THE USE OF "ENHANCED" MOISTURE STORE-AND-RELEASE COVER SYSTEMS OVER REACTIVE MINE WASTE IN COLD AND WARM SEMI-ARID CLIMATES[1]

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Abstract. Moisture store-and-release cover systems utilize the high evaporative demand in semi-arid and arid climates to reduce the infiltration of meteoric waters to underlying reactive mine waste. This paper describes the benefits of adding a thin, reduced hydraulic conductivity layer below the overlying non-compacted layer to "delay" the downward percolation of infiltrating moisture and enhance the overall performance of the cover system. The additional cover layer is not required to be a high quality "barrier" layer and therefore does not necessarily require a clay-rich material. For example, a compacted waste rock layer as a result of haul truck traffic on top of a dump lift could serve as the low hydraulic conductivity layer. A one-dimensional numerical modeling program was used to compare the performance of a conventional moisture store-and-release cover system and an "enhanced" moisture store-and-release cover system. The modeling program was based on actual climate conditions and measured soil properties from a cold semi-arid site in northern Canada and a warm semi-arid site in Australia. Two cover system alternatives examined at each site found a decrease in the average annual net percolation for the enhanced store-and-release cover system of approximately 4%-7% of annual precipitation compared to the conventional store-and-release cover system. Analysis of the simulations showed net percolation occurred during the spring after snow melt and following the autumn rainfall events at the northern Canadian site and after intense rainfall events during the rainy season at the Australian site. The thin, reduced hydraulic conductivity layer improved the performance of the store-and-release cover system by holding water within the cover system for an increased period of time, allowing increased actual evapotranspiration in the subsequent dry periods.

Additional Key Words: moisture storage, net percolation, numerical modeling program

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Introduction

Earthen cover systems, often referred to as "dry" cover systems, are increasingly being implemented as part of the reclamation and closure strategies for waste storage facilities at mine sites. In general, the objectives of dry cover systems are to minimize the influx of water and provide an oxygen diffusion barrier to minimize the influx of oxygen. Apart from these functions, dry covers are expected to be resistant to erosion and provide support for vegetation.

Dry covers can be simple or complex, ranging from a single layer of earthen material to several layers of different material types, including native soils, non-reactive tailings and/or waste rock, geosynthetic materials, and oxygen consuming organic materials (MEND, 2004). Single layer moisture "store-and-release" cover systems typically utilize the high evaporative demand prevalent at semi-arid and arid sites to store precipitation during wet periods for subsequent release back to the atmosphere during dry periods. Multi-layer cover systems can utilize the capillary barrier concept to keep one (or more) of its layers near saturation under all climatic conditions, or utilize a "barrier" layer, which typically possesses good moisture retention properties.

The main objective of this paper is to evaluate the effectiveness of a thin, reduced hydraulic conductivity layer in improving the performance of a moisture store-and-release cover system. The performance of this "enhanced" moisture storage cover system and a conventional single layer store-and-release cover system in both a cold, northern climate and a warm, semi-arid climate were investigated. Net percolation of meteoric waters through the base of the cover system and into the underlying waste is the primary indicator of cover system performance. The one dimensional (1D) numerical modeling conducted in support of this paper was completed with the VADOSE/W model (Geo-Slope International Ltd., 2004). While the effects of two dimensional (2D) flow on performance of sloping cover systems should not be discounted, this paper will focus on 1D numerical analyses.

Background

A cover system located in an arid or semi arid location will be subjected to extended dry periods and therefore the effect of evapotranspiration will be significant. However, subjecting the cover system to evaporative demands can be beneficial in arid and semi-arid climates and result in a reduction of infiltration to the underlying sulfidic waste material (MEND, 2004). A homogeneous cover system layer with a well-graded texture and possessing sufficient storage capacity can be used to retain water during rainfall events. The storage layer releases a significant portion of pore-water back to the atmosphere by evapotranspiration during extended dry periods, thereby significantly controlling the net percolation across the cover system and into the underlying waste material. The objective of this "moisture store-and-release" cover system is to control acidic drainage as a result of preventing moisture movement into and through the waste material.

