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CAPILLARY BARRIERS AND SUBTITLE D COVERS: ESTIMATING EQUIVALENCY

By Carl E. Morris[1] and John C. Stormont,[2] Members, ASCE

ABSTRACT: Accumulating data on traditional compacted soil-surface covers are demonstrating that they are likely to degrade and have reduced effectiveness as long-term barriers; therefore, suitable alternatives are being examined. One possible alternative that is receiving increased attention is capillary barriers. The U.S. Environmental Protection Agency (USEPA) allows for alternatives to be used, but requires that they achieve infiltration and erosion protection equivalent to that of designs contained in design guidance documents. A method of comparing a capillary barrier to a design that features a compacted soil layer that meets the minimum requirements for a solid-waste landfill cover (so-called Subtitle D) under identical, transient conditions is introduced in the present paper, allowing equivalency to be demonstrated. The approach uses daily climatic data rather than monthly or yearly averages, which can provide misleading results. The concept of adding a "transport layer" at the fine/coarse interface of the capillary barrier to laterally drain water and reduce the moisture content is also presented. Numerical modeling results for a variety of climates show that the capillary barriers may be equivalent (or better) compared to a Subtitle D cover at many locations. The inclusion of a transport layer may significantly improve capillary barrier performance.

INTRODUCTION

Surface-cover designs have traditionally featured compacted soil layers to restrict water movement due to their low permeability. Though the compacted soil systems can reduce the quantity of leachate produced at a site, they can suffer from degradation and loss of efficiency over time. As experience accumulates with these systems, shortcomings are becoming increasingly evident. Suter et al. (1993) and Daniel (1994) conclude that the compacted soil systems are unlikely, by themselves, to be effective long-term barriers, and cover designs should place more reliance on natural processes. The integrity of compacted soil covers is affected by freeze-thaw, shrink-swell, desiccation and subsidence cracking, as well as root and animal intrusion, all of which increase system permeability (Suter et al. 1993). Recently, synthetic materials (geomembranes and geosynthetic clay liners) have also been incorporated into designs. Although these multicomponent covers achieve specific functions and satisfy multiple regulations, combining numerous components can be expensive and have a doubtful prognosis for meeting long-term design objectives (Daniel 1994). In addition, systems incorporating geosynthetics and/or compacted soil layers require strict quality-control procedures, which may significantly increase costs. Therefore, there is a motivation to consider alternative components for cover systems for landfills, tailings, mining, and smelter wastes.

Capillary barriers have been proposed as a possible alternative to compacted soil covers and covers including geosynthetic layers for waste-disposal systems in arid and semi/arid environments. This proposed use of capillary barriers in dry climates is due to their simplicity and probable long-term stability (Johnson et al. 1983; Hakonson et al. 1989; and Reed 1989). Because capillary barriers do not rely on a low saturated hydraulic conductivity, processes that increase saturated hydraulic conductivity (e.g., freeze-thaw and desiccation) do not necessarily result in degradation of the capillary barrier. A capillary barrier consists of a fine-over-coarse soil layer sequence that acts as a barrier to downward flow under unsaturated conditions. Moisture is held in the fine layer by capillary forces and can be removed by evapotranspiration, *ET*, or, if the fine-coarse interface is sloped, by lateral transport in the fine soil above the interface. Breakthrough of water into the coarse layer occurs as the fine soil approaches saturation.

The composite fine-over-coarse soil system acts as a barrier to downward moving moisture due to the contrast in hydraulic conductivities between the two soils at similar matric potentials (soil suctions). This behavior can be explained by considering Fig. 1. At relatively high matric potentials (large negative number), the fine soil has a finite hydraulic conductivity, whereas the hydraulic conductivity of the coarse soil is immeasurably small. Under these conditions, moisture will not flow from the fine into the coarse soil layer, but instead will increase the moisture content of the fine layer. As the moisture content increases and matric potential decreases, the hydraulic conductivity of the fine soil increases slowly, remaining greater than that of the underlying coarse layer. When the matric potential at the interface approaches the effective water-entry potential of the coarse layer, the coarse soil develops a finite conductivity, and some moisture will flow from the fine into the coarse soil. Under these conditions, the system is no longer a barrier to downward moisture movement. As the matric potential decreases further, the hydraulic conductivity of the coarse soil increases rapidly and will eventually exceed that of the overlying fine layer. Flow into and through the coarse layer will now be concentrated into rapidly draining "fingers."

If moisture is not removed from a capillary barrier system, it will accumulate at the fine-coarse interface and failure will

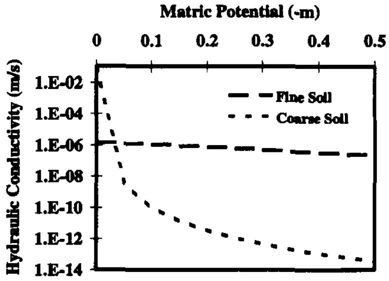

FIG. 1. Typical Hydraulic Conductivity of Fine- and Coarse-Grained Soils for Capillary Barrier

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occur. There are two methods of moisture removal: ET of the moisture via plant transpiration and near-surface evaporation, and by lateral transport of moisture along the fine-coarse interface if the interface is sloped. The ET component is strongly dependent on the type and nature of the plant cover and on climatic conditions, and therefore moisture removal is subject to seasonal and yearly fluctuations. Lateral transport of moisture along the fine-coarse interface is a function of the coarse and fine soil characteristics, the slope, and the infiltration rate. The distance down the sloping interface that the moisture may be transported or diverted before breakthrough occurs is usually of the order of several meters for commonly used materials and slopes, limiting the effectiveness of this removal mechanism.

