^{0.5} \tag{4}$$

where X represents evaporation or water storage change, n is the number of time periods evaluated (15), and the

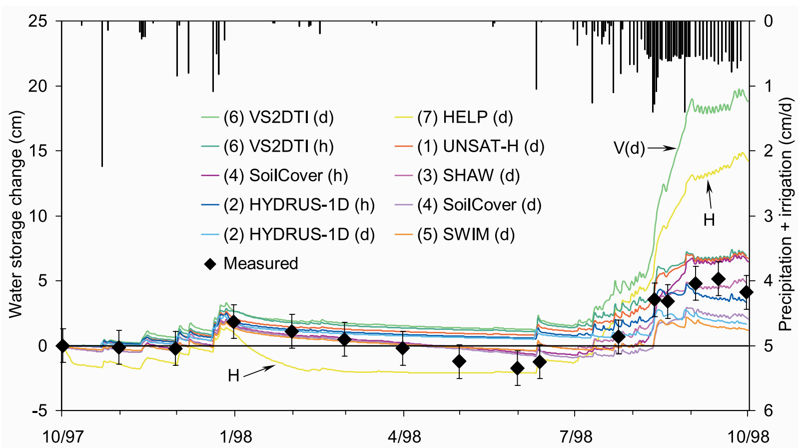

Figure 3. Time series of daily precipitation and irrigation input and measured and simulated water storage change for the Texas site. Results from the various codes listed in order in the legend from left to right correspond to the order on the graph from top to bottom on the right. Simulation numbers in parentheses correspond to Table 3. The main outliers are VS2DTI with daily precipitation input (V(d)) and HELP (H). Results from all the other codes are similar and cannot be readily distinguished. Irrigation was applied in August and September 1998. Error bars represent 2σ uncertainties in the water content measurements.

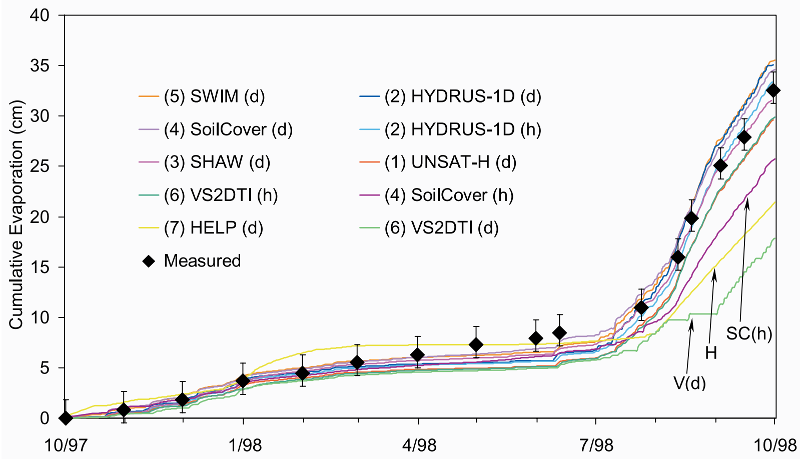

Figure 4. Time series of cumulative evaporation for the Texas site. Results from the various codes listed in order in the legend from left to right correspond to the order in the graph from top to bottom on the right. Simulation numbers in parentheses correspond to Table 3. The main outliers are VS2DTI with daily precipitation input (V(d)), HELP (H), and SoilCover with hourly precipitation input (SC(h)). Results from all other codes are similar and cannot be distinguished readily. Error bars represent 2σ uncertainties in the precipitation, water storage, and drainage measurements.

subscripts represent measured (m) and simulated (s) values. Accurate simulation of water storage change is important because large storage increases may ultimately result in drainage.

[30] The above comparisons ignore any uncertainties in the measurements. Uncertainties in the storage measurements were estimated considering counting uncertainties with the neutron probe (±0.0001 cm), neutron probe calibration slope error (±0.01 cm), and spatial variability in water content based on the 10 neutron probe access tubes (±1.3 cm, 2σ). Uncertainties in calculated evaporation incorporate uncertainties in precipitation and irrigation input and water storage. Errors result from partial filling of the tipping bucket (∼0.9 cm) and premature tipping as a result of high intensities (∼0.5 cm), and from irrigation application related to the flowmeter ((±0.1 cm). Some of these errors cancel and result in a net error of ∼+0.5 cm. Therefore the uncertainty in the evaporation estimates is ∼−1.3, +1.8 cm.

