CAPILLARY BARRIERS: DESIGN VARIABLES AND WATER BALANCE

Semiarid and arid regions have traditionally been considered ideal locations for waste disposal because of their lack of precipitation. Recent studies have shown, however, that recharge in these regions can be significant. Thus, even in semiarid and arid regions, waste can be a serious threat to groundwater and must be placed in engineered waste containment systems.

Earthen covers employing capillary barriers can be effective in minimizing percolation into underlying waste or contaminated soil in semiarid and arid regions. In its basic form, a capillary barrier consists of a finer-grained layer overlaying a coarser-grained layer. Theoretically, the contrast in unsaturated hydraulic properties between the finer and coarser-grained layers restricts movement of water across the interface between the layers. In this study simulations were performed for covers located in four different cities having different semiarid and arid climates; Denver, Phoenix, Reno and Wenatchee using the one-dimensional unsaturated flow model UNSAT-H. The more common model, HELP, was not used because HELP assumes that flow occurs under a unit downward hydraulic gradient, and thus cannot simulate the hydrological processes that govern the behavior of capillary barriers.

The results indicate two main points. First, the thickness and hydraulic properties of the surface layer and coarse layer significantly affect the water balance of the capillary barriers. As expected, increasing the thickness or reducing the saturated hydraulic conductivity of the finer-grained surface layer reduces percolation. Unsaturated hydraulic properties of the coarser layer also affect the water balance while the thickness of the coarse layer is less important. Thus, it must be determined whether adequate quantities of borrow material with the desired properties exist near the site.

Second, adequate surface layer thickness should be checked using suitable long-term simulations performed with meteorological data representing the most stressful conditions that the cover is likely to endure. Greater soil water storage capacity is required at sites where the season with precipitation does not coincide with the season having highest evapotransporation. Snowmelt in the spring can have a significant impact.

Reference

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Capillary Barriers: Design Variables and Water Balance

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Abstract: Water balance simulations were conducted with the unsaturated flow model UNSAT-H to assess how layer thicknesses, unsaturated hydraulic properties, and climate affect the performance of capillary barriers. Simulations were conducted for four locations in semiarid and arid climates. Hydraulic properties of four finer-grained and two coarser-grained soils were selected to study how saturated and unsaturated hydraulic properties affect the water balance. Results of the simulations indicate that thickness and hydraulic properties of the surface layer significantly affect the water balance of capillary barriers. As expected, increasing the thickness or reducing the saturated hydraulic conductivity of the finer-grained surface layer reduces percolation. Unsaturated hydraulic properties of the coarser layer also affect the water balance, including the storage capacity of the surface layer as well as the onset and amount of percolation from the cover. Thickness of the coarser layer has a much smaller impact on the water balance. Climate also affects the water balance. Greater soil water storage capacity is required at sites where the season with more frequent and less intense precipitation does not coincide with the season having highest evapotranspiration.

INTRODUCTION

Semiarid and arid regions have traditionally been considered ideal locations for waste disposal because of their lack of precipitation (Nativ 1991). Recent studies have shown, however, that recharge in these regions can be significant (Gee and Hillel 1988; Allison et al. 1994; Fayer et al. 1996). For example, Gee et al. (1994) reviewed the water balance of three desert sites and showed that recharge can be as much as 60% of precipitation. Thus, even in semiarid and arid regions, wastes can be a serious threat to ground water and must be placed in engineered waste containment systems.

Earthen covers employing capillary barriers can be effective in minimizing percolation into underlying waste or contaminated soil in semiarid and arid regions (Nyhan et al. 1990, 1997; Hakonson et al. 1994; Benson and Khire 1995; Stormont 1997; Ward and Gee 1997; Dwyer 1998). They can be constructed in various forms, ranging from a simple design consisting of two layers of contrasting particle size to more complex designs that include multiple layers of finer-grained and coarser-grained soils (e.g. Stormont 1995a). In its basic form, however, a capillary barrier consists of a finer-grained layer overlying a coarser-grained layer. The contrast in unsaturated hydraulic properties between the finer- and coarser-grained layers restricts movement of water across the interface between the layers.

The primary purpose of this paper is to assist designers by illustrating how several design variables affect the water balance of capillary barriers. Another purpose is to provide a method for selecting the layer thicknesses. In particular, the influence of thickness of the surface and underlying layers, saturated and unsaturated hydraulic properties of the soils, and climate are illustrated using results of water balance simulations conducted with the one-dimensional unsaturated flow model UNSAT-H (Fayer and Jones 1990). Simulations were performed for covers located in four different cities having different semiarid or arid climates. The more common model, Hydrologic Evaluation of Landfill Performance (HELP) (Schroeder et al. 1994), was not used because HELP assumes that flow occurs under a unit downward hydraulic gradient, and thus cannot simulate the hydrological processes that govern the behavior of capillary barriers (Fayer and Gee 1997; Khire et al. 1997, 1999; Wilson et al. 1999).

This paper does not address all design issues related to capillary barriers. For example, meteorological parameters used for the simulations in this paper may not necessarily be representative of long-term climatic conditions at these locations. In addition, slope, erosion, biota intrusion, desiccation cracking, and filter criteria are not considered. The reader is referred to other publications that address such issues (Ross 1990; Steinhuis et al. 1991; Morel-Seytoux 1995; Morel-Seytoux and Meyer 1995; Stormont 1995b, 1997; Albrecht 1996; Aubertin et al. 1997; Morris and Stormont 1997; Benson et al. 1998; Hakonson 1999).

WATER BALANCE MODELING

Water Storage in Capillary Barriers

The contrast in unsaturated hydraulic properties between the finer- and coarser-grained layers in a capillary barrier forms the hydraulic impedance that limits downward water movement. Data in Stormont and Anderson (1999) show that significant amounts of water will enter the coarser soil only when the matric suction at the surface of the coarser layer decreases to the value near the bend in the soil water characteristic curve near residual water content [noted as B_c in Fig. 1(a)]. The corresponding matric suction is ψ_B and the volumetric water content in the coarser layer is θ_{BC}.

Continuity in pore water pressure requires that the matric suction in the two layers must be equal at their interface. As a result, the matric suction in the finer layer at the interface must equal ψ_B before water will enter the coarser layer. The water content in the finer layer at ψ_B is noted as θ_{BF} in Fig. 1(b), and it corresponds to point B_F on the soil water characteristic curve for the finer layer. Even when B_F is reached, water still enters the coarser-grained layer slowly because the hydraulic conductivity of the coarser-grained layer is still low at B_C [Fig. 1(b)].

The hydraulic impedance provided by the capillary interface causes the finer surface layer to act as a buffer that stores infiltrated water as soil water storage (S_w) until θ_{BF} is reached. Much of the stored water in the finer-grained layer is later released back to the atmosphere via evapotranspiration (ET) (Benson and Khire 1995; Bews et al. 1997; Ward and Gee

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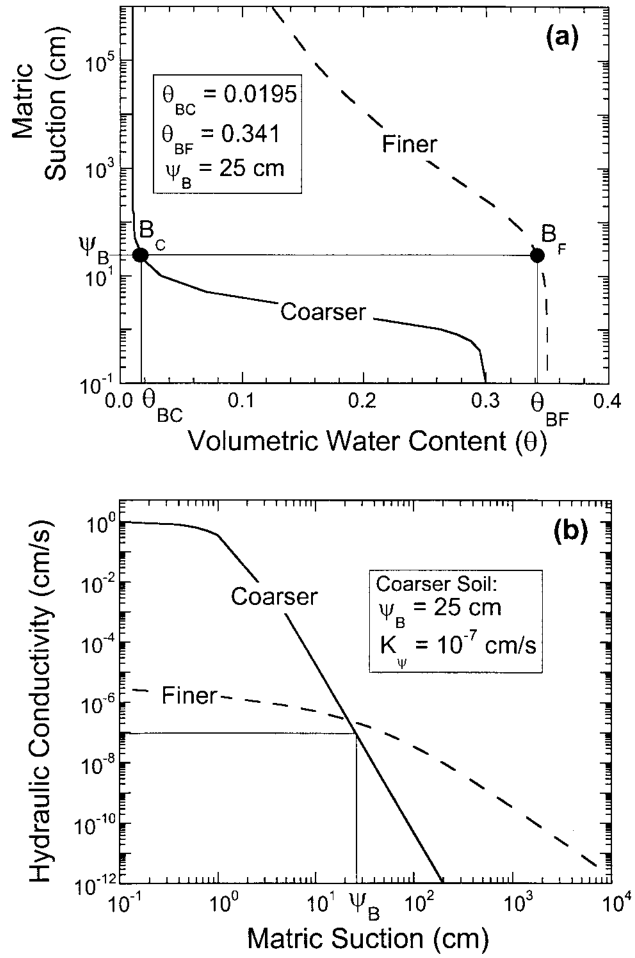

FIG. 1. (a) Soil Water Characteristic Curves and (b) Unsaturated Hydraulic Conductivity Functions for Finer- and Coarser-Grained Soils

1997). Alternatively, the water may be diverted via lateral drainage (L) in capillary barriers employing drainage layers (Stormont 1995a; Nyhan et al. 1997; Morris and Stormont 1999). If the storage capacity of the finer-grained layer is adequate, and sufficient evapotranspiration or lateral drainage exists to remove the stored water, percolation (P) into the underlying waste can be reduced to a small quantity (Ward and Gee 1997).

When relying only on soil water storage to design a two-layer capillary barrier, layer thicknesses and unsaturated hydraulic properties are manipulated to obtain a design that has adequate soil water storage capacity so that an acceptable percolation rate is obtained. In this study, UNSAT-H was used to assess how these design variables affect the water balance of capillary barriers. UNSAT-H was selected because comparisons between predictions made with UNSAT-H and field water balance data have been favorable (Fayer et al. 1992; Khire et al. 1997, 1999; Wilson et al. 1999). In addition, the program has rigorous constitutive algorithms for simulating unsaturated flow, evaporation, and transpiration. A disadvantage of using UNSAT-H is that it ignores lateral drainage. In cases where lateral drainage is significant, a one-dimensional model like UNSAT-H will overpredict percolation (Morris and Stormont 1999). However, no multidimensional currently exists that is field verified, contains rigorous constitutive algorithms for handling the soil-plant-atmosphere continuum, and is computationally efficient enough for longer-term simulations (one or more years) with realistic meteorological data (Khire et al. 1999; Wilson et al. 1999).

