A COMPARISON OF SIMULATED UNSATURATED FLOW THROUGH WASTE ROCKS USING TWO COMMONLY USED COMPUTER MODELS

by

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Abstract: A study was undertaken to examine the feasibility of using two computer programs (HELP and SoilCover) to model unsaturated flow through an inactive reclaimed tailing dam. The aim was to estimate the amount of flux at the bottom of the facility. The validity of the use of these models to analyze flow through reclaimed tailings and waste rock was examined. These two models were compared using similar geometry, climatological and hydraulic parameters. The theory of unsaturated flow for these two models and required input parameters are discussed. A sensitivity analysis of the various input parameters for the two models was performed to identify the important input parameters required for the unsaturated flow models. The study revealed that saturated hydraulic conductivity, Soil Conservation Service curve number and fraction of the area for surface runoff were the most influential parameters influencing the HELP model simulations, while the SoilCover model was most sensitive to the coefficient of volume compressibility

Additional Key Words: hydraulic conductivity, HELP, SoilCover, discharge evaluation

Introduction

Calculation of the expected discharge through reclaimed mine waste rock dumps, inactive tailings impoundments and inactive leach stockpiles are important to the design of any facility closures. Regulatory agencies are charged with the protection of surface and groundwater resources and need demonstrations that the proposed reclamation activities will prevent release of pollutants. Mining companies need assurances that analytical models used to predict discharge rates are accurate to provide economic solutions to their reclamation responsibilities. When real measurements of the discharge cannot be made, then model estimates are used.

Such models attempt to predict the base flux and unsaturated hydraulic conductivity (k_{unsat}) of the porous media involved. Base flux is defined in this case as the percolation at the base of the waste rock dump. The analytical methods for most unsaturated flow analyses assume that a modified form of Darcy's law is valid. This requires adjusting for the variation in hydraulic conductivity as a function of the negative pore-water pressure. For coarse open graded waste rock dumps, where preferential flow pathways could exist, the Darcy models may not be applicable. For such coarse rockfill dumps, the flux through a surficial cover system can be substituted for base flux.

Currently, available analytical approaches used to evaluate the seepage flux at the base of the mine waste rock dump or tailings impoundment are based on one-dimensional methods of analysis. One of the most commonly used methods to evaluate the amount of seepage expected from a reclaimed rock dump is the Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al. 1994). This program has a tendency for overestimating the flux, especially when applied to a non-vegetated deposit in an arid climate (Fleenor et. al., 1995). A more accurate calculation of flux through a waste rock stockpile may result in more efficient and reliable designs. In this paper,

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calculations from an alternative model (SoilCover, 1997), are compared with those of the HELP model. Both models are used for an evaluation of seepage through an inactive reclaimed mine tailings dam. A discussion of the required input parameters for each model and sensitivity analysis of important parameters is also presented.

Previous Work

It is essential to understand geochemical and hydrogeological properties of waste rock in order to predict discharge releases. Other issues that must be considered are climate, surface hydrology, thermal properties of waste-rock, groundwater flow conditions, vegetation, slope and erosional stability, and long term ecological stability. A review of literature indicated that there are very few sites, where field measurements were compared with predicted or calculated values. Case studies that involve the use of SoilCover and HELP models have been described, and a discussion about their relative merits has also been included.

A research program involving deployment of field instrumentation, laboratory testing and numerical modeling for the evaluation of soil covers installed on waste rock dumps at two mine sites in Canada and United States was undertaken by Wilson et. al. (1996) and Wilson (1995). One site was located in a humid environment, and the other in an arid climate. The objective of the program was to evaluate the performance of soil covers with respect to water and oxygen fluxes. Numerical modeling of water, heat and oxygen flow through the cover systems was carried out using software based on SoilCover version 1.0. The instrumentation installed consisted of thermal conductivity sensors for the measurement of matric suction and temperature, neutron probe access tubes for the volumetric water content, and a weather station for the measurement of climatic conditions. The weather station provided continuous measurement of precipitation, global and net radiation, air temperature, wind speed, and relative humidity. The soil-water characteristic curve was measured for the different layers. The relationship between hydraulic conductivity and matric suction was calculated using a commercially available software package called KCAL (Geo-Slope Int., 1993). Relationships between thermal conductivity and specific heat capacity, versus water content, were determined using the commercially available computer program – The HyProS (Tarnawski and Wagner, 1992). The hydraulic, thermal, and climatic properties described above are required input to the SoilCover model and are discussed in detail in subsequent sections. The output from the model simulations was compared to measured values obtained from the field instrumentation. Another project that utilized the SoilCover model involved designing of reclamation soil cover for a gold tailings impoundment at the Kennecott Ridgeway Mine, South Carolina (Kowalewski, et al. 1998). Besides SoilCover, another model - SEEP/W was used to evaluate potential soil cover configurations with respect to underlying tailings. The SEEP/W model simulated the three-dimensional flow under both saturated and unsaturated conditions using axisymmetric mode. It was noted that SoilCover model being one-dimensional, could not quantify all the processes that are expected to occur within soil cover-tailings systems. Based on the combination of the results of the modeling, and other issues associated cover construction, a preferred reclamation soil cover was identified for tailings impoundment.