[31] All codes except HELP and VS2DTI adequately simulated evaporation and storage change, as indicated by low RMS errors (Table 3 and Figures 3 and 4). Some codes underestimated while other codes overestimated the measured water balance values. Differences between simulated and measured annual evaporation ranged from 3% to 9% of the measured value using daily precipitation input, whereas differences between simulated and measured water storage

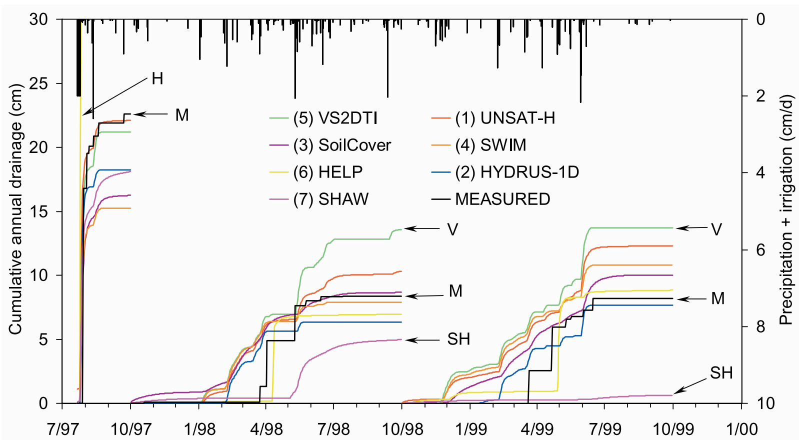

Figure 5. Time series of daily precipitation and applied irrigation and measured and simulated drainage at the Idaho Site. Drainage curves were restarted on 1 October each year. Results from the various codes listed in order in the legend from left to right generally correspond to the order in the graphs from top to bottom. Simulation numbers in parentheses correspond to Table 4. The plot was irrigated from 21–25 July 1997 until breakthrough occurred. Daily irrigation amounts for this period are not shown for clarity and were 5.4, 18.2, 17.3, 20.1, and 9.6 cm. HELP simulated 58 cm of drainage in response to this irrigation (not shown to scale). The main outliers are HELP (H) for the first few months, SHAW (SH) for 1999, and VS2DTI (V) for 1999 and 2000. Results from all other codes are similar and cannot readily be distinguished from measured (M) values.

change ranged from 17% to 63%, excluding HELP and VS2DTI. This comparison of measured and simulated values underscores the difficulties of accurately estimating a small number, such as water storage change or drainage, versus a larger number, such as evaporation, because percentage errors are amplified when a small number is estimated.

3.1.3. Explanation of Differences Between Model Results

[32] Two main outliers in the simulation results were HELP and VS2DTI (Figure 3). RMS errors for these codes ranged from 4.5 to 7.1 cm when daily precipitation data were input (Table 3). Both codes underestimate evaporation and overestimate water storage change. The overestimation of water storage change by HELP is consistent with overestimation of drainage by HELP discussed previously. The overestimation of water storage change by VS2DTI is due to the approach it uses to assign upper boundary conditions during precipitation. Specifically, VS2DTI sets PE to zero during days with precipitation. When daily precipitation is input, PE is set equal to zero for the entire day. This approach underestimates evaporation and overestimates water storage change (Table 3). The effect of the upper boundary condition is greatly reduced when actual precipitation is input at an hourly interval because the duration of precipitation is generally 1 to 2 hr and PE can occur throughout the rest of the day.

[33] Differences approaches for simulating the upper boundary condition with daily precipitation input are more appropriate than that used by VS2DTI. HYDRUS-1D subtracts PE from precipitation and applies net precipitation or net evaporation. This approach is also used in SWATRE [*Belmans et al.*, 1983] and results in slight overestimation of evaporation and underestimation of water storage change when daily precipitation is input. Examples of other approaches include that used by UNSAT-H, in which precipitation is applied at a specified rate (default value 1 cm/hr) until all precipitation is applied and evaporation is allowed to occur throughout the rest of the day. Simulation results using daily and hourly precipitation input are almost identical for UNSAT-H (Table 3), suggesting that this approach works well for approximating natural conditions with daily precipitation input when there is no runoff. SoilCover and SWIM simulate infiltration and evaporation at the same time by simulating evaporation as a sink term (equation 2). Results from SWIM and SoilCover are similar to those of HYDRUS-1D. The SoilCover simulation results with hourly precipitation input differ from the others because runoff was overestimated.

