Comparative Study of Surface Flux Boundary Models to Design Soil Covers for Mine Waste Facilities

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ABSTRACT

The design of soil covers as part of the remediation initiatives for mine waste facilities is common practice and more and more engineers are faced with designing these facilities. The design issues associated with these soil covers are complex and requires a good understanding of unsaturated flow. More engineers are making use of numerical models to predict how cover designs would perform, and this has been necessitated by the high non-linearity associated with solving unsaturated flow problems. There are numerous numerical models available to the prospective users and they are all simplifications of reality using different assumptions. The users of these models often do not understand the limitations of the models but rather select a model based on ease of use, and that lends to increasingly erroneous designs being proposed for construction.

This paper describes a comparative evaluation of a cover design using four different codes available today; SoilCover, SWIM, HYDRUS-2D and HELP. The paper does not propose to measure these codes up against each other and make statements about which is better than the other but rather illustrates how the assumptions in each code affect the outcome. The data set used for the comparative study is a well calibrated data set that that has been collected over a long period in time and that has been collected according to strict controls. The authors present the pitfalls of numerical modelling of the surface flux boundary conditions, as well as present guidelines towards appropriate use of these modelling tools.

INTRODUCTION

The design of soil covers as part of the remediation initiatives for mine waste facilities is common practice and more and more engineers are faced with designing these facilities. One of the aims of the placement of soil covers on waste rock dumps is to reduce the infiltration of water or to minimise the gas transport reaching the waste rock material.

The design issues associated with these soil covers are complex and requires a good understanding of unsaturated flow. More engineers are making use of numerical models to predict how cover designs would perform, and this has been necessitated by the high non-linearity associated with solving unsaturated flow problems. There are numerous numerical models available to the prospective users and they are all simplifications of reality using different assumptions. The users of these models often do not understand the limitations of the models but rather select a model based on ease of use, and that lends to increasingly erroneous designs being proposed for construction.

This paper describes a comparative evaluation of a cover design using four different water transport codes available today; SoilCover, SWIM, HYDRUS-2D and HELP. The codes are used to simulate a multi-layered cover that was constructed over a waste rock pile and instrumented to measure its performance. The results from these four models are compared and the differences are illustrated. The modelling presented in this paper is limited to water transport and does not include gas transport.

A number of similar comparative studies have been documented and the most relevant are briefly mentioned. Albright *et al* (2002) presented an extensive comparative model evaluation for finding the most appropriate numerical model to design landfill covers as part of the Alternative Cover Assessment Program (ACAP) in the United States. Their comparison however did not include the SWIM and SoilCover models. Christensen *et al* (2002) evaluated seven unsaturated flow models, including all those listed in this paper, to determine which model are best suited for use in the design of dry soil covers. Details of their study are not published; however they conclude that none of the models were perfectly suited to predict long-term performance of covers, without some modification. Kovaleski (1999) presented two case studies, one in a wet climate and one in a dry climate and compared uncalibrated cover modelling results between the SoilCover and HELP models. Wates and Rykaart (1994) illustrated how the HELP model diverges from the SWACROP model as applied to the design of soil covers.

The objective of this paper is to build on the current knowledge of numerical modelling using the many tools available and to highlight the potential pitfalls of numerical modelling of surface flux boundary conditions, as well as present guidelines towards appropriate use of these modelling tools.

MODEL DESCRIPTIONS

Four models were used in this modelling comparison, namely HELP, HYDRUS-2D, SoilCover and SWIM. These models are probably the most commonly used models for soil cover design, and should be familiar to practitioners. The following sections provide a brief overview of the codes.

HELP Version 3

The Hydrologic Evaluation of Landfill Performance (HELP) is provided by the US EPA and was for a long time the most widely used model for cover design. Lately however with the onset of the more advanced codes like HYDRUS-2D, HELP has become more of a support model, primarily being used for quick first order cover assessments as well as generating long-term weather data with its synthetic climate generating capabilities. HELP Version 3 is one of the very few codes that can treat geosynthetic materials as a cover material (Schroeder *et al*, 1994), and therefore the model is still relevant as a cover design tool. The following is an extract from the manual of HELP (Schroeder *et al*, 1994) which provides a good overview of its capabilities.

> *The Hydrologic Evaluation of Landfill Performance (HELP) is a quasi-two-dimensional hydrologic model of water movement across, into, through and out of landfills. The model accepts weather, soil and design data and uses solution techniques that account for the effects of surface storage, snowmelt, run-off, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane or composite liners. Landfill systems including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners may be modelled. The program was developed to conduct water balance analyses of landfills, cover systems, and solid waste disposal and containment facilities. As such, the model facilitates rapid estimation*

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of the amounts of runoff, evapotranspiration, drainage, leachate collection, and liner leakage that may be expected to result from the operation of a wide variety of landfill designs. The primary purpose of the model is to assist in the comparison of design alternatives as judged by their water balances. The model, applicable to open, partially closed, and fully closed sites, is a tool for both designers and permit writers.