Kuo et al. (2003) and Taylor et al. (2003) discuss the performance of a field-scale store-and-release cover system installed at the Rum Jungle site in the Northern Territory, Australia, in

1984. The Rum Jungle site possesses a semi-arid climate; however, the average annual rainfall (1600 mm) is only slightly less than the average annual pan evaporation (1900 mm). O'Kane and Waters (2003) investigated the performance of store-and-release cover system field trials at the Mt. Whaleback site in Western Australia, Australia. The site is more typical of an arid climate with an average annual rainfall of approximately 320 mm and annual pan evaporation of 3000 mm. Other sites implementing store-and-release cover system field trials include Ronneburg, Germany described by Hockley et al. (2003) and a site in Arizona as reported by Milczarek et al. (2003).

The application of soil-atmosphere numerical models to assist with the design of dry cover systems for waste rock piles and tailings impoundments has developed in recent years. Among the first coupled heat and water transfer models were the SWIM and 1D SoilCover models.

Bruch (1993) utilized the SWIM (Soil Water Infiltration and Movement) model to analyze the soil-atmosphere flux for a layered soil column in a laboratory setting. The SWIM model, developed within the CSIRO Division of Soils, Australia (Verburg et al., 1999) produced reasonable agreement between the measured and calculated evaporative fluxes. SoilCover is a 1D finite element package, developed by the University of Saskatchewan, Canada, which models transient water and heat transport in a soil profile (MEND, 1996). Swanson (1995) calibrated the SoilCover model to field performance monitoring data at the Equity Silver mine near Houston, BC, Canada. The calibrated model was then used to predict the long-term performance of the waste rock cover system.

Newman et al. (2002) describe the formulation of the rigorous 2D coupled soil-atmosphere numerical model, VADOSE/W, developed by Geo-Slope International. A simple cross-section was used to demonstrate the effects of a sloping cover system on runoff, evapotranspiration, and net percolation through the base a cover system. The VADOSE/W model can be used both as a simplified 1D model or a 2D model with complex geometry.

Site Background

The modeling program is based on actual climate conditions and material properties collected at the individual sites. Both sites are good candidates for the incorporation of an enhanced cover system, although for differing reasons. The site in northern Canada, similar to most sites in the region, does not possess a suitable borrow material containing a significant percentage of clay-size particles to produce a low hydraulic conductivity, "barrier" layer (< 1 x 10^{-7} cm/s). The potential cover material at the site is a sandy till possessing a saturated hydraulic conductivity approximately two orders of magnitude higher than the waste rock material to be covered as part of site closure planning. The thin, reduced hydraulic conductivity layer will be constructed by compacting the existing *in situ* waste rock surface.

Many open pit mining operations, such as the site in Australia, produce a large amount of variable waste materials including tailings, non-acid forming (NAF) waste rock and potentially acid forming (PAF) waste rock. The site being studied in Australia possesses a large amount of barren or NAF waste rock to be used in constructing a dry cover system over the tailings impoundment. The variable waste rock materials include a sodic, fine-textured waste material. This waste material possesses a lower saturated hydraulic conductivity than the other potential

cover materials; however, it is not suitable as a stand-alone cover material due to its dispersive nature, its inability to sustain vegetation, and its tendency to "crust" producing increased runoff from storm events. It is possible that the material can be placed on the tailings surface at the base of the cover system to restrict both the downward flow of moisture to the tailings and the upward migration of salts from the tailings into the cover system.

