Chapter 4
Hydraulic Analysis and Design

4.1 Introduction

This chapter provides information on select topics related to cover system hydraulic analysis and design. The specific topics discussed in this chapter are:

- characteristics of selected water balance models (Section 4.2);
- evaluation of the water balance models (Section 4.3);
- recommendations for application of the water balance models (Section 4.4);
- design of drainage layers (Section 4.5);
- design of slope transitions (Section 4.6); and
- design of filter layers (Section 4.7).

4.2 Characteristics of Water Balance Models

4.2.1 Overview

As described in Section 1.2.5, with EPA's liquids management strategy, a primary function of a cover system is to limit post-closure leachate generation by minimizing or preventing, for all practical purposes, percolation of water into the waste. A water balance analysis is used to predict the quantity of this percolation. In addition to estimating percolation, water balance analyses of cover systems are used to:

- develop an understanding of how the various cover system components will function and identify which water routing mechanisms are most important;
- compare the performance of different cover system designs; and
- define the performance criteria for various cover system components (e.g., required storage capacity of surface and protection soil layers, required flow capacity of drainage layer) so that these components can be designed.

This section of the guidance document describes the water balance concept and presents several water balance analysis methods commonly used for cover systems.

4.2.2 Water Balance Concept

In a water balance analysis, water is routed into and out of a system using a series of calculations that require conservation of water mass. The potential pathways for water movement into and out of a cover system are illustrated in Figure 4-1. A cover system water balance is expressed in terms of water inflows and outflows and storage changes for a unit area of the system over some arbitrary time interval as:

$$P = R + ET + \Delta W_{surface} + \Delta W_{soil} + L + PERC \qquad \text{(Eq. 4.1)}$$

where: P = precipitation (mm/day); R = runoff (mm/day); ET = evapotranspiration (mm/day); $\Delta W_{surface}$ = change in water storage at surface (mm/day); $\Delta W_{foliage}$ = change in water storage on plant foliage (mm/day); ΔW_{soil} = change in water storage in cover system soil (mm/day); L = lateral drainage (mm/day); and PERC = percolation through the cover system (mm/day). Water is input to the cover system as precipitation in the form of rain or snow and lost from the cover system by runoff, ET, lateral drainage, and percolation. Water also is stored on the cover system as ponded water or snow, on plant foliage, and in cover system soils by capillary action. Eq. 4.1 is cast above using a time interval of one day; the equation could be developed using any other time unit.

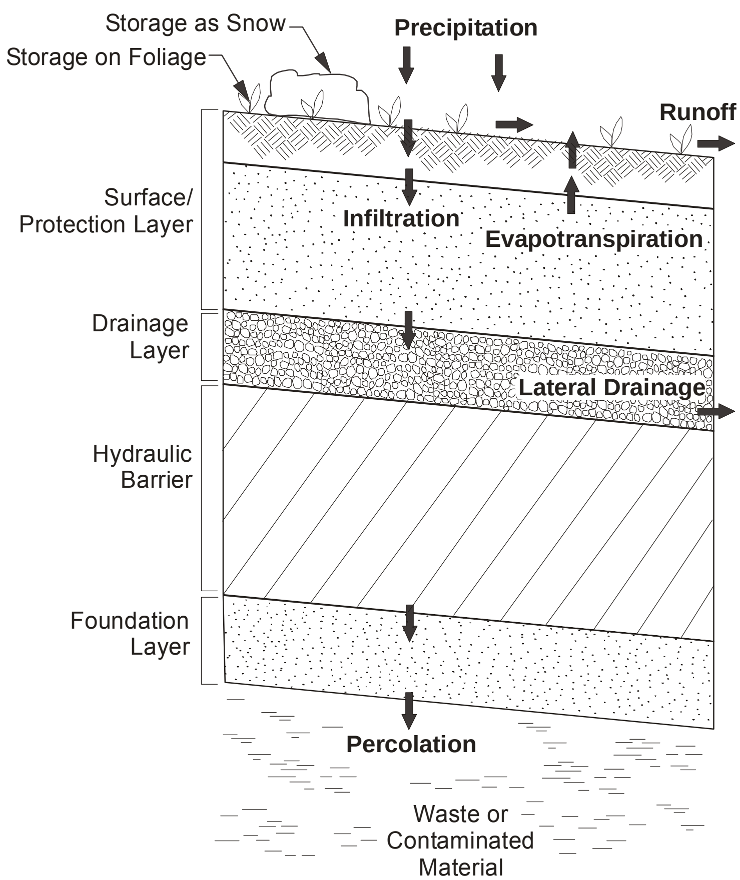


Figure 4-1. Water movement and storage in cover system.

Storage of water in soil coupled with removal of water by ET are the most important mechanisms for limiting percolation of infiltration. For most cover systems, infiltration is primarily removed from the cover system by ET. Flow from lateral drainage layers is typically a much smaller component of the water balance than is ET. It should be remembered, however, that while the internal drainage layer is typically of secondary importance to the overall cover system water balance, it is of prime importance to cover system slope stability (see Chapter 6 of this document). If even a relatively small amount of potential lateral flow is left undrained in a cover system, hydraulic heads can build up over the hydraulic barrier, leading to destabilizing seepage forces on cover system slopes.

Though Eq. 4.1 appears simple, the components of the water balance are dependent on many factors, are difficult to quantify, and are interdependent. It can be especially difficult to quantify percolation in arid and semi-arid environments where almost all precipitation is consumed by ET. Unlike in wetter climates where actual ET may approach the magnitude of potential evaotranspiration (PET) (i.e., the process is energy limited), in drier climates actual ET is generally much smaller than PET due to the lack of available water. ET is more difficult to accurately estimate under water limiting conditions. Because the magnitude of percolation in drier climates is so much smaller than the magnitudes of ET and precipitation, relatively small errors in estimated ET can result in relatively large errors in estimated percolation. Due to the difficulty in performing accurate analytical water balances, field water balances have occasionally been performed using cover system test plots to better assess the water balances components (e.g., the ACAP program, as described in Section 3.4.3). For example, field water balances have been performed for alternative cover systems without GM barriers and for cover systems at low level radioactive waste containment and disposal sites. Examples where field methods have been used to investigate one or more components of a cover system water balance include Cartwright et al., 1988; Nyhan et al., 1990; Anderson et al, 1993; Gee et al., 1994; Limbach et al, 1994; Melchior et al., 1994; Waugh et al., 1994; Dwyer, 1995; Khire, 1995; Sackschewsky et al., 1995; Schultz et al, 1995; Paige et al., 1996; Anderson, 1997; Gee et al., 1997; Karr et al., 1997; Khire et al., 1997; Laundré, 1997; Melchior, 1997a,b; Morris and Stormont, 1997; Nyhan et al, 1997; Ward and Gee, 1997; Dwyer, 1998; Khire et al., 1999; Dwyer, 2001; and Scanlon et al., 2002.

Water balance calculations are performed for time intervals that may be shorter than one hour or longer than a year. The time interval to use is dependent on the purpose of the water balance analysis. Guidance on the time interval to use for design is given subsequently.

4.2.3 Water Balance Methods

A variety of water balance methods are available to evaluate and design cover systems. They range in complexity from relatively simple empirical correlations to sophisticated computer-based finite difference and finite element mechanistic models. This guidance document describes the following water balance analysis methods: (i) simplified manual method; (ii) Hydrologic Evaluation of Landfill Performance (HELP) model; (iii) Leachate Estimation and Chemistry Model (LEACHM); (iv) UNSAT-H model: (v) SoilCover model; and (vi) HYDRUS-2D model. These are all well-documented manual methods or computer codes that consider the significant water balance processes (e.g., precipitation, runoff, and ET) and that have been used previously for cover system water balance analyses. All of the models except HYDRUS-2D are in the public domain. The characteristics of these models are compared in Table 4.1.

4.2.3.1 Simplified Manual Method

Koerner and Daniel (1997) present an updated version of the simplified method for performing manual or computer spreadsheet water balance calculations for cover systems. Their method is based on the previous work of Thornthwaite and Mather (1955, 1957), Fenn et al. (1975), and Kmet (1982). In this previous work, only monthly time steps were considered. Historically, simplified water balances using monthly time steps were used for cover system analysis and design. The computer code MBALANCE (Scharch, 1985), based on the simplified manual method with a monthly time step, was developed for landfill cover systems by Wisconsin Department of Natural Resources. This model was used in simulations that were compared to field water balances (Lane et al., 1992). Koerner and Daniel (1997) extended the method to consider a variable time step (e.g., daily, weekly, or monthly) to be selected based on the purpose of the analysis. A spreadsheet developed by Koerner and Daniel (1997) to evaluate monthly percolation through a cover system is shown in Table 4-2. The table is readily adaptable to PC-based spreadsheet computations and can be easily modified to accommodate daily or hourly time steps. Guidance on, and an example of, the use of Table 4-2 are presented in Koerner and Daniel (1997). The equation numbers given in the table are from that reference. The remainder of this section addresses several important aspects of the simplified manual method.

In the simplified manual method, it is assumed that no water is stored at the surface or intercepted by plants (i.e., $\Delta W_{surface} = \Delta W_{foliage} = 0$). For this set of assumptions, the following relationships are defined for a time interval taken as one day:

$$P = I + R \qquad \text{(Eq. 4.2)}$$

$$I = ET + \Delta W_{soil} + PERC^* \qquad \text{(Eq. 4.3)}$$

where: I = infiltration into cover soil (mm/day); and PERC* = percolation through cover soil (mm/day); and other terms are as defined previously.

In the simplified manual method, precipitation is partitioned into runoff and infiltration (Eq. 4.2). Runoff is calculated as a fraction of precipitation using the rational formula and a runoff coefficient appropriate for the cover system soil type and slope. According to Fenn et al. (1975), the rational formula will, in most cases, underestimate the quantity of cover system runoff.

From Eq. 4.3, water infiltrating the cover soil is partitioned into ET, soil water storage, and percolation through the cover soil. In the simplified manual method, ET is calculated as a function of PET, infiltration, and initial moisture content of the soil. PET is calculated using an empirical method developed by Thornthwaite and Mather (1955). If more water infiltrates the cover system than can potentially evapotranspire, the excess water will first be distributed within the root zone until the soil moisture content is at field capacity. The remaining water will be routed as percolation through the cover soil. If ET is greater than infiltration, then stored water will be lost from the cover soil root zone until the soil moisture content is at wilting point.

Table 4-1. Comparison of select water balance models.

Model	Reference	Calculation Scheme	Advantages	Disadvantages	Appropriate Use
Simplified Manual Method	Koerner and Daniel (1997)	Simplified empirical and mechanistic equations	Easy to perform Few data requirements Any time step Considers lateral drainage	Numerous simplifying assumptions must be made Steady-state conditions are assumed Essentially all calculations are uncoupled Cannot be used for unsaturated flow	Instructional tool for design of hydraulic barriers Check of computer simulations Parametric evaluations Calculation of peak lateral drainage from cover system
HELP	Schroeder et al. (1994a, 1994b) for EPA	Quasi 2-D water-routing model with multiple uncoupled subroutines Simplified empirical and mechanistic equations Simplified unsaturated flow model with unit hydraulic gradient	Widely accepted Used to design hydraulic barriers Easy to run simulations Default database of climatic, soils, and vegetation data Considers lateral drainage	Does not solve unsaturated flow equations Demonstrated overprediction of percolation in many cases Limited to daily climatic data	Design of hydraulic barriers Regulatory compliance demonstrations Parametric evaluations Calculation of peak lateral drainage from cover system
LEACHM	Hutson and Wagenet (1992) for Cornell University	Finite difference model with unsaturated flow model based on Richards' partial differential equation User specified boundary conditions	Mechanistic model Solves unsaturated flow equation May give a better estimate of ET in arid climates than other models	Maximum soil profile depth of 2 m Does not consider lateral drainage	Design of ET and capillary barriers (no lateral flow) Parametric evaluations Unsaturated flow analysis
UNSAT-H	Fayer and Jones (1990) for Pacific Northwest Laboratory	Finite difference model with unsaturated flow model based on Richards' partial differential equation User specified boundary conditions	Mechanistic model Solves unsaturated flow equation Flexibility in definition of unsaturated hydraulic conductivity-head-moisture content relationships	High computational demands Unsuitable for parametric evaluation Does not consider lateral drainage	Performance assessment of ET and capillary barriers (no lateral flow) Calibration with field data prior to making long-term predictions Unsaturated flow analysis

Table 4-1. Comparison of select water balance models (continued).

Model	Reference	Calculation Scheme	Advantages	Disadvantages	Appropriate Use
SoilCover	SoilCover (2000)	Finite element model with unsaturated flow model based on Richards' partial differential equation User specified boundary conditions	Mechanistic model Solves unsaturated flow equation Calculates actual evaporation based on matric suction at soil surface Easy to create input files with spreadsheet user interface	Limited boundary condition options High computational demands Maximum of 8 soil layers Maximum of 100 nodes Does not consider lateral drainage Requires temperature input	Performance assessment of ET and capillary barriers (no lateral flow) Unsaturated flow analysis
Hydrus 2-D	Šimůnek et al. (1999) for U.S. Salinity Laboratory	Two-dimensional finite element model with unsaturated flow model based on Richards' partial differential equation User specified boundary conditions	Mechanistic model Solves unsaturated flow equation Flexibility in definition of unsaturated hydraulic conductivity-head-moisture content relationships Considers lateral flow and anisotropy Inverse estimation of hydraulic properties from measured data Considers spatial heterogeneity	High computational demands Does not include vapor flow Does not calculate PET from climatic data Not in public domain	Performance assessment of ET and capillary barriers with lateral flow Calibration with field data prior to making long-term predictions Unsaturated flow analysis

Table 4-2. Example spreadsheet for simplified manual water balance method (Koerner and Daniel, 1997).

Row	Parameter	Reference	January	February	March	April	May	June	July	August	September	October	November	December	Total
A	Avg. Monthly Temp, °C	Input Data													
B	Monthly Heat Index (H_m)	Eq. 4.7													
C	Unadjusted Daily PET (UPET), mm	Eqs. 4.8 and 4.9													
D	Possible Monthly Duration of Sunlight (N)	Table 4.3 or 4.4													
E	PET, mm	PET = UPET - N													
F	Precipitation (P), mm	Input Data													
G	Runoff Coefficient (C)	See Table 4.1													
H	Runoff (R), mm	R = P – C													
I	Infiltration (IN), mm	IN = P – R													
J	IN – PET, mm														
K	Accumulated Water Loss (WL), mm	$WL = \sum(IN - PET)_{<0}$													
L	Water Stored (WS), mm	Section 4.3.1.12													
M	Change in Water Storage (CWS), mm	Section 4.3.1.13													
N	Actual ET (AET), mm	Eq. 4.16													
O	Percolation (PERC), mm	Eq. 4.18													
P	Check (CK), mm	Eq. 4.19													
Q	Percolation Rate (FLUX), m/s	Eq. 4.20													

If water does not flow laterally through an internal drainage layer, percolation through the hydraulic barrier is equal to percolation through the cover soil (i.e., PERC* = PERC). Conversely, if lateral flow occurs:

$$PERC^* = PERC + L \qquad \text{(Eq. 4.4)}$$

where all terms are as defined previously. In the simplified manual method, Eq. 4.4 is solved iteratively since both PERC and L are a function of hydraulic head.