HYDRUS-2D Version 2

HYDRUS-2D is the only two-dimensional model in the set of four evaluated in this paper. HYDRUS-2D is probably one of the most used models in the United States for soil cover design. It has gained a trusted reputation and regulators often specifically recommend the use of HYDRUS-2D in design applications.

HYDRUS-2D (Simunek *et al*, 1999) is a two-dimensional code that can simulate the transport of water, solute and heat in a variably saturated porous media. The water transport in HYDRYS-2D is based on the Richards' equation for the saturated-unsaturated water flow and includes a sink term for water uptake by plant roots. The boundary conditions in the water transport portion of the code can use prescribed heat and flux boundaries, boundaries controlled by atmospheric conditions, free drainage boundary conditions and a simplified representation of nodal drains.

SoilCover Version 5.2

SoilCover is probably the most widely used code for the design of soil covers for waste rock dumps and tailings impoundments worldwide. SoilCover is the only true surface flux boundary model available today (with the exception of VADOZE/W (GEOSLOPE, 2002) which is effectively a completely redesigned two-dimensional version of SoilCover). From a theoretical standpoint SoilCover is therefore the only model that can calculate actual evaporation from a soil profile based on coupled heat and mass flow as governed by the meteoric and soil conditions. The following extract from the SoilCover users manual summarises the model well (SoilCover, 2000).

SoilCover is a one dimensional finite element package that models transient conditions. The model uses a physically based method for predicting the exchange of water and energy between the atmosphere and a soil surface. The theory is based on the well known principles of Darcy's and Fick's Laws which describe the flow of liquid water and water vapour, and Fourier's Law to describe conductive heat flow in the soil profile below the soil/atmosphere boundary. SoilCover predicts the evaporative flux from a saturated or an unsaturated soil surface on the basis of atmospheric conditions, vegetation cover, and soil properties and conditions. A modified Penman formulation is used to compute the actual rate of evaporation from the soil/atmosphere boundary. A freezing and thawing formulation is used to allow year round modelling of soil behaviour where climatic conditions result in seasonal ground freezing and thawing.

SWIM Version 2

SWIM was originally developed for agricultural use, but has since been used in cover design and analysis. The model is not as widely known as the other models presented in this paper, however it does hold significant potential as a cover design tool.

SWIM is a one-dimensional model based on a numerical solution of Richards' equation, that has the capability of modelling run-off, infiltration, redistribution of water and solute, solute transport, plant uptake and transpiration, soil evaporation, deep drainage and leaching. SWIM accepts time dependent boundary conditions and uses the finite difference method. Verburg *et al* (1996) describes in detail the capabilities of SWIM which was developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia.

MODELLING

Procedure

The water transport modelling presented herein is applied to a multi-layered 'store and release' cover constructed on top of a waste rock pile. The cover is a large-scale test plot and substantial instrumentation has been installed in the cover to actually measure the cover performance. Instrumentation include a complete weather station, soil suction, moisture and temperature measurements, flow lysimeters and oxygen concentration measurements. The site is located in a continental semi-arid climate with approximately 600 mm of annual precipitation (both snow and rain) and 1000 mm of potential evaporation. The site experiences periods where the ambient air temperatures are low enough to result in some ground freezing.

The initial modelling work was carried out with SoilCover. The other three codes were then run with the same datasets and the results compared with the SoilCover results. The boundary conditions, the initial conditions, the climatic data, the soil properties, the vegetation and root distribution were in part determined by the modelling work that was originally carried out with SoilCover, and all the models were set up with equivalent conditions. The intention was not to create results that were comparable to SoilCover, but rather to set up the four models with equivalent input parameters and compare how the calculated water balance data matches. The results presented thus reflect how the four models perform using the same inputs and thus how the different inherent assumptions in each model affect the outcome.

The original SoilCover simulations were carried out in two stages. The first stage, identified as 'calibration', consisted of calibrating the model with site specific climate data and suction measurements that were obtained with tensiometers installed at various locations and depths inside the cover system. The measured soil hydraulic properties were adjusted in SoilCover to best match the field measured tensiometer data. The second stage, identified as 'prediction', consisted of using the calibrated model to predict the performance of the cover system over a five-year period using select climatic data. This five-year period included extremely dry and wet climatic years in combination with average climatic years compiled from historical climatic data.