Stormont (1995) and Schulz et al. (1995) have demonstrated that the addition of "transport layers" at the fine-coarse interface can significantly increase the lateral transport of moisture in a capillary barrier from less than a meter to more than 50 m, dependent on conditions. A lateral transport (diversion) layer is usually a fine-grained sand with a greater hydraulic conductivity than the adjacent fine and coarse soils at similar matric potentials. It serves to laterally move moisture, which accumulates near the interface while remaining unsaturated. Fig. 2 is a schematic representation of a capillary barrier with a transport layer and the associated nomenclature.

The use of a capillary barrier as the principal barrier layer in a cover system is hampered by the regulations applicable to the closure of many landfills. For example, present minimum requirements for the cover system for solid-waste landfills (so-called Subtitle D) specify a 0.15 m vegetative layer over a 0.45 m infiltration layer, which has a saturated hydraulic conductivity of 10^{-7} m/s or less [40CFR258.60 (a) 1–3]. Because capillary barriers function under unsaturated rather than saturated conditions, the saturated hydraulic conductivity requirement is not directly applicable. The saturated hydraulic conductivity of a typical capillary barrier system may be several orders of magnitude greater than the maximum permitted under Subtitle D regulations, but under normal operating conditions, may allow less percolation than a design using a compacted soil cover.

The regulations do, however, permit alternative designs if they can achieve erosion and infiltration protection equivalent to an acceptable conventional cover system [40CFR258.60 (b)]. A method to evaluate capillary barriers is needed so that performance comparisons to conventional covers can be made. Conventional cover and liner designs are commonly evaluated using the Hydrologic Evaluation of Landfill Performance (HELP) computer program developed by the U.S. Environmental Protection Agency (EPA) due to its ease of use when compared to other numerical models. This program is used by many designers to analyze landfill cover designs and is widely accepted by engineers and regulators. Because the HELP computer program uses a quasi-two-dimensional, deterministic, water-routing numerical approach to determine water balances, it cannot be used to evaluate capillary barrier performance (Schroeder et al. 1994a). Codes used for numerical analysis of capillary barriers must be capable of accommodating transient, unsaturated flow conditions.

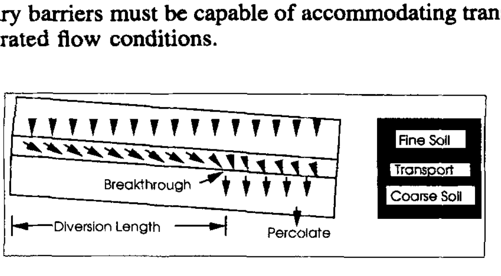

FIG. 2. Capillary Barrier with Transport Layer (Layer Thickness Not to Scale)

In the present paper, we propose a method to compare the efficiency of capillary barriers and conventional covers based on the amount of moisture (percolation) that moves through the cover systems over the modeling period. This approach is consistent with the regulatory intent of demonstrating equivalency in limiting infiltration. The performance of the cover system is estimated from a two-step procedure. First, the HELP program is used to obtain site and design specific flux variables we term as Infiltration (*I*) and Evapotranspiration (*ET*). The HELP program combines transient, daily potential infiltration, which it generates from climatic data, with cover-design-dependent runoff and evapotranspiration data to generate the two fluxes of interest. These terms are used as sources and sinks in TRACER3D (Travis and Birdsell 1991), a code that is capable of solving transient two-phase flow in the second step of the procedure. TRACER3D provides estimates of the percolation through the cover systems being modeled at a site for a given set of climatic conditions. Thus, this approach permits direct comparisons between capillary barrier and conventional cover-system performance.

To illustrate this method, it is used to compare designs featuring capillary barriers with those that meet the minimal Subtitle D requirements at five locations in the United States. The sites modeled were Albuquerque, N.M.; Chicago; Columbia, S.C.; Salt Lake City; and San Francisco, providing a broad spectrum of climatic conditions. These sites were chosen to demonstrate the effects of a variety of climates on the minimal Subtitle D cover and capillary barrier systems. The minimal Subtitle D design was used for comparison to illustrate the difference in performance of a barrier that relies on a low saturated hydraulic conductivity and one that uses a capillary break. It is recognized that neither of these cover systems may constitute an acceptable design by themselves at many locations, and that they could be combined with other elements to achieve an optimal cap.

The HELP program clearly has shortcomings, as would be expected for a program that tries to accommodate both ease of use and speed while capturing synergistic, nonlinear processes. There are efforts to improve the HELP model by continuing to update the program, as well as development of alternative programs such as FILL (Khanbilvardi et al. 1995). However, the HELP program is widely used by designers and regulators and incorporates models for many near-surface phenomena. Our use of the HELP model has been as a convenience, allowing us easy access to U.S. climatic data and the near-surface processes that it models, without having to write extensive code to adapt the routines to the TRACER3D model. These parameters are not strongly influenced by the limitations of the water-routing approach and therefore provide reasonable representations of actual processes. We are using several components incorporated into the HELP model to provide infiltration and evapotranspiration data, but are not using the often criticized water-routing portion of the program.