Assuming steady-state conditions, the maximum flow in the internal drainage layer is calculated as:

$$q_m = \frac{\ell L}{8.64 \text{ x } 10^7} = \frac{\ell \left(PERC^* - PERC\right)}{8.64 \text{ x } 10^7} \qquad \text{(Eq. 4.5)}$$

where: q_m = maximum flow rate in drainage layer per unit width perpendicular to the direction of flow (m^3/s/m);λ = slope length (m); and other terms are as defined previously. The hydraulic transmissivity of the drainage layer must be adequate to accommodate this flow. The flow capacity of drainage layers was discussed in 2.4.2.3. Hydraulic design of drainage layers is discussed subsequently in Sections 4.5 and 4.6.

Koerner and Daniel (1997) recommend that the hydraulic requirements of a cover system drainage layer be evaluated based on a single storm event. They conservatively suggest that, for design, the cover soil above the drainage layer be assumed to be saturated and that percolation through the cover soil be set equal to infiltration into the cover soil (i.e., ET = 0 and $\Delta W_{soil} = 0$). For these conditions:

$$PERC^* = P - R \qquad \text{(Eq. 4.6)}$$

where all terms are as defined previously. Applying the rational formula to the calculation of R leads to:

$$PERC^* = P\ (1 - C_r) \qquad \text{(Eq. 4.7)}$$

where: C_r = runoff coefficient (dimensionless) obtained from Table 4-3 or project-specific information.

Eq. 4.7 was developed assuming that: (i) the cover soil is at field capacity before the storm begins; (ii) there is no ET during the storm; and (iii) the cover soil is sufficiently permeable to accept the calculated infiltration. To account for this last condition, Koerner and Daniel (1997) suggest that PERC* calculated with Eq. 4.7 be adjusted in accordance with Thiel and Stewart (1993) using Eq. 4.8a or 4.8b, depending on a comparison of the rate at which water becomes available for infiltration to the saturated hydraulic conductivity of the cover soil.

Table 4-3. Runoff coefficients (from Fenn et al., 1975) suggested by Koerner and Daniel (1997) for simplified manual water balance calculations.

Soil Description	Slope	Runoff coefficient
Sandy Soil	Flat (≤ 2%)	0.05 - 0.10
Sandy Soil	Average (2 - 7%)	0.10 - 0.15
Sandy soil	Steep (≥ 7%)	0.15 - 0.20
Clayey Soil	Flat (≤ 2%)	0.13 - 0.17
Clayey Soil	Average (2 - 7%)	0.18 - 0.22
Clayey Soil	Steep (≥ 7%)	0.25 - 0.35

$$PERC^* = P(1 - C_r) \quad \text{when} \quad k_{cs} \geq P(1 - C_r) \qquad \text{(Eq. 4.8a)}$$

$$PERC^* = k_{cs} \quad \text{when} \quad k_{cs} \geq P(1 - C_r) \qquad \text{(Eq. 4.8b)}$$

where: k_{cs} = the cover soil saturated hydraulic conductivity in the same units as P. Eq. 4.8 can be used to develop a conservative estimate of peak flow into a lateral drainage layer during a single storm event, a capability available in only one (i.e., HYDRUS-2D) of the other water balance models considered in this chapter.

In the simplified manual method, percolation through CCL or GCL barriers is calculated using Darcy's equation, which describes the flow of fluids through porous media. Percolation through GM and composite liners is calculated by Koerner and Daniel using the leakage rate equations developed by Giroud and Bonaparte (1989a,b). Hydraulic head is an input parameter to these equations. It is suggested that the maximum hydraulic head calculated on a monthly basis (h_m as derived subsequently) be used to calculate leakage rates through hydraulic barriers.

Input data needs for the simplified manual method are minimal. Only precipitation and mean temperature data are required. Koerner and Daniel (1997) provide guidance for selecting all other parameters (e.g., runoff coefficient, root zone depth, and soil water storage capacity). The advantages of the method are its simplicity, ability to use a variable time step, and ability to calculate lateral flows in cover system drainage layers. The main disadvantages of the method are the steady-state nature of all calculations and the numerous simplifying assumptions. Nonetheless when appropriately used, the simplified manual method presents an acceptable approach to the design of hydraulic barrier type final cover systems. The method is in no way adequate as a simulation or predictive tool, nor is it applicable to the analysis or design of capillary barriers or ET barriers.

4.2.3.2 HELP

The HELP computer code was developed by the U.S. Army Corps of Engineers Waterways Experiment Station (WES) for EPA to enable design engineers to compare the relative hydraulic performance of alternative waste containment system designs (Schroeder et al., 1994a, 1994b). Increasingly, HELP is being used to calculate percolation rates through cover systems and peak hydraulic heads in cover systems for slope stability analyses. HELP has been updated extensively since its inception. At the time of this writing, HELP Version 3.07 is the most recent revision. The documentation for HELP by Schroeder et al. (1994a, 1994b) can be purchased from the National Technical Information Service ((800) 553-6847), downloaded from the USEPA website at http://www.epa.gov/cincl/, or downloaded from the WES website at http://www.wes.army.mil/el/elmodels. The most recent version of the code can be downloaded from the WES website. Additional guidance on using HELP to evaluate landfill hydrologic performance can be found in EPA (1991). Users should use the most current version of the HELP model at the time the analysis is to be performed. Users should also recognize that conclusions drawn from studies using older versions of the model may not be the same as the conclusions that would be drawn using the most current version of the model.

The HELP model simulates hydrologic processes for landfills by performing sequential water balance calculations using a quasi-2-D, gradually varying approach. According to Peyton and Schroeder (1993), the model is considered quasi 2-D because it considers only vertical flow in all layers except lateral drainage layers, where flow can be vertical or lateral. The model is considered gradually varying because the simulation moves through time with the water balance processes being considered steady over each time step. A conceptualization of the HELP model is presented in Figure 4-2. The model can be used to separately evaluate each subprofile shown in Figure 4-2, including the complete cover system profile.

The hydrologic processes considered in the model include precipitation, surface-water storage (i.e., storage as snow), interception of precipitation by foliage, surface-water evaporation, runoff, snow melt, infiltration, plant transpiration, soil water evaporation, soil water storage, vertical flow (saturated and unsaturated) through non-barrier soil layers, vertical percolation (saturated) through soil barriers, vertical percolation (saturated) through GM and GM/soil composite barriers, and lateral drainage (saturated). Five main routines are used in the HELP model to estimate runoff, ET, vertical drainage to barriers, vertical percolation through soil barriers, and lateral or vertical flow (saturated) through lateral drainage layers. Several other routines interact with the main routines to generate daily precipitation, temperature, and solar radiation values and to simulate snow accumulation and melt, vegetative growth, interception, and vertical percolation through GM and GM/soil composite barriers.

Runoff in the HELP model is computed using the runoff curve number method of the USDA SCS) (SCS, 1985). (Note that the Soil Conservation Service (SCS) is now the Natural Resources Conservation Service (NRCS).) The method empirically correlates total runoff with total rainfall based on daily rainfall records, vegetation type, soil type, antecedent moisture conditions (level of soil moisture prior to rainfall), and other factors. The method does not consider the time

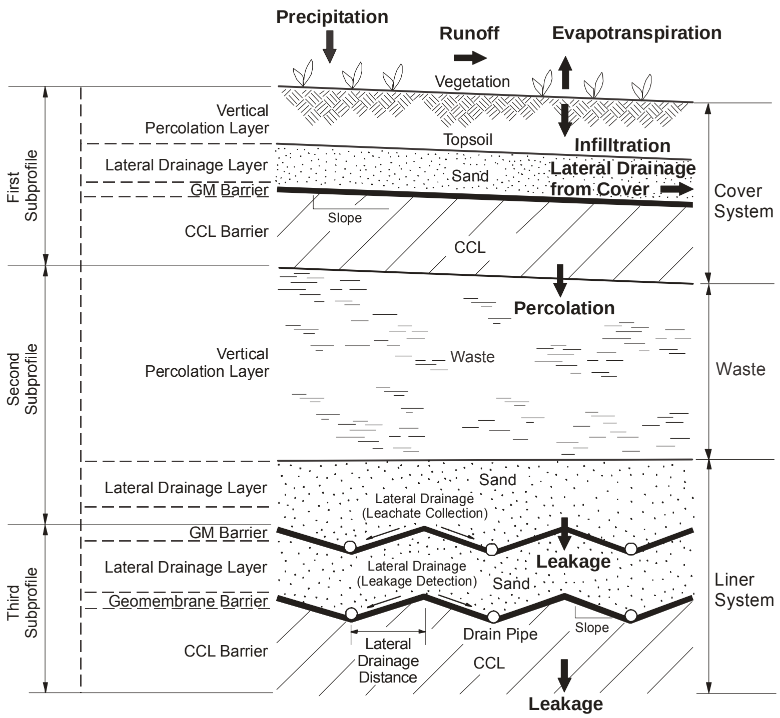


Figure 4-2. Conceptualization of HELP water balance model (from Schroeder et al., 1994a).

distribution of rainfall intensity and, therefore, does not give accurate estimates of runoff volumes for individual storm events. The daily runoff is calculated in the model as:

$$R = \frac{(P - 0.2S_r)^2}{(P + 0.8S_r)} \qquad \text{(Eq. 4.9)}$$

where: S_r = retention parameter (mm/day) dependent on SCS curve number; and R and P are as defined previously. The SCS curve number is a function of soil texture, vegetation quality, and cover system slope length and inclination. Schroeder et al. (1994a) indicate that long-term cumulative runoff should be independent of rainfall duration and intensity, since over a long simulation period a variety of precipitation events will occur. However, McBean et al. (1995) state that use of daily rainfall averages effectively decreases storm intensity (because the duration of most storms is less than 24 hours), resulting in a simulation having an overprediction of infiltration and underprediction of runoff.

ET is computed in HELP by a two-stage modified Penman energy balance method developed by Ritchie (1972). This method uses the PET concept as the basis for prediction of surface and soil water evaporation and plant transpiration. The PET demand is first met by evaporation of water or snow on foliage or on the ground, then soil water evaporation, and finally plant transpiration. ET is assumed to occur within the evaporative zone depth specified by the user and is not allowed to occur within or below a barrier. Also, the soil water content is not allowed to decrease below the wilting point, which is defined in the model as the volumetric water content at a matric potential of -1.5 MPa. Due to these controls, ET may be underestimated in arid climates. Growth and decay of surface vegetation is modeled using an algorithm taken from the Simulator for Water Resources in Rural Basins (SWRRB) model (Arnold et al., 1989).

Vertical drainage for cover soil (i.e., topsoil and protection) layers for both saturated and unsaturated flow conditions is computed using Darcy's equation. HELP assumes that soil pressure head is constant within a vertical percolation layer. Changes in either positive or negative pressure head cannot be modeled. The hydraulic gradient is due to change in elevation head only and is thus equal to 1.0. The HELP model does, however, define an unsaturated hydraulic conductivity to use with the unit hydraulic gradient for calculating unsaturated flow rates. The unsaturated hydraulic conductivity, k_u (m/s), is obtained in the HELP model using Campbell's equation (1974):

$$k_u = k_s\left[(\theta - \theta_r)/(\theta_s - \theta_r)\right]^{3+2/\lambda} \qquad \text{(Eq. 4.10)}$$

where: k_s = saturated hydraulic conductivity of soil layer (m/s); θ = volumetric water content of soil layer (dimensionless); θ_s = volumetric water content of soil layer at saturation (dimensionless); θ_r = residual volumetric water content, typically in the range of 0.01 to 0.10 (dimensionless); and λ = pore size distribution index (dimensionless), calculated as described in Schroeder et al. (1994a,b). As a result of the hybrid formulation given above, the HELP model cannot be used to simulate the physics of water movement through an unsaturated soil layer.

Lateral drainage below a cover soil layer is modeled by an analytical approximation to the steady-state solution of the Boussinesq equation. The peak daily head in a drainage layer is calculated using an equation formulated by McEnroe (1993). Vertical percolation through low-permeability soil hydraulic barriers is evaluated in HELP using Darcy's equation assuming saturated conditions. Vertical percolation through GMs and GM/soil composite barriers is evaluated based on the work of Giroud and Bonaparte (1989a,b) and Giroud et al. (1992a).

The daily water balance is calculated in the HELP model by a linking process, starting with a surface water balance, then ET in the subsurface, and finally subsurface water routing from the surface downward one soil layer at a time. The routing procedure uses a time step that can range from 30 minutes to six hours. However, only daily, monthly, annual, and long-term average output data are reported.

The HELP model requires daily and general climatic data, material properties data for the landfill components being modeled, and landfill design data. One of the strengths of the HELP model is its climatic and material property default data option. Required daily weather data are precipitation, mean temperature, and total global solar radiation. Daily precipitation may be input manually, selected from a historical database (e.g., 1974-1977 data in the HELP database, NOAA Tape, or Climatedata™ files), or generated stochastically using a weather generation model developed by the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) (Richardson and Wright, 1984) with simulation parameters available for 139 U.S. cities. It should be noted that the historic precipitation data in the database for 1974-1977 are often not used because they are for an unusually dry time period in certain parts of the U.S. Other daily climatologic data are generated stochastically using the USDA-ARS routine. Required general weather data include average annual wind speed and latitude. Default general weather data for 183 U.S. cities are used by the model. The material properties of each layer being modeled are either selected from the HELP model database of default material properties or are specified by the model user. Landfill design data, including landfill general information and layer configuration, are user specified.

Due to its method of calculating downward flux and its limiting of upward flux (i.e., no upward flux within or below a barrier), version 3.07 of the HELP model is not considered a particularly accurate simulation model for cover systems located in arid areas where the subtleties of unsaturated moisture movement can dominate the water balance. As will be discussed, there are other water balance models that better simulate the physics of water movement in arid environments.

4.2.3.3 LEACHM Model

LEACHM (Hutson and Wagenet, 1992) is a one-dimensional finite difference code that is finding increasing use in the western United States, particularly California, for design and performance analysis of cover systems with ET barriers. LEACHM was originally developed to simulate the effects of agricultural management alternatives on the movement of water and chemicals in a shallow soil profile (i.e., to a maximum depth of 2 m). Only the hydrologic component of the model will be discussed further. The code and model documentation may be obtained from the Department of Soil, Crop & Atmospheric Sciences at Cornell University, Ithaca, New York.