[34] Effects of the upper boundary condition were further evaluated by running a single code (UNSAT-H) repeatedly, using a different upper-boundary condition for each run. UNSAT-H simulations that were set up to approximate the VS2DTI approach (PE = 0 on rain days; simulation 10) and the HYDRUS-1D approach (net precipitation or net PE applied; simulation 11) generally reproduced the results from VS2DTI and HYDRUS-1D, confirming the explanation for the different simulated water balance components (Table 3). Many previous studies have used daily input for precipitation data [*Fayer and Gee*, 1992; *Rockhold et al.*, 1995; *Kearns and Hendrickx*, 1998], and some studies have used monthly precipitation input [*Wilson et al.*, 1999]. The approach used by the various codes for simulating the upper boundary condition when daily precipitation is input is critical because (1) only daily meteorological data are available for many sites, (2) most weather generators are limited to generating weather data at a minimum time resolution of one day [*Richardson*, 1981], and (3) the feasibility of conducting long-term (30- to −100 yr) simulations is greatly facilitated by using daily, as opposed to shorter term, meteorological data.

[35] The seasonal distributions in soil-water storage and evaporation were compared with those calculated from the measured water balance (Figures 3 and 4). Measured water storage increased in December 1997 because of snowmelt and gradually decreased in the spring and early summer. Increases in water storage in late summer resulted from summer rain, and large increases in August and September resulted from irrigation and rain. Most codes generally overestimated water storage in the spring and summer, which is attributed to underestimation in evaporation. Similar results were found by *Fayer et al.* [1992] and *Khire et al.* [1997]. *Fayer et al.* [1992] improved the simulation of seasonal evaporation by decreasing the pore interaction term in the Mualem hydraulic conductivity function from 0.5 to 0.0, which increased evaporation in the spring and summer and negligibly affected evaporation in the winter. The increase in evaporation was attributed to higher unsaturated hydraulic conductivity (K_u) when the pore interaction term was zero. The impact of increased K_u on the water balance parameters appears counterintuitive. One would expect that increasing K_u would increase the drainage; however, *Stothoff* [1997] conducted a series of simulations to demonstrate that increasing K_u allowed water to be transmitted up to the surface more readily, which maintained a moist surface over longer time periods that resulted in increased evaporation. These results may be restricted to semiarid regions. Reducing the pore interaction term in the UNSAT-H simulations of the Texas site increased the unsaturated hydraulic conductivity by up to a factor of 3. However, this increase in unsaturated hydraulic conductivity only resulted in a negligible increase in evaporation; therefore additional studies are required to evaluate simulation of evaporation.

3.2. Idaho Site

[36] Measured and simulated water balances for the Idaho site were compared for the initial period (21 July 1997 through 30 September 1997; pre-WY98) and water years 1998 and 1999 (WY98, WY99). UNSAT-H was used to calibrate the hydraulic properties [*Porro and Martian*, 1999]; therefore the performance of this code was not evaluated for this site. Only daily meteorological data were available for this site. Because the lysimeter cells were enclosed on all sides, runoff could not occur. SHAW simulated 4.9 cm of runoff in WY98 when the soil was frozen. A ponding depth of 10 cm was used to prohibit this code from simulating runoff.

[37] Most drainage from the profile (22.7 cm) occurred in July and August 1997 in response to irrigation in July (Figure 5). Drainage also occurred in March/April each year (5–6 cm) in response to spring snowmelt. Additional drainage (2–3 cm) occurred in May/June each year in response to long periods (∼10 d) of high precipitation. Uncertainties in the drainage measurements are considered to be less than 1%

based on uncertainties in the tipping bucket and pressure transducer data. Drainage toward the margins of the lysimeter was collected separately to ensure that there was no preferential flow along the walls of the lysimeter. Simulated annual drainage was within ±64% of measured drainage for most codes (simulations 1, 2, 4, 5, and 6; Table 4). The two main outliers were HELP, which overestimated drainage by a factor of 2.6 for the initial irrigation period, and SHAW, which generally underestimated drainage, particularly in WY99 (factor of 14.8). The time series of drainage indicates that simulated drainage generally occurred much earlier than measured drainage each year (Figure 5). The difference in the timing between the simulated and measured drainage is attributed to inability of the codes to simulate reduction in infiltration and in hydraulic conductivity due to soil freezing.