APPROACH FOR ESTIMATING EQUIVALENCY

The approach for estimating performance of capillary barriers and conventional designs given here involves comparing percolation through each cover system when exposed to identical climatic conditions. The estimate of percolation from the cover systems was determined using a two-step process. First, the HELP model was used to obtain infiltration and evapotranspiration data that was design and site specific. Second, this data was used as input into TRACER3D, from which percolation data was obtained.

Because nonsteady-state conditions were to be applied to the cover designs, a source of representative climate data was required for each site and each design. The HELP model has the ability to generate 100 years of synthetic data for each site based on measured parameters. Additionally, the model has the ability to account for near-surface processes such as snowmelt, runoff, and evapotranspiration on a daily basis using the generated climate data, an option not available in the TRACER3D code. A daily infiltration term, *I*, was calculated from the data and the near-surface processes

$$I = \text{rain} + \text{snowmelt} - \text{runoff} - \text{interception} \quad (1)$$

This term is dependent on the climate, cover slope, and material and therefore is a function of both site and cover design that is different for each cover system. The second term of importance, *ET*, is dependent on climate and cover design, and thus is different for each simulation. This data (*I* and *ET*) was written to an output file that was later reformatted for use as input to the TRACER3D code.

The second step in the process was the use of TRACER3D to model flow through the selected cover designs using the fluxes generated by HELP. The infiltration portion of the data was modeled as a source term at the top of the cover, and the *ET* term was distributed through the cover to a depth of 0.6 m (the chosen rooting depth) using the algorithm described in the HELP engineering manual (Schroeder et al. 1994b). This algorithm is based on work by Knisel (1980)

$$ED_i(j) = ED_i - W(j) \quad (2)$$

where $Ed_i(j)$ = soil moisture and plant evaporative demand on segment j on day i in mm; ED_i = total soil moisture and plant evaporative demand on day i in mm; and $W(j)$ = weighting factor for segment j in mm. The weighting factor, $W(j)$, is given by

$$W(j) = 1.0159 \left[e^{-4.16} \frac{D_{j-1}}{ED} - e^{-4.16} \frac{D_j}{ED} \right] \quad (3)$$

where D_j = depth to bottom of segment j in mm; and ED = depth of evaporative zone or rooting depth in mm.

With the exception of the capillary barrier with lateral transport, the covers were modeled as one-dimensional systems, as preliminary two-dimensional analyses showed that there was insignificant flow in the downslope direction. Moisture flow into the finite difference cell immediately below the 0.6 m depth in the case of the minimal Subtitle D design, or the first cell in the coarse layer for the capillary barrier, was calculated at each time step. A running total of this moisture flow was kept and was output on a 28-day basis for the 10-year simulation. The moisture flow into the cell was designated to be the amount of percolate from the system being modeled. The capillary barrier with lateral transport was modeled in the same fashion, but as a two-dimensional system so that the effects of the transport layer could be ascertained.

Several modifications of the HELP code were required to obtain the needed output data. The first was the simple addition of an output file so that the needed data could be obtained in an easily used format, and the second was a change in the way lateral drainage was initiated so that evapotranspiration could be reasonably simulated for a capillary barrier. Because the capillary barrier acts as an obstacle to downward flow, the moisture content of the fine soil layer increases as moisture migrates into the cover system. This stored moisture is available for evapotranspiration, and because the moisture content of the fine soil of the barrier is often greater than that in the minimal Subtitle D design, evapotranspiration of the capillary barrier system may be greater than for the minimal Subtitle D design of the same soil type and configuration. To simulate this type of behavior, a high-conductivity drainage layer and geomembrane were added below the 0.6 m of fine soil of the capillary barrier profile in the HELP model. These added layers simulated the "barrier effect" of a capillary barrier: that is the buildup of moisture near the interface once failed, its rapid drainage. The geomembrane was used to prevent moisture from flowing out of the fine soil layer of the system, simulating the capillary break. The drainage layer was used to allow rapid drainage of accumulated moisture that collected at the capillary break when failure of the system occurred. The drainage layer was inactive (no flow) until the moisture content of the overlying soil reached a set level that corresponded to the moisture content of the capillary barrier at breakthrough in TRACER3D simulations.

Upon activation (flow allowed) the drainage layer allowed moisture to flow out of the fine layer as it would when breakthrough occurs in a capillary barrier, thus resulting in moisture contents more relevant to capillary barriers. The moisture contents, in turn, influence the calculated *ET* for the cover system.

The flux terms, *I* and *ET*, used in the simulations include both climate and design-dependent factors. Thus, the use of these terms allows identical climatic conditions to be imposed on all models at a given site while accounting for differences of the soils, the moisture storage characteristics of the covers, and the subsequent infiltration and evapotranspiration. The *I* and *ET* terms are developed from identical climatic conditions being imposed at the surface of each cover to be evaluated for each site or regional area of interest. Factors such as air and soil temperatures; precipitation quantity and form; solar radiation; wind speed and duration; and plant type do not vary with the cover design, and therefore climatic conditions at the model surfaces are equivalent. Cover-element variability such as slopes, material types, and thicknesses are accounted for as they are part of the cover-system design and influence the amount of moisture that will both infiltrate into, and be removed from, the system being modeled. By combining the daily climatic conditions with the cover design, the net flux of moisture into and out of the surface can be calculated daily for each system providing a unique set of *I* and *ET* for each design at each site. Detailed descriptions of the algorithms used by the HELP model to calculate runoff, snowmelt, interception, and evapotranspiration can be found in the HELP documentation (Schroeder et al. 1994a, b).

