# Evaluation of Alternative Cover Systems in High Precipitation Environments Using Unsaturated Flow Modeling


Jason Keller[1], Mike Milczarek[2], Monisha Banerjee[3], Raul Orellana[4], William Ludwick[5], and Guosheng Zhan[6]

[1]GeoSystems Analysis, Inc., Hood River, OR, USA, jason@gsanalysis.com
[2]GeoSystems Analysis, Inc., Tucson, AZ, USA, mike@gsanalysis.com
[3]GeoSystems Analysis, Inc., Tucson, AZ, USA, monisha@gsanalysis.com
[4]Minera Barrick Misquichilca, Huaraz, Peru, rorellana@barrick.com
[5]Minera Barrick Misquichilca, San Isidro, Lima, Peru, wludwick@barrick.com
[6]Barrick Gold Corporation, Salt Lake City, UT, USA, jzhan@barrick.com



## ABSTRACT

Alternative cover systems are being evaluated at Minera Barrick Misquichilca Pierina mine in support of future closure design efforts for the heap leach and waste rock facilities. The mine is located at 4100 m elevation in the Peruvian highlands with average annual precipitation of 1225 mm occurring primarily over a six month wet season. As part of the evaluation, a variably saturated flow model was calibrated to a 2.7 year record of water balance data from two test evapotranspiration cover systems at the Pierina heap leach facility. The evapotranspiration covers use a low permeability clay liner overlain by topsoil design. The calibrated flow model was then used to predict the effect of varying cover system components of clay and topsoil thickness, clay hydraulic properties, and inclusion of a gravel drainage layer on cover system performance over a 50-year synthetic climatic record. The simulation results indicated that the clay conductivity has the greatest influence on predicted net percolation and that increasing the clay layer and/or organic soil cover thickness only nominally decreased the predicted net percolation. This latter prediction is primarily due to the defined vegetative rooting depth as the test evapotranspiration cover systems showed extensive rooting into the waste leach ore. Consequently, evapotranspiration covers over acidic waste may be more influenced by the cover layer thickness and may also show greater net percolation through thinner cover layers.



Key Words: Evapotranspiration, unsaturated flow, waste rock, ore, clay, hydraulic conductivity, drainage layer


## INTRODUCTION

The Minera Barrick Misquichilca Pierina mine (Pierina) is located on the eastern flank of the Cordillera Negra, about 10 km northwest of the City of Huaraz in the Ancash Department, Peru. The Pierina mine began production in 1998 and consists of an open pit, valley-fill heap leach, and waste rock facilities. The anticipated end of the mine life is 2015.

The elevations of the mine facilities range between 3800 m and 4200 m above sea level. The climate at the site is characterized by a bi-modal precipitation pattern with wet (October – April) and dry (May – September) seasons. Temperatures at the site rarely fall below 0°C and do not change significantly month by month; the average annual temperature is about 7.5°C. Average annual precipitation from 1997 through 2010 was about 1225 mm with most precipitation received as afternoon thunderstorms.
Average annual recorded pan evaporation and estimated reference crop evapotranspiration from a well-watered grass (ETo) were approximately 930 mm and 740 mm, respectively. Average annual precipitation exceeds pan evaporation and estimated ETo by approximately 300 and 500 mm per year.

To support closure planning, Pierina has evaluated different cover systems for side slopes that could reduce the amount of net percolation into closed waste facilities at Pierina. The main objective of the cover design is to reduce potential acid rock drainage (ARD); other considerations include providing physical stability and establishing vegetation representative of the surrounding area.

Different multiple layer evapotranspiration (ET) cover system alternatives were compared in order to evaluate their predicted long-term performance in reducing net percolation. Cover system alternatives evaluated were:

- Scenario 1: 30 cm topsoil and 30 cm clay;
- Scenario 2: 60 cm topsoil and 30 cm clay;
- Scenario 3: 30 cm topsoil and 60 cm clay;
- Scenario 4: 60 cm topsoil and 60 cm clay;
- Scenario 5: 30 cm topsoil, 15 cm drainage layer, and 30 cm clay;
- Scenario 6: Identical to Scenario 5 except that the clay saturated hydraulic conductivity was reduced by 0.2X;
- Scenario 7: Identical to Scenario 1 except that the clay saturated hydraulic conductivity was increased by 5X.