Setup

The multi-layered cover consists of a 20 cm layer of topsoil at that overlay an 80 cm storage layer. These two layers were placed on a 60 cm layer of compacted weathered waste rock, the latter being directly above the host acid generating waste rock material. The entire soil profile (cover and waste rock) was modelled using a 349 cm section as per the original SoilCover simulations. The geometry was represented using 97 nodes in SoilCover and 250 nodes in SWIM and Hydrus-2D. The node based models used 189 cm of waste rock underneath the compacted weathered waste rock layer. HELP uses layers instead of nodes and the geometry was constructed with the cover as specified (each layer was considered to be a percolating layer), but the host waste rock was modelled as a 10 cm layer. Sensitivity analysis was carried out to determine how this affects the results and it was concluded that it played no role.

The boundary condition at the surface was specified by time dependent climatic conditions. For SoilCover, this included ambient temperature, wind seed, net radiation, relative humidity, the leaf area index and precipitation. SoilCover is the only model of the four discussed in this paper that calculates the potential evaporation (PE) and potential transpiration (PT) fluxes using real climatic data and the level of vegetation cover. For the other models, the climatic conditions consist of providing the precipitation, PE, PT, or the potential evapotranspiration (PET). The values calculated by SoilCover for PE, PT and PET were used as input for SWIM and HYDRUS. HELP requires solar radiation and air temperature data as well as quarterly relative humidity values and an annual average wind speed. The precipitation data was the same for all four models.

Actual climatic data that recorded at the site was used for the calibration runs in SoilCover. The prediction simulations were then carried out using five different climatic years to represent a probable range that can be expected at the site. The climatic data for this five-year period was taken from historical climatic data available for the site. The annual precipitation used in the simulations ranged from 361 to 808 mm depending on the year being modelled. The daily rain events were distributed over an eight-hour period, except for the HELP simulation which was distributed over 24 hours. The values for PE and PT as calculated by SoilCover were used as input in SWIM and HYDRUS. The calculated PE ranged from 710 to 1023 mm while the PT ranged from 313 to 480 mm.

Two different root distributions were used in the simulations. The root depth selected for the calibration was 0.3 m and the root water uptake decreased linearly from 100 per cent at the surface down to zero per cent at bottom of the root zone. The corresponding leaf area index was set 1 to compensate for the vegetative cover that was not fully developed. The predictive simulations assumed that the vegetative cover would be fully developed and that the root depth would extend down to a depth of 1.0 m below the surface. The corresponding leaf area index was set at 3 to represent a fully developed vegetative cover. The distribution of the root effectiveness was also linear, decreasing from 100 per cent at the surface down to zero per cent at the bottom of the root zone. The roots were considered 'operational' between 15 April and 1 September. The root would not function outside that period. The wilting point was set to 1500 kPa and the moisture limiting point to 100 kPa. In HYDRUS-2D, the vegetative water uptake is based on the formulation proposed by Feddes *et al* (1978) and using values reported by Wesseling (1991) for pasture. A root length density of 5 $cm.cm^{-3}$ was used where needed. SWIM has the capability of specifying the maximum proportion of the PET that the root uptake can extract water, eg the actual transpiration (AE) is limited by the ratio of AE over PET. For the SWIM simulations presented herein, this ratio AE/PET was limited to 0.5. In the HELP model the leaf area index was set at 3 for the calibration runs and at 5 for the prediction runs. The leaf area index is differently defined in HELP than in SoilCover and as such the values were adjusted to reflect similar conditions. The evaporative zone depth in HELP was set at 160 cm for all the simulations presented in this paper. This was done to overcome the limitation in HELP that prevents upwards capillary movement of moisture beyond the extent of the evaporative zone depth.

For all cases, ponding was either not possible with the code or it was simply not enabled. The bottom boundary conditions were controlled by a constant pressure. For the calibration, a head of 9.81 kPa was maintained at the bottom boundary for the entire simulation. The predictions runs were carried out with a constant pressure of -30 kPa at the bottom boundary. Additional simulations using the calibration case were also carried out using different types of boundary conditions in SWIM, and it was concluded that it had no significant impact on the reported fluxes. The HELP model used a free draining boundary condition, since it does not have the ability to specify a constant head.

The initial conditions that were used in the simulations originated from the ones that were used with SoilCover. The initial condition for the calibration case was determined based on the measurements obtained with the tensiometers. For the predictive simulations, the five-year period was cycled twice to reduce the influence of the initial condition of the predicted water balance.

Soil properties

The cover and waste rock materials has been fully characterised during the construction of the cover, which included physical and hydraulic properties measured in the laboratory and in the field. Table 1 provides a summary of the properties of the four material types used in the numerical modelling.

