A COMPARISON OF TWO MODELS FOR SIMULATING THE WATER BALANCE OF SOIL COVERS UNDER SEMI-ARID CONDITIONS[1]

by

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Abstract. Numerical water-balance modeling of store-and-release soil covers for hypothetical mine tailings was conducted using the Hydrologic Evaluation of Landfill Performance (HELP) and SoilCover models. The objective of the modeling was to compare the utility of both models in a semi-arid environment. Although values for input parameters were chosen to make simulations as identical as possible between models, differences in model solution methods and discretization led to different water-balance predictions. Specifically, SoilCover predicted less percolation than HELP, because HELP uses simplified water-routing algorithms which may overpredict infiltration and underpredict subsequent evapotranspiration. Since SoilCover explicitly solves physically based governing equations for heat and water flow, its predictions more accurately represent the water balance in semi-arid regions where evapotranspiration dominates. HELP can only conservatively predict percolation in dry environments.

Additional Key Words: infiltration, percolation, runoff, evapotranspiration, unsaturated flow, water balance.

Introduction

Reliably simulating the near-surface water balance in store-and-release covers engineered to reduce percolation is critical not only to making final cover implementation decisions but also to dependably predict future mass loading of solutes into aquifers underlying the covers. Because of its acceptance by regulators and engineers, along with its ease of operation when compared to other water-balance models (Morris and Stormont 1997), the Hydrologic Evaluation of Landfill Performance model (HELP) (Schroeder et al. 1994a and b) is commonly used as a tool for assessing the fate of water (e.g., Wright and Turner 1987; Yanful et al. 1994; Woyshner and Yanful 1995; Ricard et al. 1997; and Khire et al. 1997). While useful under many conditions, HELP does not allow upward flux of water vapor or liquid once it moves below the user-defined evapotranspiration (ET) zone. Thus, HELP may not reliably simulate the water balance under semi-arid conditions where this upward flux can be similar in magnitude to precipitation.

A user-defined ET zone is one of the drawbacks of HELP because uncertainty in the ET-zone thickness can lead to significant differences in the resulting water balance. Furthermore, the depth of the ET zone is not static. Changes in energy input from solar radiation, soil matric suction, wind speed, and other variables impact the effective depth of the zone from which water is extracted by evaporative and transpirative forces. Even though HELP can perform rigorous estimations of climatic variables such as solar radiation and precipitation, it uses simplified sink terms to route water out of the fixed ET zone. On the other hand, the numerical computations in SoilCover (GeoAnalysis 2000 Ltd. 1997) allow for changes in the thickness of the profile impacted by evapotranspirative forces, and thus provide a more realistic description of water movement in semi-arid regions where these forces predominate.

HELP's quasi-two-dimensional, deterministic, water-routing solution has been found to be unsuitable for modeling the water balance in dry regions. In particular, the model tends to overpredict percolation (Electric Power Research Institute 1984; Fleenor and King 1995; and Khire et al. 1997), especially in semi-arid to arid climates. In their comparison of HELP version 3.01 output with field water-balance results, Khire et al. (1997) partially attributed HELP's overprediction of percolation to the model's assumption of a continual downward unit gradient. Fleenor and King (1995) observed that percolation predicted by HELP version Beta 3 was quite insensitive to considerable fluctuations in boundary conditions. For example, arid-site HELP simulations continued to predict nearly constant positive percolation for 16 months, even though no infiltration occurred. These investigators indicated that "without specific modification to the empirical HELP code to more closely account for capillary forces and to be able to remove water from below the soil evaporative zone, HELP will continue to over-predict downward vertical moisture fluxes."

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Although HELP may not accurately simulate the water balance under arid conditions, it appears to make more accurate predictions in humid climates where evapotranspirative forces do not dominate. For example, in comparing HELP model predictions to lysimeter measurements of percolation, Woyshner and Yanful (1995) found that HELP accurately predicted percolation through soil covers over mine tailings in Quebec, Canada.

The objective of this paper is to illustrate differences between the water-balance predictions of the HELP version 3.05 (March 1996) and SoilCover version 4.02 beta (November 1997) models for store-and-release covers under semi-arid conditions at a hypothetical mine tailings site.

The HELP Model

Structure

The HELP model was developed to conduct water-balance analyses of landfills, cover systems, and solid waste disposal and containment facilities (Schroeder et al. 1994b). The model calculates infiltration by removing runoff from each storm event based on the Soil Conservation Service's curve number (SCS-CN) method, and then removing water intercepted on plant leaves by evaporation. The runoff calculation accounts for the infiltration capacity of the soil by using the antecedent moisture content. The remaining precipitation is applied as a flux boundary condition over a default period of 24 hours. This default period may lead to the underprediction of runoff and the subsequent overprediction of infiltration because the applied precipitation flux may be less than the actual flux if rainfall occurs over a shorter period. Infiltrated water is extracted at a constant rate from the user-specified ET zone based on the model's estimation of potential ET using a modified Penman (1963) method.