The first five simulations approximate the cover material hydraulic properties observed in the Pierina test panels 3.5 years after ET cover placement (Orellana et al 2010). Scenario 6 approximates the initial clay hydraulic conductivity and could potentially represent better clay borrow material sources. Scenario 7 represents the potential for ongoing increases in the hydraulic conductivity of the clay over time.

To evaluate the suitability of ET cover designs a calibrated unsaturated flow model was developed to predict long-term cover system performance from different ET cover designs over neutral waste. The model incorporated a 50-year synthetic climate record based on 12 years of local climatic data developed to be statistically representative of Pierina. Prior to carrying out the long-term (50-year) simulations, model calibration runs were made using soil water potential data collected from January 2007 through August 2009 at the Pierina cover system test panels (Orellana et al. 2010).

The Pierina cover system test panels were constructed to evaluate the performance of dual layer (clay and topsoil) ET cover system constructed over neutral spent heap leach ore. Side-sloped test panels consisting of 55 cm of "uncompacted" clay (construction equipment compaction approximating 85% to 90% proctor density) and 30 cm of "compacted" clay (> 90% proctor), were both overlain with approximately 30 cm of topsoil and monitored over a 3 year period. These field trials indicated that the dual layer cover system ET closely approximated the ETo, due to extensive rooting that occurred far into the neutral leach ore that allowed ongoing ET during the dry season (Orellana et al. 2010). The model calibration runs used laboratory and field derived hydraulic parameters for the test panel topsoil, clay, and leach ore which were then adjusted to provide the best fit to the actual field measured soil water potential data at the test panels.

**Model calibration**

An unsaturated flow model was developed using the code VADOSE/W (Geo-Slope 2008) and calibrated to field data from the Pierina cover system test panels (Orellana et al. 2010). Calibration consisted of constructing one-dimensional model domains representing conditions at the location of the mid-slope station at the compacted clay and uncompacted clay panels. A one-dimensional model was considered appropriate for calibration to the test panel cover system data because of the absence of observed downslope flow at the topsoil/clay layer contact (Orellana et al. 2010). The total depth of each model domain was 10 meters. In each case the domain consisted of three layers (topsoil, clay, ore) with topsoil and clay thickness being equal to layer thickness measured at the test panel mid-slope sensor nests (Orellana et al. 2010).

The upper boundary of the calibration model domain was configured to allow infiltration of precipitation, direct evaporation, and plant transpiration as dictated by climatic conditions. The lowermost boundary at the bottom of the ore was configured as a unit gradient hydraulic boundary and a constant temperature of 7.5 degrees Celsius, equivalent to the 14-year climate record average air temperature.

Inputs into the calibration model were:

- A 2.7 year record (January 2007 through August 2009) of local precipitation and climate data from the mine site weather station;
- Above and below ground vegetation characteristics data from the Pierina cover system test panels (Orellana et al. 2010) and Moderate Resolution Imaging Spectroradiometer (MODIS) data;
- Hydraulic property characterization data for topsoil, clay and waste rock (Orellana et al. 2010);
- A 2.7 year record (January 2007 through August 2009) of in-situ soil water potentials observed from mid-slope station sensors in the Pierina cover system test panels (Orellana et al. 2010), and;
- Measured runoff at the Pierina test panel cover system (Orellana et al. 2010).

Model calibration was conducted by systematically varying soil hydraulic parameters to optimize agreement between field measured and model predicted soil water potentials.

**50-year model**

*Model domain and boundary conditions*

Two-dimensional model domains were developed to simulate net percolation through different ET cover designs including potential downslope flow that may occur at the topsoil/clay interface or in the drainage layer designs. An example of the two-dimensional model domain is provided in Figure 1. The model domain was 45 m wide by 7 m high with a 3:1 (horizontal:vertical) slope over the entire domain. A 3:1 slope was evaluated in order to be consistent with the grading design for the heap leach and waste rock facility.

Seven different cover system scenarios were evaluated by varying the thickness of topsoil, gravel, and clay layers overlying neutral ore (Table 1).