The soil water characteristic curves were fitted using the Fredlund and Xing (1994) formulation in SoilCover, and with the van Genuchten formulation (van Genuchten 1980, 1991) in HYDRUS-2D and SWIM. HELP uses a linear interpolation between a specified porosity, field capacity and wilting point for the soil water characteristic curve. For the purpose of these simulations the van Genuchten curves developed for the SWIM model was used to develop these parameters. The fitted soil water characteristic curves are shown Figure 1 and Table 2 presents the parameters used to define the soil water characteristic curves. It is worth noting that the primary difference between the van Genuchten and Fredlund and Xing curve fit is in the high suction range. The van Genuchten curves

TABLE 1

Summary of physical and hydraulic properties of the cover and waste rock materials.

Parameter	Topsoil	Storage layer	Weathered waste rock	Waste rock
% Clay	9.9	6.4	7.2	25.3
% Silt	47	38	29	16.5
% Sand	40	51	29	52.6
% Gravel	3.1	5.1	34	5.6
Compaction (%)	85	87	93	95
Dry bulk density	1.63	1.69	1.84	2.10
Specific gravity	2.64	2.64	2.68	2.75
Porosity	0.40	0.38	0.32	0.24
Gravimetric water content	0.14	0.15	0.13	0.10
Volumetric water content	0.23	0.25	0.23	0.20

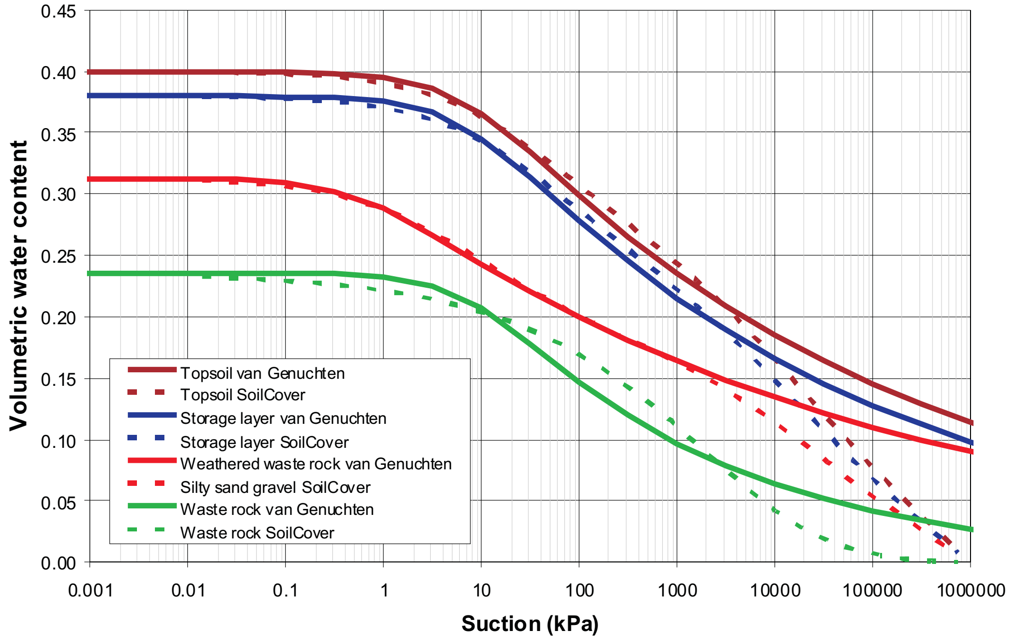

FIG 1 - Fitted soil water characteristic curves.

TABLE 2

Summary of unsaturated hydraulic properties – fitted parameters.

	Topsoil	Storage	Weathered waste rock	Waste rock
Saturated hydraulic conductivity (m s^{-1})	6.5×10^{-6}	9.1×10^{-7}	8.3×10^{-8}	1.4×10^{-7}
Fredlund and Xing (1994) fitting parameters (SoilCover) Residual matric suction (kPa)	2785	3215	2475	3000
'a' parameter	11.66	13.1	1.64	16036
'n' parameter	0.69	0.69	0.68	0.37
'm' parameter	0.38	0.43	0.4	5.98
van Genuchten (1980) fitting parameters (HELP, HYDRUS, SWIM) Residual volumetric water content	0	0	0	0
Saturated volumetric water content	0.400	0.38	0.313	0.236
α (cm^{-1}) – used to generate the soil water characteristic curve	0.0153	0.0148	0.1753	0.0130
'n' parameter	1.1050	1.1136	1.0865	1.1827
'p' parameter	0.5	0.5	0.5	0.5
α (cm^{-1}) – used to generate the unsaturated hydraulic conductivity curve using Brooks and Corey (1964) (SWIM)	0.1532	0.1481	0.0877	0.2596

has higher water contents in this high suction range, which suggests potentially less storage capacity in the profile, however in this range of suctions the unsaturated hydraulic conductivity is so low that it does not really come into play.