[38] Measured water storage increased by 48 cm after the initial irrigation in July 1997 (pre-WY98 in Table 4). Measured water storage changes in the following water years were minimal (i.e., WY98 and WY99 in Table 4). Uncertainties in the water storage measurements could not be determined because the TDR probes were not calibrated. The Topp equation [*Topp et al.*, 1980] was used to estimate water from the TDR data. Most codes generally simulated the annual water storage change, with the exception of HELP, which greatly underestimated the water storage change because it overestimated the drainage after the initial irrigation. With the exception of HELP, all codes simulated measured water storage change during the first few months (July through September 1998) to within ±7%. Much larger percentage deviations occurred in WY98 and WY99 because the measured storage values were very low.

[39] Most codes generally overestimated evaporation, with the exception of VS2DTI, which underestimated annual evaporation by a factor of as much as 1.5 (Table 4). SHAW overestimated evaporation by a factor of 1.9 during water year 1999.

3.3. Explanation of Differences Between Model Results

[40] Additional simulations were conducted to further evaluate the discrepancies in simulated results among the various codes. The main outlier is the HELP simulation results for the first time period (pre-WY98) (Figure 5). The primary difference between HELP and the other codes is the use of storage routing versus Richards' equation to simulate flow. HELP uses a unit gradient to simulate downward flow in the profile when the matric potential exceeds the potential at the wilting point. The unit gradient also applies to the lower boundary, which forces water to drain as it reaches the lower boundary. However, the most appropriate lower boundary condition to represent the lysimeter is a seepage face because it does not have wicks that would allow drainage under unsaturated conditions. The seepage face requires water to build up at the lower boundary until saturated conditions develop and then drainage occurs. HYDRUS-1D, SWIM, and VS2DTI include a seepage face option and a unit gradient lower boundary condition with a gravel layer was used in UNSAT-H and SHAW to approximate a seepage face.

[41] To evaluate the impact of the different lower boundary conditions, the various options were implemented in HDYRUS-1D, i.e., a seepage face (simulation 2), unit gradient and gravel layer (simulation 8), and unit gradient only (simulation 9) (Table 4). Simulation results based on a unit gradient and a gravel layer (8) are similar to those based on a seepage face (2), indicating that the combination of a unit gradient lower boundary condition and a gravel layer can be used to approximate a seepage face. In contrast, simulation results based on a unit gradient alone (without a gravel layer, 9) differ markedly from those based on a seepage face (2). The increased drainage simulated by HYDRUS-1D with a unit gradient lower boundary condition (9) is similar to that based on HELP (6); however, the magnitude of the drainage values simulated by HYDRUS-1D exceed those simulated by HELP by as much as 19.6 cm in pre-WY98 (Table 4). Simulation results based on UNSAT-H with a unit gradient lower boundary condition (no gravel, 11) were similar to those based on HYDRUS-1D (9). The combination of a gravel layer and a unit gradient lower boundary approximates a seepage face because the capillary barrier effect of the gravel requires water to build up almost to saturation on the gravel layer before breakthrough can occur which is similar to the saturated conditions in the seepage face. A gravel layer could not be used in HELP to approximate a seepage face because it only simulates flow in response to gravitational forces and not in response to matric potential (capillary and adsorptive) forces and cannot simulate a capillary barrier. The results of these simulations indicate that use of a unit gradient to simulate a wickless lysimeter can greatly overestimate drainage from the lysimeter. The large differences in drainage obtained using different lower boundary conditions raise the question of whether wickless lysimeters are suitable for monitoring near-surface water balance or performance of engineered covers. Unless a capillary barrier underlies the engineered cover, wickless lysimeters may overestimate water storage and, therefore underestimate drainage.