Khire et al. (1997) designed the final earthen covers for a landfill project based on results from two numerical water balance models (HELP and UNSAT-H). The HELP model is discussed in Section 4. UNSAT-H uses a finite difference implementation of Richard's equation that describes unsaturated liquid and vapor flow in soil layers, adjusted for water removal through plant roots. The HELP model overpredicted percolation significantly, while the UNSAT-H model slightly underpredicted percolation, based on measured values. However, both models captured the seasonal variation in surface runoff, evapotranspiration, soil water storage, and percolation. The UNSAT-H modeled these variations more accurately than the HELP model. Guzman et al. (1998) have developed the basic approach to unsaturated flow through leach pads, waste dumps and tailing impoundments which includes field characterization, data interpretation, calibration and prediction. The computer program UNSAT2 (modified version of UNSAT-H) was used to model the unsaturated flow. The input climatic data was generated by the HELP model. Fleenor et al. (1995) conducted a study where they compared the HELP model with a two-dimensional finite element unsaturated groundwater model, RMA42. In RMA42, Richard's equation is solved using unsaturated hydraulic conductivity calculations proposed by Van Genutchen. Comparison of results for an unvegetated soil surface demonstrated that the HELP model simulated vertical water fluxes under humid climate conditions reasonably well. However, in the case of arid and semi-arid climates, the empirical assumptions used in the HELP model increasingly limited its ability to predict rational values of vertical transport. It was concluded that without specific modification of the HELP model to account for the capillary forces and the removal of water below the soil root zone, HELP will continue to overpredict downward vertical moisture fluxes.

Theory and Unsaturated Flow Model

Suction properties constitute a key element for the functional representation of unsaturated flow conditions. To effectively predict flux, determinations of the unsaturated hydraulic conductivity (k_{unsat}) are required. Two phases of an unsaturated soil can be classified as fluids - water and air. For the purposes of this paper, only the water phase is discussed. Darcy's Law is assumed to be valid for flow of water through an unsaturated soil (Fredlund and Rahardjo 1993). However, the value of k_{unsat} is not constant. It depends on the water content and matric suction of the soil material.

Unsaturated Hydraulic Conductivity

Hydraulic conductivity for soils has a maximum value at saturation but decreases dramatically with decreasing water content. In an unsaturated soil, the hydraulic conductivity is significantly affected by combined changes in the void ratio and degree of saturation of the soil (Fredlund and Rahardjo 1993). Water flows through the pore space filled with water; therefore the percentage of the voids filled with water is an important factor. As a soil becomes unsaturated, air first replaces some of the water in the large pores, and this causes the water to flow through the smaller pores with an increased tortuosity to the flow path. A further increase in the matric suction of the soil leads to the further decrease in the pore volume occupied by water. In other words, the air-water interface is drawn closer to the soil particle. As a result, the k_{unsat} decreases rapidly with the increase of matric suction (Figure 1).

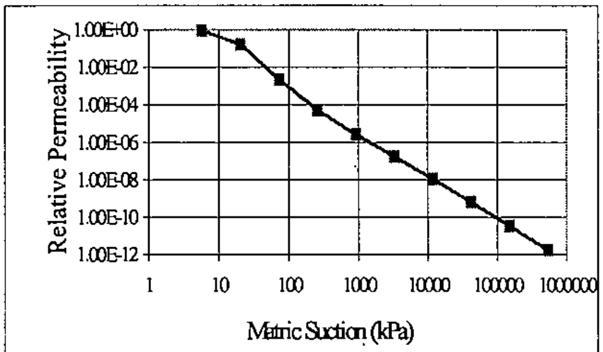

Figure 1. Variation of coefficient of permeability with matric suction

The net result is that the transition from saturated to unsaturated state generally results in a very steep decline of hydraulic conductivity. It has been shown that the decrease in its value from saturation to that at ambient field moisture content could be about nine orders of magnitude for sands and five orders of magnitude for clays (Stephens, 1994). There is a great need for developing reliable and practical tools for determining conductivity, especially in the field at a scale relevant to the problems of interest to geotechnical and environmental engineers. The unsaturated hydraulic conductivity is a relatively unique function of water content of a soil during desorption process and a subsequent absorption process. It exhibits hysteresis and it is therefore important to denote the process for which the unsaturated hydraulic conductivity was determined. The function appears to be unique as long as the volume change of the soil structure is negligible or reversible.