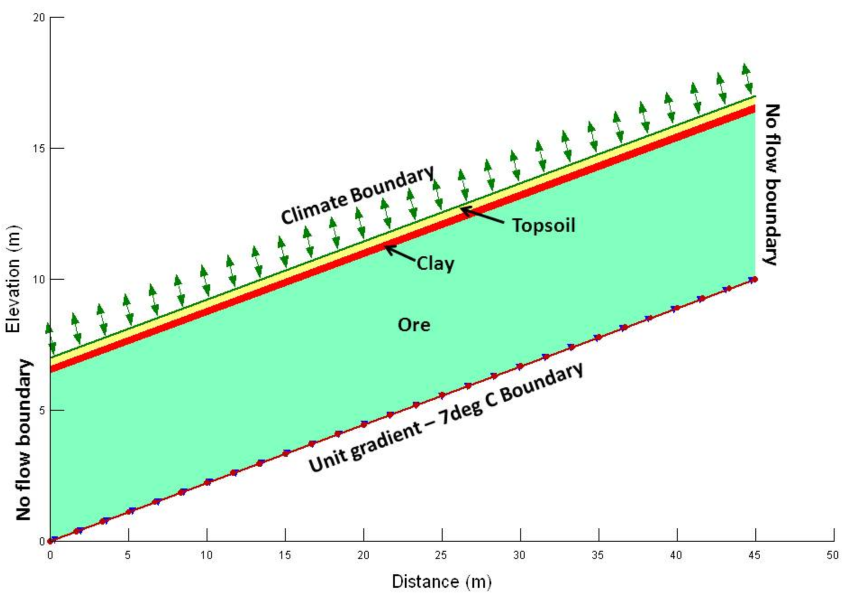


Figure 1. Example 50-year model domain.

The upper boundary of the 50-year model domain was configured to allow infiltration of precipitation, direct evaporation, and plant transpiration as dictated by climatic conditions. A unit gradient condition was assigned as the lower hydraulic boundary condition and a constant temperature of 7.5 degrees Celsius, equivalent to the 50-year synthetic climate record average surface temperature, was the assigned lower thermal boundary condition. The left and right boundary conditions were no flow boundaries. An evaluation of net percolation values throughout the model domain indicated that at the model horizontal midpoint (22.5 m) the no flow side boundaries did not influence simulated net percolation.

Table 1. 50-year model cover system scenarios.

| Scenario | Cover Material Thickness (cm) | | |
|---|---|---|---|
| | Topsoil | Drainage Layer | Clay |
| 1 | 30 | 0 | 30 |
| 2 | 30 | 0 | 60 |
| 3 | 60 | 0 | 30 |
| 4 | 60 | 0 | 60 |
| 5 | 30 | 15 | 30 |
| 6[a] | 30 | 15 | 30 |
| 7[b] | 30 | 0 | 30 |

[a] Clay saturated hydraulic conductivity (Ksat) = 0.2X uncompacted clay Ksat
[b] Clay saturated hydraulic conductivity (Ksat) = 5X uncompacted clay Ksat

Estimated daily runoff values calculated using the SCS runoff curve number method (USDA 1986) and a curve number of 91 (Orellana et al. 2010) was subtracted from the precipitation record and this modified daily precipitation was applied to the upper boundary. Estimated runoff using this method was equivalent to 15.1 percent of precipitation and no additional runoff was simulated by the two-dimensional model.

*Hydraulic properties*

50-year model hydraulic parameters used the calibration model topsoil, uncompacted clay, and ore hydraulic parameters (see “Model Calibration”). The 50-year model simulations used the uncompacted clay parameters because of the similarity between the hydraulic properties of the uncompacted and compacted clay and Pierina test panel cover system study findings that little benefit is realized by compacting the clay layer (Orellana et al. 2010). The drainage layer hydraulic parameters were assigned the ore calibrated hydraulic parameters. A drainage layer would be constructed from coarse textured, highly permeable material with similar hydraulic characteristics of the ore.

*Climatic inputs*

A 50-year climate record for Pierina does not exist and instead the computer code ClimGen v 4.1 (Stockle and Nelson 1999) was used to generate synthetic climate data based on the statistical distribution of the existing data. Climate input to ClimGen included the 14-year (1997-2010) Pierina mine site record of daily precipitation depth, maximum and minimum temperature, maximum and minimum relative humidity, solar radiation, wind speed, and solar radiation.