[42] The second notable outlier from the Idaho site simulations is the SHAW simulation results. SHAW generally overestimated evaporation and underestimated water storage change and drainage, particularly during WY99. The upper boundary condition for SHAW assumes that all precipitation occurs in the first hour and evaporation is simulated for the remaining 23 hr. This boundary condition is similar to that for UNSAT-H, which assumes precipitation occurs at a default rate of 1 cm/hr until all precipitation is input. An additional UNSAT-H simulation was run in which all precipitation was applied in the first hour and the results were identical to those in which precipitation was applied at a rate of 1 cm/hr. One of the differences between SHAW and the other codes is that SHAW uses the Campbell water retention function (= Brooks and Corey water retention function with zero residual water content) and the Burdine hydraulic conductivity function. Although UNSAT-H simulations incorporating similar retention and hydraulic conductivity functions as SHAW (simulation 12) were unable to replicate SHAW simulation results exactly, they demonstrate the sensitivity of water balance simulations to water retention functions because of their impact on unsaturated hydraulic conductivities. UNSAT-H simulations set up to replicate SHAW (simulation 12) differ from the UNSAT-H base case (simulation 1) in these three factors: Brooks and Corey versus van Genuchten water retention function, residual water content = 0 versus > 0, and Burdine versus Mualem hydraulic conductivity function. Additional simulations were conducted to evaluate the impacts of each of

these factors separately (Table 4). The Brooks and Corey function (simulation 14) results in much greater annual evaporation (by as much as a factor of 2) and lower drainage (by as much as a factor of 3.6) than the van Genuchten function (simulation 1). These differences are attributed to the higher unsaturated hydraulic conductivity that results from using the Brooks and Corey versus the van Genuchten water retention functions (Figure 6). As discussed earlier, increasing unsaturated hydraulic conductivity increases upward flow rather than drainage in these settings, similar to the results of *Stothoff* [1997]. Varying the residual water content from zero to the values for the different materials (0.005 to 0.035 m^3/m^3; Table 2) had a negligible impact on the simulation results (12 versus 13) because it did not vary the unsaturated hydraulic conductivity. The different hydraulic conductivity functions also impacted simulation results (13 versus 14). The Burdine function (simulation 13) resulted in lower annual evaporation (as much as a factor of 1.5) and higher drainage (as much as a factor of 2.8) relative to the Mualem function (simulation 14) because of the lower unsaturated hydraulic conductivity resulting from the Burdine function (Figure 6). This trend is in the opposite direction to the differences in evaporation and drainage between SHAW (Burdine function) and UNSAT-H (Mualem function); therefore the main factor controlling the difference between SHAW and UNSAT-H is the water retention function.

[43] As at the Texas site, simulation results from the Idaho site demonstrate the importance of the approach used to simulate the upper boundary. VS2DTI overestimates annual drainage by as much as a factor of 1.6 (Table 4 and Figure 5), which is similar to the overestimation of water storage change suggested by the Texas site data. The impact of the upper boundary condition was evaluated by conducting UNSAT-H simulations, with the upper boundary condition specified as in VS2DTI (PE = 0 on days with precipitation; simulation 15). These UNSAT-H simulations generally reproduced the results from the VS2DTI simulations, particularly in WY98. A similar approach was used to evaluate the impact of the upper boundary condition used in HYDRUS-1D. The UNSAT-H simulations that applied net precipitation or PE on precipitation days (similar to HYDRUS-1D) generally reproduced the simulation results from HDYRUS-1D, particularly during pre-WY98 (Table 4, simulation 16). These results indicate that variations in the upper boundary condition can generally explain the differences in simulation results among the codes HYDRUS-1D, UNSAT-H, and VS2DTI and emphasize the impact of the approach used to simulate the upper boundary condition on the simulation results.