EVALUATION OF CAPILLARY BARRIER MODELING USING TRACER3D

The TRACER3D computer program was chosen to model the cover systems in this study due to its availability, ease of use, and our familiarity with the code. Other codes such as SWMS_2D (Šimunek et al. 1992), the UNSAT-H code (Fayer and Jones 1990), and the FILL code (Khanbilvardi et al. 1995) are also able to perform unsaturated flow simulations but were not evaluated for use in this application. TRACER3D solves transient two-phase flow and multicomponent transport in deformable, heterogeneous, sorptive, porous media using an implicit finite-difference scheme (Travis and Birdsell 1991). TRACER3D has been used and tested extensively for many conventional flow configurations with good agreement with analytical solutions and other numerical codes (Birdsell et al. 1994). However, there is no documented use of the code for simulating capillary barriers, which due to the highly contrasting materials at the fine-coarse interface can prove to be numerically difficult. Thus, to ensure the code was capable of reasonably representing capillary barrier behavior, a verification simulation was conducted comparing model results to an analytical solution by Ross (1990).

We modeled a capillary barrier using the TRACER3D code to compare numerical results to Ross's (1990) closed-form analytical solution. The model consisted of 0.60 m of a fine soil overlying 0.30 m of gravel with an interface slope of 5%. The entire domain was 100 m long with a constant flux of 10^{-9}m/s applied to the top boundary. The analytical solution of Ross

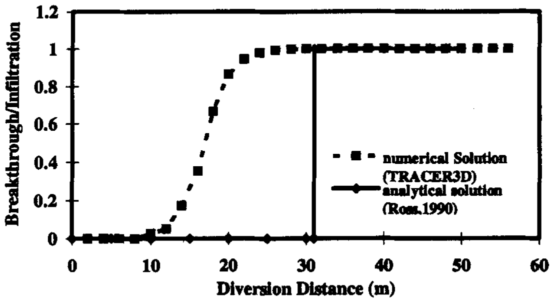

FIG. 3. Ratio of Breakthrough to Infiltration for Capillary Barrier for Numerical and Analytical Solutions

(1990), and the numerical solution of the TRACER3D code, using upstream weighing of mobility and permeability, are shown for comparison in Fig. 3. TRACER3D predicts a downslope diversion length of approximately 20 m versus a 31 m length given by the analytical solution. These results from TRACER3D underpredict the downslope diversion distance compared to Ross's (1990) analytical solution, providing a conservative estimate of capillary barrier behavior.

It should be noted that because this test was conducted using steady-state infiltration, a variety of mobility-permeability weighing schemes could have been used, some of which would reduce the difference between the analytical and numerical results as shown by Oldenburg and Pruess (1993). Because the actual simulations in this study were transient in nature, upstream weighing was used in the simulations of the five sites to avoid gross errors introduced by other weighing schemes. To maintain consistency, the upstream weighing was also used in the test case. Although upstream weighing is the best scheme for use in transient problems, it underpredicts downslope diversion lengths for capillary barriers because the contrast between the layers is not "felt" until moisture has penetrated the interface (Oldenburg and Pruess 1993). This behavior is seen in Fig. 3. Considerable additional discussion of numerical modeling of capillary barriers can be found in Oldenburg and Pruess (1993).

COVER DESIGNS AND PROPERTIES

Two basic cover designs, one conventional (minimal Subtitle D design) and one capillary barrier system, were modeled at each of the five sites. The minimal Subtitle D design met the prescriptive requirements of 0.15 m of vegetative layer and 0.45 m of soil with a hydraulic conductivity of less than 10^{-7} m/s required by Subtitle D. The corresponding capillary barrier cover consisted of 0.6 m of the vegetative soil overlying a gravel coarse layer. A low conductivity layer was not included in the capillary barrier system so that the system relied only on soils that did not require compaction. Also, it was obvious that if a low conductivity layer was included in the capillary barrier design, the capillary barrier would always outperform the minimal Subtitle D design, but would be a more costly alternative. The minimal Subtitle D and standard capillary barrier designs used in this study are illustrated in Fig. 4.

The quantity of percolate produced by both systems was measured by determining the moisture flow into the finite-difference cell immediately below the 0.6 m point in the model and thus takes into account only the fine soil layer of the capillary barrier. The 0.3 m thickness used in this study is arbitrary. The coarse layer thickness does not influence the capillary barrier system performance as long as it is greater than the minimum required to create the break. The capillary barriers with the included transport layers do have an additional 0.2 m of sand that provides some additional storage capacity over that of the minimal Subtitle D design. Because the sand readily drains, this is equivalent to about 0.02 m of water and is not considered significant. In addition, the rooting depth is set at 0.6 m, so water held below this level is not directly available for plant use.