ET takes place within the ET zone only if water is available in excess of the wilting point. HELP does not estimate upward movement of liquid water due to a gradient in total head nor vapor diffusion. Rather, water is extracted in a sink term, emulating capillary rise (Schroeder et al. 1994b). Next, the vertical unsaturated drainage is computed by Darcy's law using Campbell's (1974) equation for unsaturated hydraulic conductivity based on predicted moisture content from the Brooks and Corey soil water characteristic curve (Brooks and Corey 1964). Unsaturated vertical drainage proceeds as long as any of the segments in the model profile have moisture contents above field capacity (or the wilting point in the ET zone). The percolation computation starts at the uppermost segment and continues until the bottom of the profile is reached. Percolation is calculated using gravitational gradients alone (a "unit gradient" or "gravity flow" assumption). Since the matric suction gradient is ignored, unsaturated drainage and the velocity of the wetting front may be underestimated if the ET-zone depth is overestimated or, conversely, overestimated if the ET-zone depth is underestimated.

The entire solution procedure is applied repetitively for each day as the model predicts water routing throughout the simulation period. HELP does not iterate in order to converge to a solution. Rather, it directly calculates the water-balance calculations using input values and simplified algorithms. HELP model computations as they pertain to the modeling discussed herein are summarized in Table 1.

Input Data

Depending on the purpose and hydraulic nature of the various cover layers, the HELP model requires the user to specify each component as either a vertical percolation, barrier, lateral drainage, or geomembrane liner layer. Only vertical drainage layers were used in the mod-

Table 1
HELP Model Computations

1. **Atmospheric boundary condition**
   21-year central Arizona meteorological record includes daily precipitation (P), average daily temperature, average quarterly relative humidity (RH), daily solar radiation, and average yearly windspeed.

2. **Runoff and plant water interception removed**
   Runoff (R) calculated using user-input or model-estimated Curve Number (CN):

   $$R = [(P-0.2S)^2/(P + 0.8S)] \text{ where } S = (1000/CN) - 10$$

   Plant water interception removed by evaporation.

3. **Remainder of P applied as a uniform daily flux boundary condition**

   infiltration = constant flux (over 24 hours)

4. **Soil (surface) evaporation and transpiration calculation**
   Potential evapotranspiration given by modified Penman (1963) equation: f(radiation, RH, windspeed, water stress, air temperature, etc.)

   Evapotranspiration is extracted using a constant sink term; water liquid/vapor is not explicitly moved upward.

5. **Moisture status checked (Brooks and Corey) and percolation calculated (Campbell/Darcy)**

   $$Percolation = K_u = K_s\left[\frac{\theta - \theta_r}{\varphi - \theta_r}\right]^{3 + \left(\frac{2}{\lambda}\right)}$$

   where:
   K_u and K_s are the unsaturated and saturated hydraulic conductivities, respectively,
   θ is the actual moisture content,
   θ_r is the residual moisture content,
   φ is the porosity, and
   λ is the pore-size distribution index

eling described in this paper. Input data for the HELP model can be categorized into: (1) hydraulic parameters, (2) climatic parameters, (3) vegetation parameters, and (4) initial conditions. Values for input data for the two material types used in the simulations discussed in this paper (hypothetical cover soil and tailings) are provided in Table 2.

Hydraulic Parameters. Hydraulic data required by HELP include saturated hydraulic conductivity, porosity, SCS-CN, and volumetric moisture content at field capacity and the wilting point. SCS-CNs for runoff calculations are generated in one of three ways: (1) direct user-input of the SCS-CN, (2) HELP modification of the user-input SCS-CN using the surface slope and length, or (3) HELP-