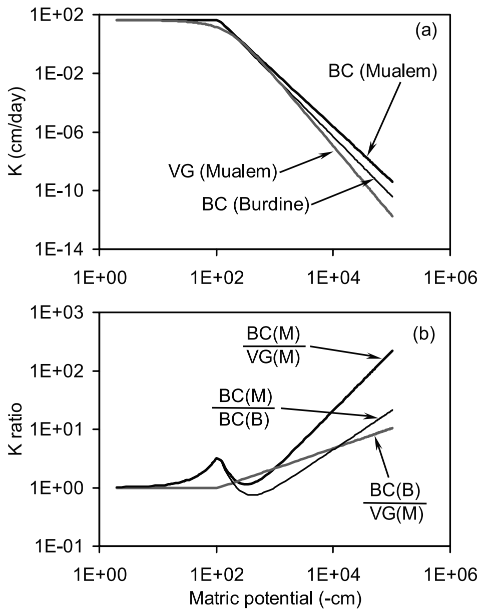

Figure 6. (a) Unsaturated hydraulic conductivities and (b) ratios of hydraulic conductivities calculated from van Genuchten (VG) and Brooks and Corey (BC) water retention functions and from Mualem (M) and Burdine (B) hydraulic conductivity functions. The various ratios are used to show differences in unsaturated hydraulic conductivity on the basis of different water retention functions (BC versus VG), different hydraulic conductivity functions (M versus B), or both.

3.4. Implications for Water Balance Modeling

[44] The results of this study have important implications for modifying existing, or developing new, water balance codes and for applying such codes to simulate water balances. Results from this study suggest that the Richards' equation-based codes are more appropriate for simulating the near-surface water balance than those based on storage routing, such as HELP. The storage-routing approach assumes that gravity is the only driving force in water movement, and the approach approximates upward flow using a depth zone for evaporation. Although the storage-routing approach accurately simulated drainage in the latter 2 years at the Idaho site, it greatly overestimated drainage during the first few months when the site was irrigated and overestimated water storage change at the Texas site. Previous studies also demonstrate that this approach generally overestimates drainage [*Berger et al.*, 1996; *Khire et al.*, 1997; *Wilson et al.*, 1999]. The greater accuracy of the Richards' equation based models, the increased computational efficiency of these codes in recent years, recent advances in computer technology, and the availability of online hydraulic parameter data make the use of Richards' equation based codes more feasible.

[45] This study demonstrated the difficulties of simulating infiltration-excess runoff because of high intensity precipitation and irrigation inputs and uncertainties in hydraulic conductivities. The results suggest that it may be infeasible to represent actual precipitation intensity and to measure hydraulic conductivity accurately enough to reproduce measured runoff. An alternative approach may be to calibrate the model to simulate runoff by varying the hydraulic conductivity of the shallow soils. Use of daily precipitation input had a large impact on partitioning of water between evaporation, water storage, and drainage because of the different approaches used by the various codes for simulating the upper boundary condition. Many previous studies have used daily precipitation input to predict near-surface water balance [*Fayer and Gee*, 1992; *Rockhold et al.*, 1995; *Kearns and Hendrickx*, 1998] and some studies have used monthly precipitation input [*Wilson et al.*, 1999]. While some codes (SoilCover, SWIM) simulate evaporation as a sink, allowing evaporation and infiltration to occur at the same time, many codes simulate these processes separately. Setting PE to zero

on rain days underestimates evaporation (VS2DTI), whereas subtracting PE from precipitation and applying net precipitation or net PE overestimates evaporation (HYDRUS-1D) (Tables 3 and 4). Applying precipitation at a specified rate and allowing evaporation to occur during the remainder of the day seemed to approximate hourly precipitation data best as shown by results from the UNSAT-H simulations of the Texas data (Table 3). Therefore researchers who use daily precipitation as input should understand how the code distributes precipitation and PE and should assess the impact of daily data by comparing simulation results with those based on hourly or shorter precipitation input, if possible. Previous studies by *Stothoff* [1997] noted that use of daily precipitation input underestimated infiltration by as much as a factor of 3, relative to hourly precipitation input using the BREATH code (evaporation simulated as a sink, no measured runoff) because spreading precipitation input throughout the day allowed more evaporation to occur. Schemes to disaggregate daily precipitation to smaller time steps have been developed for select locations [*Egbuniwe*, 1975; *Econopouly et al.*, 1990; *Socolofsky et al.*, 2001], but parameters need to be developed for other regions. Such disaggregation could help simulation of water partitioning more accurately among the various water balance components.