Description of Numerical Modeling Inputs

The VADOSE/W soil-atmosphere model was used for this study. VADOSE/W is a two-dimensional (2-D) finite element model that predicts pressure head (suction) and temperature profiles in the soil profile in response to climatic forcing (such as evaporation) and lower boundary conditions (such as a water table). A key feature of VADOSE/W is the ability of the model to predict actual evaporation and transpiration based on potential evaporation and predicted soil suction using the Penman-Wilson method (Wilson, 1994), as opposed to the user being required to input these surface flux boundary conditions. The actual evapotranspiration rate is generally well below the potential evapotranspiration rate during prolonged dry periods because the suction, or negative water pressure, in the soil profile increases as the surface desiccates reducing the hydraulic conductivity of the material. This reduces the amount of water that can move upward to the soil surface and be released to the atmosphere. In addition, evaporation can occur through the movement of water vapor. VADOSE/W is a fully coupled (through the vapor pressure term) heat and mass transfer model which is capable of predicting water vapor movement.

VADOSE/W is a physically based model, although modelling of vegetation is based on an empirical formulation. The potential transpiration rate is based on the leaf area index (LAI). The model user can apply "excellent", "good", or "poor" LAI values (which change during the growing season), which are based on agricultural crops, or rooting characteristics and transpiration rates indicative of native species can be input. The potential transpiration predicted by the LAI method is limited based on the negative water pressure predicted by VADOSE/W.

VADOSE/W is also capable of evaluating the impact of frozen conditions on moisture storage and transport for a given soil or rock material. The change of phase from liquid to solid (i.e. water to ice) is accounted for using the apparent specific heat capacity approach, which is standard in thermal modelling. A heat source or sink is added at each time step based on the amount of heat released when a set volume of water changes to ice. When the ground becomes frozen, the permeability must be reduced. In the physics of freezing, there is a phenomenon whereby even in a saturated soil, a "suction" develops at the ice-water interface much like the one at the air-water interface in an unsaturated soil. In fact, if the temperature below freezing is known, then the suction can be computed using the Clausius Clapeyron phase equilibrium equation (Black and Tice, 1989). VADOSE/W does not account for this suction at the microscopic level in the mass transfer equation, but does use the actual temperature to compute what the suction should be so that the program can apply a reduced permeability from the

material's hydraulic conductivity function (suction versus hydraulic conductivity). VADOSE/W simulations can be run with or without this functionality.

Climate Data

VADOSE/W requires daily precipitation, air temperature, relative humidity, wind speed, and net radiation or potential evaporation values in order to conduct soil-atmosphere cover design simulations. A database consisting of 29 years of climate data was constructed for the Canadian site using site-specific data collected from a nearby weather station. The climate database for the Australian site is based on 10 years of collected weather station data. Table 1 summarizes the average climate conditions for each site.

Table 1. Summary of average climate conditions for the northern Canada and Australia sites.

Parameter	Northern Canada	Australia
Years of climate data	29	10
Average annual precipitation	544 mm	403 mm
Average annual potential evaporation	800 mm[*]	2,100 mm
Daily maximum temperature	+ 0.9 $^{\circ}$C	+ 33.3 $^{\circ}$C
Daily minimum temperature	- 8.1 $^{\circ}$C	+ 16.3 $^{\circ}$C
Daily maximum relative humidity	86%	42%
Daily minimum relative humidity	64%	22%
Average daily wind speed	3.7 m/s	2.5 m/s

[*] Potential evaporation estimated by the VADOSE/W sub-module.

Material Properties

Material properties or functions required for each layer in the VADOSE/W model are as follows:

- soil-water characteristic curve (suction versus volumetric water content);
- hydraulic conductivity function (suction versus hydraulic conductivity);
- thermal conductivity function (volumetric water content versus thermal conductivity); and
- volumetric specific heat function (volumetric water content versus volumetric specific heat).

The materials examined in the laboratory study include waste rock, compacted waste rock, and sandy till from the Canadian site, and oxidized waste rock (potential cover material) and tailings from the Australian site. The soil-water characteristic curves (SWCCs) input to the model are based on the curves measured in the laboratory during the materials characterization program completed for both sites. The hydraulic conductivity functions were estimated using the van Genuchten (1980) formulation based on the saturated hydraulic conductivity values from

large-scale laboratory constant head permeameter tests and the shape of the SWCC. The saturated hydraulic conductivity, dry density, porosity, and air-entry values input to VADOSE/W for the different materials modeled in this study are shown in Table 2. The thermal conductivity and volumetric specific heat functions were estimated using the VADOSE/W sub-modules; each of these is based on the material layer modeled and assumed *in situ* conditions.