Table 2
Input Parameters for HELP and SoilCover Simulations

PARAMETER	UNIT	SOIL LAYER	INPUT VALUE	APPLICABLE MODEL	REFERENCE
HYDRAULIC PARAMETERS					
Porosity	cm^3/cm^3	Cover Soil	0.40	HELP/SoilCover	Hypothetical Cover Soil and Tailings
		Tailings	0.41		
Field Capacity	cm^3/cm^3	Cover Soil	0.19	HELP	
		Tailings	0.27		
Wilting Point	cm^3/cm^3	Cover Soil	0.09	HELP	
		Tailings	0.09		
Saturated Hydraulic Conductivity	cm/sec	Cover Soil	7.2×10^{-4}	HELP/SoilCover	
		Tailings	2×10^{-6}		
Particle Density	$grams/cm^3$	Cover Soil	2.73	SoilCover	
		Tailings			
Soil Conservation Service Runoff Curve Number	unitless	Cover Soil	77.0	HELP	HELP-model estimated based on surface slope and length, surficial soil texture, and vegetation cover quality
Soil Water Characteristic Curve (SWCC)	See Figure 1			SoilCover	SoilCover generated based on hypothetical data
Unsaturated Hydraulic Conductivity Curve					
Thermal Conductivity as a Function of Water Content	$Watts/m^2/C$	Cover Soil/Tailings	Data Not Shown		SoilCover generated using Johansen (1975) method
Volumetric Specific Heat Capacity as a Function of Water Content	$Joules/m^3/C$	Cover Soil/Tailings	Data Not Shown		Calculated using de Vries (1963) method
CLIMATIC PARAMETERS					
Precipitation, Net Radiation, Windspeed, Maximum and Minimum Air Temperature and Humidity	-	-	21-Year Daily Actual/Synthesized Record (1975-1995)	SoilCover	Precipitation, relative humidity, windspeed, and temperature data from central Arizona NOAA weather stations; solar radiation data synthesized using HELP-model algorithm; net radiation calculated from solar radiation data using Shuttleworth's (1993) method
Precipitation, Average Air Temperature, and Solar Radiation	-	-	21-Year Daily Actual/Synthesized Record (1975-1995)	HELP	
Average Annual Windspeed	miles per hour	-	8.59	HELP	
Average Quarterly Relative Humidity	%	-	43.5, 25.4, 44.0, 42.9	HELP	
Latitude	degrees N	-	33.24	HELP/SoilCover	
VEGETATION PARAMETERS					
Evapotranspiration Zone Depth	inches	-	32	HELP	Estimated for coarse soil in central Arizona
Root Zone Thickness	inches	-	18	SoilCover	Estimated average root-penetration depth
Leaf Area Index	unitless	-	0.75	HELP	Estimated average leaf area index for desert vegetation
			Varied from 0 to 1	SoilCover	"Poor" vegetation setting assumed to represent desert plants
Growing Season	Julian Days	-	58 to 331	HELP/SoilCover	Estimated based on professional judgement
Moisture Limiting Point	kiloPascals	-	100	SoilCover	Typical value
Moisture Wilting Point	kiloPascals	-	1500	SoilCover	Typical value
BOUNDARY AND INITIAL CONDITIONS					
Percolation Monitoring Depth	inches	-	32	HELP/SoilCover	Estimated average ET-zone depth
Finite Element Mesh Geometry	-	-	Model Generated	SoilCover	Based on user-specified soil layer data
Atmospheric Boundary Condition	inches	-	Daily Precipitation	SoilCover	Central Arizona NOAA weather station data
Soil Surface Temperature Boundary Condition	degrees C	-	Model Calculated	SoilCover	-
Initial Temperature Condition of Profile	degrees C	-	25	SoilCover	Estimated based on professional judgement
Lower Temperature Boundary Condition (@ 200 feet)	degrees C	-	25	SoilCover	Estimated based on professional judgement
Initial Profile Matric Suction (upper 2.75 feet)	kiloPascals	-	33	SoilCover	Approximately field capacity; matches HELP simulations
Initial Profile Matric Suction (lower 197.25 feet)	kiloPascals	-	Linear decrease from 33 to 0	SoilCover	Suction decreases approaching water table
Lower Matric Suction Condition (@ 200 feet)	kiloPascals	-	0	SoilCover	Assumed water table presence to increase model efficiency
Initial Profile Moisture Content (upper 2.75 feet)	cm^3/cm^3	-	Field Capacity	HELP	Matches SoilCover simulations
Surface Area Allowing Runoff	%	-	100	HELP	No surface water ponding on covers assumed

estimation of the SCS-CN based on surface slope and length, soil texture of the top layer, and vegetative cover quality. SCS-CNs used in the modeling described herein were calculated using option 3.

Climatic Parameters. HELP meteorological input includes site latitude, daily precipitation, average daily air temperature, daily solar radiation flux, quarterly average relative humidity, and average annual windspeed. Twenty-one years (1975 to 1995) of detailed climatic data were used in the simulations. Actual precipitation, temperature, relative humidity, and windspeed data were gathered from National Oceanic and Atmospheric Administration weather stations in central Arizona. Average annual precipitation over the 21-year period was 20.75 inches, with a maximum of 36.42 and a minimum of 12.92 inches per year (in/yr). Daily solar radiation fluxes were synthesized by an internal HELP algorithm conditioned by the rainfall data (to account for cloudiness).