The LEACHM model considers precipitation, runoff, ET, soil water storage, and percolation in the water balance. Infiltration of water into the soil profile and vertical drainage are simulated using a finite difference solution to Richards' partial differential equation (Richards, 1931). This equation is obtained by combining the differential form of Darcy's equation for unsteady vertical flow with the one-dimensional differential form of the conservation of mass equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[k_u(\theta)\frac{\partial \psi(\theta)}{\partial z} - 1\right] - S(z,t) \qquad \text{(Eq. 4.11)}$$

where: ψ = matric potential (negative) due to capillary suction forces (N/m^2); θ = soil volumetric water content (dimensionless); k_u = unsaturated hydraulic conductivity (m/s); z = vertical coordinate, positive downward (m); t = time (s); and S(z,t) = sink term representing uptake by transpiration (s^{-1}).

Unsaturated soil hydraulic conductivity in LEACHM is calculated using the Campbell (1974) relationship. Precipitation in excess of the infiltration capacity of the soil is shed as runoff. Evaporation and transpiration are modeled separately based on the methods of Childs and Hanks (1975). With this method, the potential evaporation and transpiration are first estimated based on the pan evaporation rate, a pan factor, and a crop cover fraction. The actual evaporation is then calculated as the lesser of the potential evaporation and the possible evaporation calculated using Richards' equation and the selected boundary condition. Any remaining PET demand is applied to transpiration. However, transpiration is not allowed if the matric potential head of the soil is less than –1.5 MPa, the potential assumed to correspond approximately to the soil wilting point.

LEACHM requires that climatic data, soil properties, vegetation data, and initial and boundary conditions be input. Unlike the HELP model, there are no default data; the user must specify each input parameter. Required weather data are precipitation magnitude, rate, and start time, minimum and maximum air temperatures, and pan evaporation rate. The precipitation option allows rainfall data for short, intense storms to be input. Thus, LEACHM may be used to estimate the head of water in the cover system due to a design storm. In the absence of pan evaporation rate data, the rate can be calculated by LEACHM using the Linacre equation (Hutson and Wagenet, 1992) with site-specific data (i.e., latitude, elevation, temperature, and precipitation). Required soil data are bulk dry density, initial moisture content, saturated hydraulic conductivity, and soil water retention curve. If a soil water retention curve is not available, LEACHM contains a routine to compute fitting parameters for Campbell's soil-water retention curve from the particle size distribution, bulk density, and organic matter content of the soil. However, there is considerable uncertainty in the use of the regression equations to compute these parameters. Vegetation data to be input are root depth and distribution, plant growth options (i.e., constant vegetation or growing vegetation), wilting point, minimum root potential, maximum ratio of actual to potential transpiration, root resistance, and plant growth timeline (e.g., germination, emergence, maturity, etc.). Very little guidance is provided in the LEACHM model documentation on selection of values for the various input parameters.

To set up the finite difference grid used by LEACHM, the soil profile is divided into a number of horizontal layers of equal thickness with nodes at the center of each layer. Soil properties are then specified for each layer. Two additional nodes are required for boundary conditions, one above the ground surface and one below the profile being modeled. The upper boundary condition can be changed with time by adjusting the head to simulate ponded or non-ponded infiltration, evaporation, or zero flux. The lower boundary condition can be selected as a fixed water table, free drainage (or unit gradient), zero flux, or lysimeter boundary. The initial condition is specified by assigning an initial head or water content to each node in the finite-difference nodal grid. Simulation output includes cumulative infiltration, evaporation, transpiration, and percolation at select times.

4.2.3.4 UNSAT-H

UNSAT-H is a one-dimensional finite-difference water balance model developed at Pacific Northwest Laboratory (Fayer and Jones, 1990) to assess the water dynamics of waste disposal facilities at the U.S. Department of Energy (DOE) Hanford site. The model also simulates soil heat flow and nonisothermal vapor flow. Vapor flow can be an important transport mechanism in near surface soils at arid sites. The UNSAT-H model was derived from the UNSAT model of Gupta et al. (1978) and has retained many of the same routines. At the time of this writing, Version 3.0 of UNSAT-H was the most current. The code can be obtained from the Energy Science and Technology Software Center, Department of Energy, Oak Ridge, Tennessee.

The UNSAT-H model considers precipitation, runoff, ET, soil water storage, and percolation in the water balance. Like the LEACHM model, infiltration of water into, and vertical movement of moisture in, the soil profile is governed in the UNSAT-H model by a finite difference solution to Richards' partial differential equation. However, the unsaturated soil hydraulic conductivity term in the UNSAT-H model is calculated using polynomials, Haverkamp functions, Brooks-Corey functions, or van Genuchten functions rather than the Campbell equation. Precipitation in excess of the infiltration capacity of the soil is shed as runoff. Evaporation and transpiration are considered separately.

Evaporation in the UNSAT-H model is calculated using one of two approaches: (i) an integrated form of Fick's law of diffusion that considers the flow of heat to and from the soil surface, the flow of water from the subsurface to the soil surface, and the transfer of water vapor from the soil surface to the atmosphere; or (ii) a Penman-type equation that is a modification of the diffusion equation and is dependent on net radiation and soil heat flux rather than on soil-surface temperature. Transpiration is calculated using a method based on leaf-area index or cheatgrass data and is limited by PET.

The UNSAT-H model requires that climatic data, soil properties, vegetation data, and initial and boundary conditions be input. There are no default data; the user must specify each input parameter. Required data for the meteorological data option are daily precipitation, daily maximum and minimum air temperatures, daily solar radiation, average daily dew point, and average daily wind speed. Daily precipitation and PET may be input instead of daily meteorological data. The precipitation option allows rainfall data for short, intense storms to be input. Required soil data are fitting parameters for the soil water characteristic functions and the unsaturated hydraulic conductivity functions. An option for including hysteresis is available. Vegetation data to be input include root depth, leaf area index, growing season, and percent bare area. Very little guidance is provided in the UNSAT-H model documentation on selection of values for the various input parameters.

The finite difference grid used by UNSAT-H is set up in a manner similar to that for LEACHM. The soil profile is divided into a number of horizontal layers with nodes located at the center of each layer. Two additional nodes, one above the ground surface and one below the profile being modeled, are used to set boundary conditions. The upper boundary condition can be changed with time by adjusting the head to simulate ponded or non-ponded infiltration, evaporation, or zero flux. The lower boundary condition can be selected as a fixed water table, free drainage (or unit gradient), zero flux, or specified flux boundary. The initial condition is specified by assigning an initial head or water content to each node in the finite-difference nodal grid. Simulation output includes infiltration, evaporation, transpiration, and percolation at hourly or daily intervals.

4.2.3.5 SoilCover

SoilCover model was developed in 1990 at the University of Saskatchewan for the analysis of the flow of water and heat between the atmosphere and the soil surface, particularly for land based disposal systems. Since then the model has been modified by Geo-Analysis 2000 Ltd., Saskatoon, Canada to include oxygen diffusion, an enhanced vegetation routine, freeze/thaw considerations, and soil property function revisions. SoilCover Version 5.2 was the most recent release at the time of this writing. The code and accompanying user's manual is available for download from http://www.members.shaw.ca/geo2000/page12.html.

SoilCover uses a finite-element method to solve the one-dimensional heat and mass transfer partial differential equations derived by Wilson (1990). The mass transfer equation is obtained by combining the differential forms of Darcy's law and Fick's law for unsteady vertical flow with the one-dimensional differential form of the conservation of mass equation. Both liquid flow and nonisothermal vapor flow are incorporated into the model. There is no option for isothermal vapor flow, nor is there an option for shutting off vapor flow altogether like is available with UNSAT-H. The unsaturated hydraulic conductivity function in the SoilCover model may be either user-defined (i.e., tabulated data) or predicted based on a Fredlund-Xing curve (Fredlund and Xing, 1994) fit to the water content versus matric potential data. The method used to predict the unsaturated hydraulic conductivity function was developed by Fredlund et al. (1994), and, according to SoilCover (2000), is especially well-suited for modeling fine-grained soils. Precipitation, runoff, ET, soil water storage, and percolation are included in the water balance.

SoilCover calculates evaporation using a modified Penman equation developed by Wilson (1990):

$$E_v = \frac{\Gamma R_n + \nu\left[0.35(1 + 0.15U_a)P_a\left(\frac{1}{h_a} - \frac{1}{h_r}\right)\right]}{\Gamma + \frac{\nu}{h_r}} \qquad \text{(Eq. 4.12)}$$

where: E_v = vertical evaporative flux (mm/day); Γ = slope of the saturation vapor pressure versus temperature curve at the mean temperature of the air (dimensionless); R_n = net radiant energy available at the surface (mm/day); ν = psychrometric constant (dimensionless); U_a= wind speed (km/hr); P_a = vapor pressure in the air above the evaporating surface (Pa); h_a = relative humidity of the air (dimensionless); and h_r = relative humidity at the soil surface (dimensionless). The model also offers the option of calculating evaporation based on user-input PET, in which case it uses the following equation:

$$E_v = PET\left[\frac{(h_r - h_a)}{(1 - h_a)}\right] \qquad \text{(Eq. 4.13)}$$

where all terms are as defined previously. Unlike the other models described in this report, SoilCover calculates evaporation as a sink term directly from the surface relative humidity, which is a function of the matric suction and the temperature at the soil surface. The developers of SoilCover claim this method of calculating evaporation is a strength of the model.

Runoff is calculated as any precipitation that cannot infiltrate. Transpiration is calculated by applying fluxes at nodes in the root zone. Plant water stress and canopy shading effects are also considered by SoilCover.

The SoilCover model requires that climatic data, soil properties, vegetation data, and initial and boundary conditions be input Required climatic data include daily maximum and minimum air temperature, daily net radiation, daily maximum and minimum relative humidity, and daily wind speed. If the option for entering daily PET is chosen, then daily net radiation and wind speed are not required. Precipitation is entered on a daily basis as a constant flux top boundary condition, but intensity may be accounted for by constraining the precipitation between specified hours. Climatic data input is relatively easy because of the SoilCover's Microsoft Excel user interface. Daily data may be copied from a spreadsheet source and pasted directly into SoilCover.

Properties for up to eight soils may be entered. Required soil properties are porosity, specific gravity, saturated hydraulic conductivity, and coefficient of volume change. In addition, up to 20 water content vs. suction data points may be input. SoilCover then fits the Fredlund-Xing (1994) soil-water characteristic function to the data points. The unsaturated hydraulic conductivity function, the thermal conductivity function, and the volumetric specific heat function can then be generated using the fit soil-water characteristic function. The user may also choose to enter tabulated data for these functions. Very little guidance is provided in the SoilCover user's manual on selection of values for the various input parameters, however a short list of coefficients of volume change for typical soils is provided. Required input parameters for vegetation include growing season start and stop day, moisture wilting and limiting points, daily depths to top and bottom of roots, and selection of either poor, good, or excellent grass quality

The bottom boundary condition may be specified as either constant pressure or constant water content. There is no option for constant flux, constant gradient, or seepage face lower boundary conditions. The sparse lower boundary condition options necessitate that the user pay very close attention to the bottom boundary fluxes throughout the duration of the simulation to ensure that a realistic boundary is being modeled. For many landfill cover simulations, including a coarse-grained soil beneath the soil profile and adjusting the value of the bottom boundary condition is necessary to avoid "wicking" water from the boundary condition itself. If a gravel layer is added below the profile, percolation results may be obtained by utilizing the SoilCover option of cumulating fluxes at a selected internal node. The bottom temperature boundary condition must also be specified on a daily basis.

The finite element mesh is generated by SoilCover from input depths and thickness of the soil layers. Maximum and minimum node spacing for each layer must be specified along with the node spacing expansion factor. Only 100 nodes are permitted, so spacing and expansion factors may need to be adjusted. Initial conditions (either water content or suction) are also assigned to each node based on the initial conditions input for the top and bottom of each layer. SoilCover linearly interpolates the initial conditions. However, the assigned initial conditions may be overwritten by the user after the mesh has been generated. Simulation output includes infiltration, evaporation, transpiration, and percolation at daily intervals.

4.2.3.6 HYDRUS-2D

HYDRUS-2D is a two-dimensional unsaturated flow model developed at the U.S. Salinity Laboratory (Šimůnek et al., 1999). The model also simulates heat flow and solute transport. The current model is an extension of the earlier unsaturated flow codes SWMS_2D and CHAIN_2D. At the time of this writing version 2.02 of HYDRUS-2D was the most current. The model may be purchased from the International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado or http://www.Mines.EDU/research/igwmc/software/igwmcsoft/. The documentation and a free demo version of HYDRUS-2D may be downloaded from http://www.ussl.ars.usda.gov/models/hydrus2d/htm.

HYDRUS-2D uses a finite element method to solve Richards' equation in a plane oriented either vertically or horizontally. The two-dimensional domain may take on any geometric shape. Because the model is two-dimensional, lateral flow and anisotropy may be simulated. A sink term is included in Richards' equation for removal of water via plant transpiration. Vapor flow cannot be simulated. The model has an option for allowing soil properties to be temperature dependent, and it also allows hysteresis and spatial variability through a scaling transformation. The unsaturated hydraulic conductivity is calculated by either a Brooks-Corey, van Genuchten-Mualem, or modified van Genuchten method. Precipitation, runoff, ET, soil water storage, and percolation are included in the water balance.

Precipitation and potential evaporation are the only climatic inputs required. HYDRUS-2D does not have an option for internally calculating potential evaporation, so the user must use another model or method to generate data to input. Vegetation parameters required include the heads between which transpiration occurs and also the heads between which transpiration is optimal. A menu containing a variety of properties for plants is available. The distribution of roots must also be specified. Input required for soil properties includes saturated hydraulic conductivity and fitting parameters from the selected soil-water retention function. A menu of soil properties is available. In addition, van Genuchten properties can be predicted by inputting the percentage of sand, silt and clay, density, field capacity, and/or wilting point water content. HYDRUS-2D also has the option for inverse estimation of soil hydraulic properties from measured flow data.

The two-dimensional profile is created through a pre-processing module called Meshgen2D within the HYDRUS-2D graphical user interface. After the domain geometry is defined, Meshgen2D assists in generating the finite element mesh.

Boundary conditions may be specified flux, specified pressure head, unit gradient, atmospheric, seepage face, or deep drainage. Precipitation and potential evaporation are specified using the atmospheric option, which allows the boundary condition at the soil surface to change from either prescribed flux or prescribed head. The user inputs the upper and lower limits of head for which the prescribed flux boundary operates. Therefore, evaporation and precipitation will proceed at the potential rate until the soil surface dries or wets to a specified head. Once below the specified head, the boundary changes to a prescribed head boundary condition, and evaporation is limited by the ability of water to flow to the surface. If the surface becomes saturated during precipitation, excess precipitation is removed as runoff. The seepage face option allows water to exit the domain when the soil adjacent to the boundary becomes saturated. Deep drainage provides an option for a variable flux depending on the level of the groundwater table. Initial conditions may be specified as either water contents or pressure heads.