[46] Although conducting sensitivity analysis to hydraulic parameters was not the primary objective of this study, some of the simulation results demonstrated sensitivity to hydraulic parameters. Model input parameters for the Idaho site were based on calibration using the UNSAT-H code with van Genuchten water retention functions and Mualem hydraulic conductivity functions; therefore codes that use similar functions were expected to calculate water balances that better match measured values than the other codes. Results from simulations of the Idaho site in this study showed that use of the Campbell water retention function (Brooks and Corey with zero residual water content, simulation 12) and the Burdine hydraulic conductivity function (SHAW, simulation 3) resulted in increased evaporation and reduced drainage relative to the van Genuchten water retention and Mualem hydraulic conductivity functions (UNSAT-H, simulation 1). The main difference between the codes resulted from different water retention functions. The Brooks and Corey water retention function resulted in much higher unsaturated hydraulic conductivity relative to the van Genuchten function (Figure 6), which translates into higher evaporation and lower drainage (Table 4).

[47] Simulation results from this study showed much greater sensitivity to water retention and hydraulic conductivity functions than previously demonstrated. Previous studies show that the impact of using different hydraulic conductivity functions (Mualem versus Burdine) in a sandy soil resulted in = 10% variation in the simulated water balance [*Fayer and Gee*, 1992]. The Fayer and Gee study also showed that reducing residual-water content from 0.05 m^3/m^3 to 0.00 decreased drainage by 27%. *Andraski and Jacobson* [2000] showed that use of different water retention functions (*van Genuchten* [1980] and *Rossi and Nimmo* [1994]) resulted in differences in simulated water potentials in the shallowest nodes but had little impact on the simulated water balance components.

[48] Previous sensitivity analyses by *Fayer and Gee* [1992] indicated that inclusion of isothermal vapor flow was significant (reduced simulated drainage by as much as 65%). Vapor flow was not simulated using any of the codes in this study except SoilCover. Simulations conducted with and without isothermal vapor flow using UNSAT-H were similar (simulations 1 and 12, Table 3; 1, 17, Table 4), indicating that isothermal vapor flow was not important for simulating the water balance of these sites. *Fayer et al.* [1992] indicated that hysteresis was critical in simulating drainage in a capillary barrier engineered cover. Most codes evaluated in this study do not simulate hysteresis, with the exception of HYDRUS-1D and UNSAT-H; therefore the impact of hysteresis could not be evaluated using all codes. Additional simulations were conducted with HYDRUS-1D and UNSAT-H to evaluate hysteresis. Water retention functions for the wetting curves were estimated by assuming that the van Genuchten α parameter for wetting is $2\times$ that for drying and allowing 10% for entrapped air during rewetting. Results from these simulations indicate that hysteresis has a negligible impact on the simulation results for the Texas site (simulations 9 and 13; Table 3). Hysteresis had little impact on the HYDRUS-1D simulations of the Idaho site (simulation 10; Table 4); however, hysteresis resulted in higher drainage, particularly in pre WY 98 when UNSAT-H was used (simulation 18; Table 4). This result is consistent with the results from *Fayer et al.* [1992].

[49] Use of the appropriate lower boundary condition is important in accurately simulating water balance of lysimeters. *Flury et al.* [1999] also point out the importance of the lower boundary condition on solute transport in wickless lysimeters because the soil has to be saturated before drainage can occur. Wickless lysimeters are most accurately represented by a seepage face; however, some codes do not include a seepage-face option. Many previous modeling studies of engineered covers monitored by wickless lysimeters used a unit gradient lower boundary condition [*Fayer and Gee*, 1992; *Khire et al.*, 1997]. Results from this study indicate that the unit-gradient lower boundary condition could greatly overestimate drainage from a wickless lysimeter that does not contain an overlying gravel layer (Table 4). Simulations of the Idaho site demonstrate that models using Richards' equation can approximate a seepage face by simulating a thin layer of gravel with a unit-gradient lower boundary condition. Because many studies try to accurately simulate drainage from lysimeters on the order of millimeters, specifying the most appropriate boundary condition is critical. The impact of the seepage face versus unit gradient lower boundary condition only applies to wickless lysimeters, and not the natural system. Unit gradient lower boundary conditions should work well for the natural system.