Vegetation Parameters. ET-zone depth, leaf area index (LAI), and growing season dates comprise the vegetative data input. Thirty-two inches was selected for the ET-zone depth to approximate the average depth from which soil water is extracted by evaporation and transpiration in coarse soils in central Arizona. This depth is about halfway between the minimum (18 inches) and maximum (60 inches) evaporative depths for the region as given by Schroeder et al. (1994b). A LAI of 0.75 was selected because this value is believed to be representative of desert vegetation. This value is somewhat less than the maximum LAI given for the region (1.2) by Schroeder et al. (1994b). A growing season of between February 27 (Julian day 58) and November 27 (Julian day 331) was designated because the region receives little frost.

Initial Conditions. HELP allows the option of prescribing the initial moisture content throughout the profile. Otherwise, the model assigns a steady-state value approximately equal to field capacity. Soil moisture in both hypothetical materials were initially set to field capacity. The percent surface area allowing runoff was set to 100. The domain of each modeled profile was 32 inches in depth, with percolation being monitored at that depth.

The SoilCover Model

Structure

SoilCover is a one-dimensional, finite-element computer program that simulates water flow within variably saturated porous media. Table 3 summarizes the computations used in SoilCover. The model uses heat and mass transfer equations developed by Wilson (1990) to simulate coupled heat and mass flow in the soil profile. The theory is based on Darcy's and Fick's laws which describe the flow of liquid water and water vapor, respectively, and Fourier's law which describes conductive heat flow in the soil profile below the soil/atmosphere boundary. SoilCover calculates the soil evaporative flux using a modified Penman (1963) formula as detailed by Wilson (1990). Soil temperatures are calculated on the basis of conductive and latent heat transfer. Effects of vegetation are accounted for through the influence of LAI, rooting depth, and water stress. Because SoilCover numerically solves equations which govern the flow of water and heat, approximation errors occur. Cumulative water-balance errors for the simulations presented in this paper were less than 5%.

Table 3
SoilCover Model Computations

1. **Atmospheric boundary condition:**
21-year daily meteorological record includes precipitation (P), maximum and minimum temperature, maximum and minimum relative humidity (RH), net solar radiation, and average windspeed.

2. **Runoff (R) is calculated as follows:**
(a) if the surface is not saturated, R = 0.
(b) if the surface is saturated, R = P - Evaporation - Infiltration.

3. **Water vapor and liquid movement by Fick's Law and Darcy's Law:**

$$\frac{\delta h_w}{\delta t} = C_w^1 \frac{\delta}{\delta y}\left(k_w \frac{\delta h_w}{\delta y}\right) + C_w^2 \frac{\delta}{\delta y}\left(D_v \frac{\delta P_v}{\delta y}\right)$$

h_w is the total head (m)
t is time (s)
C_w^1 is the coefficient of liquid water consolidation
C_w^2 is the coefficient of water vapor consolidation
k_w is the hydraulic conductivity (m/s)
y is the position (m)
D_v is the water vapor diffusion coefficient (kg • m/kn • s)
P is the total gas pressure in the air phase (kPa)

4. **Heat transmitted through the profile:**
Fourier's Law used for conductive heat flow.

Actual evaporation given by modified Penman (1963) equation: f(radiation, RH, windspeed, water stress, air temperature, etc.).

Soil temperature predicted on the basis of conductive and latent heat transfer.

5. **Transpiration calculation:**
Transpiration governed by water stress, vegetation characteristics, and growing season.

Input Data

Input data for SoilCover can be categorized into: (1) hydraulic parameters, (2) climatic parameters, (3) vegetation parameters, and (4) boundary and initial conditions. Input data for the hypothetical cover soil and tailings materials used in the simulations are provided in Table 2.

Hydraulic Parameters. Hydraulic data include soil porosity, specific gravity, the soil-water characteristic curve (SWCC), hydraulic conductivity as a function of matric suction [K(h)], and thermal conductivity and specific heat as a function of water content. Figure 1 illustrates the