Background on UNSAT-H

A detailed description of UNSAT-H can be found in Fayer and Jones (1990); an overview of the model is presented in Khire et al. (1997, 1999). In brief, UNSAT-H is a one-dimensional, finite-difference computer program for simulating water and heat flow in unsaturated soil that solves a modified-Richards' partial differential equation for liquid and vapor water flow. The modified-Richards' equation that is solved is

$$\frac{\partial\theta}{\partial\psi}\frac{\partial\psi}{\partial t} = -\frac{\partial}{\partial z}\left[K_T\frac{\partial\psi}{\partial z} + K_\psi + q_{vT}\right] - S(z, t) \quad (1)$$

where ψ = matric suction; t = time; z = vertical coordinate; K_ψ = unsaturated hydraulic conductivity; $K_T = K_\psi + K_{v\psi}$, where $K_{v\psi}$ is isothermal vapor conductivity; q_{vT} = thermal vapor flux density; and $S(z, t)$ is a sink term representing water uptake by vegetation. The thermal vapor flux density (q_{vT}) is computed using Fick's law of vapor diffusion. Hysteresis in unsaturated hydraulic properties is not considered.

The sink term, S, in (1) is for water uptake by roots. Water uptake is simulated by applying the transpiration demand amongst nodes in the root zone in proportion to the root density profile. Potential transpiration demand is determined by separating potential evapotranspiration (ET_p) into potential evaporation (E_p) and potential transpiration (T_p) as a function of leaf area index (LAI) via the formulation by Ritchie and Burnett (1971). Potential evapotranspiration is computed using a modified form of Penman's equation employing daily minimum and maximum air temperatures, net solar radiation, relative humidity, and daily wind speed. The potential transpiration demand that is applied equals T_p multiplied by the fraction of ground cover. Actual transpiration demand at each node is set at a fraction of the applied potential transpiration demand depending on the water status in the root zone (Fayer and Jones 1990). Actual transpiration is set to zero if anoxic conditions exist (i.e., suction is less than the anaerobiosis point ψ_A, which is near saturation) or if the suction exceeds the wilting point (ψ_{WP}). For suctions between the wilting point and the limiting point (ψ_D), the applied transpiration demand is assumed to vary linearly between zero and the potential transpiration. Typical values (Feddes et al. 1978; Hillel 1980) were used for each of these limiting points for all simulations in this study: ψ_{WP} was 15,000 cm; ψ_D was 3,000 cm; and ψ_A was 10 cm.

When simulating covers, a flux boundary is applied to (1) at the upper surface (Fayer et al. 1992; Khire et al. 1997, 1999; Wilson et al. 1999). The flux corresponds to infiltration or evaporation, the latter being computed using Fick's law. During precipitation events, the upper flux boundary condition equals the infiltration rate. Precipitation is separated into infiltration and runoff, with the fraction that infiltrates equaling the infiltration capacity of the soil profile (Fayer et al. 1992; Khire et al. 1997). The extra water is shed as runoff, which prevents ponding on the surface. UNSAT-H does not consider absorption and interception of water by the plant canopy or delayed infiltration due to residence time on the slope. Despite these limitations, Khire et al. (1997) show that UNSAT-H predicts runoff and infiltration with reasonable accuracy.

The lower boundary is normally specified as a unit gradient when simulating earthen covers (Fayer et al. 1992; Khire et al. 1999; Wilson et al. 1999). Flux from the lower boundary is then percolation. Soil water storage is computed by integrating the water content profile.

Previous Applications of UNSAT-H

Fayer et al. (1992) and Fayer and Gee (1997) compared predictions of matric suction, soil water storage, and percolation from UNSAT-H with field data from eight unvegetated lysimeters located in Hanford, Washington. The lysimeters contained capillary barriers consisting of a 150 cm thick surface layer of silt loam overlying 5–10 cm thick layers of sand and gravel (Gee et al. 1993). The lysimeters were subjected to natural precipitation and ''breakthrough'' (inundation) precipitation. Water contents and percolation from the lysimeters were continuously monitored. The lysimeters were not sloped and consequently did not generate any runoff.

Percolation predicted by UNSAT-H equaled the measured percolation during most of the comparison period, but percolation was underpredicted by 1.5 cm during a heavy snowmelt. Predicted soil water storage was generally within 1 cm of measured soil water storage, and predicted suctions typically were within 0.5 m of measured suctions. Evaporation generally was overpredicted in winter and underpredicted during the remainder of the year, but the magnitude of the error was not reported. Fayer et al. (1992) also observed that the model is sensitive to the hydraulic conductivity function and the existence of snow cover. Fayer and Gee (1997) report that the accuracy of the predictions improved when hysteresis was included.

Khire et al. (1997) used UNSAT-H to simulate the water balance of earthen final cover test sections designed as resistive barriers (i.e., covers where the primary resistance to flow is a layer of finer-grained soil with low saturated hydraulic conductivity). One test section was located in a humid climate, and the other was in a semiarid climate. Both test sections had on-site monitoring systems to measure meteorological and water balance data. Benson et al. (1994) and Khire et al. (1994) describe the test sections in detail. Field measured unsaturated hydraulic properties were used as input. Khire et al. (1997) report that UNSAT-H predicted percolation with 0.2 cm of the actual percolation at the semiarid site and within 3 cm at the humid site over a three-year period. For both test sections, soil water storage predicted by UNSAT-H was generally within 2 cm of the measured soil water storage. Evapotranspiration was generally predicted within 5 cm at the semiarid site and 2 cm at the humid site.

Khire et al. (1999) describe a comparison between predictions made with UNSAT-H and the field performance of a capillary barrier test section consisting of a 15 cm layer of silt overlying a 75 cm thick layer of sand. A detailed description of the test section is in Benson et al. (1994) and Khire et al. (1994). The comparison shows that UNSAT-H predicted the water balance of a capillary barrier conservatively, with runoff typically being underpredicted (within 10 cm) and percolation being overpredicted (within 5 cm). Most of the overprediction of percolation was attributed to the underprediction of runoff. Soil water storage was typically predicted within 3 cm of measured soil water storage.

Wilson et al. (1999) used UNSAT-H, HELP, and HYDRUS-2D (Simunek et al. 1996) to predict percolation from unvegetated lysimeters at the Hanford site. They found that UNSAT-H predicted percolation within 0.25 cm of the actual percolation. HYDRUS-2D performed comparably, predicting percolation within 0.5 cm of measured value. In contrast, HELP overestimated the measured percolation by 6.7 cm.

PARAMETRIC STUDY

The parametric study described herein consisted of simulating the water balance of basic capillary barriers (finer-grained surface layer overlying a coarser-grained layer) without lateral drainage for four locations in the United States having different climates, ranging from semi-arid to arid. The location, thickness of surface and underlying layers, and hydraulic properties were varied to assess how they affect the water balance, especially percolation.

In most cases, one-year simulations were performed with UNSAT-H. A ''wet'' year was selected for each site. The annual precipitation for the ''wet'' exceeded the normal annual precipitation. The wet years that were used do not necessarily represent the most critical condition for the capillary barriers simulated. The critical condition can only be identified by conducting long-term (multiple year) simulations using meteorological data representative of the most stressful conditions to which a cover is likely to be exposed. Although long-term simulations were not possible in most cases because of the computing time required, a limited number of long-term simulations were conducted to illustrate their importance during design.

Locations

The four locations selected for this study are Wenatchee, Washington; Denver, Colorado; Phoenix, Arizona; and Reno, Nevada. All of these locations are in the western United States. The field tests described by Khire et al. (1997, 1999) were located at Wenatchee, Washington. Summary data describing the meteorology at each site are listed in Table 1. The climate at each location is distinctly different. The major differences are distribution and quantity of precipitation, type of precipitation (i.e., rain or rain and snow), air temperature, relative humidity, and solar radiation.

At Wenatchee and Reno, precipitation occurs more frequently and with less intensity in winter relative to spring, summer, and fall. Both Wenatchee and Reno receive snow, but at Reno the quantity of snow is much smaller and the snow pack does not persist. Reno is also warmer and receives greater solar radiation than Wenatchee (Khire 1995). Most of the precipitation at Phoenix occurs in fall and winter, although storms of high intensity occur in summer and fall. Snow rarely occurs at Phoenix, and it has the highest air temperature, greatest solar radiation, and largest potential evapotranspiration of the four locations. In Denver, most of the precipitation occurs during spring and summer from storms of high intensity and short duration. Snow at Denver occurs primarily in late winter and early spring and does not persist. The air temperature at Denver is similar to Reno, but Reno receives more solar radiation.