*Thermal properties*

The 50-year model and calibration model described thermal conductivity as a function of water content using the estimation relationship developed by Johansen (1975) as implemented in VADOSE/W. This method requires that the soil mineral thermal conductivity be defined, which was estimated from quartz content using the empirical relationship of Farouki (1981).

Table 2. Material thermal properties

| Material | Soil Mineral Thermal Conductivity (kJ/day*m*°C) | Mass Specific Heat Capacity (kJ/kg*°C) |
|---|---|---|
| Topsoil | 363 | 0.88 |
| Clay | 262 | 1.13 |
| Ore/Drainage Layer | 399 | 0.79 |

The specific heat of the material was calculated by summing the product of the specific heat of the porous material, water, and air and their respective volumetric fractions. This calculation is performed in VADOSE/W with definition of the soil mineral specific heat. Specific heat of the different material types was estimated from published specific heat data for various soil types (Bowers and Hanks, 1962). Table 2 lists the mineral thermal conductivity and mass specific heat values used in the calibration and 50-year models.

*Vegetation inputs*
50-year model vegetation inputs were identical to the calibration model. The rooting depth was set equal to 2 m below ground surface (bgs), as supported by field rooting surveys (Orellana et al. 2010), and root density was defined to decrease linearly from the surface to the maximum root depth. The maximum root depth was maintained throughout the year (i.e. no killing frost). A wilting point of -2,000 kPa was assigned and appeared to be representative during the calibration runs. The annual progression of leaf area index (LAI), defined as the one-sided green leaf area per unit ground area, was estimated from MODIS data for nearby areas that were not visibly disturbed and at the same approximate elevation as Pierina. A maximum LAI of 2 was assigned.

## RESULTS

### Model calibration
Laboratory measured and derived van Genuchten (1980) hydraulic parameters were initially applied in the compacted clay model. For the compacted clay panel, the initial parameters under predicted soil water potentials during the rainy season (January through April) and the rate at which soil water potential decreases as the soil profile begins to dry was under predicted. The alpha parameter for the compacted clay and ore was increased to produce less negative soil water potentials during the rainy season. The L parameter for all material layers were also varied to increase the rate of soil water potential decrease during drying conditions and to offset the reduced response to wetting conditions that resulted with the increase in the alpha parameter. The ore N parameter was also decreased to increase the maximum soil water potential conditions in the ore layer. Final calibrated parameters are shown in Table 3 and corresponding measured and predicted soil water potentials are presented in Figure 2. A further increase in model predicted soil water potentials in the ore layer during the rainy season could not be accomplished without adversely affecting the agreement between model-predicted and measured soil water potentials in the topsoil and clay layers. It was deemed most important to achieve agreement in the topsoil and clay layers since these material layers will predominately control net percolation.

Table 3. Calibrated hydraulic parameters

| Material | Saturated Hydraulic Conductivity (cm/s) | Unsaturated Hydraulic Parameters | | | | |
|---|---|---|---|---|---|---|
| | | Saturated Water Content ($cm^3/cm^3$) | Residual Water Content ($cm^3/cm^3$) | Alpha ($cm^{-1}$) | N (-) | L (-) |
| Topsoil | 1.45E-03 | 0.517 | 0.050 | 0.016 | 1.213 | -1.75 |
| Compacted Clay | 6.05E-05 | 0.450 | 0.100 | 0.025 | 1.195 | -7.00 |
| Uncompacted Clay | 7.67E-05 | 0.450 | 0.050 | 0.025 | 1.312 | -2.00 |
| Ore | 4.50E-02 | 0.256 | 0.010 | 0.200 | 1.300 | -1.00 |

Calibrated topsoil and ore parameters were applied to the uncompacted clay panel model and the uncompacted clay hydraulic parameters were adjusted to improve agreement between measured and simulated soil water potentials. The uncompacted clay layer alpha parameter was increased and the L parameter decreased to achieve the same effect as that for the compacted clay. The final uncompacted clay calibrated parameters are shown in Table 3 and corresponding measured and predicted soil water potentials are presented in Figure 2. As with the compacted clay model, further increase in ore water potentials during the rainy season could not be achieved without reducing the agreement between model-predicted and measured soil water potentials in the topsoil and clay layers. Additionally, it was not possible to match the minimum observed matric potentials in the uncompacted clay and ore, however, the simulated uncompacted clay soil water potentials are reasonably predicted for soil water potentials greater than -1000 cm (excluding the June 2007 through December 2007 time period). Since the majority of net percolation occurs during the wet season due to greater hydraulic conductivity of the soil and ore materials, the reasonable match of model and observed soil water potentials at conditions greater than -1000 cm are most important.