The HYDRUS-2D post-processor allows a variety of options for viewing output. Results can be displayed graphically, including an animation of changes in pressure head or water content through time. Cross-sections plotting pressure head or water content vs. depth or length may be taken from the profile at any time of the simulation. Other output options include viewing the instantaneous or cumulative water boundary fluxes over time, run time information, graphical display of soil hydraulic properties, or converting output to ASCII format.

4.3 Evaluation of Water Balance Models

4.3.1 Overview

A number of researchers have performed field studies and analytical assessments to evaluate the HELP, LEACHM,UNSAT-H, SoilCover, and HYDRUS-2D models (Thompson and Tyler, 1984; Peters et al., 1986; Barnes and Rodgers, 1988; Peyton and Schroeder, 1988; Nyhan, 1989; Wilson, 1990; Nichols, 1991; Udoh, 1991; Fayer et al., 1992; Lane et al., 1992; Benson et al., 1993; Peyton and Schroeder, 1993; Martian, 1994; Tratch, 1994; Fleenor and King, 1995; Khire, 1995; Khire et al., 1997; Webb et al., 1997; Zornberg and Caldwell, 1998; Scanlon et al., 2002). These studies were used to either simulate field or laboratory water balance data or to investigate trends and magnitudes of the different water balance components (i.e., infiltration, runoff, etc.). The conclusions of these studies are not always in general agreement. For example, some studies found that a certain model overpredicted or underpredicted infiltration or percolation in a certain climate, whereas, other studies using the same model concluded just the opposite. In many of the comparisons between measured and calculated water balances, site-specific field data were used in the water balance predictions. However, in the current state of practice for the majority of projects, measurement of site-specific parameters required for the models, such as soil field capacity, wilting point, and evaporation depth or rooting depth, is not performed. Thus, the model user is left to depend on default data, which may lead to an inaccurate representation of a site. At present, these hydrologic models should be used carefully to ensure a conservative and reasonable basis for design. As a true predictive tool, the value of the models is limited unless site-specific calibrations are performed. The results of a few of the more significant field studies are presented below.

4.3.2 Lysimeters at DOE Hanford Site

Fayer et al. (1992) compared field water balances for eight unvegetated lysimeters at DOE's Hanford site to water balances simulated using the UNSAT-H, Version 2 model. The Hanford site is located about 35 km northwest of Richland, Washington, in the northern cold desert of the Columbia Basin. Average annual rainfall at the site is only 162 mm and average potential evaporation is 1,600 mm (Gee et al., 1994). On average, over 70% of precipitation falls during October through April. The soil profile in the lysimeters and the simplified profile used for simulations are shown in Figure 4-3. The uppermost soil in the lysimeters is a silt loam material. The soil profile in the lysimeters is intended to simulate a capillary barrier.

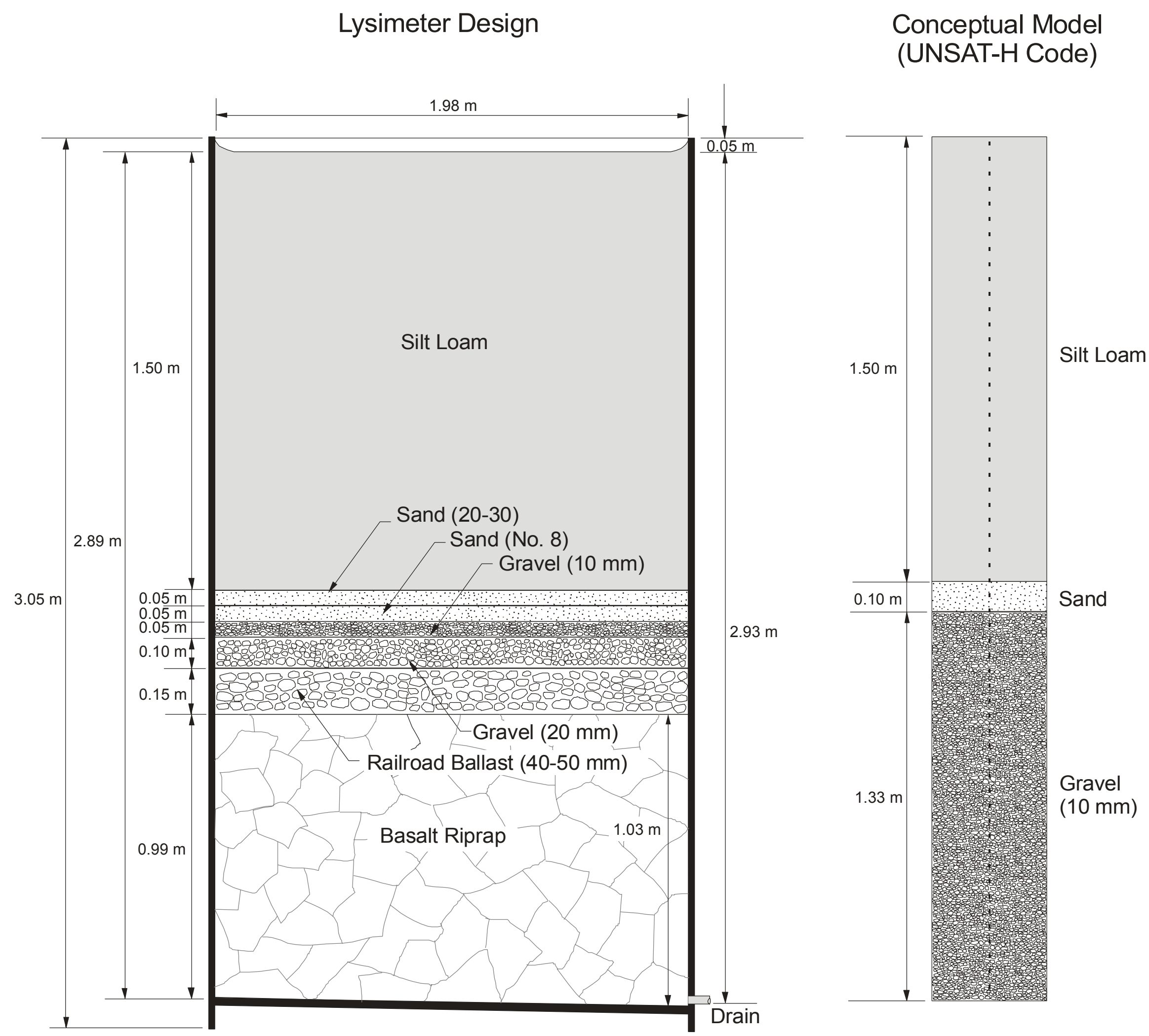


Figure 4-3. Lysimeter design and conceptual model used to compare measured and simulated water balance for DOE Hanford site (from Fayer et al., 1992).

Of the eight lysimeters constructed by Fayer et al. (1992), six were drainage lysimeters and two were weighing lysimeters. The drainage lysimeters comprised two replicates of three precipitation treatments: (i) ambient; (ii) two times the average annual precipitation; and (iii) breakthrough (i.e., water added until drainage occurred). The weighing lysimeters served as additional replicates, with one of the lysimeters receiving the normal precipitation and the other receiving two times the average annual precipitation. Soil water content and percolation data were collected for the lysimeters from November 1987 to April 1989.

The field water balances for the lysimeters were compared to water balance simulations performed using UNSAT-H. The simulations were performed with actual weather data from a nearby meteorological station, measured soil properties data for the silt loam, and assumed properties for the sand and gravel layers beneath the silt loam. The lower boundary of the drainage lysimeters was modeled as a unit gradient and the lower boundary of the weighing lysimeters was represented as a zero-flux condition. The upper boundary condition was allowed to vary depending on climatic conditions.

Measured and simulated water contents for the drainage lysimeters under the three precipitation conditions are shown in Figures 4-4 to 4-6. Measurable percolation only drained from the lysimeters with the “breakthrough” precipitation treatment. In general, the simulated soil water profiles showed reasonable agreement with measured water contents. However, UNSAT-H tended to underestimate somewhat the amount of soil water storage during the spring and overestimate the amount of soil water storage during the winter. Fayer et al. (1992) attributed this discrepancy primarily to the underestimation of evaporation in the winter and the overestimation of evaporation in the summer. This effect is also apparent in the plot of measured and simulated soil water storage in Figure 4-7(a). By decreasing evaporation, increasing the saturated hydraulic conductivity of the silt loam, and adding a snow cover, simulated soil water storage shows better agreement with measured soil water storage (Figure 4-7 (b)).

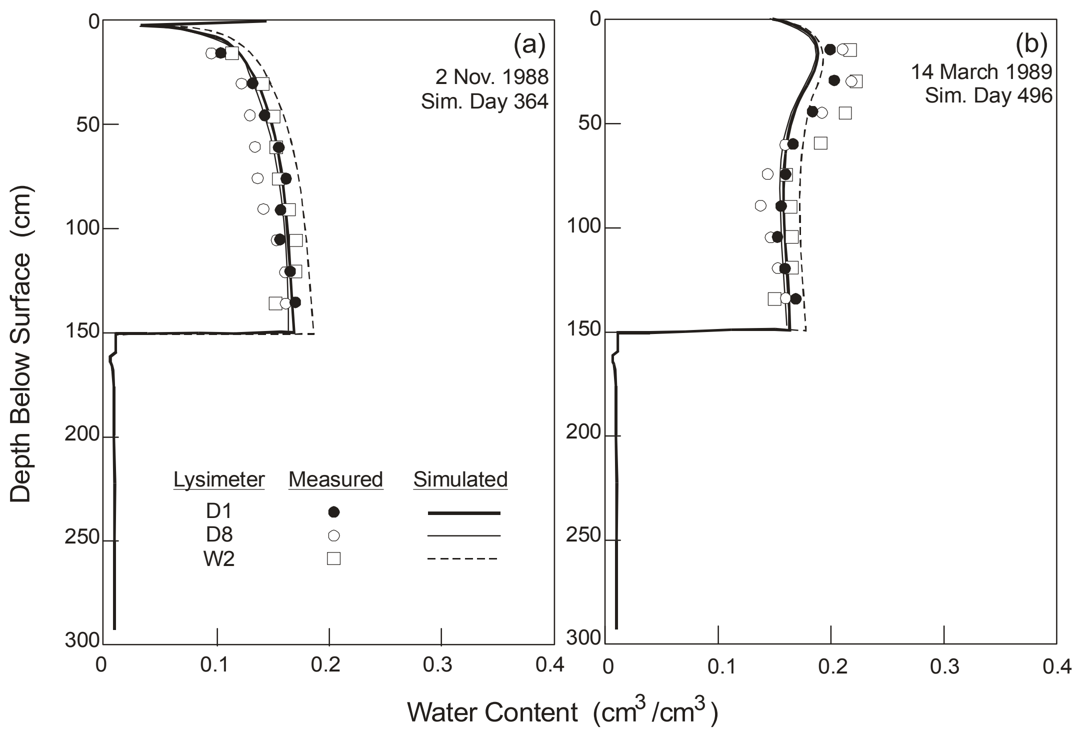


Figure 4-4. Measured and simulated (UNSAT-H) water contents for the ambient precipitation treatment at DOE Hanford lysimeters (from Fayer et al., 1992).

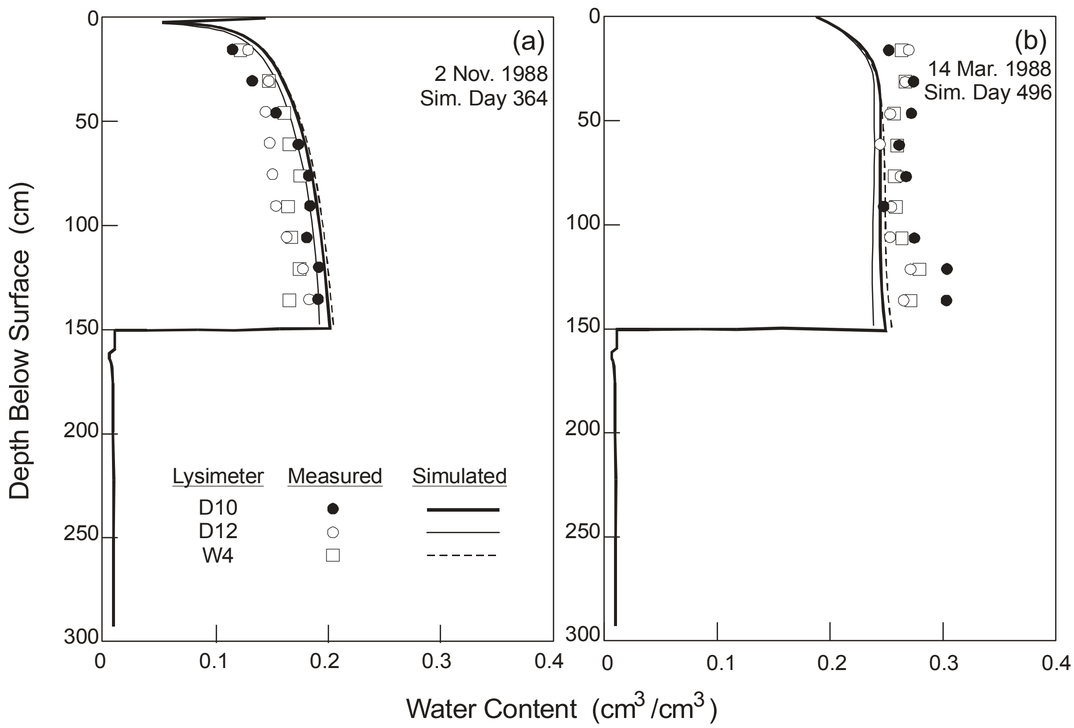


Figure 4-5. Measured and simulated (UNSAT-H) water contents for the 2x average precipitation treatment at DOE Hanford lysimeters (from Fayer et al., 1992).