A one-year data set of hourly meteorological data was obtained form the National Weather Service for the ''wet year'' at each site. The data are summarized in Table 1 and the precipitation records are shown in Fig. 2. During the simulation years, Wenatchee and Denver received significant amounts of snow (170 cm and 90 cm, respectively), whereas Reno and Phoenix did not receive snow. Snow was input to UNSAT-H

TABLE 1. Data for Simulation Locations

Location (1)	Elevation (m) (2)	Latitude (3)	Normal annual precipitation (cm) (4)	Simulation year (5)	Simulation year precipitation (cm) (6)	Quarterly relative humidity (%) (7)	Growing season (Julian days) (8)	Simulation year potential evapotranspiration (cm) (9)
Wenatchee	383	47.4°N	20	1992–1993	27	47/53/78/73	91–261	97
Denver	1,626	39.77°N	39	1987	49	56/46/43/56	74–304	176
Phoenix	337	33.26°N	20	1993	32	54/19/26/36	21–244	220
Reno	1,341	39.30°N	19	1986	22	57/38/35/51	105–259	194

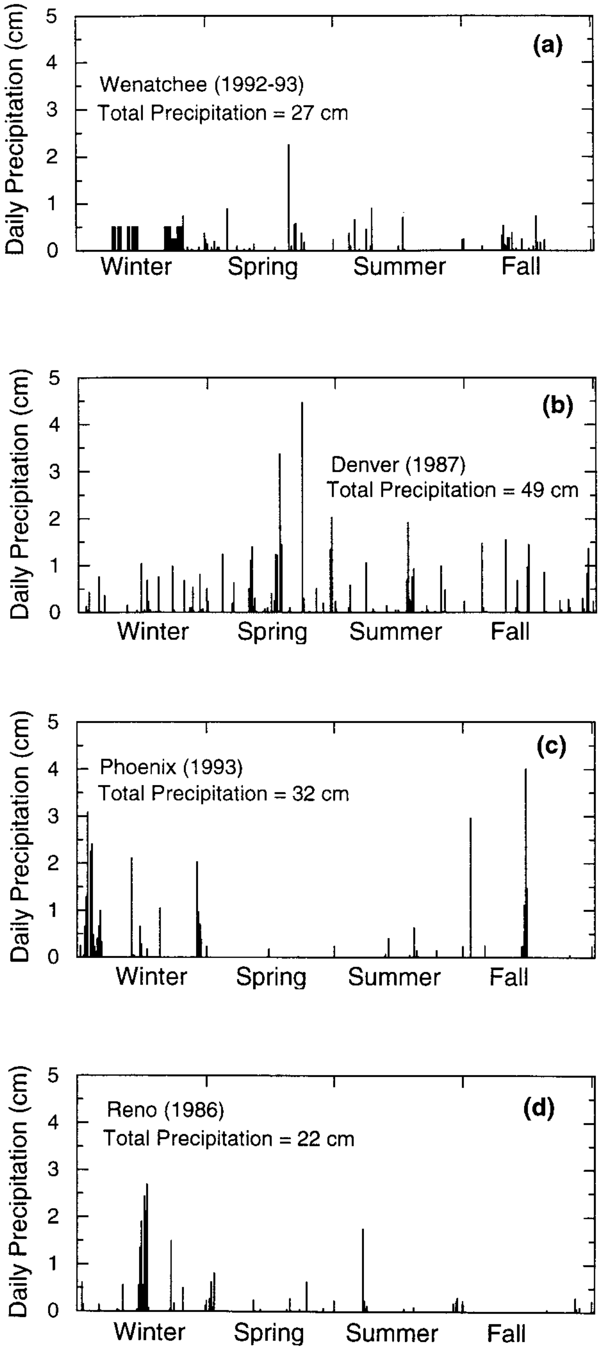

FIG. 2. Precipitation Records for Wet Years; (a) Wenatchee; (b) Denver; (c) Phoenix; (d) Reno

as rain using the snowmelt algorithm by Kustas et al. (1994). Subfreezing air temperatures occurred at Wenatchee, Reno, and Denver, but not Phoenix, during the simulation years. Complete records of the meteorological data for the simulation years are in Khire (1995).

Soil Properties

Properties of four finer-grained soils and two coarser-grained soils were used in the simulations. The soil water characteristic curves (SWCCs) and the hydraulic conductivity curves [Figs. 3(a and b), respectively] are described in terms of the van Genuchten [(2*a*)] and van Genuchten-Mualem [(2*b*)] functions (Mualem 1976; van Genuchten 1980):

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left\{\frac{1}{1 + (\alpha\psi)^n}\right\}^m \tag{2a}$$

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

In (2), θ_s = water content at saturation; θ_r = residual water content; α, n, and m ($m = 1 - n^{-1}$) are fitting parameters; K_s = saturated hydraulic conductivity; and K_ψ = hydraulic conductivity at matric suction ψ. Table 2 contains K_s, θ_s, θ_r, α, and n for each soil along with the sources containing the unsaturated hydraulic property data.

These soils cover a wide range of water retention properties and saturated and unsaturated hydraulic conductivities. The finer-grained soils, with their Unified Soil Classification (USC), are a silty sand (SM), a nonplastic sandy silt (SM-ML), low plasticity silt (ML), and lean clay (CL). The coarser-grained soils are uniformly graded medium sand (SP) and uniformly graded pea gravel (GP). These soils are referred to herein by their USC. As shown in Fig. 3(b), the finer-grained soils are less permeable than the coarser-grained soils when the matric suctions are low (<10 cm) and the soils are wet, whereas the coarser-grained soils are less permeable than the finer-grained soils when the matric suctions are higher (>1,000 cm) and the soils are drier. Moreover, the coarser-grained soils typically have lower air entry suction [suction at the knee of the SWCC near saturation, as defined by Bouwer (1966)] and a relatively flat region in the SWCC between θ_s and θ_r.

All of the curves shown in Fig. 3 were obtained by desorption. In the field, both desorption and sorption are important because cover soils undergo wetting and drying, and both processes affect the ingress and egress of water from a cover (Fayer and Gee 1997; Khire et al. 1997, 1999). During design, both wetting and drying curves should be considered if pos-

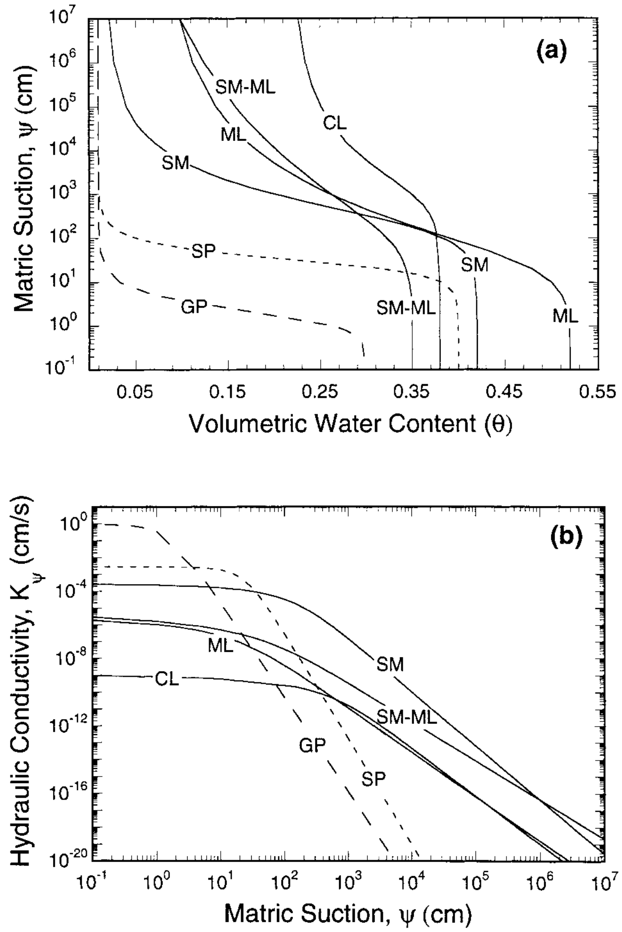

FIG. 3. (a) Soil Water Characteristic Curves and (b) Unsaturated Hydraulic Conductivity Functions for Soils Used in Simulations

TABLE 2. Parameters for Soil Water Characteristic Curves and Unsaturated Hydraulic Conductivity Functions

USCS classification (1)	Particle size (2)	K_s (cm/s) (3)	θ_s (4)	θ_r (5)	α (1/cm) (6)	n (7)	Source (8)
SM	Finer	2.7×10^{-4}	0.42	0.02	0.005	1.48	Khire et al. (1994)
SM-ML	Finer	9.0×10^{-6}	0.35	0.02	0.012	1.123	CEC (1997)
ML	Finer	3.2×10^{-6}	0.52	0.08	0.035	1.25	Khire et al. (1994)
CL	Finer	1.0×10^{-9}	0.38	0.22	0.00124	1.34	Tinjum et al. (1997)
SP	Coarser	2.9×10^{-3}	0.40	0.01	0.038	2.69	Khire et al. (1994)
GP	Coarser	1.0	0.30	0.01	0.574	2.44	CEC (1997)

sible. The parametric studies described in this paper were conducted to illustrate how various design factors affect the behavior of capillary barriers. In this context, the relative difference between the curves for the coarser and finer-grained layers are more important than the differences in a particular curve attributed to sorption versus desorption.

Vegetation

Cheatgrass was assumed to be the vegetation on the covers. Root length density functions for cheatgrass reported by Fayer and Walters (1995) were used along with a rooting depth of 15 cm. Fayer and Walthers (1995) used much deeper rooting depths for these plants. The 15-cm rooting depth was used so that predictions of percolation would be conservative. Results reported by Fayer et al. (1996) show that deeper-rooted vegetation is more effective in removing water and reducing percolation.

Growing seasons for grasses reported by Winkler (1999) were used at each location. A percent bare area (PBA) of 75% was input for all simulations to represent an unmanaged ground cover. The temporal distribution of leaf area index (LAI) reported in Fayer and Walters (1995) was used after scaling the distribution to the length of the growing season at each location. A peak LAI of 1 was used. These LAI are characteristic of many grasses in the semiarid and arid portions of the United States (Winkler 1999). The distribution of LAI and the PBA were not varied parametrically. Winkler (1999) shows that these parameters generally have a less pronounced effect on the water balance provided vegetation exists on the cover; i.e., the presence of vegetation has a much larger influence on the water balance than detailed phenological characteristics of the vegetation. A soil surface albedo of 0.2 was used for all simulations.

Grid Characteristics, Initial and Boundary Conditions, and Control Parameters

A finite-difference grid similar to that described in Khire et al. (1999) was used to model the two-layer system. The grid consisted of at least 64 nodes. The nodal spacing was 0.1 cm at the boundaries and was expanded to as much as 4.0 cm using a maximum expansion factor of 1.5. Waste beneath the cover was not included in the model. Excluding the waste should have minimal effect on the predictions, since water retention curves for waste are similar to those of coarse-grained soils (Benson and Wang 1998), i.e., similar to a lower layer in a capillary barrier.