The unsaturated hydraulic conductivity was approximated in SoilCover using the formulation presented by Fredlund *et al* (1994). The unsaturated hydraulic conductivity was fitted in HYDRUS-2D with the van Genuchten formulation and by using the feature that limits the air entry value (AEV) to -2 cm. For SWIM and HELP, the unsaturated hydraulic conductivity curves were fitted using the Brooks and Corey formulation (Brooks and Corey, 1964). For the SWIM simulations however, these curves were adjusted independently of the soil water characteristic curves to match the SoilCover curves. Figure 2 illustrates how the use of different unsaturated hydraulic conductivity formulations impacts the curves for the weathered waste rock layer used in the modelling.

DISCUSSIONS

Calibration results

Table 3, Figures 3 and 4 present the results of applying the calibration dataset to the four different models. The calibration dataset had a total precipitation of 641.2 mm, a potential evaporation of 1023 mm and a potential transpiration of 313 mm. The total precipitation used in SWIM and HYDRUS was slightly different (643.3 mm) because of rounding errors when calculating the distribution of the rain events over an eight-hour period.

TABLE 3

Calibration modelling results.

Model	Run-off (mm)	Transpiration (mm)	Evaporation (mm)	Evapotranspiration (mm)	Infiltration (mm)
HELP	1.2	-	-	552	87
HYDRUS	0.0	21	563	584	37
SoilCover	5.5	126	451	577	35
SWIM	0.0	271	345	617	27

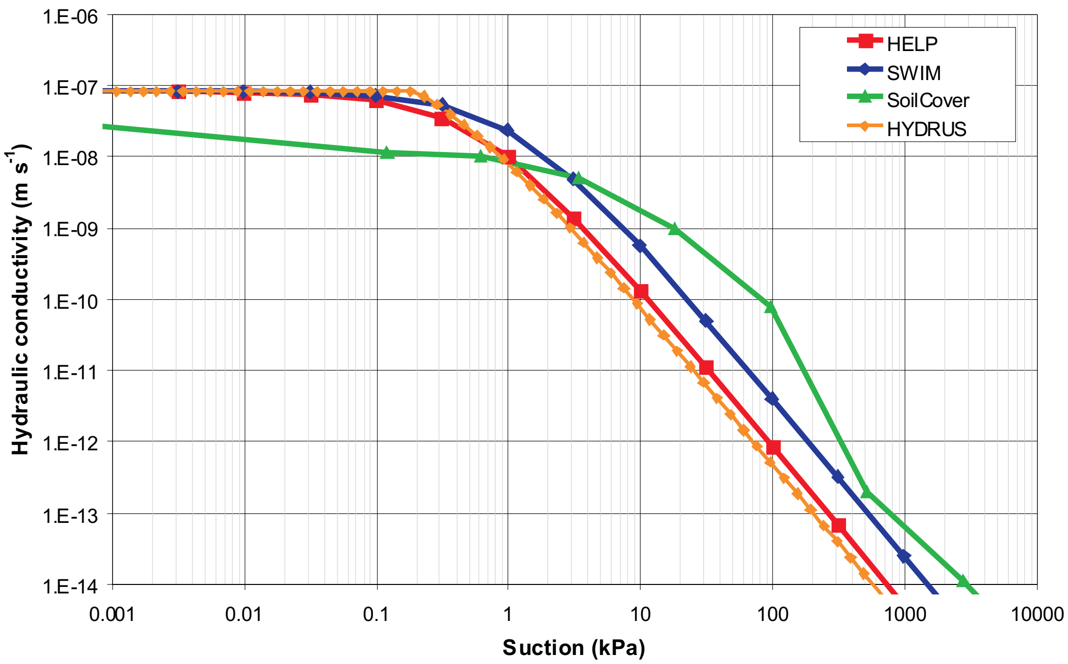

FIG 2 - Fitted unsaturated hydraulic conductivity functions for weathered waste rock.