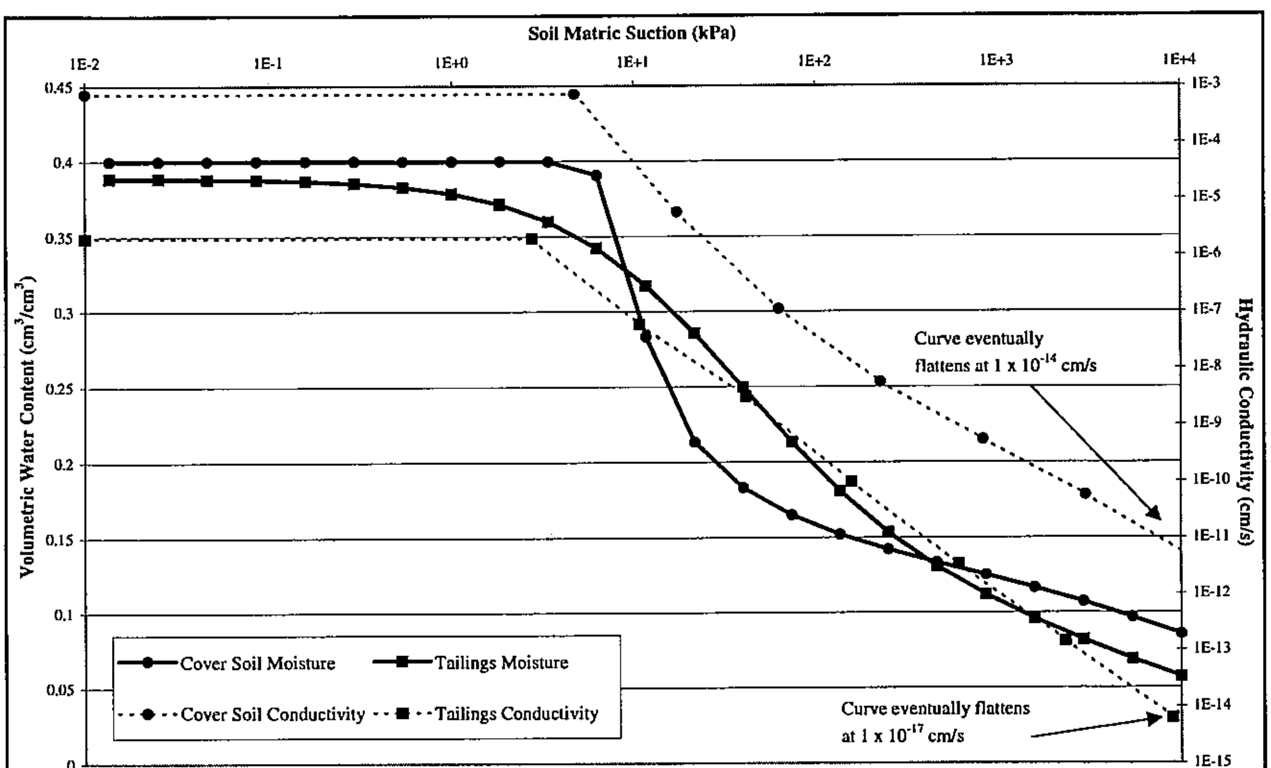
SWCC and K(h) curves for the hypothetical cover soil and tailings. The SWCC for each soil type was fitted using the technique of Fredlund and Xing (1994). The K(h) relationship was derived using the methods of Fredlund et al. (1994). The user is obligated to use the Fredlund and Xing (1994) technique for SWCC fitting but can opt to modify the program-generated or create a unique K(h) curve if desired. We used the program-generated K(h) curves but increased the excessively low predicted hydraulic conductivities at high matric suctions to increase the efficiency and accuracy of the water-balance computations and not allow the model to use unrealistically low values (i.e. less than 10^{-17} cm/sec). Thermal conductivity as a function of water content was calculated by SoilCover based on the Johansen (1975) method. Finally, soil specific heat capacity as a function of water content was input using values calculated from the de Vries (1963) method.

Climatic Parameters. The user has the option of inputting detailed or limited meteorological data into SoilCover. We used the same 21-year climatological record used in the HELP simulations to input a detailed record of daily maximum and minimum temperature and relative humidity, site latitude, average daily windspeed, daily net radiation, and daily precipitation. Net radiation values were derived from the daily solar radiation flux values generated by the HELP model using a conservation of energy approach outlined by Shuttleworth (1993).

Vegetation Parameters. Vegetative input includes length of the growing season, moisture limiting and wilting points, root zone depth, and vegetative quality. LAI functions during the growing season are generated by SoilCover based on the vegetative quality (poor, good, and excellent). Depths to the top and bottom of the root zone are required for each day of the growing season. The root zone was assumed to extend from the surface to 18 inches in depth in the simulations. Although roots may not penetrate beneath shallow soil covers into tailings, this depth was selected based on professional judgement to make SoilCover transpiration calculations correspond to the HELP ET sink estimations.