Vegetation

    The soil-atmosphere modeling program considered a vegetated surface with a "poor" grass vegetation cover. This scenario is associated with a leaf area index (LAI) of 1.0 during the growing season. The growing season for cover vegetation at the northern Canada site was assumed to start on May 15th and end on September 15th. The rooting depth at the Canadian site was limited to 30 cm below the surface of the non-compacted cover layer. A five-month growing season for vegetation was assumed to start on November 1st and end on March 31st for the Australian site. The rooting depth for all Australian simulations was limited to 50 cm below the surface of each cover system alternative.

Table 2. Summary of saturated hydraulic conductivity and porosity values for the materials simulated in the soil-atmosphere modeling program.

Material	Saturated Hydraulic Conductivity	Density	Porosity	Air Entry Value
Non-compacted waste rock	5×10^{-5} cm/s	1,950 kg/m^3	0.27	0.1 – 1.0 kPa
Compacted waste rock	5×10^{-6} cm/s	2,050 kg/m^3	0.25	0.1 – 1.0 kPa
Non-compacted till	2×10^{-3} cm/s	1,800 kg/m^3	0.32	0.5 – 1.0 kPa
Tailings	3×10^{-6} cm/s	1,450 kg/m^3	0.44	1.0 – 5.0 kPa
Intermediate waste rock	1×10^{-5} cm/s	1,900 kg/m^3	0.32	0.5 – 1.0 kPa
Sodic waste rock	1×10^{-6} cm/s	1,700 kg/m^3	0.35	0.5 – 2.0 kPa

Presentation of Modeling Program Results

Description of the Cover System Alternatives

    The 1D modeling program examined two cover system alternatives with and without the thin reduced hydraulic conductivity layer at both sites. At the Canadian site, 0.5 m and 1.0 m moisture store-and-release cover systems were evaluated, whereas 1.0 m and 2.0 m cover systems were examined at the Australian site. Table 3 summarizes the design details of each cover system evaluated in the numerical modeling program. For purposes of this paper, an "enhanced" cover system will include a thin, reduced hydraulic conductivity layer, while a "conventional" cover system does not.

Table 3. Summary of the cover system alternatives examined in the numerical modeling program.

Cover System	Design Details
Canadian Site	
0.5 m Store-and-release	**0.5 m Non-compacted till** **+/- 0.2 m Compacted waste rock** 9.5 m Non-compacted waste rock
1.0 m Store-and-release	**1.0 m Non-compacted till** **+/- 0.2 m Compacted waste rock** 9.0 m Non-compacted waste rock
Australian Site	
1.0 m Store-and-release	**1.0 m Intermediate waste rock** **+/- 0.3 m Sodic waste rock** 7.0 m Tailings
2.0 m Store-and-release	**2.0 m Intermediate waste rock** **+/- 0.3 m Sodic waste rock** 6.0 m Tailings

Net Percolation Predictions for Cover System Alternatives

Fig. 1 summarizes the average net percolation predicted for the cover system alternatives based on simulating each year within the climate database. The predicted annual net percolation for the conventional 0.5 m cover system is 96 mm (18% of average annual precipitation), while the predicted net percolation for the 0.5 m enhanced cover system is 58 mm (11% of average annual precipitation). The predicted net percolation for the 1.0 m cover systems is 65 mm (12%) and 37 mm (7%) for the conventional and enhanced store-and-release cover systems, respectively. The inclusion of a thin, reduced hydraulic conductivity layer at the base of the store-and-release cover system reduced the average annual net percolation from 18% to 11% for the 0.5 m cover system and 12% to 7% for the 1.0 m cover system.