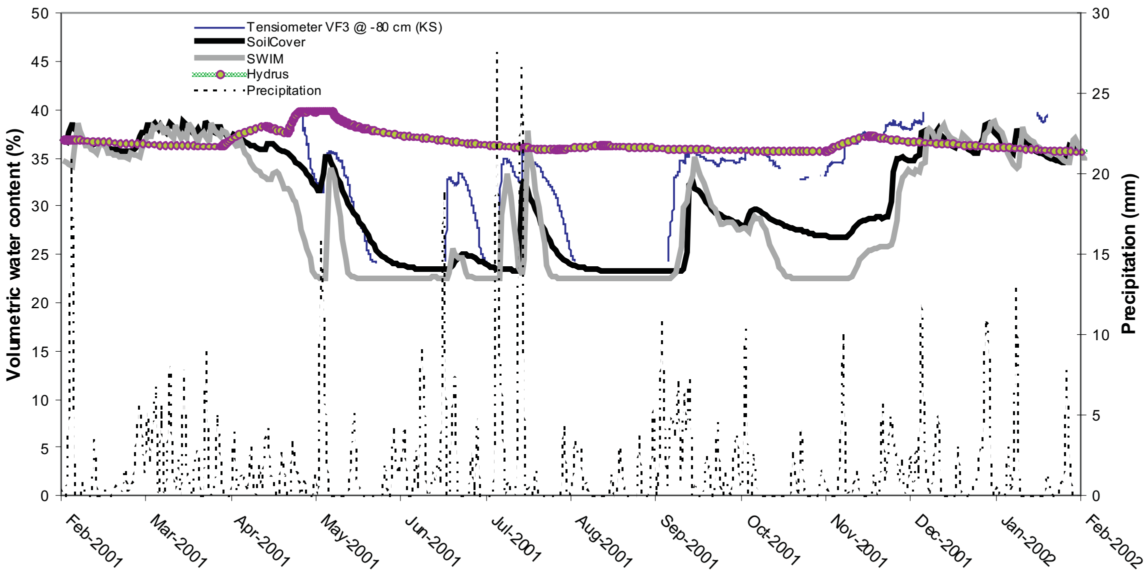

FIG 3 - Volumetric water content and precipitation vs time, modelling results and tensiometer measurements at bottom of topsoil layer.

The amount of run-off varies between zero and 0.9 per cent of the total precipitation in all four models, showing similar trends with no meaningful differences.

A similar result is observed for the evapotranspiration component of the water balance, which varies between 86 per cent and 96 per cent with the HELP model showing the least evapotranspiration and SWIM the greatest. In terms of actual flux volume there is less than ten per cent variance between these numbers. Evapotranspiration is the sum of evaporation and transpiration, and all the models except HELP actually report these fluxes individually. The reported HYDRUS transpiration numbers is substantially lower than any of the other models, and even between SoilCover and SWIM there is a two-fold variance in actual transpiration reported with SWIM having the highest numbers. This is in turn reflected in the reverse trend shown for the evaporative flux, where the SoilCover model reports a number more than 30 per cent greater than SWIM, but less than HYDRUS.

Probably the most pronounced impact that this difference has on the outcome of the models can be seen in the time plots of moisture content shown in Figure 3. The SoilCover, HYDRUS and SWIM data is presented against actual field data. HELP does not have the ability to report water contents or suctions at any specified location in the profile, and as such time series calibration such as illustrated in Figure 3 is not possible. It is evident, that the SWIM model appears to be more responsive than the SoilCover model. The greater transpirative flux in the SWIM model suggests that water is extracted more rapidly and efficiently from depth in the SWIM model, resulting in the greater response seen in Figure 3. The HYDRUS model does not appear to match field measured suction profiles well, and probably the primary reason for this divergence is the low transpirative flux observed for the HYDRUS model, which does not allow deep water extraction, but rather moisture is rapidly evaporated from the profile as it falls.

The final water balance component in Table 3 is the actual infiltration flux that passes the cover, ie the flux that will contribute towards deep recharge. This flux was reported at 10 cm below the compacted weathered waste rock layer. The infiltration flux varies between four per cent for the SWIM model and 14 per cent for the HELP model. The six per cent flux reported with SoilCover and HYDRUS is a close match to the SWIM result. The increased infiltration observed in the HELP result is as a result of the decreased evaporative flux, which in turn is as a result of the linear interpolation used for the water retention curve.

It would thus appear that for the calibration period, the four models used show similar overall water balance results, with the possible exception of the infiltration flux through the cover where the HELP model reports fluxes almost three times higher than the other models. The difference in the overall water balance calculations is illustrated in Figure 4. Other than the HELP model, the biggest variance in the other three model results are the transpiration numbers.

It is however important to note that daily model comparisons and subsequent calibration with field data such as suction or moisture content at specific locations in the profiles such as illustrated in Figure 3 cannot be done with HELP. HYDRUS has the ability to perform such comparisons, but for the case modelled the results appeared insensitive to daily changes.

Predictive modelling

The annual fluxes over a five-year period for the predictive modelling performed are presented in Tables 4 and 5, and Figure 5. For these predictive runs there is a significant difference between the HELP results and the other models presented. The run-off reported by the HELP model averages 4.4 per cent as compared to being practically negligible in the other models. On average the evapotranspiration of the HELP simulations are 69 per cent, which is almost 30 per cent less than for the SWIM and SoilCover simulations, which are between 99 per cent and 96 per cent respectively. Since less water is lost via evapotranspiration in HELP model, this contributes towards the large infiltration flux through the cover of 27 per cent as compared to approximately one per cent for SWIM and SoilCover. Kowaleski (1999) presented similar results in a comparative HELP and SoilCover modelling where HELP predicted two to three times more infiltration than SoilCover. The comparison of the predicted water balance is also shown in Figure 5.