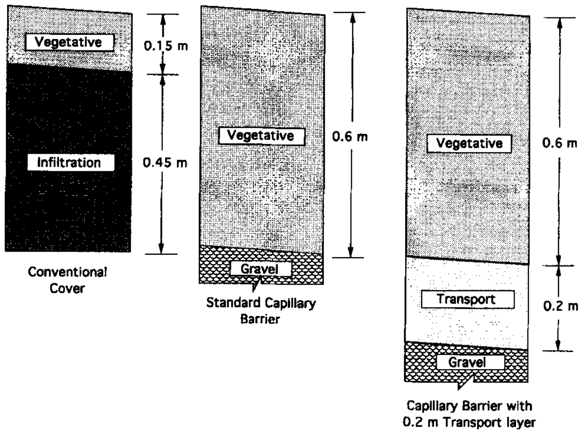

FIG. 4. Three Cover Designs Modeled

TABLE 1. van Genuchten Parameters for Cover-System Soils

Soil/layer (1)	K_s(m/s) (2)	θ_s (3)	θ_r (4)	α (mm^{-1}) (5)	n (6)
Vegetative[a]	1.4×10^{-6}	0.442	0.077	0.0015	2.03
Infiltration[a]	6.9×10^{-8}	0.42	0.160	0.0013	1.70
Transport[b]	2.1×10^{-4}	0.39	0.031	0.0038	4.95
Gravel[c]	0.1	0.42	0.005	0.493	2.19

[a] From McTigue (1994).
[b] From Pease (1995).
[c] From Stormont (1995).

The soil properties for the covers are given in Table 1 using the van Genuchten functions (van Genuchten 1980). The moisture content, θ, and the matric potential, h, are related by means of

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = [1 + (\alpha h)^n]^{-m} \qquad (4)$$

and the hydraulic conductivity is given as

$$K = K_s \Theta^{1/2}[1 - (1 - \Theta^{1/m})^m]^2 \qquad (5)$$

where K_s = saturated hydraulic conductivity; θ_s = saturated moisture content; θ_r = residual moisture content; $m = 1 - 1/n$; and n and α are fitting parameters.

The soil properties for the vegetative and infiltration layers were based on soils from Albuquerque, N.M. Ultimately, the soils used and the cost for the construction of a capillary barrier system will be site specific. In general, on-site, near-surface soils will be used for the fine layer, and thus will usually consist of loams to silts. The coarse layer should be sized to be as coarse as possible to create the capillary break, yet retain the overlying soil.

An additional capillary barrier design was modeled in a study that included a lateral transport layer of 0.2 m thickness. The capillary barriers with an added lateral transport layer were modeled to illustrate the increased capability of reducing percolation using a specially designed soil layer as part of the cover system. Simulations using this additional model were conducted for San Francisco, Chicago, and Columbia. The use of a transport layer was not required at Albuquerque and Salt Lake City since no percolate was produced by the standard capillary barrier cover system. The design used the basic 0.6 m barrier with a 0.2 m transport layer added between the fine soil and the gravel interface, as shown in Fig. 4. The properties of the transport layer are given in Table 1, measured by Pease (1995).

Finally, all covers were sloped at 5%. Small changes in slope have little effect on surface runoff quantities due to the assumption of a fair stand of vegetation, and therefore little change in the production of percolate would be seen for the conventional and standard capillary barrier systems. A change in slope would effect the covers with the included transport layer since the downslope diversion distance is directly proportional to the interface slope.

MODEL PARAMETERS

The HELP code allows input of evaporative depth, runoff coefficient, leaf-area index (LAI), and vegetation amount in addition to the actual cover design and climatic data. These inputs were held constant to allow direct comparison between designs. The values used were 0.6 m for the evaporative depth, 0.82 for the runoff coefficient, and 2 for LAI and fair vegetation cover. The TRACER3D code was run using the default options for most parameters with no changes made between designs. Boundary conditions were no flow with the exception of the bottom boundary for all models and for the downslope end of the transport layer for the capillary barrier with transport, which were set to maintain atmospheric conditions, an option in TRACER3D. Additionally, both the HELP and TRACER3D models were run using an initial soil saturation determined by HELP based on the first year of simulation (Schroeder 1994a, b).

RESULTS

Simulations of capillary barriers and minimal Subtitle D design systems were conducted for five sites in the United States: Albuquerque, Salt Lake City, San Francisco, Chicago, and Columbia. The results of the simulations are presented and discussed in the following section.

All simulations were conducted for 10 years so that the cumulative effects of precipitation and evapotranspiration on cover performance could be examined. This multiyear time period is extremely important for the standard capillary barrier system in which downslope drainage is insignificant and the major moisture removal process is evapotranspiration. If *ET* is lower than infiltration in a particular period of time, the fine soil may accumulate moisture over time, leading to a large breakthrough event. At each site a 10-year period was chosen from the available 100-year record. The chosen period contained the 5-year record with the highest cumulative precipitation. This 5-year record was preceded by 3 years of data and followed by an additional 2 years, making up the 10 years of climate data used in the simulations. Therefore, the covers were subjected to the highest realistic 5-year stress. The five sites modeled represent a large range of precipitation and potential evapotranspiration regimes. Figs. 5 and 6 provide the cumulative infiltration and potential *ET*, as calculated by the HELP code for the five sites, respectively.