A maximum time step of 0.25 h and a minimum time step of 10^{-4} h were used for the simulations. Nodal spacing was selected to minimize mass balance errors while maintaining reasonable CPU times. The mass balance criterion was selected so that error in water content at any node did not exceed 10^{-4}. This mass balance criterion resulted in mass balance errors less than 0.1%. Simulations described in this paper required 1–5 days of computation time on a Hewlett-Packard 9000 C110 workstation equipped with 128 MB RAM.

The initial head assigned to each node in the finite-difference grid corresponded to the wilting point (15,000 cm). The wilting point was chosen because all available water is typically removed by vegetation by the end of the growing season in semiarid regions (Khire et al. 1997; Nyhan et al. 1997; Ward and Gee 1997). In several simulations, however, the initial suction was varied around the wilting point (within 500 kPa) to assess how varying the initial water content affected the water balance predictions. These changes had a small impact (<1%) on runoff, evaporation, and percolation, since the soil was ''dry'' regardless of which value was used for the initial suction.

A flux boundary condition corresponding to the infiltration rate or evaporation rate was applied at the surface. Percolation was defined a flux from the base of the cover. The boundary condition at the base of the cover was a unit gradient, which results in conservative predictions of percolation (Khire et al. 1999). For example, in some cases the hydraulic gradient at the base of a cover may be directed upward as ground water is discharged to the atmosphere (RMA 1997). Khire et al. (1997, 1999) used similar boundary conditions when simulating resistive and capillary barrier test sections, as did Fayer et al. (1992) and Wilson et al. (1999) when simulating the water balance of drainage lysimeters at the Hanford site. Simulations were conducted to assess whether depth to the lower boundary had a significant effect on the results by increasing the thickness of the lower layer of the capillary barrier. Results of these tests showed that depth to the lower boundary had a negligible effect for the covers that were modeled.

SIMULATION RESULTS AND ANALYSIS

Climate

The significance of climate was evaluated by simulating the water balance of a capillary barrier having a 30 cm thick surface layer of silty sand (SM) and a 75 cm thick underlying layer of sand (SP) subjected to the wet years at Wenatchee, Reno, Phoenix, and Denver. The water balance predictions are shown in Fig. 4.

Percolation from the capillary barriers (i.e., flow from the base of the cover) is not directly related to the annual amount of precipitation [Figs. 2 and 4(a)]. Among the four locations, Denver has the greatest precipitation (49.2 cm) during the wet year. Nevertheless, the capillary barrier at Denver transmits the least percolation (0.1 cm). The capillary barrier at Wenatchee received an intermediate amount of precipitation (27.2 cm), but transmitted the most percolation (1.4 cm). Precipitation at Phoenix was comparable to that at Wenatchee, but percolation at Phoenix is about one-half that of Wenatchee. The capillary barrier at Reno, which received the least precipitation (21.5 cm), transmitted an intermediate amount of percolation (0.6 cm).

The differences in percolation can be interpreted by examining soil water storage [Fig. 4(b)] in the finer layer. The capillary barriers at Wenatchee, Phoenix, and Reno began transmitting percolation during winter, after a period during fall and early winter when precipitation occurred more frequently and

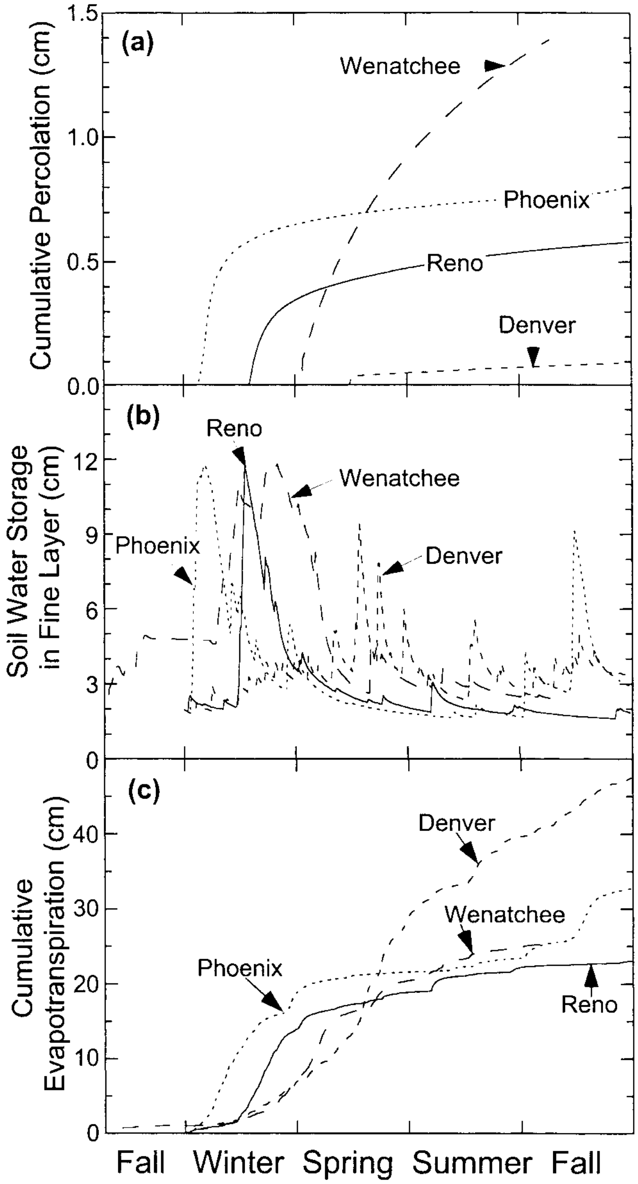

FIG. 4. (a) Cumulative Percolation; (b) Soil Water Storage; and (c) Cumulative Evapotranspiration for Wet Year Simulations in Wenatchee, Reno, Phoenix, and Denver

less intensely (Fig. 2). During the same period, potential evapotranspiration is generally lower due to lower solar radiation, lower air temperatures, and dormant vegetation. As a result of reduced precipitation intensity and lower evapotranspiration, only a portion of precipitation is shed as runoff or to the atmosphere. The remaining water accumulates in the surface layer, which is reflected as an increase in soil water storage [Fig. 4(b)]. Eventually the soil water storage capacity is exceeded (~11 cm), and percolation occurs. The same effect has been demonstrated in the field by Nyhan et al. (1990, 1997), Hakonson et al. (1994), Ward and Gee (1997), and Khire et al. (1997, 1999).

In contrast to the other locations, precipitation at Denver occurs more frequently in spring and summer, when solar radiation is higher, the air temperature is warmer, and the vegetation is active, all of which yield greater evapotranspiration [Fig. 4(c)]. Consequently, nearly all precipitation is shed as runoff or evapotranspiration, and thus water does not accumulate in the surface layer. Water that does enter the surface layer is rapidly removed soon after a precipitation event, as shown by the rapid fluctuations in soil water storage [Fig. 4(b)] at Denver. Because the water is removed rapidly, the storage

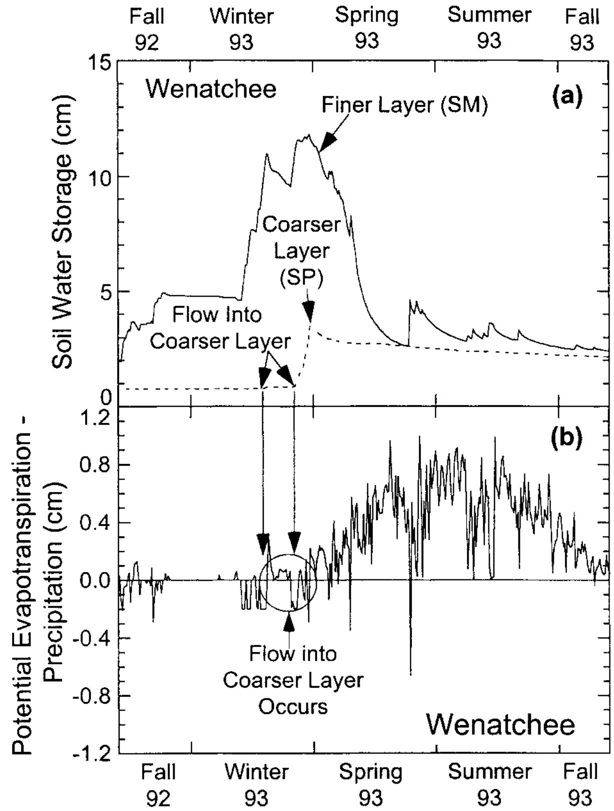

FIG. 5. (a) Volumetric Water Content and (b) Potential Evaporation Minus Precipitation for Wenatchee Capillary Barrier

capacity of the surface layer is rarely exceeded, and negligible percolation occurs [Fig. 4(a)].

These results indicate that the critical meteorological conditions for a capillary barrier are site dependent, as has been observed in the field (Nyhan et al. 1990, 1997; Hakonson et al. 1994; Ward and Gee 1997; Khire et al. 1999). They generally occur when precipitation (P_r) is more frequent during periods of low potential evapotranspiration (ET_p). This effect is illustrated by the difference $ET_p - P_r$, which is shown in Fig. 5(b) for Wenatchee. In this case, ET_p was computed with Penman's (1948) equation, using meteorological data for the wet year. Flow into the coarser layer occurred after a sustained period when P_r equaled or exceeded ET_p (i.e., $ET_p - P_r \leq 0$). In many cases, the critical period is in winter, when potential evapotranspiration is low and more frequent and less intense storms occur. Such storms generate less runoff and more infiltration into the surface layer. Snowfall also occurs during winter, and inundation by snowmelt during winter can overwhelm the soil water storage capacity of the finer-grained layer, resulting in percolation (e.g., Khire et al. 1999). Field studies at sites in Utah (Hakonson et al. 1994), at the Hanford site (Gee et al. 1993; Ward and Gee 1997), and in Wenatchee, Washington (Khire et al. 1999), have illustrated the importance of snowmelt. In each of these cases, large snowmelt events resulted in substantial infiltration, higher than expected soil water storage, and greater than anticipated percolation.