[50] The ultimate goal of most water balance modeling studies is to predict drainage. The drainage term is generally much smaller than many of the other terms in the water budget in semiarid regions, particularly precipitation and evaporation. In contrast, drainage is generally much higher in humid regions (e.g., 6 to 51 cm; 1985–1994, Coshocton, Ohio) and more easily simulated [*Wilson et al.*, 1999]. In addition, the drainage term generally accumulates errors in all other terms in the water budget. Therefore it is important to consider the uncertainty in simulating various water balance components, such as runoff, evaporation, and water storage change, when estimating uncertainty in drainage estimates.

[51] In addition to providing insight on important features of codes for simulating near-surface water balance, the intercode comparison also provided information on the computational efficiency of various codes. Most codes tested in this study required less than 1 min to run a 1-year simulation; however, longer times were required by SHAW (~10 min), SoilCover (~1 hr), and VS2DTI (8 min) on a personal computer (Pentium 4, 1.4 GHz CPU, 256 MB RAM). A variety of factors impact the computational efficiency of codes. Internal tabulation of water retention functions can result in reduced computational times by as much as a factor of 3 because table lookup (HYDRUS-1D, SWIM) is much faster than calculating results from an analytical function.

[52] Code comparisons should be conducted regularly so that more can be learned about code performance and important factors in simulating the near-surface water balance can be assessed. Because source codes are generally not provided and only executable versions of codes are generally available, it is often difficult to determine how a code simulates a particular process. The proliferation of codes and the inability of user manuals to address all potential applications increase the need for code comparison studies. To facilitate future model testing and code-comparison studies, a database should be developed of water balance monitoring data for different climate and soil conditions.

4. Conclusions

[53] This study demonstrates the variability in simulated water balance components using a variety of different codes (HELP, HYDRUS-1D, SHAW, SoilCover, SWIM, UNSAT-H, and VS2DTI) on the basis of field monitored data from engineered covers at warm (Texas) and cold desert (Idaho) sites and provides some indication of the expected reliability of simulated water balances. Simulation results from most codes were similar and generally reproduced measured water balance components at the Texas and Idaho sites. Both sites consisted of unvegetated loam soil.

[54] Simulation of infiltration-excess runoff was a problem for all codes, underscoring the difficulties of representing actual precipitation intensities and of measuring hydraulic conductivity of surficial sediments (as shown by the data from Texas). Drainage is the most critical parameter for evaluation of contaminant transport, engineered covers for waste containment, and groundwater recharge. Drainage could be estimated to within ~±64% by most codes. Outliers for the various simulations could be attributed to the following factors: (1) the modeling approach, i.e., water storage routing versus Richards' equation, (2) the upper boundary condition during precipitation and time discretization of precipitation input, (3) water retention functions (i.e., van Genuchten versus Brooks and Corey), and (4) the lower boundary condition (i.e., unit gradient versus seepage face).

[55] The water storage routing approach does not seem to adequately represent the flow system in semiarid regions. By assuming that gravity is the only driving force and ignoring matric-potential gradients that are often upward in semiarid regions, downward flow is generally overestimated and ultimately results in overestimation of drainage.

[56] The approach used to simulate the upper boundary condition during precipitation is crucial when precipitation is input on a daily or larger time step. Setting PE to zero on rain days (VS2DTI) greatly underestimated evaporation and overestimated drainage. Subtracting PE from precipitation and applying net precipitation or net PE on a daily basis (HYDRUS-1D) had a much lesser impact on simulation results. The best approach is to disaggregate daily precipitation and apply it at a specified rate, allowing PE to occur throughout the rest of the day, as shown by the UNSAT-H simulations.

[57] The impact of water retention functions was demonstrated at the Idaho site, where increased unsaturated hydraulic conductivity based on the Brooks and Corey functions relative to the van Genuchten functions resulted in overestimation of evaporation and underestimation of drainage. In contrast, the input value of residual water content (0 for Campbell function versus > 0 for Brooks and Corey) had little impact on simulation results.

[58] The most appropriate lower boundary condition for simulating wickless lysimeters is a seepage face. Simulations using HYDRUS-1D demonstrated that this boundary condition could be approximated by simulating a thin bottom layer of gravel with a unit gradient boundary condition in codes that use Richards' equation but do not include a seepage face option. However, use of a unit-gradient lower boundary condition alone greatly overestimated drainage. This study demonstrates the usefulness of conducting intercode comparisons to evaluate the reliability of water balance simulations and to determine important factors controlling water balance simulation results.

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