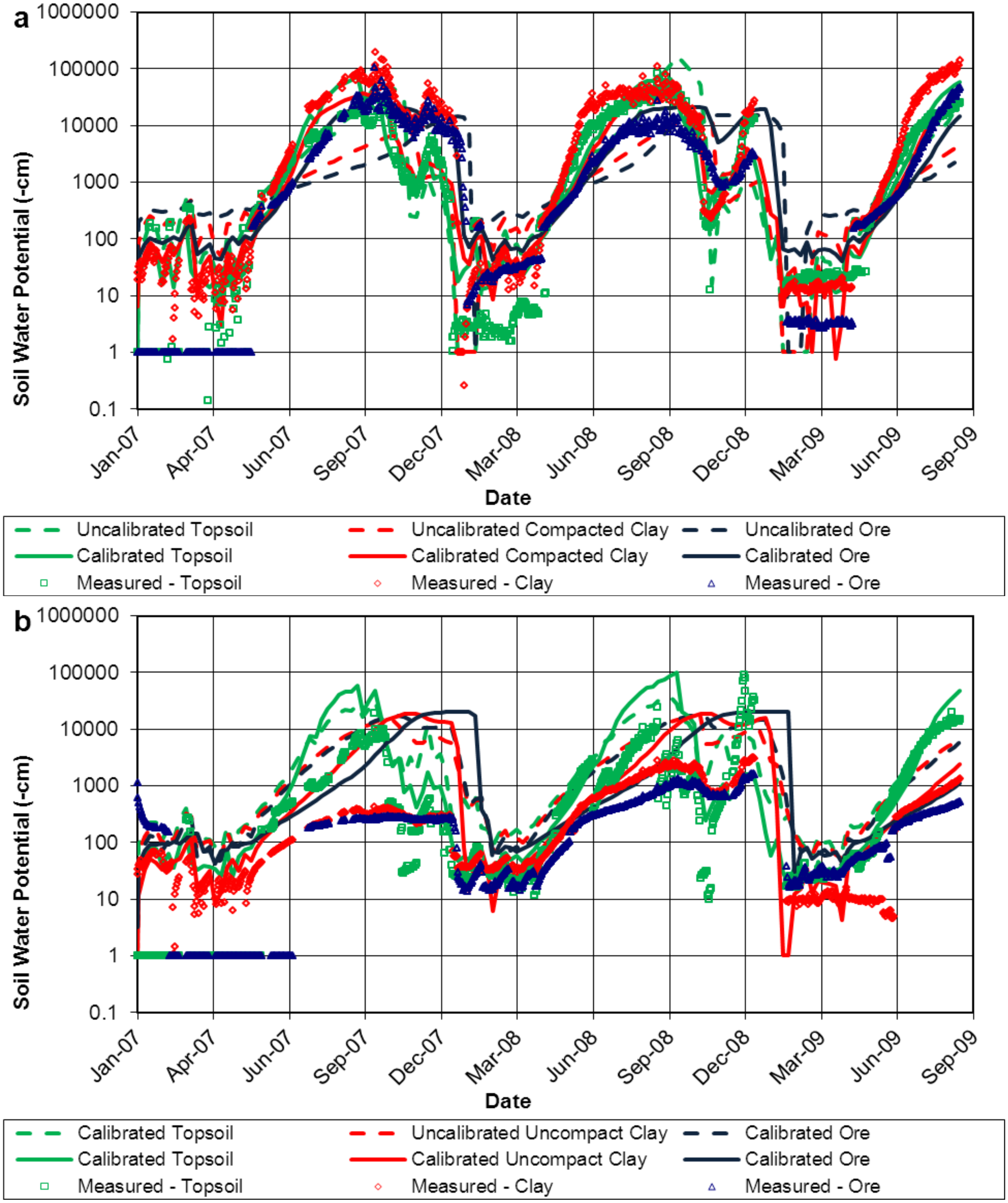

Figure 2. Model predicted and measured soil water potentials for (a) the compacted clay panel, and (b) the uncompacted clay panel.