Layer Thickness

Finer-Grained Surface Layer

Water balance predictions for capillary barriers at Wenatchee having finer-grained surface layers (SM) 15, 30, 45, and 60 cm thick and an underlying coarser-grained layer (SP) 75 cm thick are shown in Fig. 6. Percolation decreases as the thickness of the surface layer increases [Fig. 6(a)] because the soil-water storage capacity of the surface layer becomes larger, which allows the surface layer to store more water for a longer period of time without drainage to the underlying layer. Increasing the surface layer thickness from 15 to 30 cm results in a reduction in percolation from the base of the cover from 5.8 to 1.4 cm. Increasing the surface layer to 45 or 60 cm reduces percolation to a very small quantity [Fig. 6(a)]. Similar decreases in percolation occur for the simulated capillary barriers at Denver, Phoenix, and Reno when the surface layer thickness is increased. (Fig. 7).

Soil water storage provided by thicker finer layers is evident in Fig. 6(b). When the surface layer is thicker, the soil water storage curve has a higher peak and greater breadth. The larger and more prolonged soil water storage provided by the thicker finer-grained surface layer also permits a greater quantity of water to be removed by evapotranspiration [Fig. 6(c)]. An increase in surface layer thickness form 15 to 60 cm results in evapotranspiration increasing from 19 to 25 cm. The surface layer cannot be made indiscriminately thick, however, because water may accumulate below the rooting zone, which may cause greater percolation (Morris and Stormont 1997).

Underlying Coarser-Grained Layer

Water balance results for the capillary barrier at Wenatchee are shown in Fig. 8. Coarser layers of SP 75 cm thick or 45 cm thick were used along with a 30 cm thick surface layer of SM. Results at Wenatchee are shown, because the difference in percolation obtained by changing the thickness of the coarser layer was largest at this location. Thickness of the coarser layer had the greatest effect at Wenatchee because the meteorological conditions at this location imposed the most stressful condition, all other factors being equal, as illustrated in Fig. 4(a). Differences at other locations were less than 0.1 cm (Khire 1995).

Percolation increases when the thickness of the coarser-

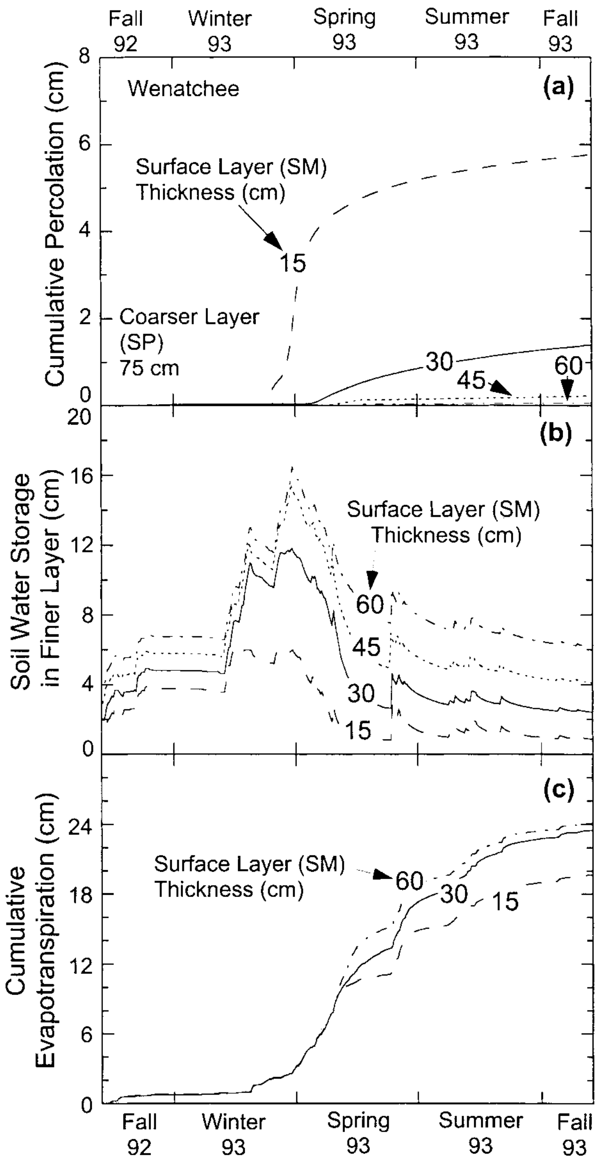

FIG. 6. (a) Cumulative Percolation; (b) Soil Water Storage; and (c) Cumulative Evapotranspiration for Simulations for Wenatchee with Surface Layers of SM 15, 30, 45, and 60 cm Thick

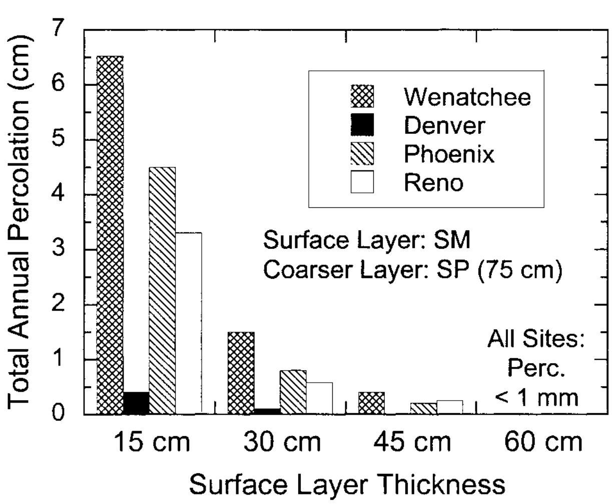

FIG. 7. Total Annual Percolation for Wet Year Simulations in Wenatchee, Reno, Phoenix, and Denver with Surface Layers of SM 15, 30, and 60 cm Thick

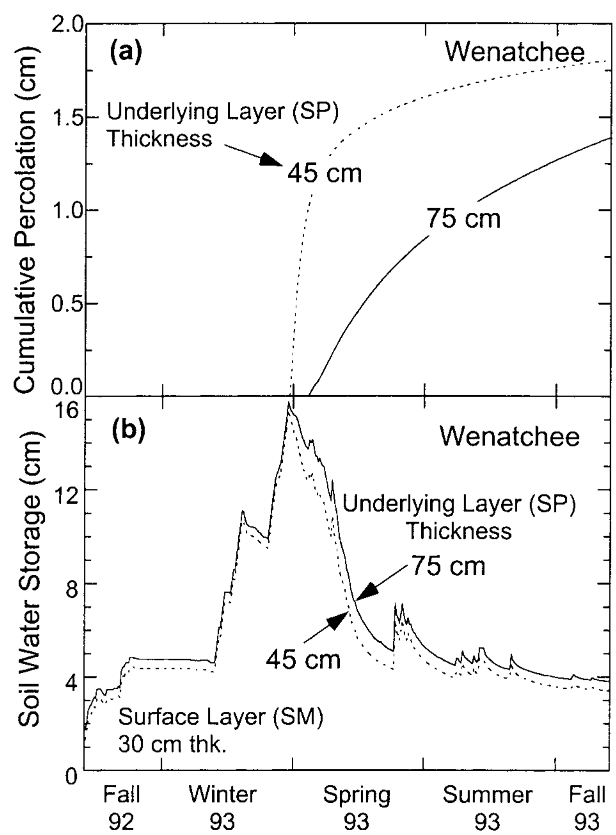

FIG. 8. Effect of Coarser Layer Thickness on (a) Cumulative Percolation and (b) Total Soil Water Storage in Wenatchee

grained layer decreases, but the increase in percolation is small (0.5 cm) [Fig. 8(a)]. Also, the onset of percolation occurs slightly earlier when the coarser layer is thinner. Decreasing the thickness of the coarser layer from 75 to 45 cm has a much smaller effect than reducing the thickness of the finer-grained layer, say from 45 to 30 cm [Fig. 6(a)], because coarser materials drain readily, and thus a thicker coarser layer provides little additional storage capacity [Fig. 8(b)].

Hydraulic Properties

Finer-Grained Surface Layer

The importance of hydraulic properties of the finer-grained surface layer was studied by simulating capillary barriers with 30 cm thick surface layers comprised of SM, SM-ML, ML, or CL and a 75 cm thick underlying coarser layer of SP.

Similar results were obtained for all sites (Khire 1995), so only those from Wenatchee will be given in Fig. 9. Percolation from the simulated capillary barrier at Wenatchee decreases from 1.4 to 0.15 cm when the ML or SM-ML is used instead of SM; when the CL is used, percolation is negligible [Fig. 9(a)]. Percolation decreases because the ML, SM-ML, and CL soils have lower hydraulic conductivity (Fig. 3), with the CL having the lowest saturated and unsaturated hydraulic conductivity. Consequently, the infiltration capacity is smaller and more runoff occurs [Fig. 9(d)].

Soil water storage also fluctuates less when the ML, SM-ML, and CL soils are used for the surface layer, which is consistent with the increase in runoff associated with these soils [Figs. 9(b and d)]. Evapotranspiration is also smaller, because less water is available for evapotranspiration when the ML, SM-ML, and CL soils are used [Fig. 9(c)]. Because less water enters these soils, there is also additional unused soil water storage capacity in the finer layer. Consequently, more severe precipitation conditions (e.g., heavier storms or more prolonged periods of rainfall or snowmelt) can be handled without percolation when these soils are employed.