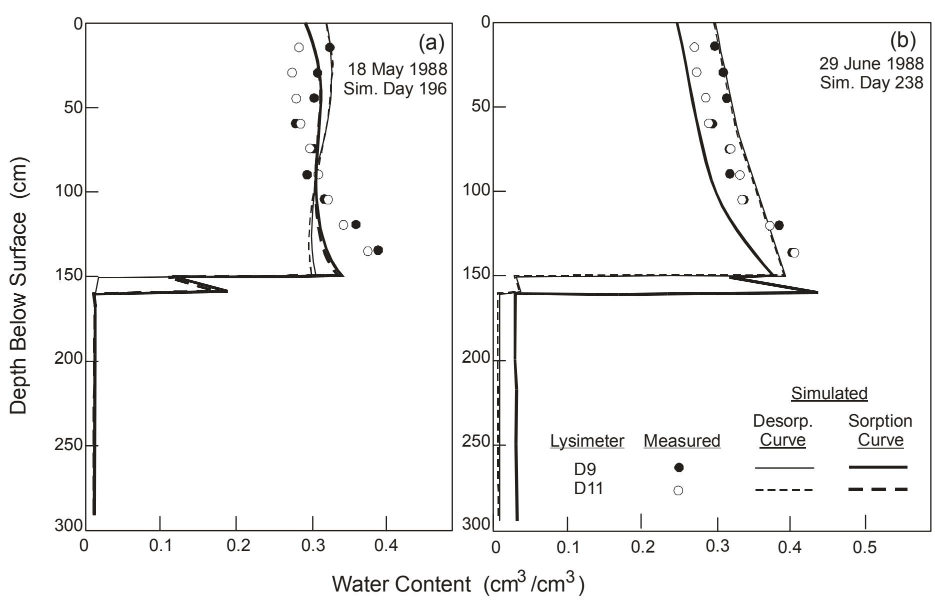


Figure 4-6. Measured and simulated (UNSAT-H) water contents for the breakthrough precipitation treatment at DOE Hanford lysimeters (from Fayer et al., 1992).

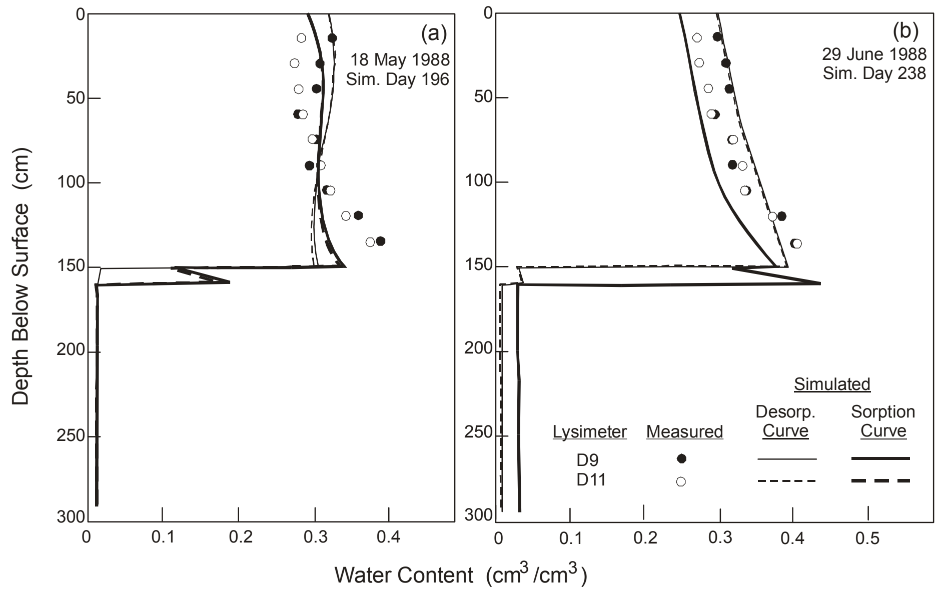


Figure 4-7. Measured and simulated (UNSAT-H) water storage for the 2x average precipitation treatment at DOE Hanford lysimeters: (a) initial simulation; (b) simulation with improved calibration (from Fayer et al., 1992).

4.3.3 Test Plots at Hill Air Force Base

Paige et al. (1996) described calibrating Version 2 of the HELP model to field measurements from two cover system test plots constructed at Hill Air Force Base (Hill AFB), in Layton, Utah and monitored for a four-year period. The calibrated models were then used to simulate the long-term performance of the cover systems. One test plot had an ET-type soil cover ("control soil cover") consisting of a 0.9-m thick sandy loam topsoil layer. The other test plot had a cover system consisting of the following components, from top to bottom: 1.2-m thick sandy loam topsoil layer; 0.3-m thick sand lateral drainage layer; and 0.6-m thick CCL. Both cover systems were constructed over a 0.3-m thick gravel layer with lysimeters so that percolation could be monitored. Cross sections of the cover systems are shown in Figure 4-8. After construction, the plots were vegetated with native grasses. Water balance data measured over the four-year monitoring period include precipitation, lateral flow in the sand drainage layer, percolation, soil moisture content, and runoff.

Using the HELP model default values for the ET-type cover, HELP overpredicted annual ET by approximately 30% and underpredicted annual percolation by approximately 95%. For the hydraulic barrier-type cover, ET was overpredicted by 48%, runoff was overpredicted by 150%, and lateral drainage was underpredicted by 97% when the HELP model was run with default values. The HELP model was subsequently calibrated to the field water balances primarily by modifying the soil properties of the cover systems (e.g., saturated hydraulic conductivity, soil water storage capacity). The measured and calibrated values of the water balances for the ET-type cover system and the hydraulic barrier-type cover system are shown in Tables 4-4 and 4-5, respectively. As can be seen from these tables, even with the site-specific calibration, significant differences between field and simulated water balance components occurred. In particular, for the ET cover system, correlation between measured and predicted percolation was not good.

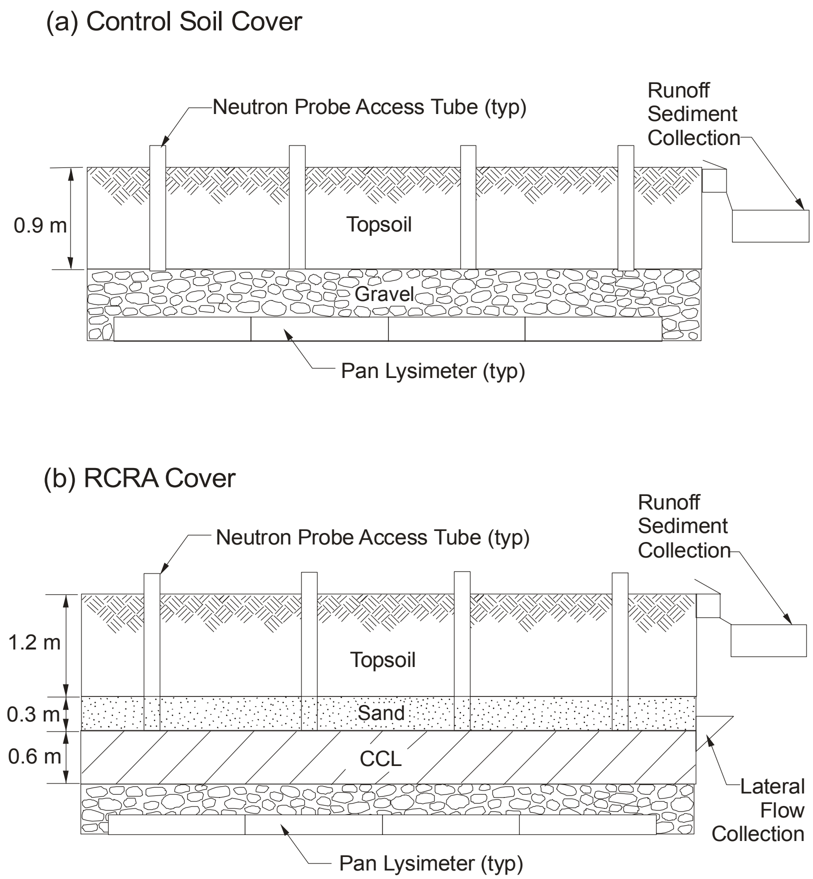


Figure 4-8. Hill Air Force Base test plots: (a) ET-type cover system; and (b) hydraulic barrier-type soil cover system (from Paige et al., 1996).

Table 4-4. Difference between measured annual values and HELP simulation values for the control ET-type cover system at Hill AFB (modified from Paige et al., 1996). Results obtained using input parameters calibrated from site water balance data.

Water Balance Variable	Measured		HELP Predicted		Difference	
	(cm)	(% meas. precip.)	(cm)	(% pred. precip.)	(cm)	(% meas. precip.)
1991						
Precip.	53.72	100.00	53.70	100.00	-	-
Runoff	1.50	2.79	1.14	2.14	0.36	0.67
Perc.	9.09	16.93	17.09	31.84	-8.00	-14.90
ET	34.70	64.58	34.64	64.53	0.06	0.11
Soil water[1]	8.43	15.70	0.81	1.49	7.62	14.19
1992						
Precip.	39.09	100.00	39.26	100.00	-	-
Runoff	0.10	0.26	0.25	0.63	-0.15	-0.38
Perc.	5.79	14.81	10.84	27.62	-5.05	-12.92
ET	33.30	85.18	28.47	72.50	4.83	12.36
Soil water	-0.10	-0.26	-0.30	-0.75	0.20	0.51
1993						
Precip.	41.78	100.00	41.85	100.00	-	-
Runoff	0.25	0.61	0.61	1.49	-0.36	-0.86
Perc.	23.80	56.96	10.49	25.08	13.31	31.86
ET	30.66	73.37	32.18	76.88	-1.52	-3.64
Soil water	12.93	-30.94	-1.44	-3.44	14.37	34.39

[1] Change in soil water storage.

Table 4-5. Difference between measured annual values and HELP simulation values for the control soil cover system at Hill AFB (modified from Paige et al., 1996). Results obtained using input parameters calibrated from site water balance data.

Water Balance Variable	Measured		HELP Predicted		Difference	
	(cm)	(% meas. precip.)	(cm)	(% pred. precip.)	(cm)	(% meas. precip.)
1991						
Precip.	53.72	100.00	53.70	100.00	-	-
Runoff	1.14	2.13	0.84	1.57	0.30	0.56
Lat. Drain	19.00	35.37	17.25	32.11	1.75	3.26
Perc.	0.00	0.00	0.28	0.51	-0.28	-0.52
ET	24.59	45.77	34.36	63.98	-9.77	-18.19
Soil water[1]	8.99	16.73	0.99	1.84	8.00	14.89
1992						
Precip.	39.09	100.00	39.26	100.00	-	-
Runoff	0.05	0.13	0.13	0.32	-0.08	-0.20
Lat. Drain	6.70	17.15	11.23	28.60	-4.53	-11.59
Perc.	0.00	0.00	0.28	0.69	-0.28	-0.72
ET	30.12	77.06	27.86	70.99	2.26	5.78
Soil water	2.21	5.65	-0.22	-0.59	2.43	6.22
1993						
Precip.	41.78	100.00	41.85	100.00	-	
Runoff	0.71	1.70	0.43	1.02	0.28	0.67
Lat. Drain	23.32	55.80	11.10	26.53	12.22	29.25
Perc.	0.00	0.00	0.28	0.64	-0.28	-0.67
ET	27.94	66.87	31.80	75.96	-3.86	-9.24
Soil water	-10.18	-24.37	-1.73	-4.16	-11.91	-28.51

[1] Change in soil water storage.

4.3.4 Test Plots in Live Oak, Georgia and Wenatchee, Washington

Of all the available studies, the one reported by Lane (1992), Khire (1995), and Khire et al. (1997, 1999) is perhaps most interesting because of the scope and practical applicability of the study to cover system analysis and design. The study involves field water balance evaluations for three 30 m x 30 m cover system test plots at two landfills, one near Atlanta, Georgia ("Live Oak") and the other near East Wenatchee, Washington ("Wenatchee"). The sites were selected to represent humid and semi-arid climates, respectively. The Live Oak test plot has a cover system with a 0.6-m thick CCL overlain by a 0.15-m thick vegetated silty topsoil layer. In Wenatchee, one test plot has the same cover system as at the Live Oak site except that the CCL is 0.6 m thick, and the other test plot models a capillary barrier consisting of a 0.75 m thick layer of medium sand overlain by a 0.15-m thick silt topsoil layer. Climate, runoff, percolation, and soil moisture data collected between 1992 and 1995 were reported by Khire (1995) and Khire et al. (1997, 1999), and data collection is still ongoing as of 2002. Runoff and percolation is collected in tanks and measured, while soil moisture content is measured by time domain reflectrometry.

Khire (1995) and Khire et al. (1997) used their test plot data to assess the predictive capabilities of the HELP and UNSAT-H models. The models were assessed by comparing model predictions to measured hydrologic data for the three cover system configurations. The predictions were performed using climatic data and laboratory-measured soil properties. Input parameters that were not measured were estimated from published information. The input parameters for this study were better defined than for most actual design projects. The UNSAT-H predictions were conducted with a unit gradient lower boundary condition and a specified flux upper boundary condition. Khire (1995) and Khire et al. (1997) drew the following conclusions from their study:

- Properly simulating runoff is essential because the fraction of precipitation that is not shed enters the cover system and may ultimately become percolation. Throughout most of the monitoring period, HELP underpredicted runoff for the humid Live Oak site (Figure 4-9) and overpredicted runoff for the semi-arid Wenatchee site with a CCL (Figure 4-10). Overall, HELP underpredicted runoff by 740 mm (≈ 90%) for the Live Oak site and overpredicted it by 30 mm (≈ 30%) for the Wenatchee site. Cumulative runoff predictions made using UNSAT-H were reasonably accurate for the Live Oak site (i.e., less than 3% error); however, season-to-season differences in runoff amounts were significant. For the Wenatchee site, UNSAT-H underpredicted runoff by 50 mm (≈ 270%) for the plot with a CCL and predicted no runoff for the plot with a capillary barrier. The underpredictions resulted in more water entering the soil in the simulations than in the field. This resulted in higher soil water storage in the simulations than in the field.
- Although HELP predicted ET fairly accurately for the Live Oak site, it was underpredicted by only 70 mm (≈ 4%), an accurate prediction of ET was not expected given that more water entered soil due to the underprediction of runoff. Instead, an overprediction of ET was expected unless the PET demand had already been met.

UNSAT-H underpredicted ET for the Live Oak site by 300 mm (≈ 15%). Examination of the water-balance equation indicates that underpredicting runoff and fairly accurately predicting ET, or vice versa, results in an overprediction of soil water storage and/or percolation. Both HELP and UNSAT-H overestimated ET at the Wenatchee sites by about 20 to 165 mm (≈ 20 to 40%).

- HELP somewhat captured the trends in percolation at the Live Oak site, but overpredicted total percolation by more than 700 mm (≈ 300%) (Figure 4-11).