Methods To Calculate Unsaturated Hydraulic Conductivity. There are many methods to determine unsaturated hydraulic conductivity using either direct techniques or indirect methods. The direct methods involve methods that are conducted either in the field or in a laboratory. These methods are difficult and time-consuming. Indirect methods involve determination and prediction of the soil-water characteristic curve and prediction of the k_{unsat} function. A detailed discussion of the soil-water characteristic curve is presented in the following section. There are numerous relationships proposed and can be divided into mainly three categories - empirical, macroscopic and statistical methods (Leong and Rahardjo 1997). The statistical methods are the most rigorous models. They are based on the measured soil-water characteristic curve. It will of great value for a practicing engineer, if there is a relationship that can predict the unsaturated hydraulic conductivity function. Relative hydraulic conductivity functions typically provide reasonably good predictions of the measured unsaturated hydraulic conductivity for relatively high-permeability soils, such as sands and sandstones. However, in the case of relatively low-permeability soils, it provides less accurate predictions (Chiu and Shackelford 1998). Reviewing the past literature, it is clear that there is no relationship to date that is able to predict this function for all ranges of suction.

Soil-water Characteristic Curve

The soil-water characteristic curve (SWCC) is probably the most widely used method of characterizing hydraulic properties of unsaturated porous media such as soils and tailings (Aubertin et al, 1998).

The SWCC is defined as the variation of water storage capacity within the macro and micro pores of a soil, with respect to suction (Fredlund et al. 1994). This relationship is generally plotted as the variation of gravimetric water content, ω, volumetric water content, θ_w, or degree of saturation, S, with respect to soil suction (Figure 2). The total suction (ψ) is comprised of both matric (u_a-u_w) and osmotic suction. However, the matric suction component has proven to govern the hydraulic behavior of unsaturated soils in the lower suction range encountered at most field conditions (Fredlund and Xing 1994). At high suction values, the matric and the total suctions are generally assumed to be similar in magnitude. The suction that corresponds to the point where the curve realizes a sharp drop in water content is referred to the air-entry value (AEV). The air entry value indicates the suction pressure at which the soil begins to desaturate and, depending on the soil type, may or may not be well defined. To determine each point on a soil-water characteristic curve requires a great deal of time and effort. Hence, it is more convenient to perform the minimum amount of tests required to obtain a good and representative SWCC and then, fit the experimental points obtained to an assumed mathematical model.

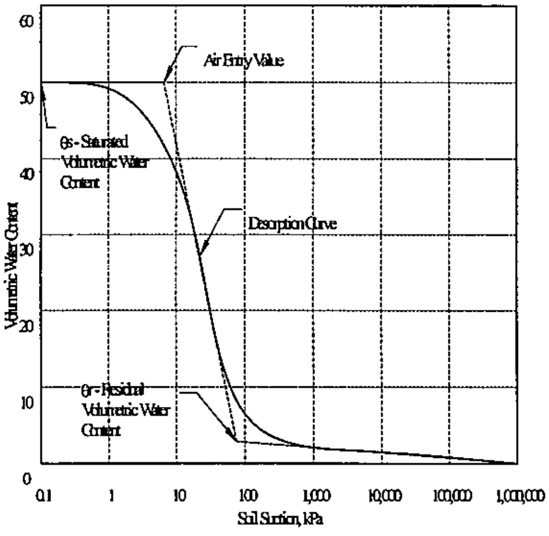

Figure 2 Typical Soil Water Characteristic Curve

Methods To Determine Soil-Water Characteristic Curve. Several mathematical equations have been proposed for the SWCC. Most of the equations are empirical in nature and have been formulated to fit experimental data as closely as possible. In these equations, the fitting parameters depend on the basic soil properties. By experimental observation, the general shape of the SWCC resembles a sigmoid. The limitation of using these models is that they are only strictly valid for certain soils and certain ranges in suction.

It can be seen at this point that in order to obtain the entire SWCC, by fitting data to one of the proposed equations, a minimum of 3 or 4 experimental points are required to start the fitting process. For this reason, it is important to look at the current methods used to measure the SWCC. The soil-water characteristic curve can be determined by monitoring the suction and water content values during a cycle of either wetting or drying of the soil. The laboratory methods include the pressure plate/pressure membrane, Tempe cell (Fredlund & Rahardjo 1993), and filter paper method (Houston et al. 1994).