An important limitation of these results is that UNSAT-H (as with most other codes) does not account for preferential flow in the finer-grained layer that might occur as a result of desiccation cracking. While cracks are usually hydraulically inactive under matric suctions exceeding a meter (Bouma and Denning 1972), preferential flow may occur during heavy rains or during snowmelt. For example, extensive desiccation cracking of the finer layer occurred during a field trial of a capillary barrier by Montgomery and Parsons (1990). At their site, the finer layer was a CL soil, and the dominant mechanism of water movement was preferential flow through cracks in the finer layer during heavy precipitation and snowmelt. Albrecht (1996) has also shown that the saturated hydraulic conductivity of the CL soil used for these simulations increases nearly 1,000 times after it undergoes several wetting and drying cycles. Another related problem is raveling of fine particles on the surfaces of desiccation cracks, which may result in degradation of the capillary break at the interface (Stormont 1997).

The formation of cracks and the corresponding increase in saturated hydraulic conductivity would probably outweigh the advantages of using a surface layer of CL soil that are shown in Fig. 9. Better performance is likely to be obtained with soil that is resistant to desiccation cracking, such as the SM, SM-ML, or ML soils used in the simulations. In addition, even without cracking of the CL soil, the ML and SM-ML soils yield nearly the same low percolation. Test pits in earthen final covers constructed with these ML, SM-ML, or ML soils have shown that these types of soils are resistant to cracking, even when exposed to extensive desiccation (Benson et al. 1993;

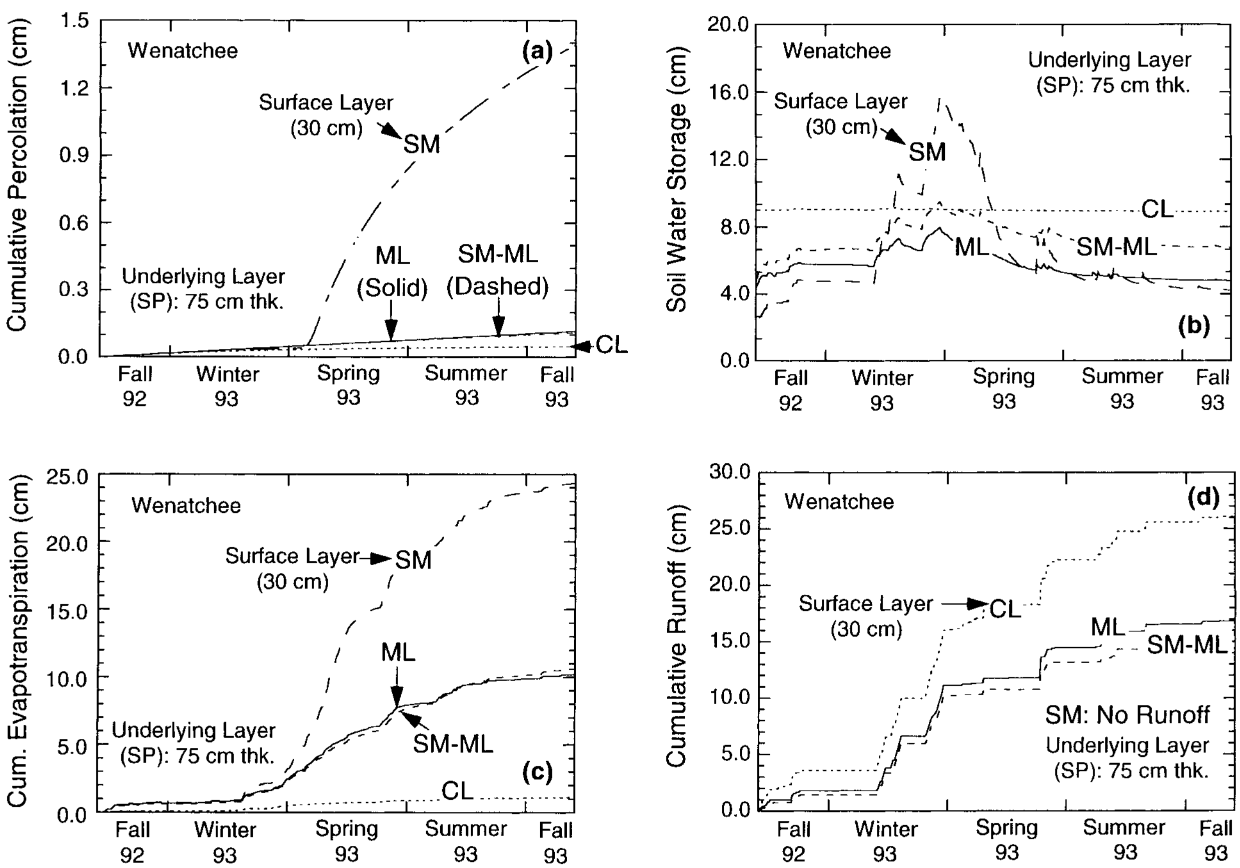

FIG. 9. (a) Cumulative Percolation; (b) Soil Water Storage; (c) Cumulative Evapotranspiration; and (d) Cumulative Runoff at Wenatchee for Surface Layers of SM, ML, SM-ML, and CL

Khire et al. 1994; Boehm et al. 1998). Soils resistant to desiccation cracking are likely to be classified as ML, SM, SC, or a dual symbol combination of these classifications (Daniel and Wu 1993; Albrecht 1996). These soils are also more suitable for vegetation, but can be more susceptible to erosion.

Underlying Coarser-Grained Layer

Hydraulic properties of the underlying coarser layer were evaluated by simulating capillary barriers at Wenatchee. The coarser layer was a 75 cm thick layer of SP (sand) or GP (gravel). The surface layer was a 30 cm thick surface layer of SM. Results of the simulations are shown in Figs. 10 and 11.

The storage capacity of the finer layer increases about 1.5 cm when the coarser layer is GP instead of SP, as illustrated in Fig. 10. The additional storage capacity afforded by using GP delays the increase in soil water storage in the coarser layer by about 5 weeks, as shown in Fig. 11(b). Greater storage in the finer layer, and the corresponding delay of flow into the coarser layer, occurs because the GP has lower ψ_B than SP (ψ_B = 23 cm for GP; 200 cm for SP; Fig. 3), which results in greater θ_{BF} for the SM when GP is used [for SM, θ_{BF} = 0.42 when GP is used versus 0.34 when SP is used; Fig. 3(a)].

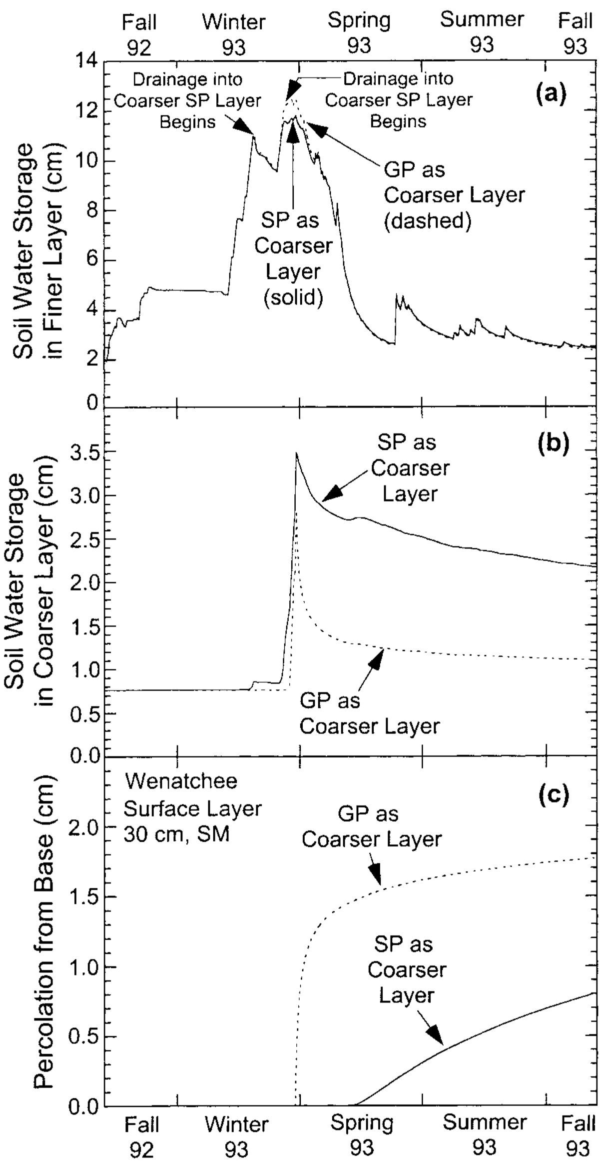

FIG. 10. (a) Soil Water Storage in Finer Layer; (b) Soil Water Storage in Coarser Layer; (c) Percolation from Base of Cover for Wenatchee (Surface Layer Is SM and 30 cm Thick; Coarser Layers Are SP and GP and 75 cm Thick)

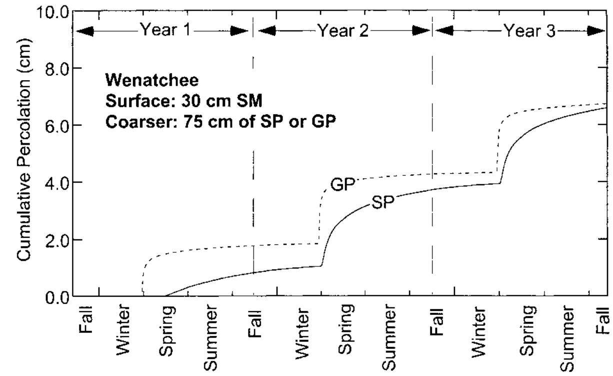

FIG. 11. Cumulative Percolation in Wenatchee with Surface Layer of SM 30 cm Thick and Coarser Layers of SP or GP 75 cm Thick (Meteorological Data for Wet Year Used Three Years in a Row)

Although using GP increases the storage capacity of the finer layer, percolation from the cover began earlier when the GP was used since the GP is more permeable than the SP when flow into the coarser layer occurs, i.e., at ψ_B. In particular, at ψ_B the hydraulic conductivity of GP is an order of magnitude higher than that of SP. Percolation is also greater with GP than with SP [Fig. 10(c)], because the coarser GP drains more readily and completely than the SP [Fig. 10(b)]. However, greater percolation from the GP does not necessarily persist, since the extra storage provided within the SP during the first year is not necessarily available during subsequent years, as shown in Fig. 11. The results in Fig. 11 are from simulations where the ‘‘wet year’’ meteorological conditions were repeated three years in a row. Over time, the cumulative percolation becomes increasingly similar, and eventually percolation from the capillary barrier with SP might exceed that from the capillary barrier with GP.