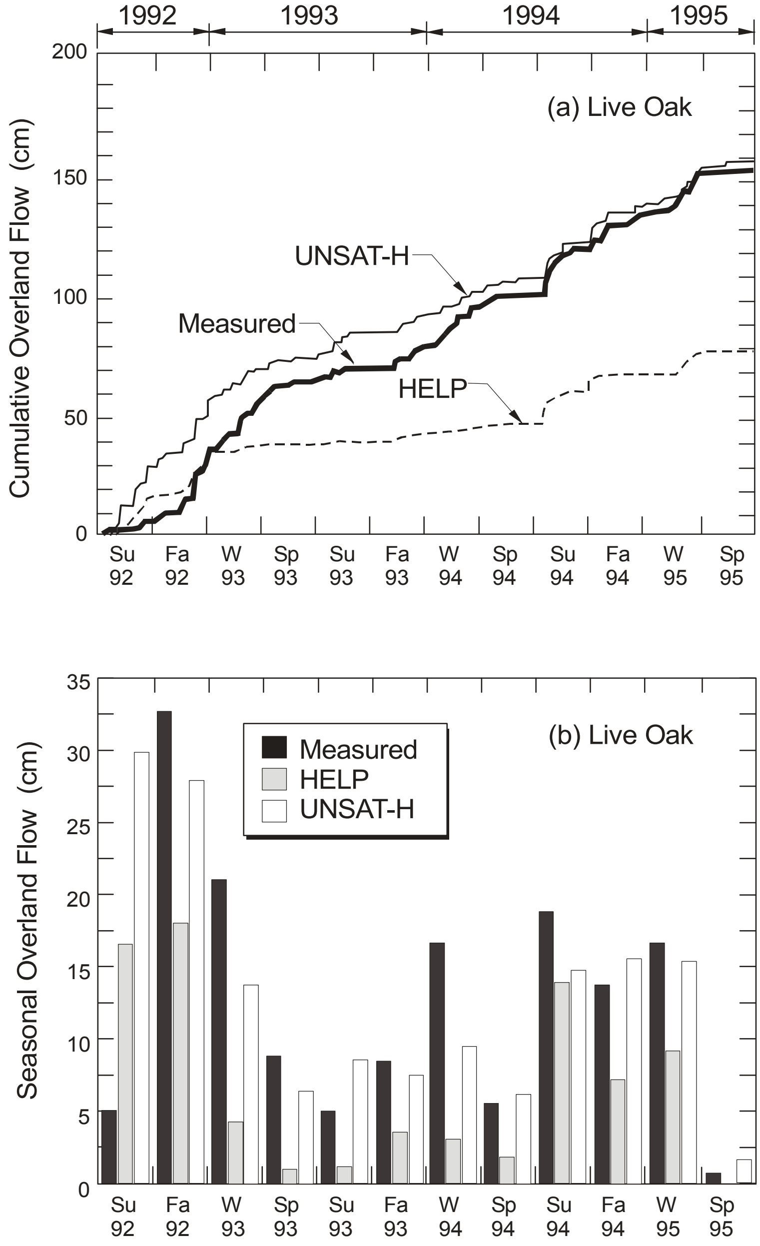


Figure 4-9. Measured and predicted cover system runoff at Live Oak site: (a) cumulative; and (b) seasonal (from Khire, 1995).

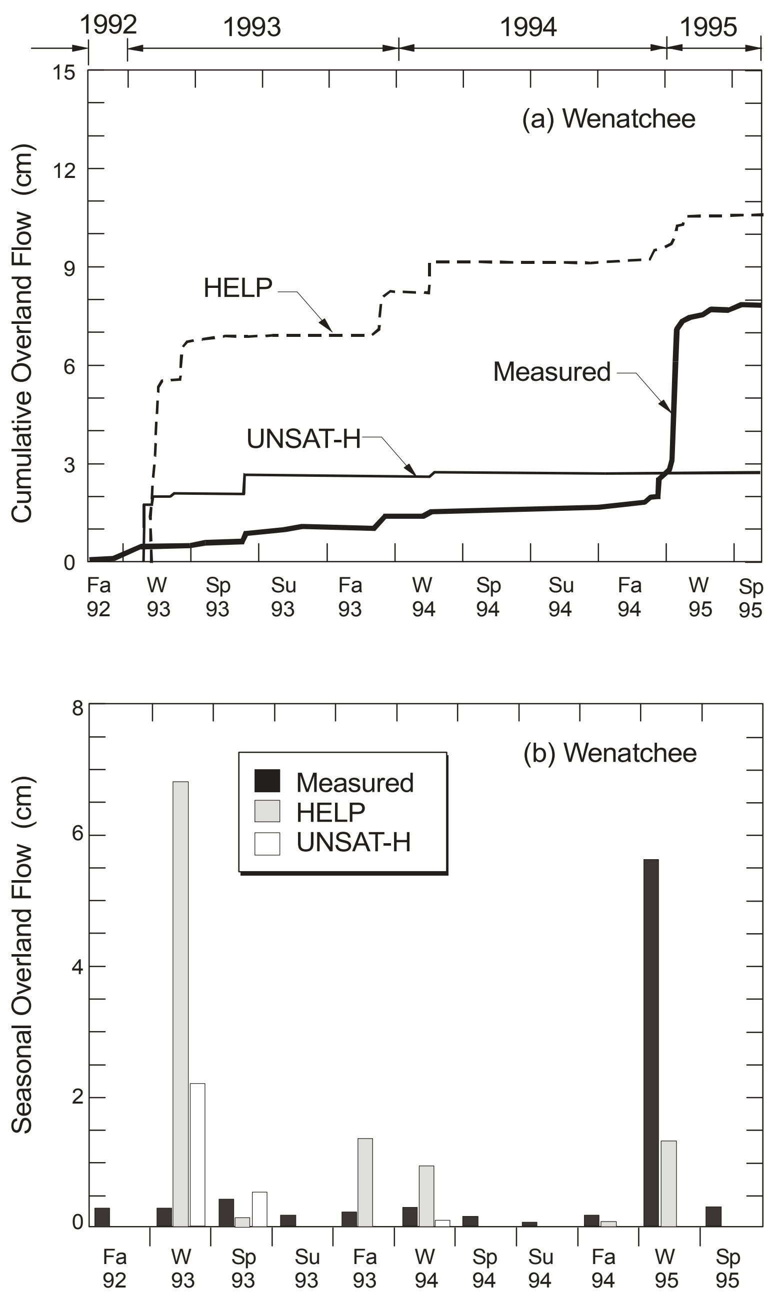


Figure 4-10. Measured and predicted runoff for hydraulic barrier-type cover system at Wenatchee site: (a) cumulative; and (b) seasonal (from Khire, 1995).

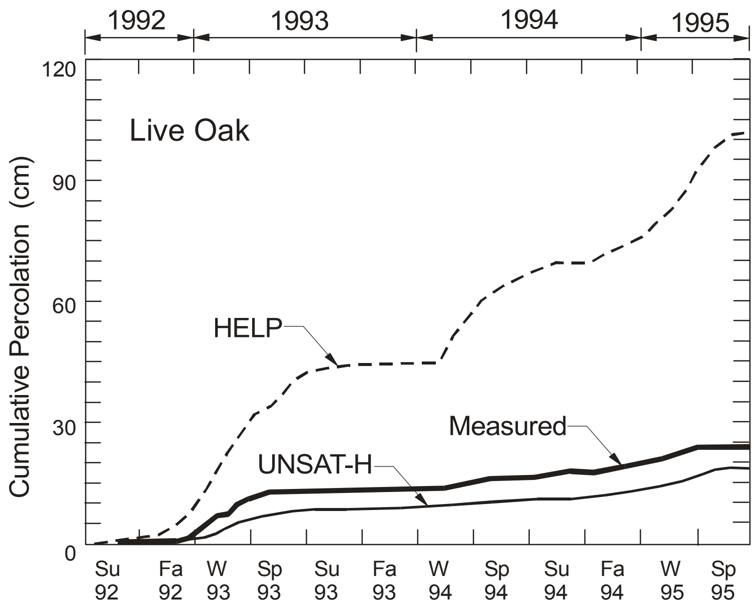


Figure 4-11. Measured and predicted cover system percolation at Live Oak site (from Khire, 1995).

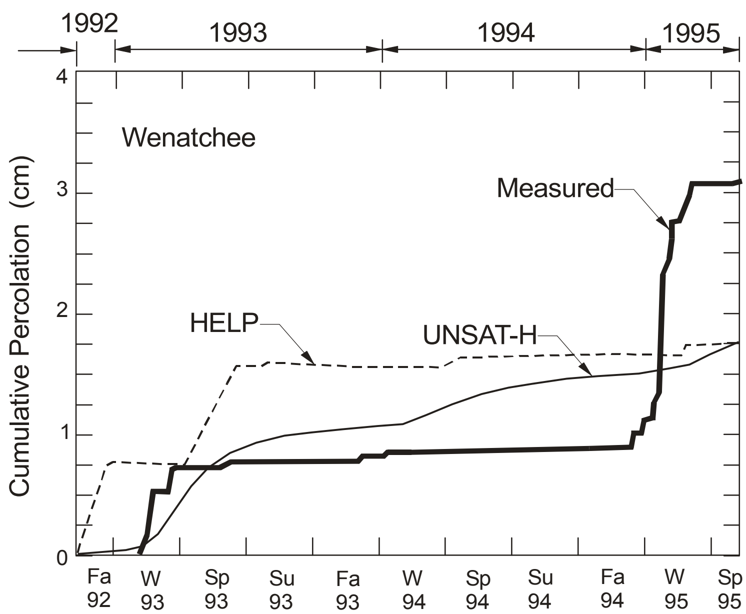


Figure 4-12. Measured and predicted percolation for hydraulic barrier-type cover system at Wenatchee site (from Khire, 1995).

One reason why percolation was overpredicted is that there was additional water in the soil caused by the underprediction of runoff. Another factor that contributed to the overprediction of percolation is the unit hydraulic gradient used by HELP to model unsaturated vertical flow. HELP assumes that water in the soil flows vertically downward under a unit hydraulic gradient (i.e., hydraulic gradient = 1). Khire (1995) and Khire et al. (1997) indicate that the hydraulic gradient in the field rarely equaled "1" and, for most of the time, was oriented vertically upward. UNSAT-H underpredicted percolation for the Live Oak site only slightly, by about 60 mm. Both HELP and UNSAT-H underpredicted percolation for the Wenatchee site with a CCL barrier (Figure 4-12). However, at least part of this difference is believed to have been caused by the preferential flow of water and snow melt through cracks and animal burrows in the winter of 1995. Prior to that time, both models had overpredicted percolation. UNSAT-H significantly overpredicted percolation for the Wenatchee site with a capillary barrier (Figure 4-13). One reason why percolation was overpredicted by over 90 mm (≈ 2,000%) is that there was additional water in the soil caused by the underprediction of runoff.

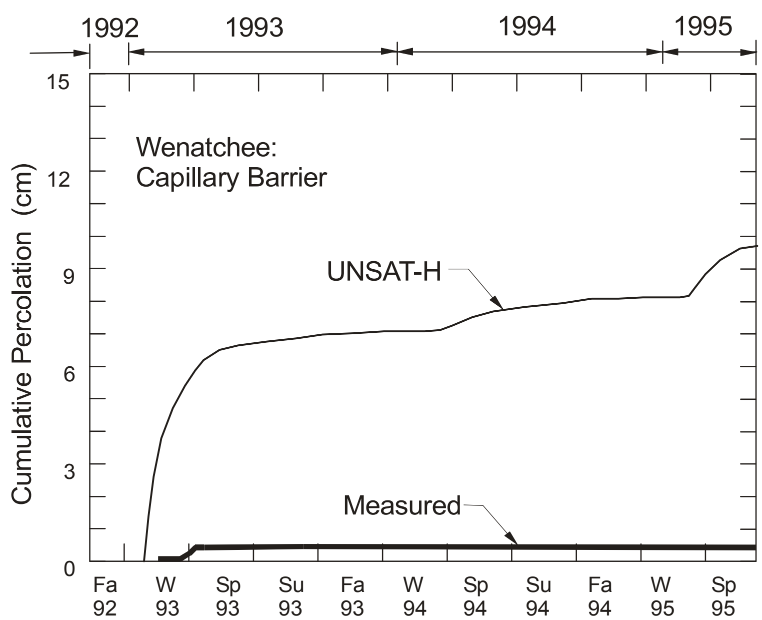


Figure 4-13. Measured and predicted percolation for capillary barrier-type cover system at Wenatchee site (from Khire, 1995).

4.4 Recommendations for Application of Water Balance Models

The specific water balance analysis method and input parameters to use for analysis and design of a cover system should be selected based on the purpose of the analysis and project-specific factors such as climate, type of cover (i.e., hydraulic barrier, ET barrier, or capillary barrier), and cover system components. Given the inconsistencies in water balance analysis results (e.g., the models sometimes overpredict and sometimes underpredict the various components of the water balance), uncertainties in soil properties and long-term barrier integrity (e.g., CCL hydraulic conductivity may increase over time if the CCL is not adequately protected), and other factors, significant engineering judgment must be applied when performing a water balance analysis for a specific site. The following general recommendations are made regarding the use of water balance methods for the design of cover systems:

- Percolation rates through cover systems with GM, GM/CCL, or GM/GCL hydraulic barriers should be very low when these barriers are properly constructed due to the effectiveness of these barrier types in preventing water migration through the barrier. Both the simplified manual method and the HELP model are well suited to performing analyses to demonstrate the effectiveness of these type of barriers in minimizing percolation.
- Estimated percolation rates through hydraulic barriers layers containing GMs for various categories of annual rainfall were provided by Gross et al. (1997) (Table 4-6). These estimates can be used by design engineers as a check of percolation rates calculated on a project-specific basis using either the simplified manual method or the HELP model. Percolation rates were calculated by Gross et al. (1997) using the HELP model with synthetic rainfall data generated by the model for several different cities in each rainfall category and the following ranges of input parameters: (i) fair grass vegetation; (ii) sandy loam and silty clay loam topsoil; (iii) 5 and 20% cover system slopes; (iv) coarse sand and GN internal drainage layers; and (v) 10-year synthetic weather records.

Table 4-6. Percolation Rates through Cover Systems with Barriers Incorporating GMs Estimated Using the HELP Model (from Gross et al., 1997).