Boundary and Initial Conditions. SoilCover requires specification of upper and lower hydraulic and temperature boundary conditions, initial moisture and temperature conditions throughout the profile, and convergence, time step, and mesh geometry parameters. Convergence and time-stepping parameters were kept constant across each

Figure 1
Soil-Water Characteristic and Hydraulic Conductivity Curves Used in the SoilCover Modeling



simulation. The model normally simulates a maximum of 365 days but we had the model developer modify the code to simulate multiple years. In all simulations, percolation was monitored at a depth of 32 inches to maintain consistency with the HELP simulations. A water table was assumed to exist 200 feet below land surface to reduce the water balance error in the simulations by increasing the total amount of water in the profile.

Model Comparison

Two 21-year simulations run by both models are presented for comparison: 6- and 12-inch thicknesses of cover soil over tailings (Figure 2). Water-balance results for the top 32 inches of the modeled profiles are summarized on an annual average basis in Table 4.

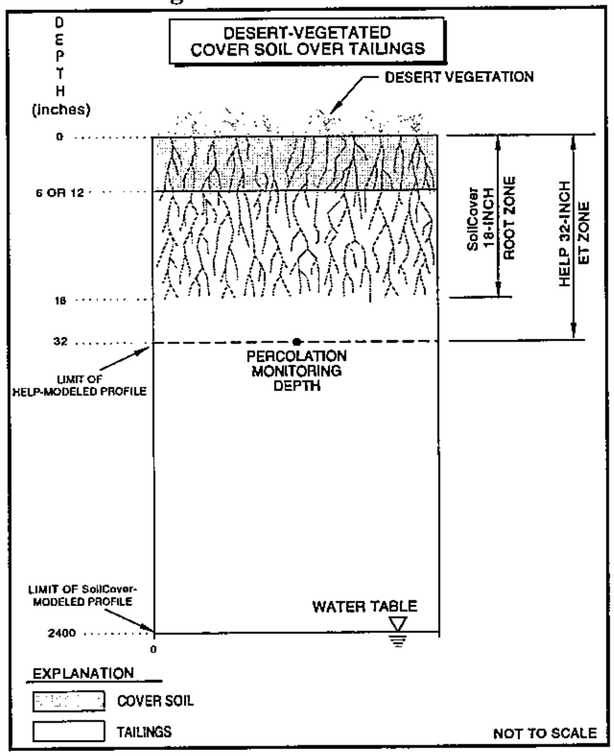
6-Inch Cover Scenario

Both models predicted similar average annual ET and water storage changes for the 6-inch cover soil scenario. However, runoff predicted by SoilCover was nearly two times higher than that predicted by HELP (2.29 vs. 1.27 in/yr). Thus, more water infiltrated into the profile modeled by HELP than that modeled by SoilCover. This fact, coupled with HELP's inability to route water upward once it percolates beyond the user-prescribed ET zone, led HELP to predict 0.9 in/yr of percolation while SoilCover predicted no net percolation. HELP-predicted percolation occurred mainly in about 5 distinct events during the 21-year simulation (Figure 3). No net percolation was predicted by SoilCover (Figure 3) because water that infiltrated into the profile was subsequently removed by evapotranspiration.

12-Inch Cover Scenario

Both models predicted similar average annual ET, water storage changes, and runoff for the 12-inch cover scenario, showing that about the same amount of water infiltrated the cover in both models. However, HELP-predicted percolation was over 10 times greater than SoilCover-predicted percolation (0.98 vs. 0.09 in/yr). This indicates that even if HELP's simple algorithms predict the same amount of infiltration as SoilCover, they may still overpredict percolation. Figure 3 shows that most of the percolation predicted by HELP occurred in about 5 or 6 main events during the same time intervals observed for the 6-inch cover scenario. On the other hand, percolation predicted by SoilCover occurred primarily in two events.

Figure 2
Configurations of Modeled Profiles



Summary and Conclusions

The HELP and SoilCover models were used to estimate the water balance of two hypothetical store-and-release covers to compare the utility of both models in a semi-arid climate. HELP allowed a greater amount of water to infiltrate a 6-inch cover than SoilCover. This fact,