Long-Term Simulations

The importance of site-specific climate (Figs. 4 and 7) and the multiyear effects shown in Fig. 11 suggest that extended site-specific meteorological time series should be used when designing capillary barriers to ensure that long-term accumulation of water is not problematic and that the barrier will perform as intended. Methods currently employed in practice include using the wettest year on record three or five years in a row or the 10-year period with the highest average precipitation (*Rocky* 1997; Benson et al. 1998; Boehm et al. 1998; Winkler 1999).

Examples of results from long-term simulations at Wenatchee are shown in Figs. 12 and 13. In this case, the surface layer was SM and 30, 45, 60, or 90 cm thick, and the coarser layer was 30 cm of SP. One set of simulations was conducted for three years using meteorological data from 1983 each year. This year has the highest annual precipitation (36 cm) in the 36-year record at this location (Benson et al. 1998). Another simulation was conducted using the 10-year span of meteorological data from 1980 to 1989, the wettest 10-year period on record. For simplicity, snow was applied directly as rainfall in all simulations, resulting in greater percolation, because the storage capacity of the finer-grained layer is exceeded earlier than when snow is stored as a snow pack (Khire et al. 1994). Otherwise, all other input was the same as previously described.

Percolation and soil water storage predicted from the three-year simulations of 1983 are shown in Fig. 12. Percolation from the cover with a 30 and 45 cm thick surface layer occurs during the first winter (<91 days) because the storage capacity (~11 or 15 cm) is exceeded due to the high precipitation. In

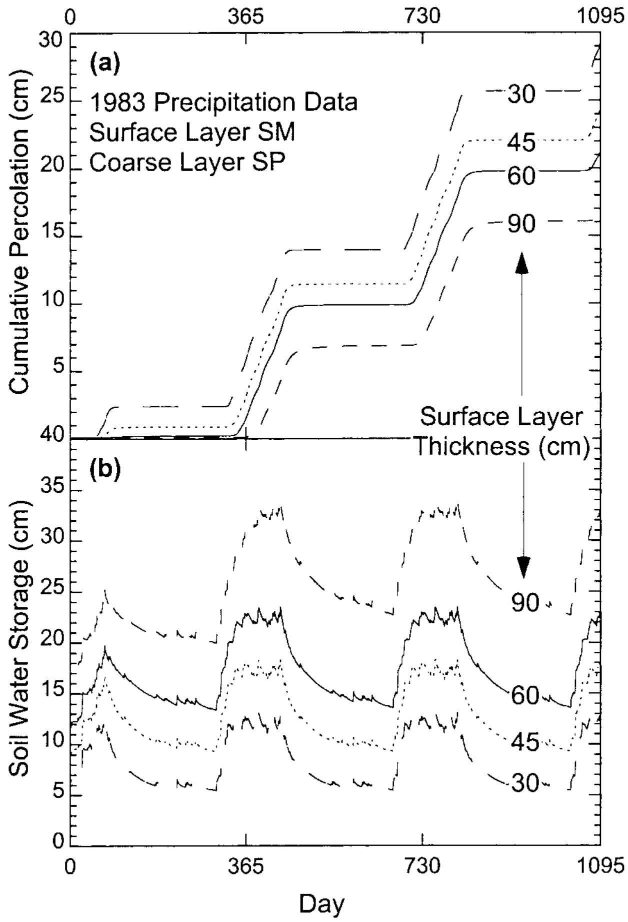

FIG. 12. (a) Cumulative Percolation and (b) Soil Water Storage during Three-Year Simulation in Wenatchee Using Meteorological Data from Wettest Year on Record (1983) Each Year

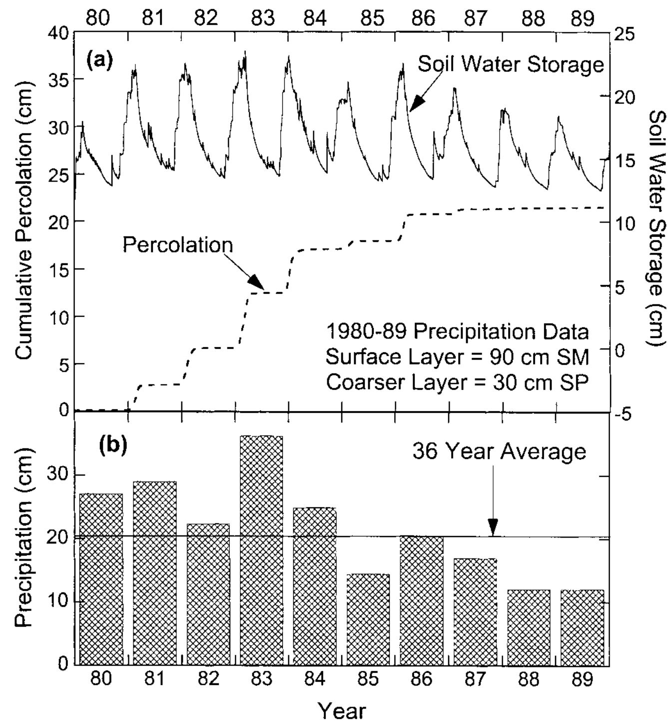

FIG. 13. (a) Cumulative Percolation and Soil Water Storage and (b) 1980–1989 Precipitation Record for Wenatchee Cover with 90 cm Thick SM Surface Layer and 30 cm Thick SP Coarser Layer

contrast, the covers with thicker surface layers do not transmit significant percolation during the first winter, because their storage capacity is not exceeded. However, because precipitation during 1983 is high and, correspondingly, the air temperature and solar radiation are lower, not all of the stored water is removed in the first summer. This results in lower storage capacity during the next wet season (late fall and winter). Consequently, the storage capacity of the covers with thicker surface layers is exceeded during the late fall of the first year (surface layer thicknesses of 45 and 60 cm) or early winter in the following year (surface layer thicknesses of 90 cm). As a result, percolation is transmitted. This behavior would not be observed if simulations were conducted for a single wet year. Nevertheless, the trends observed in single-year simulations are still valid. That is, thicker surface layers have greater storage capacity and transmit less percolation during the wet periods. For example, during the last wet period (day 650 to day 800), percolation from the cover with a 30 cm thick surface layer was 12 cm, whereas it was 9 cm for the cover with a 90 cm thick surface layer.

Percolation and soil water storage for the simulation conducted with the 10-year record are shown in Fig. 13(a) along with the annual precipitation during this period [Fig. 13(b)]. In this case the surface layer was 90 cm thick SM. No percolation was transmitted during 1980, but percolation (~2 cm) was transmitted in 1981 because the storage capacity was exceeded [Fig. 13(a)]. Percolation begins to diminish towards the end of 1984, when the annual precipitation falls below the average annual precipitation [Fig. 13(b)]. However, the storage capacity of the surface layer is not fully recovered until 1989 after three years of below average precipitation.

The percolation results shown in Figs. 12 and 13 must be considered in light of the input used, particularly the shallow rooting depth. In reality, less percolation would probably be transmitted. Nevertheless, these examples illustrate that percolation obtained from a single year simulation may not be representative of the long-term percolation under stressful conditions. The long-term simulation that is selected must be balanced against an acceptable probability of exceedance and the risk associated with exceeding the percolation requirement. The three wettest years is an extreme case; the probability of exceedance for this simulation is approximately one in 50,000 based on the existing meteorological record at Wenatchee. The wettest ten-year period is far more likely to occur, but it may not be severe enough to cause contamination of ground water above an acceptable risk level. Indeed, the risk to be used must be selected on a site-specific basis. This topic is in need of additional research.

LAYER THICKNESS SELECTION METHOD

The previous sections have illustrated the key factors affecting percolation from capillary barriers. Thickness of the surface layer and unsaturated hydraulic properties of both layers are the most important geotechnical properties. Varying them can result in percolation ranging from practically zero to a significant fraction of precipitation. For example, at Wenatchee percolation can vary from 24% of precipitation to near zero by adjusting the surface layer thickness (Fig. 7; Table 1). Gee et al. (1992) report similar findings for natural capillary barriers at the near surface of the Hanford site. They show that recharge at the Hanford site is practically zero for regions with finer-textured surficial soils, but as much as 59% of precipitation for coarser-textured surface layers. Laboratory data reported by Stormont and Anderson (1999) also show that storage capacity is a function of the properties of both the finer and coarser layers.

Once potential soils have been selected, the thickness of the surface layer and underlying layers need to be selected to reduce percolation below the maximum amount permitted. Thickness of the coarser layer can be selected as suggested in the previous section (e.g., the minimum practical thickness of a single uniform layer of coarse soil, say, 30 cm). The thickness of the finer surface layer depends on the unsaturated hydraulic properties of both layers and the meteorological conditions at the site. The following four-step design procedure can be used to estimate the thickness of the surface layer. The thickness is first estimated by hand calculation (or via spreadsheet) and then is adjusted based on numerical simulations. The purpose of the hand calculation is to provide a good first estimate of the thickness so that the number of computationally intensive simulations can be minimized.

Step 1: Determine Critical Meteorological Period

Step 1 consists of examining the meteorological record at the site and determining the critical time period (t_c) each year that may result in percolation. The critical period occurs when $ET_p - P_r$ is near zero or negative [Fig. 5(b)]; during this period water accumulates and percolation may occur [Figs. 4(a) and 5(a)]. This condition should normally correspond to the period outside the growing season. For example, the growing season at Wenatchee begins on Julian day 91, which corresponds closely to the end of the period when $ET_p - P_r$ is near zero, as shown in Fig 5(b).