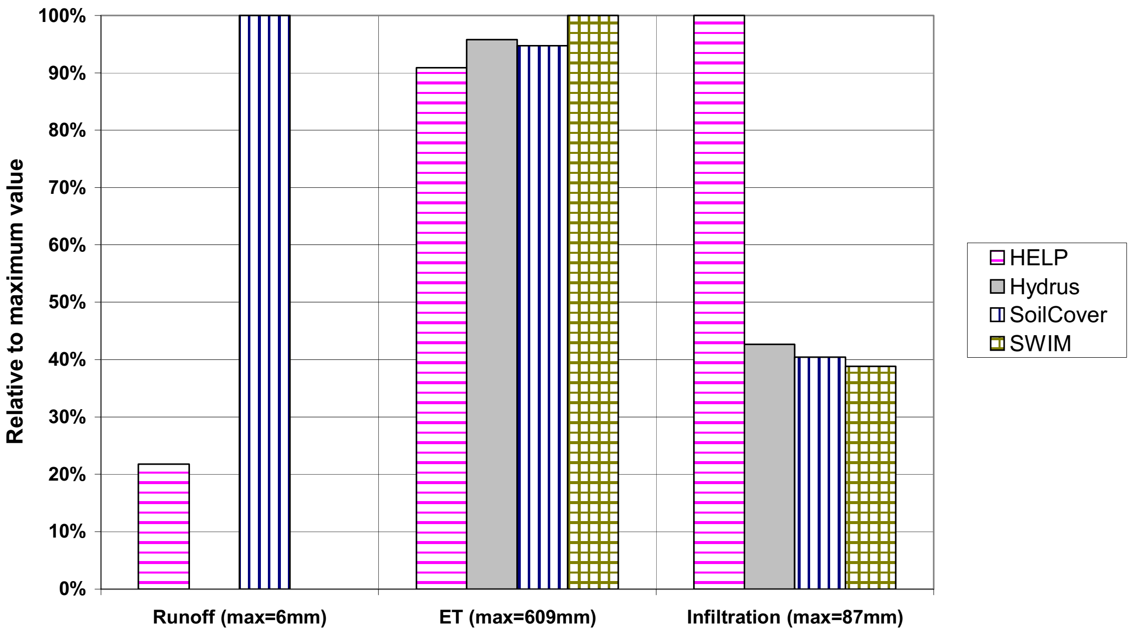

FIG 4 - Water balance comparison, calibration case.

TABLE 4

Prediction modelling results (overall average for five year simulation, based on average precipitation of 618 mm).

Model	Run-off (mm)	Transpiration (mm)	Evaporation (mm)	Evapotranspiration (mm)	Infiltration (mm)
HELP	27.3	-	-	425	166
SoilCover	0.7	303	293	596	5.8
SWIM	0.0	300	312	611	8.1

TABLE 5

Annual predictive simulation results.

Year	Precipitation (mm)	Run-off (mm)	Transpiration (mm)	Evaporation (mm)	Evapotranspiration (mm)	Infiltration (mm)
HELP						
Year 1	361	7	-	-	367	130
Year 2	561	11	-	-	431	120
Year 3	773	29	-	-	425	207
Year 4	591	58	-	-	431	138
Year 5	808	30	-	-	473	236
SoilCover						
Year 1	361	0	246	225	471	-7
Year 2	561	3	284	270	554	-6
Year 3	773	0	339	336	676	-10
Year 4	591	0	286	288	573	9
Year 5	808	0	361	346	707	42
SWIM						
Year 1	361	0	198	249	447	15
Year 2	561	0	301	276	576	9
Year 3	778	0	372	363	734	6
Year 4	586	0	266	301	567	4
Year 5	812	0	389	372	761	7