Average Annual Rainfall (mm)	Average Percolation Rates (mm/yr)	
	GM Barrier	GM/CCL or GM/GCL Barrier
100-300	0-0.05	0-0.005
300-600	0.002-0.3	0.0002-0.03
600-800	0.1-1	0.01-0.1
800-1,000	0.3-2	0.03-0.2
1,000-1,600	1-5	0.1-0.5

- Either the simplified manual method or the HELP model can be used for the design of internal drainage layers underlain by hydraulic barriers containing a GM. A discussion of the design storm to use with each method is given below.
- Neither the simplified manual method nor HELP are capable of serving as a water balance predictive tool using estimated or default input data. The HELP model has limited capability as a predictive tool when calibrated using site-specific data.
- Any of the water balance analysis methods may be used for evaluating percolation through cover systems with CCL or GCL hydraulic barriers. While methods that incorporate unsaturated flow models are potentially more accurate than methods where saturated conditions are assumed for flow through the hydraulic barrier, the latter methods (i.e., simplified manual method and HELP model) are easier to use. These latter methods are likely to overpredict actual percolation rates for humid sites.
- For capillary-barrier and ET-barrier cover systems, a water balance analysis method that can correctly model unsaturated flow is preferred. Thus, LEACHM, UNSAT-H, SoilCover, or HYDRUS-2D is preferable to the HELP model for evaluation of these types of systems.
- For cover systems in any climate that rely on enhanced ET to minimize percolation, methods that correctly model unsaturated flow and that allow different vegetation scenarios to be input, such as LEACHM, UNSAT-H, SoilCover, or HYDRUS-2D, are preferred.
- Reference should be made to the available technical literature for the best available information on the tendencies of the various water balance models to either underpredict or overpredict the various components of the water balance for both wet and arid climatic conditions. This information should be considered in interpreting the results of project-specific water balance analyses.
- Reference should be made to the technical literature for new models that may be developed in the future with enhanced capabilities for the performance of cover system water balance analyses. All of the available models have their strengths and weaknesses. There remains room for improvement of the models and their specific applications
- Due to the difficulty in performing accurate analytical water balances, field water balances should be performed, whenever possible, to verify the analytical results. This is especially the case for alternative cover systems.
- An important input parameter in the design of cover system internal drainage layers for hydraulic barrier cover systems is rainfall intensity and duration. As previously discussed, the HELP model is limited to using daily rainfall data, and this does not capture short-term intense peaks in storm events. Koerner and Daniel (1997) have suggested that hourly rainfall data be considered along with the simplified manual method to calculate percolation through the cover soil into the internal drainage layer (PERC*). They presented an example calculation of the sensitivity of PERC* to the use of monthly, daily, or hourly precipitation data. The example assumes a site near Austin,

Texas, with a 200-m long 3H:1V slope and a surface runoff coefficient of 0.4. The results of their analysis were as follows:

  - PERC* = 0.011 mm/hr, using the simplified manual method with the average monthly temperature, duration of sunlight, and precipitation data from Austin;
  - PERC* = 1.3 mm/hr using the HELP model with historical daily precipitation data from 1974-1977 for San Antonio and all other climatic data generated for Austin; and
  - PERC* = 50 mm/hr using Eq. 4.7 with the probable maximum 6-hr precipitation event for the project vicinity (i.e., 500 mm).

- Koerner and Daniel (1997) noted that the calculated peak flow rate based on hourly storm data is more than one order of magnitude larger than the calculated peak flow based on daily precipitation values. Because of this, they recommended that hourly precipitation data be considered to conservatively calculate peak flow rates into the drainage layer and to determine if the drainage layer has adequate capacity to transmit the peak flow during extreme storm events.

For this guidance document, PERC* was calculated for the same example as above using the HELP model with climatic data generated synthetically for Austin for a 20-year simulation period. For the authors' simulation, PERC* = 3.1 mm/hr. This calculated PERC* is about 2.5 times larger than the value obtained by Koerner and Daniel (1997) of 1.3 mm/hr using the historical weather data for 1974-1977 for San Antonio. This result reinforces the comment made previously in this chapter that the HELP precipitation database for the period 1974-1977 reflects unusually dry weather for certain parts of the U.S. More generally, short-duration rainfall records may not contain wet weather cycles or intense storm events that control design. Also, as Koerner and Daniel (1997) noted, the rate of infiltration into a cover system soil will be limited by the hydraulic conductivity of the cover soil materials. If it is assumed in the above example that the cover soil has a saturated hydraulic conductivity of 1×10^{-6} m/s, then from Eq. 4.8, the maximum possible rate of infiltration into the cover for a non-ponded surface condition is 3.6 mm/hr , approximately the rate of percolation calculated with the HELP model and daily rainfall data generated synthetically for Austin, Texas, (i.e., 3.1 mm/hr). Thus, for typical cover systems with low to moderately permeable surface and protection layers, it will often be adequate to use the HELP model and a synthetic rainfall record with a sufficiently long simulation period (e.g., 20 years) to calculate lateral drainage and hydraulic head. Alternatively, Eq. 4.8b can be used directly to obtain a conservative value of PERC* for design.

4.5 Design of Drainage Layers

4.5.1 Simplified Manual Method

The required hydraulic properties of the cover system drainage layer are a function of the expected peak rate of percolation into the drainage layer (PERC* in Sections 4.2 and 4.3), the length of the cover system slope, the inclination of the cover system slope, and other factors.

Assuming no change in water storage in the drainage layer material, lateral flow in that layer is equal to percolation through the cover soil into the layer (PERC*) minus percolation through the hydraulic barrier (PERC). From Eq. 4.4:

$$L = PERC^* - PERC \qquad \text{(Eq. 4.14)}$$

where all terms are as defined previously. Assuming steady-state conditions, the maximum flow in the drainage layer is given by Eq. 4.5, repeated here:

$$q_m = \frac{\ell L}{8.64 \times 10^7} = \frac{\ell \left(PERC^* - PERC\right)}{8.64 \times 10^7} \qquad \text{(Eq. 4.5)}$$

where: q_m = maximum flow rate in drainage layer per unit width perpendicular to the direction of flow ($m^3/s/m$); ℓ = slope length (m); and other terms are as defined previously. For design of drainage layers, PERC can be conservatively assumed to be zero: that is, all percolation through the cover soil (PERC*) is assumed to become lateral flow in the drainage layer. For this case:

$$q_m = \frac{\ell \left(PERC^*\right)}{8.64 \times 10^7} \qquad \text{(Eq. 4.15)}$$

The hydraulic transmissivity of the drainage layer must be adequate to accommodate this flow. In the simplified manual method, the DuPuit-Forcheimer assumptions are used along with the further assumption that the line of seepage is parallel to the cover system slope to calculate the required drainage layer hydraulic transmissivity. For these assumptions, the hydraulic gradient is constant and equal to the sine of the slope angle:

$$i = (\sin\beta) \qquad \text{(Eq. 4.16)}$$

where β = slope angle (degrees). The required hydraulic transmissivity of the drainage layer is then obtained using Darcy's equation and the known values of q_m and i:

$$\theta_h = (q_m/i)\ FS \qquad \text{(Eq. 4.17)}$$

Substituting Eqs. 4.15 and 4.16 into Eq. 4.17 results in:

$$\theta_h = \frac{\ell\, PERC^*}{8.64 \times 10^7 \sin\beta} FS \qquad \text{(Eq. 4.18)}$$

where: θ_h = required hydraulic transmissivity of drainage layer (m^2/s); FS = factor of safety (dimensionless); and other terms are as defined previously. As previously discussed in Section 2.4.2.3, a minimum FS value of 2 is recommended for cases where the uncertainty in input parameters is low and the consequences of failure are small. For many situations, a larger FS may be appropriate. Koerner and Daniel (1997) have recommended using a FS value of at least 5 to 10 to account for uncertainities in the hydraulic conditions.

The maximum hydraulic head in the drainage layer for the assumptions given previously is:

$$h_m = \frac{q_m}{k_d \tan\beta} \qquad \text{(Eq. 4.19)}$$

where: h_m = maximum hydraulic head (m); k_d = hydraulic conductivity of drainage layer (m/s); and q_m is as defined previously. The maximum hydraulic head for this set of assumptions occurs at the base of the slope. The required thickness (measured perpendicular to the slope) of the internal drainage layer is obtained from the equation:

$$t_m = (h_m / \cos\beta)\ FS = \theta/k \qquad \text{(Eq. 4.20)}$$

where: t_m = the required thickness of the internal drainage layer (m); and other terms are as defined previously. The actual thickness of the internal drainage layer must be larger than t_m in order for pressure head not to build up in the layer. The definition of the thickness, head, and depth of flow on a slope is shown in Figure 4-14.

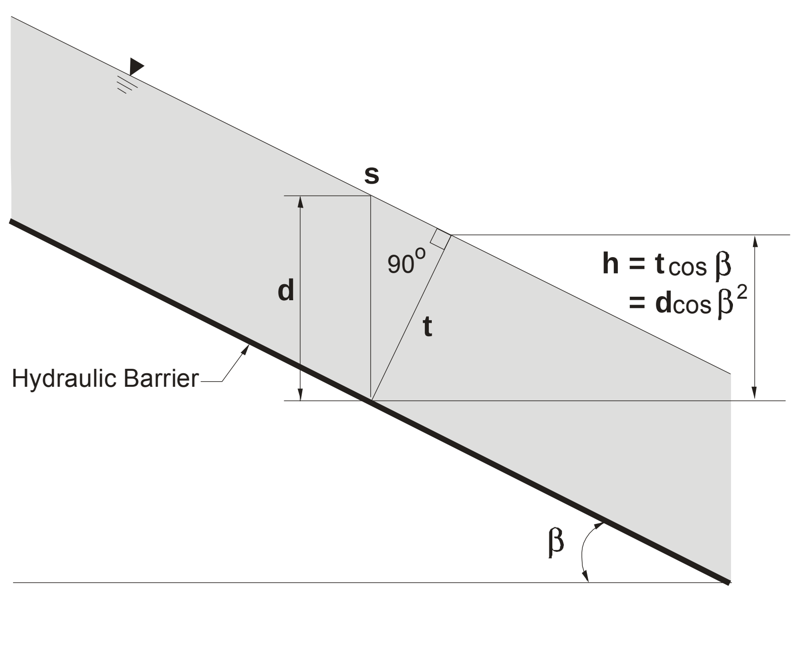


Figure 4-14. Definition of liquid depth (d), thickness (t), and hydraulic head (h), above a hydraulic barrier.

4.5.2 Refinement to Simplified Manual Method

For a sloping drainage layer receiving a constant rate of percolation (PERC*), flow in the layer is not actually parallel to the slope as assumed in the previous subsection. Rather, as the hydraulic head builds up on the slope, the phreatic surface takes on a curved shape. Figure 4-15 illustrates this condition for a cover system slope with a toe drain. For this condition, the hydraulic gradient is not constant but varies along the slope length.

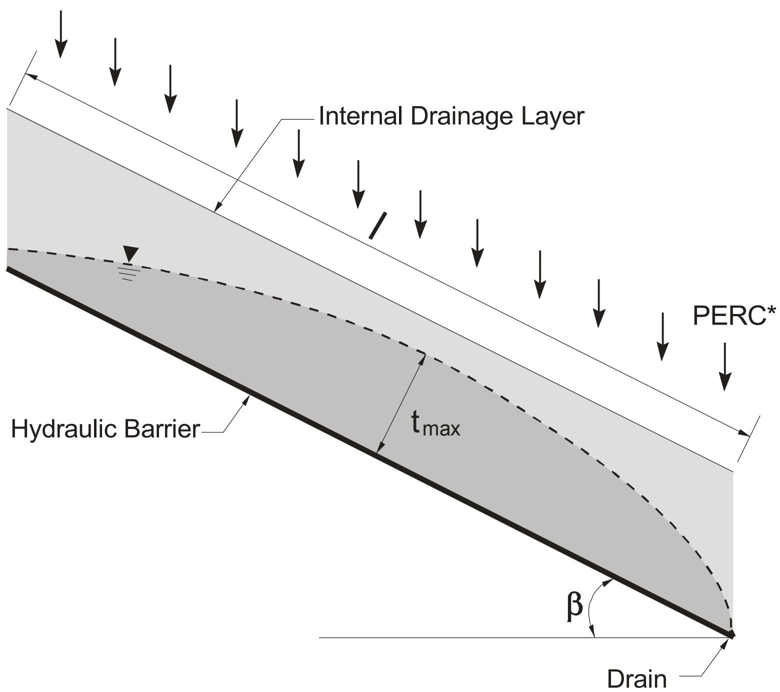


Figure 4-15. Hydraulic head distribution on a cover system slope with a toe drain.

An improved estimate of maximum hydraulic head in the internal drainage layer that takes account of the varying hydraulic gradient (while maintaining use of the DuPuit-Forcheimer assumptions) can be obtained using the equations from Giroud et al. (1992b) and Giroud and Houlihan (1995):

$$h_m = (j\ell \cos\beta / 2)\left[\left(\tan^2\beta + \frac{4\ \text{PERC}^*}{k\cos\beta}\right)^{1/2} - \tan\beta\right] \qquad \text{(Eq. 4.21)}$$

where all terms are as defined previously, and j is given by Eq. 4.21:

$$j = 1 - 0.12\exp\left[-\left(\log(8\lambda/5)^{5/8}\right)^2\right] \qquad \text{(Eq. 4.22)}$$

where:

$$\lambda = \frac{PERC*}{k \tan\beta \sin\beta} \qquad \text{(Eq. 4.23)}$$

It is noted that Eq. 4.20 tends to the simplified solution of Eq. 4.18 when PERC*/k tends towards zero and/or β is very large. Values of average hydraulic head, h_{avg} (m), for a given value of h_m can be obtained from Figure 4-16. For the case of (PERC*/k cosβ) < 0.25 $\tan^2\beta$:

$$h_{avg} = \frac{PERC * \ell}{2k \sin\beta \cos\beta} \qquad \text{(Eq. 4.24)}$$

It is suggested that for design of internal drainage layer, h_m be used from single storm event analyses to size the drainage layer. In contrast, it is suggested that h_{avg} be used to calculate long-term PERC values. For the simplified manual method, PERC* to calculate h_m should be derived using hourly water balance calculations for the design storm (limited by Eq. 4.8 as previously discussed) and PERC* to calculate h_{avg} should be derived using monthly water balance calculations.

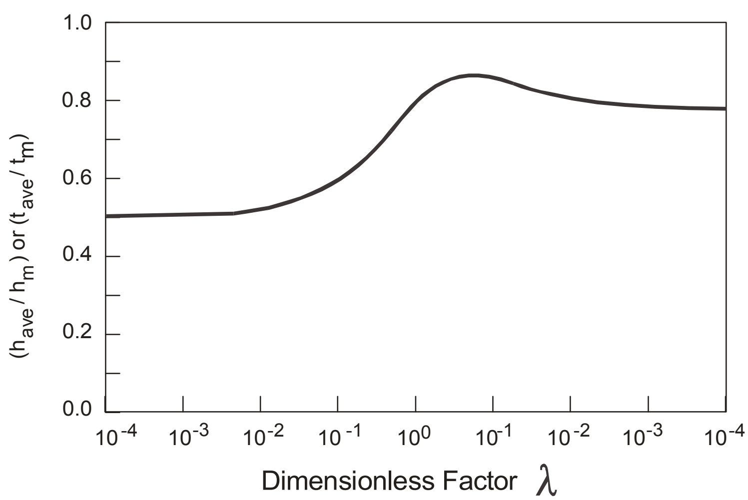


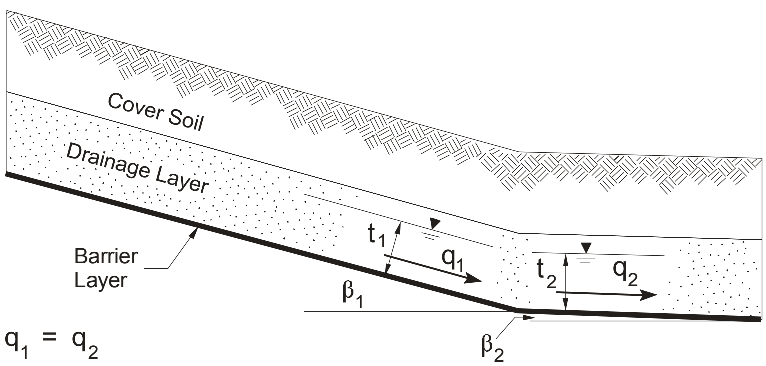
Figure 4-16. Dimensionless factor for calculating (h_{ave}/h_m) for internal drainage layers. (from Giroud and Houlihan, 1995).