**50-year model**
Net percolation through the cover system and underlying ore was estimated as the cumulative downward flux observed at 3 m bgs at the horizontal mid-point of the model domain. A review of simulated net percolation at various depths indicated that 3 m bgs lies below the zero flux plane and thus represents percolating water that is no longer available to be removed from the cover/ore profile by evaporation or transpiration. Analysis of model results also indicated that net percolation at the horizontal mid-point are not influenced by the left and right no flow boundary conditions.

Table 4 summarizes the estimated average net percolation over the 50-year simulation period, the daily average net percolation per hectare, and the downslope flow within the topsoil (Scenarios 1 through 4 and 6) or within the drainage layer and topsoil (Scenarios 5 and 6) at the horizontal mid-point of the model domain. Figure 3 shows the estimated annual net percolation and precipitation for each scenario.

Table 4. Summary of predicted net percolation for 50-year model simulations.

| Scenario | Cover | 50-Year Total Net Percolation | | Downslope Flow (percent of precipitation)[a] | Average Annual Net Percolation (cm) | Average Flow per Hectare ($m^3$/day/ha) |
|---|---|---|---|---|---|---|
| | | (cm) | (percent of precipitation) | | | |
| 1 | 30 cm topsoil/30 cm clay | 1675 | 27.6 | 0.5 | 33.5 | 92 |
| 2 | 60 cm topsoil/30 cm clay | 1485 | 24.4 | 0.4 | 29.7 | 81 |
| 3 | 30 cm topsoil/60 cm clay | 1530 | 25.2 | 1.1 | 30.6 | 84 |
| 4 | 60 cm topsoil/60 cm clay | 1415 | 23.2 | 0.5 | 28.3 | 78 |
| 5 | 30 cm topsoil/15 cm drainage/30 cm clay | 1675 | 27.5 | 0.9 | 33.5 | 92 |
| 6 | 30 cm topsoil/15 cm drainage/30 cm clay[b] | 1185 | 19.5 | 4.5 | 23.7 | 65 |
| 7 | 30 cm topsoil/30 cm clay[c] | 1655 | 27.3 | 0.1 | 33.1 | 91 |

a – Downslope flow within topsoil for Scenarios 1 – 4 and 6, within topsoil and drainage layer for Scenarios 5 and 6
b - Clay saturated hydraulic conductivity (Ksat) = 0.2X uncompacted clay Ksat
c - Clay saturated hydraulic conductivity (Ksat) = 5X uncompacted clay Ksat

General conclusions from the 50-year model data are:

- Net percolation generally correlated to the annual precipitation, that is, years with more precipitation usually lead to larger net percolation (Figure 3).
- Net percolation nominally decreased with increasing topsoil and clay thickness, with net percolation decreasing by 4.4% of precipitation/year going from a 30 cm topsoil/30 cm clay cover (Scenario 1) to a 60 cm topsoil/30 cm clay cover (Scenario 4) (Table 4). Increasing the topsoil thickness from 30 cm to 60 cm (Scenario 2) had greater effect on reducing net percolation than increasing the clay thickness by the same amount (Scenario 3), however, the difference was small (0.8 percent of precipitation) (Table 4).
- The addition of a drainage layer did not decrease net percolation compared to other cover scenarios (Scenario 5), however, including a drainage layer and decreasing the clay Ksat by 0.2X reduced net percolation by 8.0% of precipitation/year (Scenario 6) compared to Scenario 5 (Table 4). These results indicate the importance of clay Ksat on the effectiveness of the clay drainage layer.
- Estimated average net percolation per hectare ranged from 65 $m^3$/day/ha (Scenario 6) to 92 $m^3$/day/ha (Scenarios 1 and 5) (Table 4).