Numerical Procedure

Water movement through soils or waste dumps can be divided into three component system consisting of the soil-atmosphere interface, the near surface unsaturated zone, and the deeper saturated zone. In the past, seepage modeling has primarily focused on the saturated zone. This focus creates a discontinuity in the natural system, as the unsaturated zone and the soil atmosphere is not represented in the model. Advances in unsaturated soil technology during the past decade have led to the development of routine modeling techniques for saturated and unsaturated flow systems. The HELP and SoilCover models are used in this section to calculate the seepage from a reclaimed mine tailings.

Assumptions and Input Parameters for HELP and SoilCover

The input parameters for both the Soil Cover and HELP models are listed in Table 1. The parameters listed in the table are only those that are relevant for the reclaimed mine tailings being modeled.

Table 1 Comparison of Input Parameters for HELP and SoilCover

Description	**HELP**	**SOIL COVER**	**COMMENTS**
Layers:			
Fine Tailings	vertical percolation layer	the soil layers are defined based on the soil properties	Soil cover has no lateral drainage
Coarse Tailings	lateral drainage layer		
Bed rock	barrier layer		
Thickness of layer	required	required	
Soil parameters:			
Plan area	required	not required	
Porosity	required	required	
Field capacity	required	not required	
Wilting point	required	not required	
Saturated hydraulic conductivity	required	required	Soil cover is very sensitive to this parameter
% of area available for runoff	required	not required	Portion that is not infiltrating is accounted as runoff
Runoff curve number	required	not required	
Specific Gravity	not required	required	
Soil Water Characteristic Curve (SWCC)	not required	required	HELP calculates SWCC from other parameters
Coefficient of volume change	not required	required	HELP & Soil cover are very sensitive to this parameter
Unsaturated hydraulic conductivity function	predicted using Campbell, 1974	predicted using Fredlund et al, 1994 method	
Quartz content	not required	required	to predict thermal conductivity
Solids Specific Heat	not required	required	to predict volumetric specific heat
Soil Temperature	not required	required	
Climatic Parameters:			
radiation	required	required	Help - solar radiation; Soil cover-net radiation
precipitation	required	required	
minimum and maximum relative humidity	not required	required	
daily air temperature	required	required	
wind speed	not required	required	
latitude	required	required	
evapotranspiration data	required	required	
Boundary Conditions:			
Upper boundary condition	none	Precipitation	
Bottom boundary condition	none	Suction or water content	

HELP model. The HELP model requires general climatic, soil and design data to compute the water balance of a landfill. The model efficiently estimates the amounts of runoff, evapotranspiration, drainage, leachate collection and liner leakage that may be expected to result from the operation of a landfill. The bottom flux estimation is of particular importance to the evaluation of a mine tailings dam. Some of the assumptions and essential features of this model are listed below.

1. Surface runoff is modeled using the SCS curve-number method. Storm runoff is calculated as follows:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{1}$$

   where, S = (1000/CN) – 10
   Q = runoff, P= precipitation, S= maximum potential retention and CN = curve number

2. The algorithm assumes that once the water content of a given horizon within the cap drops below the field capacity , flow into lower horizons are non-existent.

3. Water is assumed to move only due to gravity effects.

4. Unsaturated hydraulic conductivity is calculated using Campbell's equation

$$k_{unsat} = k_{sat}\left[\frac{\theta - \theta_r}{\phi - \theta_r}\right]^{3+\frac{2}{\lambda}} \tag{2}$$

   where, k_{unsat} = unsaturated hydraulic conductivity
   k_{sat} = saturated hydraulic conductivity
   θ = actual volumetric water content
   θ_r = residual volumetric water content
   ϕ = total porosity
   λ = pore-size distribution index

   The value of λ is calculated using the following equation

$$\frac{\theta - \theta_r}{\phi - \theta_r} = \left(\frac{\psi_b}{\psi}\right)^{\lambda} \tag{3}$$

   where ψ = capillary pressure (bars)
   ψ_b = bubbling pressure (bars)

   The computer program solves the above equation for two different capillary pressures simultaneously to determine the pore-size distribution index and the bubbling pressure.

5. Evapotranspiration calculations are based on the Penman Model that incorporates wind and humidity effects, as well as long wave radiation losses (heat loss at night).

6. The computer program recognizes four general types of layers. These are as follows:

   Vertical percolation layers (Fine Tailings) - Flow in this layer is by unsaturated vertical downward drainage due to gravity. Upward flux due to evapotranspiration is modeled as an extraction. The main role of a vertical percolation layer is to provide moisture storage and the hydraulic conductivity specified for this layer should be in the vertical direction.

   Lateral Drainage Layers (Coarse Tailings) - Vertical flow in a lateral drainage layer is modeled in the same manner as a vertical percolation layer, but saturated lateral drainage is also allowed. The hydraulic conductivity specified should be in the lateral direction.