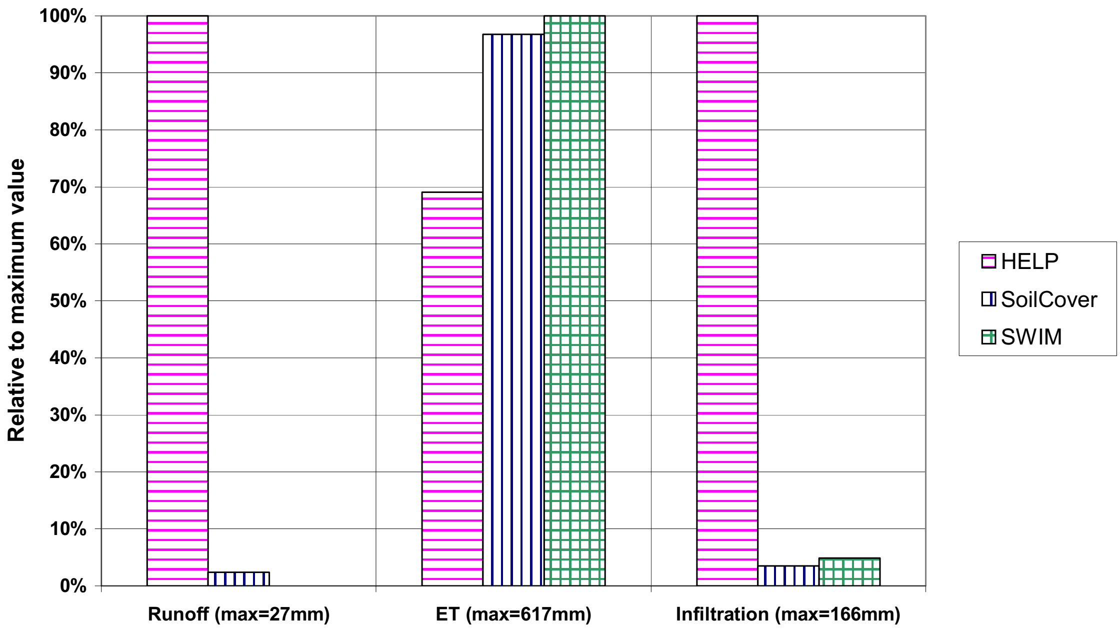

FIG 5 - Water balance comparison, prediction case, average over the five-year period.

The split between evaporation and transpiration fluxes for the SWIM and SoilCover models show similar results, which is different than in the calibration runs, suggesting that as the rooting depth and leaf area index increases the model performance become more similar.

Table 5 contains the individual annual water balance calculated for the five years of predictive simulations reported in this paper. This data illustrates the impact of different climatic periods on the individual models. In interpreting this data, it should be brought in mind that a year identical to Year 5 with 808 mm preceded Year 1, and therefore the large evapotranspirative flux is directly as a result of remnant moisture in the profile. From the individual yearly results, it is evident that both SWIM and SoilCover show similar trends with respect to run-off, evaporation and transpiration, however the yearly infiltration numbers does reflect some differences. SoilCover predicts a negative flux through the cover of two per cent in Year 1, while SWIM predicts a positive flux of four per cent. The biggest difference stems form the increased evapotranspiration in the SoilCover results which suggest that more moisture is stored in the profile than for the SWIM simulations.

The reverse situation is true in the Year 5 simulation, where the SoiCover model predicts five per cent infiltration as opposed to one per cent for SWIM.

CONCLUSIONS

Based on the modelling results presented in this paper the following general conclusions can be drawn:

- With the exception of HELP, the three other models tested appear to yield similar overall water balance results for the cover system modelled.
- HELP does not have the ability to calculate moisture contents or soil suctions at specific locations within the cover profile, thus not making it conducive towards calibration with *in situ* field data.
- SoilCover is the only true surface flux boundary model that calculates actual evaporation, however the closeness of the results obtained with the other models suggest that the simplifications are not adversely affecting the modelled outcome.
- The biggest difference between the three models SWIM, HYDRUS and SoilCover appear to be the way in which transpiration is calculated. The different algorithm used in each model can yield substantially different results, and although the overall evapotranspiration numbers match well, care should be taken when designing covers which rely on transpiration, eg store-and-release covers.
- HELP is by far the simplest model to set up and run, and the actual simulations can be done rapidly, allowing for many sensitivity analysis runs to be performed. The ten year simulations reported in this paper took less than 15 seconds to run.
- The other three models require substantially more input preparation, making for little preference in ease of setup between these models. Once the models are set up however, SWIM by far outperforms the other models in terms of running multiple sensitivity analysis runs. The ten-year simulations presented here are solved in a few minutes with SWIM, while it takes several hours for SoilCover and HYDRUS.

Overall, none of the four models compared in this paper are theoretically flawed when considering them for the design of soil covers for mine waste applications. HELP is probably the least rigorous in its theoretical approach, and those simplifications can lead to erroneous results if appropriate care is not applied. HELP would not be the appropriate tool to do a final cover design, however HELP is a useful first order screening tool to identify the macro sensitivities of a system.

SoilCover, HYDRUS and SWIM are perhaps equally rigorous although each in different areas. From a purely theoretical perspective SoilCover is the only true surface flux boundary model, however the results presented here has shown that the simplifications used in the other codes are not so drastic as to distrust the results. The authors believe that SoilCover should probably be used to do final calibration of any cover design; however SWIM would be better suited to run sensitivity analysis, especially when a design is primarily dependant on predictive modelling, and no detailed performance monitoring is planned.

None of the models are particularly well suited to model transpiration, and the user should take care when interpreting these results, and perhaps consider other tools or actual reported transpiration rates to calibrate against.

Finally, regardless of the model selected to design soil covers, it is essential that the performance of the covers be properly monitored to confirm the assumptions used in the design.

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