- With the exception of Scenario 6, estimated downslope flow was minimal, being 1.1 percent or less of precipitation, with the exception of the decreased clay Ksat scenario (Scenario 6) (Table 4). These results are consistent with the test panel data (Orellana et al 2010).
- Simulated net percolation for the 30 cm topsoil/30 cm clay scenario with a 5X increased clay Ksat (Scenario 7) was similar to Scenario 1 (Table 4), indicating that rooting in the leach ore material is sufficient to extract additional percolation that may have passed the clay layer.

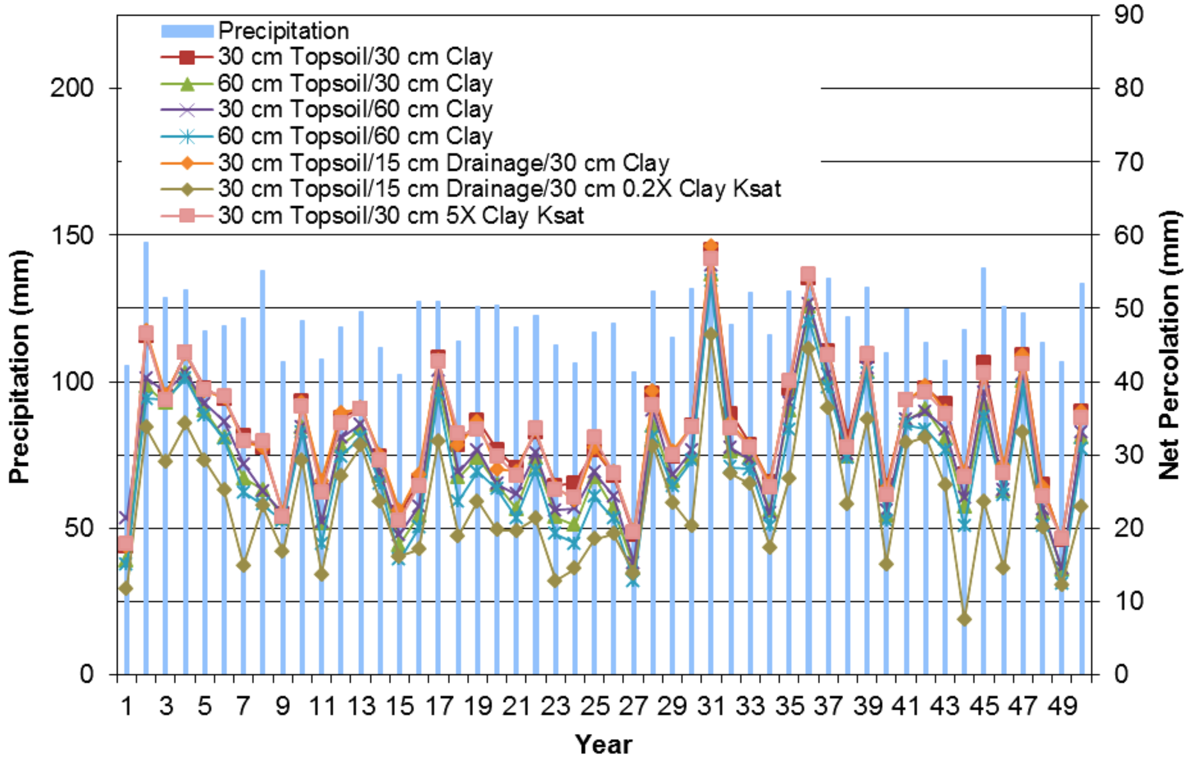


Figure 3. Model predicted annual net percolation and precipitation.

The majority of the precipitation was simulated to be lost to ET, ranging from 60.7 to 64.0 percent of precipitation. Simulated ET amounts equated to 94 to 99 percent of ETo. Although the 50-year simulations showed that ET increases with cover depth, the relatively small decrease in predicted net percolation indicates that the majority of net percolation occurs from episodic events that wet the subsurface to depths below the ET region.