The site with the lowest average annual precipitation that was studied was Albuquerque. The total precipitation over the 10-year study period was 2.19 m, or an average of 0.219 m/yr. This low precipitation, combined with a very high potential *ET*, yields a benign climate in which many cover systems provide adequate protection. This benign climate was demonstrated in the modeling, which showed that no percolate was produced for either the conventional cover or the standard capillary barrier for the 10-year simulation period.

The results for Salt Lake City are the same as for Albuquerque, with no percolate being produced by either cover system. The total precipitation for the area is approximately

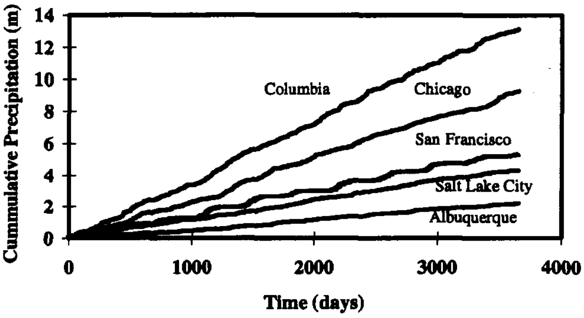

FIG. 5. Cumulative Precipitation for Five Modeled Sites

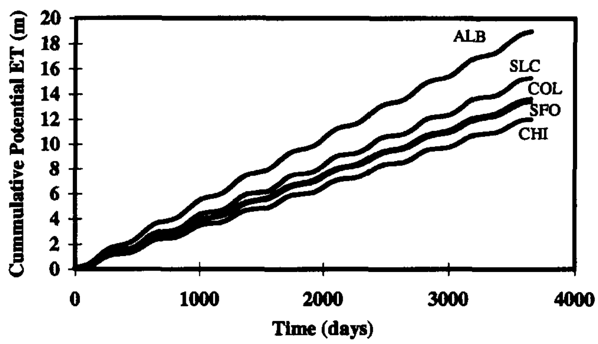

FIG. 6. Cumulative Potential ET for Five Sites Modeled

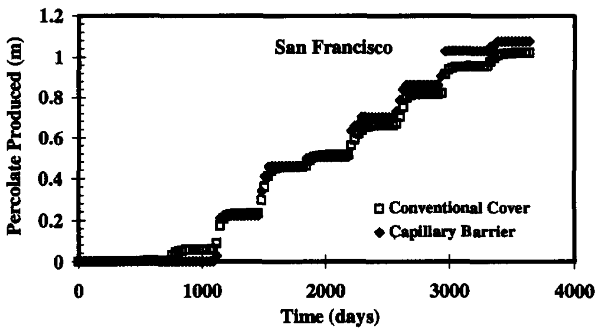

FIG. 7. Percolate Production, San Francisco

4.29 m for the 10-year modeling period or an average of 0.429 m/yr. However, the potential evaporation is still high, and the moisture is removed from the cover systems. Although Salt Lake City receives about twice as much precipitation as Albuquerque, the high potential *ET* removes all added moisture from the soil if that moisture is held within the root zone.

San Francisco represents a site that receives the bulk of its moisture during the winter and spring months and little, if any, rain during the rest of the year. The dry season is long, but the potential *ET* is lower than that of Salt Lake City. The total rainfall over the 10-year modeling period was approximately 5.25 m, or roughly 1.2 times that of Salt Lake City and 2.4 times more than Albuquerque. The cumulative percolation for the conventional cover over the 10 years is approximately 1.02 m, as illustrated in Fig. 7. This large increase in percolation is due to several factors. First the rainfall is not spread out over the entire year, but rather is concentrated into a few months. Second, the precipitation occurs when the *ET* rate is low. This combination of factors leads to little removal of infiltrated moisture by evapotranspiration and hence, a high percolate production once the soil becomes saturated. The results for the standard capillary barrier are also included in Fig. 7, and it is seen that it produces slightly more percolate, 1.07 m

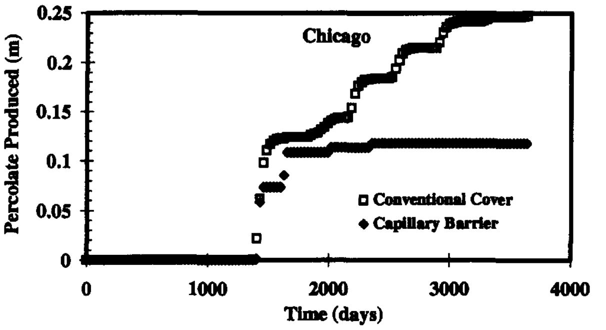

FIG. 8. Percolate Production, Chicago

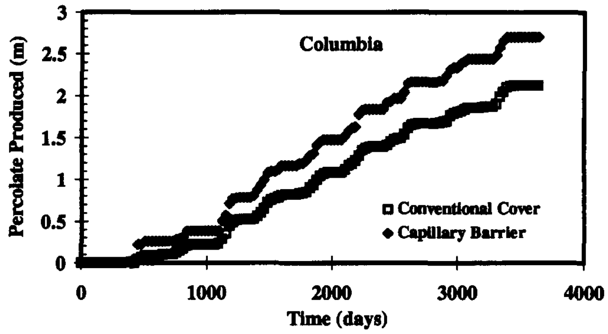

FIG. 9. Percolate Production, Columbia

versus 1.02 m for the minimal Subtitle D cover, over the simulation period. This difference is small and the two systems can be said to be comparable. Only small amounts of infiltrating moisture can be removed from the capillary barrier system due to low *ET* during the wet months and thus it accumulates at the interface until breakthrough occurs and large amounts of moisture move into and through the coarse layer.