4.5.3 HELP Model

In the HELP model, lateral drainage in internal drainage layers is modeled by an analytical approximation to the steady-state solution of the Boussinesq equation (Darcy's equation coupled with the continuity equation), employing the Dupuit-Forcheimer assumptions. Hydraulic heads calculated for internal drainage layers in the HELP model are similar to those that would be calculated using the equations presented by Giroud and Houlihan (1995) for equal values of PERC*. Based on the example calculation in Section 4.4 of this document, the HELP model can be used directly for calculating lateral flow and hydraulic heads in cover system internal drainage layers. However, in using the model, the user should select a weather data generating option that produces extreme wet weather periods for the project site. Use of the 1974-1977 HELP model internal weather database will not typically be adequate.

4.6 Design of Slope Transitions

Design of internal drainage layers at benches and other slope transitions is critical to the effective functioning of the drainage layer. If not properly designed, flow will back up and generate hydraulic pressure at the slope transition. For flow not to back up in a drainage layer flowing full, flow capacity (q) across the slope transition must not decrease. Flow capacity for laminar flow parallel to a slope is equal to the hydraulic gradient multiplied by the hydraulic transmissivity of the drainage layer material. This design requirement is illustrated in Figure 4-17.



$$q_1 = q_2$$

$$T_1 \sin\beta_1 = T_2 \sin\beta_2$$

$$k_1 t_1 \sin\beta_1 = k_2 t_2 \sin\beta_2$$

Figure 4-17. Continuity of flow across a slope transition for laminar porous media condition.

For many conventional cover system designs, the hydraulic gradient on the flatter part of the slope transition will be about one order of magnitude lower than the hydraulic gradient on the steeper part. For example, the gradient of a 3H:1V slope is 0.32, whereas the gradient reduces to 0.03 for a 3% slope inclination typical of a cover system bench. For this condition, to prevent backup of flow and build-up of hydraulic head for drainage layer flowing full, the hydraulic transmissivity of the drainage layer on a cover system bench or slope transition will need to be about one order of magnitude larger than that of the drainage layer on the sideslope.

More generally, based on Figure 4-17, the slope transition should be designed such that:

$$\theta_{h2} > \theta_{h1} (\sin\beta_1/\sin\beta_2) \qquad \text{(Eq. 4.25)}$$

where all terms are as defined previously. The subscript 1 refers to the portion of the drainage layer on the steeper upslope side of the transition, and the subscript 2 refers to the drainage layer on the flatter downslope side of the transition (Figure 4-17). Eq. 4.25 can be used directly to analyze and design geosynthetic drainage layers for which hydraulic transmissivities are either known or measured in the laboratory. For granular drainage materials where materials are typically specified in terms of a required hydraulic conductivity and thickness, Eq. 4.25 is recast as:

$$k_2 \geq k_1 \, (t_{m1}/t_{m2}) \, (\sin\beta_1/\sin\beta_2) \qquad \text{(Eq. 4.26)}$$

where all terms are as defined previously. For Eq. 4.25 to be valid, t_{m1} and t_{m2} must be less than the total thickness of the drainage layer.

The concept of having a larger internal drainage layer hydraulic transmissivity (or hydraulic conductivity) on a slope bench compared to the adjacent upslope portion of the cover is illustrated in Figure 4-18(a). This approach is conveniently achieved with geosynthetic drainage layers; it is more difficult to implement with granular drainage materials because it requires very coarse-grained materials on the benches or slope transitions while meeting filter criteria at the interface between drainage materials. Other options for designing benches and slope transitions are shown in Figures 4-18(b), (c), and (d). These include:

- installing a perforated pipe within the slope transition to convey water to outlet pipes (Figure 4-18(b)); this approach is technically acceptable, but there can be a problem with the pipes freezing and plugging; also, it is essential that the pipes remain open and not be plugged or damaged by maintenance personnel; in addition, the discharge from the pipes may tend to erode soil beneath the pipes, and the surface should be adequately protected to prevent excessive erosion;
- installing a perforated pipe within the slope transition to convey water to a downdrain or downchute; this has the advantage of keeping the piping below the surface, where it can be protected from freezing; because the surface of the bench is normally sloped to provide surface drainage, the perforated pipe can follow the slope of the bench and provide gravity drainage to the outlet point; the outlet must still be protected and cannot be obstructed or clogged; and
- allowing the drainage layer to daylight on the bench. The bench must be suitably protected to prevent erosion; also, the outlet cannot freeze, which makes this approach questionable in northern climates.

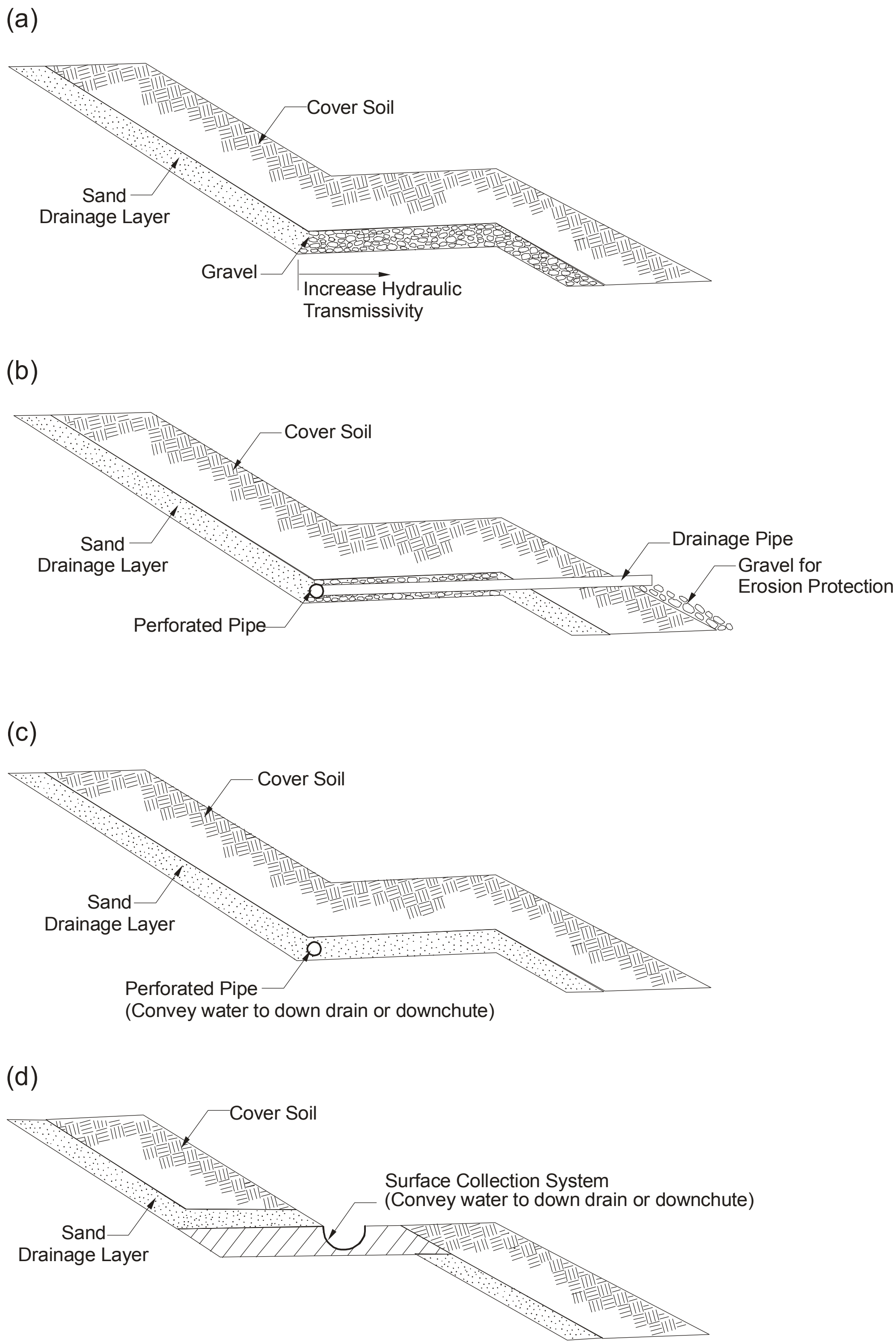


Figure 4-18. Design options for cover system slope transitions.

4.7. Design of Filter Layers

4.7.1 Overview

To prevent clogging of internal drainage layers, it is often necessary to install a granular or GT filter layer directly over the drainage layer material. Several of the cover system slope stability problems described in Chapter 7.4 of this document were due, at least in part, to inadequate filter layer design. The function of the filter in cover system applications is to limit the migration of fines from the overlying cover soil into the internal drainage layer, while allowing unimpeded percolation from the cover soil into the drainage layer. If the drainage material is a granular soil, the filter material may be either soil or GT. If the drainage material is itself a geosynthetic, the filter layer will also need to be a GT.

Filter criteria establish the relationship of grain sizes necessary to retain adjacent materials and prevent clogging of a drainage layer, while allowing unimpeded percolation. Criteria for the design soil and GT filter layers are discussed below.

4.7.2 Soil Filters

Soil filters usually consist of fine to medium sands when placed over coarse sand or fine gravel drainage layers. The filter particle size distribution must be carefully selected. Fortunately, there is a considerable body of information available to use in selecting a filter particle size distribution (Koerner and Daniel, 1997). Typically, the criteria described in Cedergren (1989) are used. To prevent piping from the overlying cover soil into the filter layer, and from the filter into the drainage layer, these criteria require, respectively:

$$D_{15} \text{ (filter)}/D_{85} \text{ (cover soil)} < 4 \text{ to } 5 \qquad \text{(Eq. 4.27)}$$

and:

$$D_{15} \text{ (drainage layer)}/D_{85} \text{ (filter)} < 4 \text{ to } 5 \qquad \text{(Eq. 4.28)}$$

To maintain adequate permeability of the filter layer and drainage layer, these criteria require, respectively:

$$D_{15} \text{ (filter)}/D_{15} \text{ (cover soil)} > 4 \text{ to } 5 \qquad \text{(Eq. 4.29)}$$

and:

$$D_{15} \text{ (drainage layer)}/D_{15} \text{ (filter)} > 4 \text{ to } 5 \qquad \text{(Eq. 4.30)}$$

where: D_{85} = particle size at which 85% by dry weight of the soil particles are smaller (mm); and D_{15} = particle size at which 15% by dry weight of the soil particles are smaller (mm). The criteria should be satisfied for all layers or media in the drainage system, including cover soil, filter material, and drainage material.

4.7.3 GT Filters

A GT must be installed over a GN or drainage core when the overlying material is to be a cover soil. The primary function of the GT in this application is as a filter layer. As with soil filter layers, GT filters must allow percolation from the cover soil to pass unimpeded into the drainage layer while retaining the cover soil and limiting the migration of particles from the cover soil.

As with soil filters, the design of GT filters involves a two-step process: first to assess permeability (or permittivity) and second to evaluate soil retention (or apparent opening size).

The first step in design of a GT filter is to establish the GT permittivity (Ψ) requirements. The usual formulation involves expressing the minimum allowable GT permittivity (Ψ_{min}) as a multiple of the required permittivity (Ψ_{req}) to maintain flow continuity from the cover soil, as follows:

$$\Psi_{min} = FS\Psi_{req} \qquad \text{(Eq. 4.31)}$$

and:

$$\Psi = \frac{k_n}{t} \qquad \text{(Eq. 4.32)}$$

where: Ψ = GT permittivity (s^{-1}); k_n = GT cross-plane hydraulic conductivity (m/s); and t = thickness of GT at a specified normal pressure (m). A minimum FS of 5 to 10 is recommended.

The testing of a GT for permittivity is conceptually similar to the testing of granular soils for permeability. In the U.S., the testing is usually performed using the permittivity test, ASTM D 4491. Alternatively, some design engineers prefer to work directly with permeability and require the GT's hydraulic conductivity to be some multiple of the adjacent soil's hydraulic conductivity (e.g., 5 to 10, or higher).

The second step of the design of a GT filter is intended to assure adequate retention of the cover soil. There are several methods available for establishing the soil retention requirements of GT filters. Most of the available approaches, as applied to a cover system, involve a comparison of the cover soil particle size characteristics to the 95% opening size of the GT (i.e., defined as 0_{95} of the GT). The 0_{95} is the approximate largest soil particle size that can pass through the GT. Various test methods are used to estimate 0_{95}: (i) in the U.S., wet sieving is used and the value thus obtained is called the apparent opening size (AOS), ASTM D 4751; (ii) in Canada and some European countries, hydrodynamic sieving is used and the value thus obtained is called the filtration opening size (FOS); and (iii) in other European countries, wet sieving is used.

The simplest of the available design methods involves a comparison of the GT AOS to standard soil particle sizes as follows (Koerner, 1998):

- for soil with $\leq$ 50% passing the No. 200 sieve (0.074 mm): $0_{95} < 0.59$ mm (i.e., AOS of the GT $\geq$ No. 30 sieve); and
- for soil with > 50% passing the No. 200 sieve: $0_{95} < 0.33$ mm (i.e., AOS of the GT $\geq$ No. 50 sieve).

Alternatively, a series of direct comparisons of GT opening size (0_{95}, 0_{5o}, or 0_{15}) can be made to some soil particle size to be retained (D_{90}, D_{85} or D_{15}). The numeric value depends on the GT type, soil type, flow regime, etc. For example, Carroll (1983) recommends the following relationship:

$$0_{95} < (2 \text{ or } 3)D_{85} \qquad \text{(Eq. 4.33)}$$

where: D_{85} = particle size at which 85% by dry weight of the soil particles are smaller (mm); and 0_{95} = the 95% opening size of the GT (mm). As shown by Giroud (1992, 1996), Eq. 4.33 should only be used if the coefficient of uniformity of the soil to be protected is less than four. General procedures, applicable for all values of the coefficient of uniformity of the soil to be protected, are available: see Giroud (1982), Lafleur et al. (1989), and Luettich et al. (1992).

Occasionally, a drainage layer is placed directly against a GCL. For GT-encased GCLs, the GT components may not be adequate to prevent migration of bentonite into the drainage layer. The required filter criteria for this condition are under study, and the manufacturer's and technical literature should be consulted. One study indicated that a 350 g/m^2 nonwoven, needlepunched GT provided adequate protection from bentonite migration for all GCLs investigated (Estornell and Daniel, 1992).