## CONCLUSIONS

Results from the two-dimensional unsaturated flow model estimate that about 23-28% of precipitation (65-92 $m^3$/ day/ha) will percolate through an ET cover overlying neutral waste. The relatively narrow range of simulation results indicates that increasing the cover thickness only nominally decreases the predicted net percolation. This is primarily due to the defined vegetative rooting within the 50-year model; the test panel study at Pierina showed extensive rooting into the waste leach ore (Orellana et al. 2010). Consequently, ET covers over acidic waste, where vegetative rooting is limited to the cover layers, may be more influenced by the cover layer thickness and may also show greater net percolation through thinner cover systems. Results also showed that the hydraulic conductivity of the clay layer largely influences the effectiveness of ET cover systems with a drainage layer. Maintaining a low saturated hydraulic conductivity in clay layer below a drainage layer could significantly decrease the amount of net percolation into the waste material. However, results of Orellana et al. (2010) and many other field studies (i.e. Albright et al. 2006, Waugh 2004, Taylor et al. 2003, Wilson et al. 2003), indicate that clay

Ksat in soil covers increases over time due to factors such as root penetration, desiccation, thermal expansion and contraction, and animal activity.

This modeling study was conducted primarily to assess the relative performance of different cover designs in controlling net percolation through the underlying ore. These simulations cannot estimate the long-term efficacy of vegetation on the cover system and actual performance can be expect to vary due to variability in the ore properties and vegetative cover. Nonetheless, climatic and vegetation parameter inputs were selected to provide conservative estimates of percolation. Therefore, the predicted net percolation estimates may reasonably be applied as an upper bound on average rates. The relative predicted changes in cover system efficiency can be used to evaluate the cost effectiveness of adding additional cover material in terms of reduction of short-term versus long-term costs and other issues such as erosion control and vegetative success.

## REFERENCES


Albright, W.H., Benson, C.H. Gee, G.W., Abichou, T., Mcdonald, E.V., Tyler, S.W. and Rock, S. (2006) Field performance of a compacted clay landfill final cover at a humid site, Journal of Geotechnical and Geoenvironmental Engineering 132(11), pp. 1393–1403.

Bowers, S.A. and Hanks, R.J. (1962) Specific heat capacity of soils and minerals as determined with a radiation calorimeter. Soil Science, Vol 94, pp. 392-396.

Farouki, O. (1981) Thermal properties of soils. CRREL monograph 81-1, U.S. Army Corps of Engineers, Hanover, New Hampshire.

GEO-SLOPE, 2008. Vadose zone modeling with Vadose/W 2007. GEO-SLOPE International, Ltd. Calgary, Alberta, Canada.

Orellana, R., Ludwick, W., Zhan, G., Baumann, W., Milczarek, M., Rice, R.C., Yao, T-M., and Keller, J. (2010) Final results of the cover system test panel trials at the Pierina Mine. In, Proceeding of the Fifth International Conference on Mine Closure, Editors A. Fourie, M. Tibbet, and J. Wiertz, November 23-26, 2010, Viña del Mar, Chile.

Stöckle C.O. and Nelson, R. (1999) ClimGen, a weather generator program. Biological Systems Engineering Department, Washington State University, Pullman, WA.

Tarnawski, V.R., Momose, T., and Leong, W.H. (2009) Assessing the impact of quartz content on the prediction of soil thermal conductivity. Gèotechnique, Vol 59, pp. 331-338.

Taylor G., Spain, A., Timms, G., Kuznetsov, V. and Bennett, J. (2003) The medium-term performance of waste rock covers – Rum Jungle as a case study, Proceedings of the 6th International Conference on Acid Rock Drainage, July 12–18, Cairns, Australia.

USDA, See United States Department of Agriculture.

United States Department of Agriculture (1986) Urban hydrology for small watersheds, Technical Release 55, Natural Resources Conservation Service.

Van Genuchten, M Th. (1980) A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J., Vol 44, pp. 892-898.

Waugh, W.J. (2004) Design, performance, and sustainability of engineered covers for uranium mill tailings, Proceedings of Long-term Performance Monitoring of Metals and Radionuclides in the Subsurface:

Strategies, Tools, and Case Studies. U.S. Environmental Protection Agency, U.S. Department of Energy, U.S. Geological Survey, Nuclear Regulatory Commission, April 21–22, 2004, Reston, VA.

Wilson, G.W., Williams, D.J. and Rykaart, E.M. (2003) The integrity of cover systems – An update, Proceedings of the 6th International Conference on Acid Rock Drainage, July 12–18, Cairns, Australia.