The precipitation in Chicago is greater than the sites previously discussed and is also more evenly spread throughout the year. Total precipitation over the 10-year modeling period is approximately 9.28 m (0.928 m/yr) or about 1.75 times that of San Francisco. However, as seen in Fig. 8, the percolate production from the conventional cover is approximately one-quarter that of San Francisco. This is due to the precipitation being spread throughout the year, allowing significant quantities to be removed by evapotranspiration, even though the site has the lowest potential *ET*, as seen in Fig. 6. The standard capillary barrier at Chicago also shows significantly lower percolate production than at San Francisco, allowing only 0.1 m over the 10 years. This is significantly better than the conventional cover, which produces 0.25 m of percolate over the same period. Like the conventional cover, the capillary barrier system produced less percolate than its counterpart at San Francisco, though precipitation was significantly greater, demonstrating that timing is an important factor in cover-system performance.

Columbia has the highest 10-year precipitation of approximately 13.12 m (1.3 m/yr), or about 1.4 times that of Chicago. The percolate production from the minimal Subtitle D design at Columbia, as seen in Fig. 9, is much greater than Chicago, producing 2.1 m of percolate over the 10-year simulation. Though the evapotranspiration at the site is higher than Chicago, the moisture cannot be removed as quickly as it migrates through the cover. This leads to large amounts of percolate being produced. The capillary barrier system shows similar results, producing 2.7 m of percolate for the simulation period. Rainfall moves rapidly to the interface of the capillary barrier and accumulates until breakthrough occurs, which is several times per year. The capillary barrier system performs very poorly at this site, allowing about 0.6 m more of percolate to be produced, and thus the standard capillary barrier is not a suitable alternative for this climate regime. The poorer results are due to lower runoff amounts for the capillary barrier system due to the greater depth of higher permeability soil (0.6 m for the capillary barrier versus 0.15 m for the minimal Subtitle D design) and the rapid resaturation of the capillary barrier after breakthrough.

The results previously presented provide a comparison between the minimal Subtitle D design and the standard capillary barrier system for five widely different sites. At two sites, both the capillary barrier and compacted soil covers permitted no breakthrough. At San Francisco, the minimal Subtitle D cover and capillary barrier allowed large amounts of percolate to be produced and no significant difference was seen between their performances. At Chicago the capillary barrier was superior, producing less than half the percolate. The minimal Subtitle D design outperformed the capillary barrier at one site only, Columbia. These results indicate that a properly designed capillary barrier can provide equal or better protection than a minimal Subtitle D design at many sites and may merit consideration as an alternative.

CAPILLARY BARRIERS WITH LATERAL-TRANSPORT LAYERS

Two methods of removing moisture from the fine layer of a capillary barrier system, evapotranspiration and lateral transport near the interface, were briefly mentioned in the introduction to the present paper. Though the fine/coarse interface was sloped in the standard model, insignificant lateral transport takes place due to the soil properties, slope, and rate of infiltration at breakthrough. The major limiting factor in the development of substantial downslope diversion distances is the ability of moisture to move laterally through the fine soil under unsaturated conditions.

One method to increase the downslope diversion distance and enhance the removal of moisture is to increase the lateral hydraulic conductivity of the material just above the interface. Increasing the lateral hydraulic conductivity increases the amount of moisture that can flow through the soil at the interface, and the layer remains sufficiently dry so that flow into the underlying coarse layer does not take place. This flow into the coarse soil will occur when the matric potential of the fine layer approaches the water entry potential of the underlying coarse material. If sufficient moisture can flow downslope through the fine soil while maintaining a matric potential more negative than the water entry value, it can be removed from the system. Since the volume of moisture increases as it moves downslope due to contributions from the overlying soil, a distance is reached where the matric potential equals the water-entry value of the coarse layer, breakthrough occurs and the moisture is no longer diverted. If this distance is equal to or greater than the capillary barrier downslope length, significant volumes of moisture can be removed successfully from the system.

Simulations of capillary barriers using a transport layer were conducted for San Francisco, Chicago, and Columbia to determine if the method would decrease percolation through the system. Transport layers were not required at Albuquerque and Salt Lake City because the standard capillary barrier system was sufficient to prevent the production of percolate. A 0.2 m transport layer was tested at each of the three sites. The barrier simulated was 100 m in length and of unit width, with a slope of 5%. All soil properties and thicknesses were the same as those used in the earlier simulations. To avoid influences from the downstream boundary, only the first 50 m of each barrier were evaluated.