The storage capacity required (S_R) during this period can be estimated by the cumulative precipitation (including snowmelt) and assuming that runoff and evapotranspiration are zero (i.e., $S_R = P_r$ during t_c). If S_R determined this way seems too large, runoff can be assumed to be 5–10% of precipitation during t_c (Khire et al. 1997, 1999). In most cases, the critical period can be estimated from the wettest year on record.

Step 2: Estimate Surface Layer Thickness

The surface layer thickness is selected so that its storage capacity is greater than S_R. A first estimate of the storage capacity of the surface layer can be made using a method proposed by Stormont and Morris (1998), with slight modifications. Stormont and Morris (1998) show that a unit gradient in suction head exists (i.e., a no flow condition) in the finer layer just prior to the onset of flow into the coarser layer. Accordingly, soil water storage in the finer layer (S_{Fo}) just prior to the onset of flow is

$$S_{Fo} = \int_0^L \theta(z + \psi_B)\, dz \tag{3}$$

where $\theta(\cdot)$ = relationship between water content and suction (i.e., the SWCC); z = distance above the finer-coarser interface; and L = thickness of the finer layer. Eq. (3) is the same as (8) in Stormont and Morris (1998), except ψ_B is h_z^* in their equation. Stormont and Morris (1998) refer to h_z^* as the ''water entry head,'' i.e., the suction at which flow into the coarser layer first occurs. Thus, h_z^* is analogous to ψ_B. The term h_z^* should not be confused with the more traditional ''water entry value'' coined by Bouwer (1966), which corresponds to the knee in the SWCC near saturation when the soil is wetting.

The storage capacity of the finer layer (S_{Fc}) is the portion of S_{Fo} that can be used to store infiltrating water. In most semiarid and arid climates, vegetation will remove all available water from a cover each growing season (Khire et al. 1997, 1999; Ward and Gee 1997). The water content at this condition can be estimated as the wilting point of the surface layer soil (θ_{WP}), which is commonly assumed to correspond to a suction of 15,000 cm (Hillel 1980). Thus, S_{Fc} can be defined as

$$S_{Fc} = \int_0^L \theta(z + \psi_B)\, dz - \theta_{WP} L \tag{4}$$

The required thickness of the surface layer (L_R) is the value of L in (4) that yields $S_{Fc} = S_R$. Estimating L_R using (4) should be conservative, since many plants in semiarid and arid regions can extract water to suctions in excess of 15,000 cm. For example, Gee et al. (1999) report that the wilting point of some desert plants can correspond to suctions exceeding 600 m.

The estimate of L_R made with (4) is a function of the unsaturated hydraulic characteristics of both the finer and coarser soils, since ψ_B depends on the shape of the SWCCs for both layers. For example, if the coarser layer becomes more broadly graded, ψ_B will increase (Chiang 1998), which will reduce S_{Fc}. In contrast, if the average particle size of coarser layer decreases, or the coarser layer becomes more uniformly graded, ψ_B will decrease, which increases S_{Fc}. Any change in the SWCC of the finer layer for suctions greater than ψ_B will also affect S_{FC}. Experimental results reported by Stormont (1997) and Stormont and Anderson (1999) demonstrate these effects.

Step 3: Adjust Thickness

Eq. (4) provides an estimate of the required surface layer thickness. The thickness can then be adjusted by conducting water balance simulations with an unsaturated flow model such as UNSAT-H that incorporates constitutive equations for evaporation from the surface, transpiration, and runoff. Input to the model should include meteorological data (e.g., a contiguous time series of the three wettest years), vegetative data, and unsaturated soil properties. Site-specific input data should be used whenever possible, including measured unsaturated soil properties. Otherwise, gross errors can be made (Khire et al. 1995). An assessment should also be made of variability in the soil properties, and worst-case properties should be used in an analysis to assess the potential worst-case condition.

Results of these simulations are used to adjust the surface layer thickness so that percolation predicted by the model is comparable to, but less than the maximum acceptable percolation. Maximum acceptable percolation is a function of the type of waste contained, the type of lining system (if any), and the consequences of ground-water contamination. Maximum percolation values ranging between 0.1 and 0.3 cm/yr have been used for earthen covers intended to be equivalent to composite covers required for hazardous waste landfills in the United States (*Rocky* 1997; Boehm et al. 1998), and 0.05 cm/yr has been used for radioactive disposal sites (Link et al. 1995). Higher percolation rates are sometimes used for solid waste facilities employing traditional earthen resistive covers (Benson et al. 1998). Equivalency criteria stipulated in U.S. Environmental Protection Agency's Alternative Cover Assessment Project (ACAP) include 1 cm/yr for sites where the prescriptive cap employs an earthen resistive design (e.g., a compacted clay barrier layer with an overlying vegetative layer) and 0.3 cm/yr when a composite cap is prescribed (Science 1999).

Step 4: Account for Other Factors

After conducting the water balance simulations, the surface layer thickness may be increased to account for other factors, such as water erosion, deflation (wind erosion), and desiccation cracking, or to provide additional safety against excessive percolation. Methods to limit erosion from earthen covers in arid regions are discussed in Litgoke (1994). Once these design modifications have been made, additional water balance simulations should be conducted to ensure the design still meets the percolation objective. Also, since covers incorpo-

TABLE 3. Thickness of Surface Layer for Percolation Less than 0.3 cm/yr from Numerical Simulations Shown in Fig. 7 and Estimated Thicknesses Obtained Using Eq. (4); for All Locations, Surface Layer is SM, Coarser Layer is SP (75 cm), and θ_{BF} = 0.34

Location (1)	Critical period (2)	S_R (cm) (3)	Surface layer thickness yielding <0.3 cm/yr, L_s (cm) (4)	L_R from Eq. (4) (cm) (5)
Wenatchee	Mid-fall to spring	13.5	45–60	50.4
Denver	Mid-fall to mid-winter	5.9	15–30	21.9
Phoenix	Mid-fall to mid-winter	13.3	45	49.5
Reno	Mid-fall to mid-winter	17.5	45–60	65.0
Wenatchee 1983	Mid-fall to spring	28.5	>90	106.3

rating capillary barriers are relatively new, a monitoring system including a lysimeter may be included in the design. Guidance on design of monitoring systems and lysimeters can be found in Tanner (1967), Gee et al. (1994), and Benson et al. (1994, 1999). The storage capacity of the finer layer can also be tested in the field, as suggested by Gee et al. (1993).

Application of Method

Comparisons were made between L_R selected using (4) and the surface layer thicknesses at Wenatchee, Denver, Phoenix, and Reno that resulted in percolation less than 0.3 cm/yr (the ACAP criteria for composite covers) based on the one-year UNSAT-H simulations. The meteorological data used in the parametric simulations were used to determine S_R. A comparison was also made for the wettest year on record at Wenatchee (1983). Results of the comparisons are shown in Table 3. A range of thickness is sometimes reported for the UNSAT-H simulations, since the simulations were conducted only for thicknesses of 15, 30, 45, 60, and 90 cm and thus a specific thickness yielding percolation less than 0.3 mm/yr cannot be defined. The values of L_R obtained using (4) generally fall within the range obtained from the UNSAT-H simulations, which suggests that (4) provides a good first estimate of L_R.

SUMMARY AND PRACTICAL IMPLICATIONS

The water balance of capillary barriers consisting of a finer grained surface layer and coarser-grained underlying layer was simulated using the model UNSAT-H. Simulations were conducted for the four locations in the United States (Wenatchee, Washington; Denver, Colorado; Pheonix, Arizona, and Reno, Nevada) having different types of semiarid and arid climates. The influence of thickness of the surface and underlying layers was evaluated via simulations conducted with layers of various thicknesses. The importance of hydraulic properties of the surface and underlying layers was assessed using the properties of four finer-grained soils and two coarser-grained soils having contrasting saturated and unsaturated hydraulic characteristics. Based on the results of these simulations, the following practical implications have been formulated:

- Capillary barriers should be designed for site-specific meteorological and hydrological conditions. The critical period for a capillary barrier is frequently during the winter months, when evapotranspiration is minimal and precipitation occurs more frequently, less intensely, and sometimes as snow. These conditions generally result in accumulation of water in the surface layer and breakthrough across the interface between the finer and coarser layers if the soil water storage capacity of the surface layer is exceeded. Others have observed similar behavior in field experiments.
- Thicker surface layers generally yield less percolation, because they have greater storage capacity. Methods to estimate the surface layer thickness have been presented. However, adequate surface layer thicknesses should be checked using suitable long-term simulations performed with meteorological data representing the most stressful conditions that the cover is likely to endure. In addition, surface layers must not be made too thick, or long-term accumulation of water and percolation may occur if deep-rooted vegetation is not present.
- Surface layers having lower saturated hydraulic conductivity will generate more runoff, less infiltration into the surface layer, and less percolation. Because less infiltration into the surface layer occurs, finer-grained layers with lower saturated hydraulic conductivity may be exposed to more severe precipitation before their soil water storage capacity is exceeded. However, care must be used when selecting surface layer soils. Soils should be selected that are resistant to desiccation cracking and erosion and are suitable for vegetation. Silts, silty sands, sandy silts, and clayey sands are likely to be suitable surface layer soils.
- The thickness of the coarser layer is less important than that of the finer layer, but the hydraulic properties of the coarser layer affect the storage capacity of the finer layer and percolation from the cover. Clean sands and gravels are suitable soils for the coarser-grained layer, and in most cases a 30 cm thick coarser layer should be adequate.

Although not explored directly in this study, vegetation has an important role in the performance of capillary barriers, because vegetation is largely responsible for water removal from the barrier. Accordingly, design teams for capillary barriers should include a soil scientist or agronomist with expertise in the water-using capabilities of vegetation at the design location.

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