   Barrier soil liners (Rock/ Impermeable layer) – This layer is intended to restrict vertical drainage. The saturated hydraulic conductivity of this layer is substantially lower than other layers. Liners are assumed to be saturated at all times but leak only when there is a positive head on the top surface of the liner. The algorithm allows only downward saturated flow in this layer. Evapotranspiration and lateral drainage is not permitted from this layer.

   Geomembrane liner – These are virtually impermeable synthetic membranes that reduce the area of vertical drainage to a very small fraction of the area located near manufacturing flaws and installation defects. A small quantity of vapor transport across the membrane also occurs and can be modeled by specifying the vapor diffusivity as the saturated hydraulic conductivity of the geomembrane.

   These layers should be arranged according to certain basic rules. For example the HELP model does not permit a vertical percolation layer below the lateral drainage layer, or a barrier soil-liner underlying another barrier soil-liner.

SoilCover. SoilCover is a one dimensional finite element model for transient conditions (SoilCover, 1997). The computer model uses a physically based method for calculating the exchange of water and energy between the atmosphere and a soil surface. Darcy's Law and Fick's Law describe the flow of liquid water and water vapour, and Fourier's Law describes conductive heat flow in the soil profile. Some of the assumptions and essential features of SoilCover model are listed below.

1. It assumes that any precipitation that cannot infiltrate runs off the surface. The runoff is calculated as follows: Runoff = Precipitation - Actual Evaporation – infiltration (calculated as Darcy's flux) across the first two gauss points between the top and second node in the mesh.

2. It requires input of a soil-water characteristic curve and relative conductivity vs. suction data. SoilCover version 4.01 uses an equation for the soil water charcteristic curve developed by Fredlund and Xing (1994).

$$\theta = C(\psi)\frac{\theta_s}{\{\ln[e+(\psi/a)^n]\}^m} \tag{4}$$

with

$$C(\psi) = \frac{\ln(1+\psi/\psi_r)}{\ln[1+1000000/\psi_r]} \tag{5}$$

where,

θ = Volumetric water content

ψ = Suction

θ_s = Saturated volumetric water contents

ψ_r = Suction corresponding to the residual water content θ_r

a, n, and m = Curve fitting parameters

3. It requires a coefficient of volume change M_v, as measured in a normal consolidation test. This is also the slope in the positive pore water pressure region. The slope defines the volume of water taken or released by a change in pore water pressure. This function controls the transient nature of soil moisture movement. As such, it is crucial that the slope function be smooth and continuous from zero pore pressure to 1 million kPa suction. The slope function should approach the user M_v values near saturation, then increase towards the air entry value of the soil, and then decrease as the suction values increase.

4. The following boundary conditions are used in the computer program:
   (a) For the unsaturated case: Liquid flux boundary condition at top node = Precipitation (user specified) - Internally calculated actual evaporation.
   (b) For saturated case : Fixed surface pressure = 0 kPa at the upper boundary.

5. The evapotranspiration calculation is based on Penman's equation for potential evaporation from a free surface..

6. Layers: User specified layers and their assumed parameters are used.

Results of Help and SoilCover Model Simulations

Sensitivity Analysis

Sensitivity analysis of various inputs to HELP and Soil Cover models were performed.

The simple situation depicted in Figure 3 used to simulate unsaturated flow through an inactive reclaimed mine tailings and the flux at the bottom of the tailings was calculated.

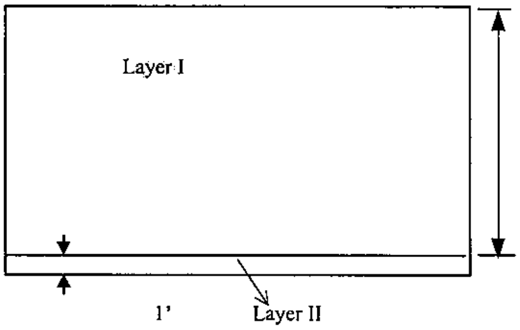

Figure 3. Example problem

Input Parameters common to both the models.
Total depth of soil: 100 ft
Number of layers: 2
Thickness of Layer I: 99 ft
Porosity of Layer I: 0.45
Thickness of Layer II: 1 ft
Porosity of Layer II: 0.4
The duration of the simulation: 1 year
Identical weather, temperature, precipitation and evapotranspiration data

Data used exclusively in the HELP model.

Area of the dump projected to the horizontal plane = 2.3 acres

Solar radiation data for Phoenix, Arizona during 1996 was used.

Field capacity: 0.2 [volumetric water content @ 0.33 bars of suction]

Wilting point: 0.1 [volumetric water content @ 15 bars of suction]

Data used exclusively in the Soil Cover model.