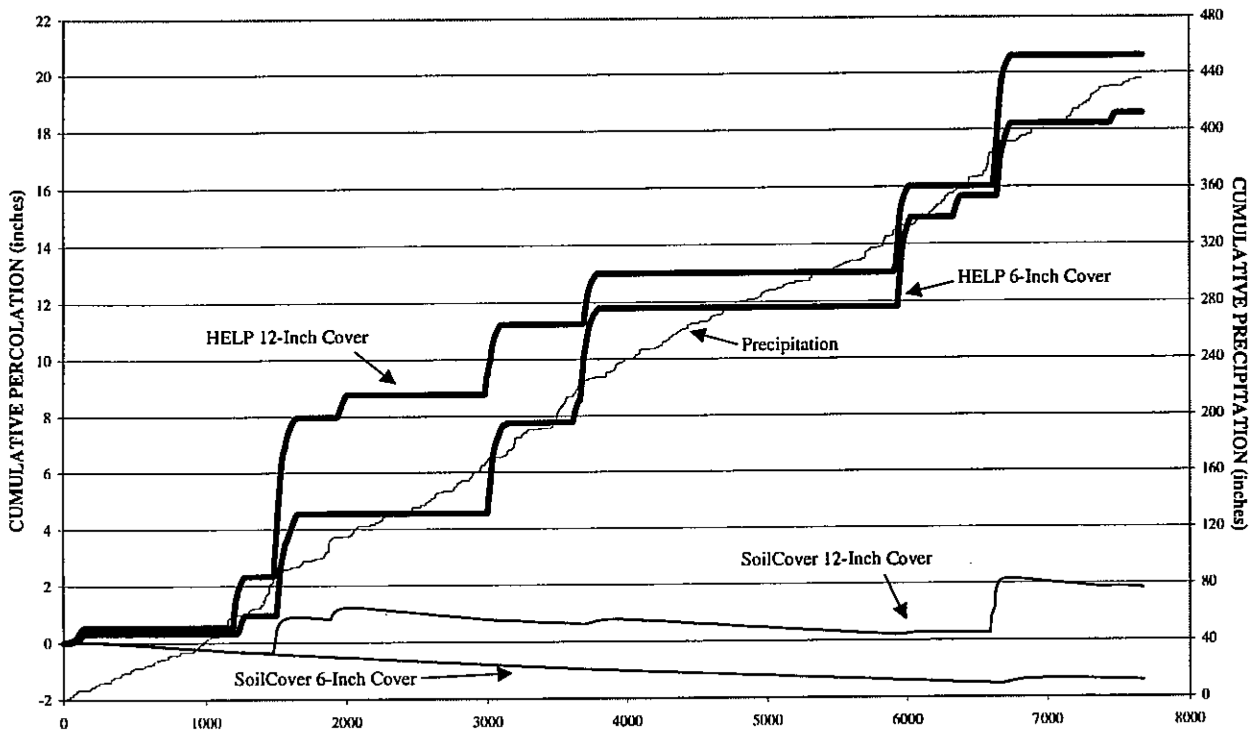
Table 4
Comparison of SoilCover and HELP Results:
Average Annual Values for Simulations of the 1975 to 1995 Climate Record

Component	Unit	6-inch Cover Scenario		12-inch Cover Scenario	
		SoilCover	HELP	SoilCover	HELP
Precipitation	in/yr	20.75 (100%)	20.75 (100%)	20.75 (100%)	20.75 (100%)
Runoff		2.29 (11%)	1.27 (6%)	0.79 (4%)	0.69 (3%)
Evapotranspiration		18.99 (92%)	18.85 (91%)	19.72 (95%)	19.32 (93%)
Water Storage Change[a]		-0.19 (-1%)	-0.26 (-1%)	-0.35 (-2%)	-0.23 (-1%)
Percolation		-0.07[b] (0%)	0.89 (4%)	0.09 (0.4%)	0.98 (5%)

[a]Negative values indicate net stored water loss.

[b]Negative value indicates upward (negative) percolation.

Figure 3
Model-Predicted Cumulative Percolation



coupled with HELP's inability to accurately route infiltrated water upward as a result of evapotranspiration, led to larger predictions of percolation than SoilCover. In 12-inch cover simulations, about the same amount of infiltration occurred in both the HELP and SoilCover scenarios. Nevertheless, HELP predicted percolation to be an order of magnitude higher than SoilCover because of its underestimation of evapotranspirative losses in a semi-arid climate. Many field studies have shown negligible (<0.1 in/yr) percolation in vegetated areas in semi-arid to arid climates (Scanlon et al. 1997). SoilCover predictions match these field observations much more closely than HELP. If the user wishes to obtain rigorous and accurate predictions of the soil-water balance in semi-arid regions, the more physically based equations utilized in the SoilCover model are probably more appropriate than simplified equations used in the HELP model.

References

Brooks, R.H. and A.T. Corey. 1964. Hydraulic properties of porous media. Colorado State University, Fort Collins, CO. Hydrology Paper 3. 27 pp.

Campbell, G.S. 1974. A simple method for determining unsaturated conductivity from moisture retention data. Soil Science 117(6):311-314.
https://doi.org/10.1097/00010694-197406000-00001

de Vries, D.A. 1963. Thermal properties of soils. *In* Physics of Plant Environment, W.R. van Wijk (ed.). North-Holland Publishing Company, Amsterdam. Chapter 7, pp. 210-235.