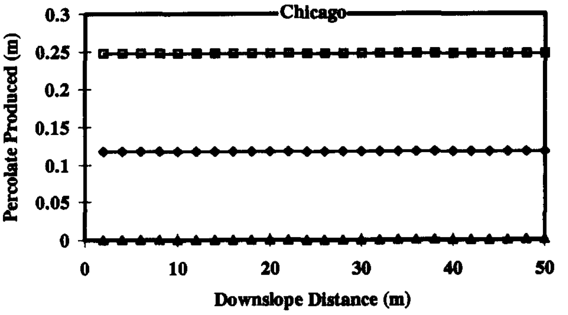

FIG. 10. Percolate Production as Function of Downslope Distance for Three Cover Designs Tested at Chicago (□ Minimal Subtitle D; ◆ Standard Capillary Barrier; △ Capillary Barrier with 0.2 m Transport Layer)

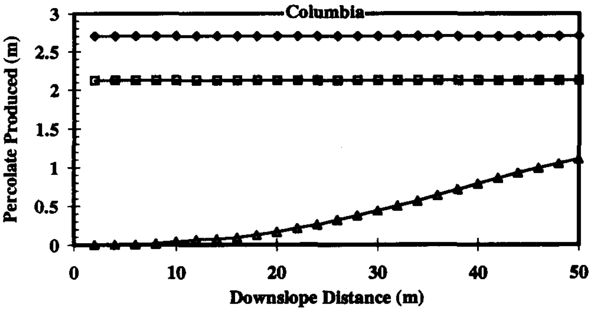

FIG. 11. Percolate Production as Function of Downslope Distance for Three Cover Designs Tested at Columbia (□ Minimal Subtitle D; ◆ Standard Capillary Barrier; △ Capillary Barrier with 0.2 m Transport Layer)

At Chicago, the addition of a 0.2 m thick transport layer reduced the percolate production for a 50 m slope length from approximately 0.1 m–0, as seen in Fig. 10. No percolate is generated over the entire 50 m span of the model. Under this scenario a one-hectare site could be covered with a capillary barrier with a 0.2 m thick transport layer and insignificant quantities of percolate would be produced.

Results using the capillary barrier with a transport layer at Columbia are equally good, with the production of percolate reduced from over 2.7 to 1.1 m for a 50 m downslope diversion distance and a 0.2 m transport layer. For shorter slope lengths, the percolate is reduced further, as seen in Fig. 11, to near 0 for slope lengths of less than 10 m. Though percolate is not reduced to 0 as it was for Chicago, the level of reduction is greater, removing over 1.4 m of moisture during the 10-year simulation at a slope length of 50 m and a transport layer thickness of 0.2 m.

Similar results were obtained at San Francisco where the transport layer reduced the percolate production by over 50%, as shown in Fig. 12. The standard capillary barrier produced 1.07 m of percolate over the 10-year modeling period compared to 0.51 m at a slope distance of 50 m for the system with an included transport layer. Percolate production is eliminated for downslope distances of 10 m and less. The reduced diversion by lateral transport at San Francisco is due to the concentration of precipitation into a 3–4 month period, which increases the rate of infiltration.

These results demonstrate that significant lateral transport can be obtained in a capillary barrier through the use of a transport layer. This lateral transport capability can be used to remove significant quantities of moisture from the cover system reducing percolate production to essentially zero in some cases. The results presented here are for only one material and one interface slope angle and hence, we would expect improved performance as the configurations are optimized.

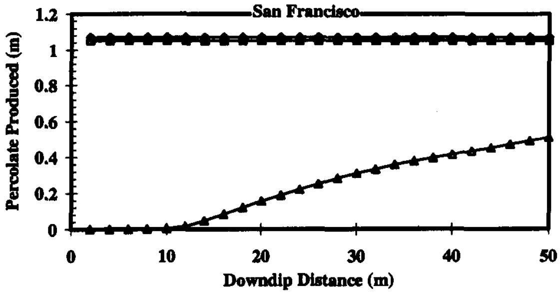

FIG. 12. Percolate Production as Function of Downslope Distance for Three Cover Designs Tested at San Francisco (□ Minimal Subtitle D; ◆ Standard Capillary Barrier; △ Capillary Barrier with 0.2 m Transport Layer)

CONCLUSIONS

This paper presents a method by which capillary barrier and conventional Subtitle D cover performance can be compared using identical climatic conditions. The methodology could be used to demonstrate the equivalency of an alternative cover system for acceptance as required by EPA. The use of the familiar HELP program to model climate and near-surface processes may aid in the approval of the methodology due to its widespread use and general acceptance by designers and regulators.

Simulations were conducted and comparisons made between the two cover systems for five sites: Albuquerque, Salt Lake City, San Francisco, Chicago, and Columbia. In four of the five cases, the capillary barrier provided equal or better performance than the minimal Subtitle D design system. At Columbia, the standard capillary barrier proved to be less effective due to high precipitation over the modeling period.

If a transport layer is added to the capillary barrier system between the fine soil and the coarse layer, percolate production can be reduced below that of the minimal Subtitle D design system for slope lengths of up to 50 m. In some cases no percolate was produced for the entire 10-year modeling period, though precipitation was over 9 m. Similar reductions occurred for slope lengths of 10 m and less, though precipitation was over 13 m for the simulation period.

APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

D_j = depth to bottom of segment j in mm;
$ED_i(j)$ = soil moisture and plant evaporative demand on segment j on day i in mm;
ED_i = total soil moisture and plant evaporative demand on day i in mm;
ED = depth of evaporative zone or rooting depth in mm;
ET = evapotranspiration;
h = matric potential in cm of water;
I = infiltration;
K = hydraulic conductivity;
m = $1\text{-}1/n$;
n = fitting parameter;
q = infiltration rate;
$W(j)$ = weighting factor for segment j in mm;
α = fitting parameter; and
θ = moisture content.

Subscripts

r = residual; and
s = saturated.