Coefficient of volume change M_v: 1×10^{-6} kPa^{-1} and 9.1×10^{-6} kPa^{-1}

Radiation data: Net all wave radiation is required. It was calculated as follows: (Jensen et.al. 1990)

$R_n = a_3R_s + b_3$

R_n = net all wave radiation

R_s = solar (short wave) radiation = $(0.35 + 0.61S)\ R_{SO}$

S = ratio of actual to possible sunshine.

In this case, values used ranged from 0.75 - 0.96, depending on the time of year.

R_{SO} = cloudless day solar radiation received at the earth's surface (depends on the latitude and the month).

a_3, b_3 = regression coefficients of net radiation on solar radiation depending on the location. In a semi-arid environment, the values of a_3, b_3 are 0.75 and –0.28, respectively.

Sensitivity Analysis of HELP model

Several simulations, using the problem described above, were run using the HELP model to conduct a sensitivity analysis. The effect of following parameters on the determination of seepage at the bottom of the tailings was investigated.

1. Saturated hydraulic conductivity
2. Soil Conservation Service (SCS) runoff curve number
3. Fraction of the area allowing runoff

Table 2 summarizes the result from the HELP model.

Saturated hydraulic conductivity. The saturated hydraulic conductivity k_{sat} was varied between 1 and 1E-5 (cm/sec). The SCS curve number of 95 was used for all cases. The results indicated a significant amount of decrease in the bottom flux and increase of surface runoff when the saturated hydraulic conductivity decreased from 1E-3 to 1E-4 (Figure 4). The situation was reversed when the hydraulic conductivity is increased from 1E-2 to 1. This indicated that the results are extremely sensitive to k_{sat} values for fine-grained soils and coarse grained soils.

SCS curve number. The values for the SCS runoff curve number were varied from 57 to 98 and the their effect on runoff and bottom flux is shown in Figure 5. At 57, there was no runoff. There was a three-fold increase in runoff when the SCS number changed from 85 to 98. There was a corresponding decrease in the bottom flux. This indicates that as the curve number increases in the range of 85 to 95, its effect on the results is significant.

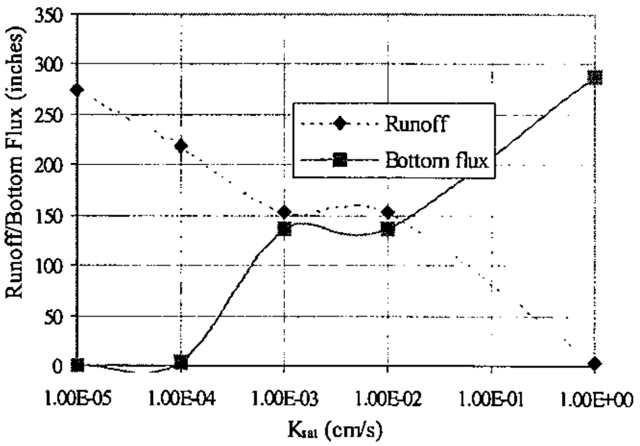

Figure 4. Effect of Saturated Hydraulic Conductivity on Surface Runoff and Bottom Flux (HELP MODEL).

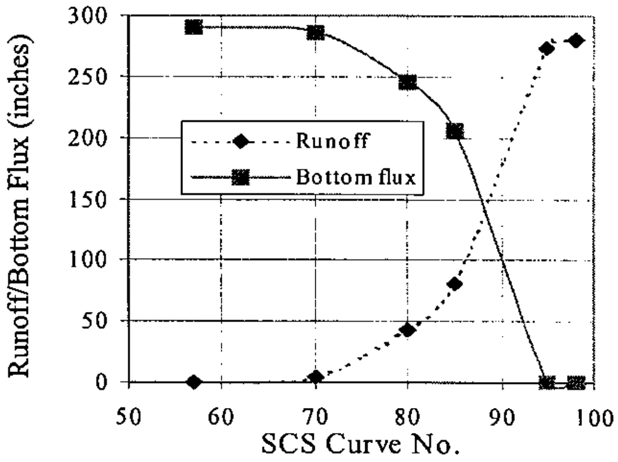

Figure 5. Effect of SCS Curve no. on Surface Runoff and Bottom Flux (HELP MODEL)

Fraction of the area allowing runoff. As the fraction of the area allowing runoff is reduced, there is a corresponding decrease in runoff values and increase in bottom flux. Unless a chamber is designed in the reclamation cover system, the mine tailings will subside over time. Hence, the fraction of area allowing surface runoff could also change with time.