Electric Power Research Institute (EPRI). 1984. Comparison of two groundwater flow models - UNSAT1D and HELP. EPRI CS-3695, Project 1406-1, October 1984 by F. L. Thompson and S.W. Tyler. EPRI, Palo Alto, CA.

Fleenor, W.E. and I.P. King. 1995. Identifying limitations on use of the HELP model. *In* Landfill Closures, Environmental Protection and Land Recovery, Dunn, R.J. and U.P. Singh, editors. American Society of Civil Engineers Geotechnical Special Publication No. 53, New York. pp. 121-138.

Fredlund, D.G. and Anqing Xing. 1994. Equations for the soil-water characteristic curve. Canadian Geotechnical Journal 31:521-532.
https://doi.org/10.1139/t94-061

Fredlund, D.G., Anqing Xing, and Shangyan Huang. 1994. Predicting the permeability function for unsaturated soils using the soil-water characteristic curve. Canadian Geotechnical Journal 31:533-546.
https://doi.org/10.1139/t94-062

Geo-Analysis 2000 Ltd. 1997. SoilCover User's Manual, Version 4.0. 202 Kerr Road, Saskatoon, Saskatchewan, Canada. June, 1997.

Johansen, Ö. 1975. Thermal conductivity of soils. Institute for Kjöletechnik, 7034 Trondheim-NTH, Norway.

Khire, M.V., C.H. Benson, and P. J. Bosscher. 1997. Water Balance Modeling of Earthen Final Covers. Journal of Geotechnical and Geoenvironmental Engineering 123(8):744-754.
https://doi.org/10.1061/(ASCE)1090-0241(1997)123:8(744)

Morris, C.E. and J.C. Stormont. 1997. Capillary barriers and subtitle D covers: estimating equivalency. Journal of Environmental Engineering 123(1):3-10.
https://doi.org/10.1061/(ASCE)0733-9372(1997)123:1(3)

Penman, H.L. 1963. Vegetation and hydrology. Technical Comment No. 53, Commonwealth Bureau of Soils, Harpenden, England.

Ricard, J.F., M. Aubertin, F.W. Firlotte, R. Knapp, J. McMullen, and M. Julien. 1997. Design and construction of a dry cover made of tailings for the closure of Les Terrains Auriferes Site, Malartic, Quebec, Canada. *In* Proceedings of the Fourth International Conference on Acid Rock Drainage, Vancouver, B.C. May 31 to June 6, 1997. Volume IV, pp. 1515-1530.

Scanlon, B.R., S.W. Tyler, and P. J. Wierenga. 1997. Hydrologic Issues in Arid, Unsaturated Systems and Implications for Contaminant Transport. Reviews of Geophysics 35(4):461-490.
https://doi.org/10.1029/97RG01172

Schroeder, P.R., C.M. Lloyd, P.A. Zappi, and N.M. Aziz. 1994a. The Hydrologic Evaluation of Landfill Performance (HELP) Model: User's Guide for Version 3. EPA/600/R-94/168a. U.S. Environmental Protection Agency Risk Reduction Engineering Laboratory, Cincinnati, OH.

Schroeder, P.R., T.S. Dozier, P.A. Zappi, B.M. McEnroe, J.W. Sjostrom, and R.L. Peyton. 1994b. The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3. EPA/600/R-94/168b. U.S. Environmental Protection Agency Risk Reduction Engineering Laboratory, Cincinnati, OH.

Shuttleworth, W.J. 1993. Evaporation. Chapter 4 *In* Handbook of Hydrology, D.R. Maidment (ed.). McGraw-Hill, Inc. New York.

Wilson, G.W. 1990. Soil evaporative fluxes for geotechnical engineering problems. Ph.D. Thesis, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

Woyshner, M. and E.K. Yanful. 1995. Modelling and field measurements of water percolation through an experimental soil cover on mine tailings. Canadian Geotechnical Journal 32(4):601-609.
https://doi.org/10.1139/t95-062

Wright, W. and A. K. Turner. 1987. A combined modeling program for evaluating the cover design at a uranium mill tailings disposal site. *In* Proceedings of the Solving Ground Water Problems with Models, February 10-12, 1987, Denver, CO. Sponsored by The Association of Ground Water Scientists and Engineers, The International Ground Water Modeling Center, and the Holcomb Research Institute. pp. 853-869.

Yanful, E.K., B.C. Aube, M. Woyshner, and L.C. St-Arnaud. 1994. Field and laboratory performance of engineered covers on the Waite Amulet tailings. *In* Proceedings of the International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. April 24-29, 1994. Volume 2, pp. 138-147.
https://doi.org/10.21000/JASMR94020138