Sensitivity Analysis for Soil Cover

The results are extremely sensitive to k_{sat} and to the coefficient of volume change (M_v), as shown in Figure 6. It was also found that for $k_{sat} \geq 1$ cm/s, the simulations did not yield good results. The soil properties were changed for the simulations. The remaining parameters were kept constant for both the simulations. It can be seen that net cumulative bottom flux is very sensitive to the soil properties. The input and output of the simulations have been presented in Table 3.

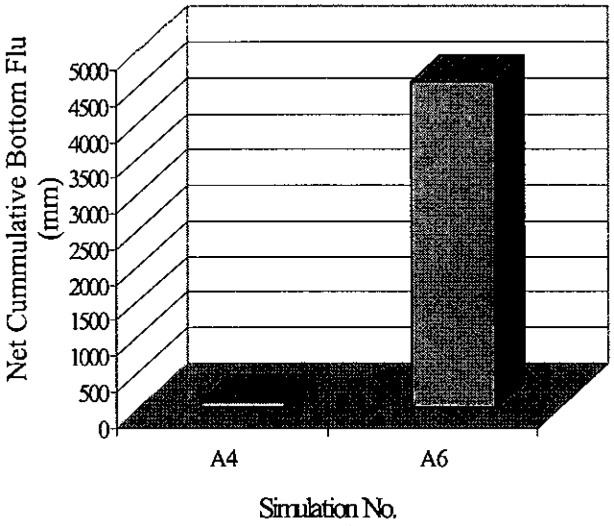

Figure 6. Effect of Saturated Hydraulic conductivity and M_v on Bottom Flux (SOILCOVER)

Comparison of HELP and Soil Cover

The common inputs for these models were of the same value. Simulation A6 of Soil cover matched with Simulation #27 of HELP. Simulation A4 matched with Simulation #21 of HELP model. This comparison is presented in Table 4, Figure 7 and Figure 8. The bottom flux seems consistent in both the models, although HELP seems to give slightly higher values for similar input parameters (Figure 7). Figure 8 presents the comparison of runoff and evaporation between the two models. Evaporation seems to be matching very well between HELP and SoilCover, while runoff estimation shows significant variation.

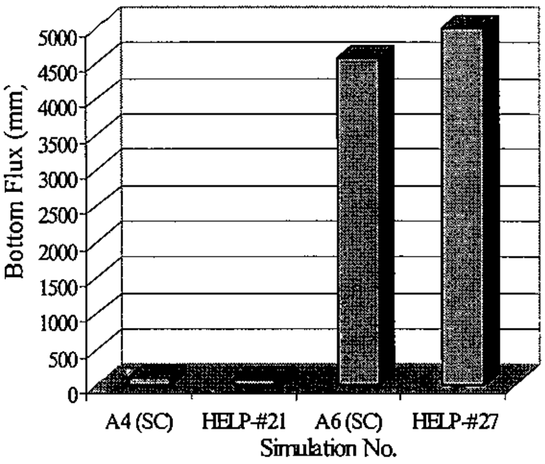

Figure 7. Comparison of Bottom flux Between HELP and SOILCOVER

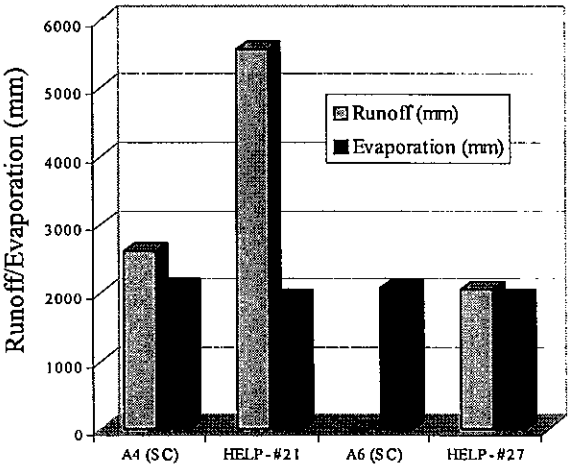

Figure 8. Comaprison of Runoff/Evaporation Between HELP and SOILCOVER

Table 2. Summary of the results from HELP Model

Simulation No.	Ksat cm/sec	SCS curve #	% of area allowing runoff	Runoff (inches)	Runoff (mm)	Bottom flux(inches)	Bottom flux (mm)
Parameter Varied: Ksat							
18	1	95	100	3.7	92.9	286.7	7283.2
20	1.00E-02	95	100	152.0	3860.8	136.9	3477.0
22	1.00E-03	95	100	152.2	3866.7	136.9	3477.1
21	1.00E-04	95	100	219.0	5562.6	2.7	68.8
19	1.00E-05	95	100	273.9	6956.0	0.0	0.5
Parameter Varied: SCS curve #							
25	1.00E-04	57	100	0.0	0.0	290.0	7365.1
23	1.00E-04	70	100	4.1	105.2	286.0	7264.1
26	1.00E-04	80	100	43.7	1110.1	246.1	6249.7
27	1.00E-04	85	100	80.5	2043.6	205.9	5230.1
19	1.00E-04	95	100	273.9	6956.0	0.0	0.5
24	1.00E-04	98	100	281.0	7137.4	0.1	3.2
Parameter Varied: Fraction of area allowing runoff							
21	1.00E-04	95	100	219.0	5562.6	2.7	68.8
28	1.00E-04	95	80	175.0	4445.0	69.9	1775.2
29	1.00E-04	95	50	112.7	2861.6	167.9	4265.2
30	1.00E-04	95	25	56.3	1431.0	233.1	5920.5
31	1.00E-04	95	0	0.0	0.0	290.0	7365.1

Table 3. Summary of the results of the SoilCover Simulations

Simulation	Specific Gravity	Mv (Kpa-1)	Ksat (cm/s)	Bottom Flux (mm)	Precipitation (mm)	Runoff (mm)	Evaporation (mm)
A4	2.73	1.00E-06	1.40E-05	103	9271	2620	2102
A6	2.65	9.10E-06	1.00E-04	4577	9271	0	2078

Table 4. Comparison of simulations between HELP and SoilCover models

Simulation	Specific Gravity	Ksat (cm/s)	Bottom Flux(mm)	Precipitation (mm)	Runoff (mm)	Evaporation (mm)
A4	2.73	1.40E-05	103	9271	2620	2102
HELP-#21	-	1.00E-04	69	9296	5571	1929
A6	2.65	1.00E-4	4577	9271	0	2078
HELP-#27		1.00E-04	5230	9296	2044	1929

Conclusions and Recommendations

The seepage from an inactive reclaimed mine tailings was computed using two computer models, HELP and SoilCover. The required input parameters for these two commercially available computer programs were discussed. A sensitivity analysis for important input parameters was performed to compare the results of both programs. The study revealed that saturated hydraulic conductivity, Soil Conservation Service curve number and fraction of the area for surface runoff were the most sensitive parameters influencing the HELP model. The SoilCover model was found to be most sensitive to the coefficient of volume compressibility. The saturated hydraulic conductivity was identified as an important parameter for the seepage calculation in both programs. The saturated hydraulic conductivity for unsaturated flow is determined for any soil based on SWCC . The determination of SWCC and uncertainties associated with the hydraulic conductivity function for unsaturated soils were discussed.

HELP model does not allow for capillary rise from below the evaporative depth. Studies indicate (Gardner and Fireman 1958) that evaporation from bare soils can take place even when the water table is 30 feet below the surface. In arid and semi-arid climates and in the presence of fine-grained materials (such as tailings) capillary rise may account for significant moisture movement through the ground-atmosphere interface. Evaporation and infiltration across the soil surface are functions of not only the available precipitation and potential evaporation, but also the ability of the soil to transport moisture under the prevailing moisture content and head gradient conditions. Under such conditions, evaporation from the soil may be greater than precipitation, as long as water can move upward in the profile because of capillary forces. Residual volumetric water content (θ_r) is calculated within the HELP simulation model using a regression equation based on the value of wilting point. This may have a significant effect on the flux calculations. It is advisable to use actual θ_r, values determined from the soil-water characteristic curve.

In the SoilCover model, there is a better control on the soil-water characteristic curve. The various parameters that define the curve (Van Genutchen parameters) can be adjusted to fit the in-situ soil conditions. In case of HELP, the user is forced to use Campbell's equation to predict the unsaturated hydraulic conductivity. Studies indicate that this equation may not be suitable for all soils and for all ranges of suction.

We believe that the flux of water through reclaimed mine facilities is modeled better by the Soil Cover model than the HELP model. Use of the more realistic model does necessitate the understanding on the effect of each parameter. Appropriate laboratory or field studies will be required to accurately determine unsaturated soil parameters, climatic parameters and boundary conditions. Unfortunately, such data is not always available for proposed reclaimed sites.

The HELP computer program is useful for preliminary analysis of cover design when relevant climatological data covers a large time frame. HELP simulations may be carried out to identify general periods of concern with regards to dry years (based on total precipitation), wet years and mean years. SoilCover can then used to make more detailed seepage estimates for each specific period of concern.

It may be noted that the models discussed here mostly represent the flow through the homogeneous system. The mine waste rock dumps often consists of highly heterogeneous materials varying in size from boulder to silts. The preferential flow or channeling is often observed through these rock dumps (Herasymuik et. al. 1995). This type of flow behavior can not be modeled using the above numerical codes. For this reason, research is needed to more realistically characterize the preferential flow of water through mine spoil materials.

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