Similar results were predicted for the 1.0 m and 2.0 m store-and-release cover systems at the Australian site. The predicted annual net percolation is 62 mm and 37 mm for the conventional and enhanced 1.0 m store-and-release cover system, respectively. The net percolation predicted for the 2.0 m cover system is 41 mm for the conventional cover system and 21 mm for the enhanced cover system. The addition of the thin, reduced hydraulic conductivity layer reduced the predicted net percolation from 14% to 10% for the 1.0 m cover system and 9% to 5% for the 2.0 m store-and-release cover system.
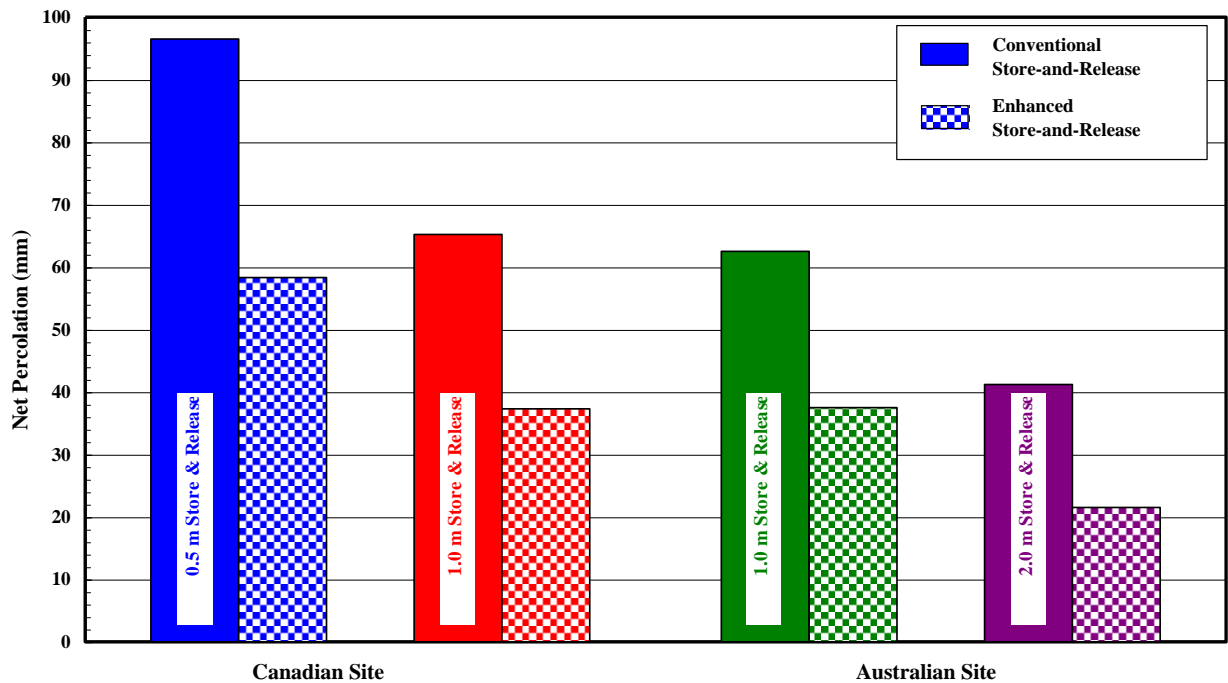
Figure 1. Average annual net percolation predicted for the cover system alternatives evaluated at the Canadian and Australian sites.

The thin, reduced hydraulic conductivity layer produced a distinct improvement in cover system performance at both sites. The layer "holds" infiltration within the overlying cover material for an increased period of time during periods of high saturation within the cover system, such as during spring snow melt and fall rainfall events at the Canadian site, providing the opportunity for evapotranspiration to remove the moisture back to the atmosphere, rather than the moisture reporting as net percolation into the underlying waste material. Fig. 2 shows the cumulative net percolation through the 1.0 m store-and-release cover systems at the Canadian site during an average climate year.

A small amount of net percolation occurred through both cover systems in November before winter freeze-up stopped the movement of moisture. During the simulations, spring snow melt occurred in late April and early May; however, percolation did not occur through the base of the cover system until its thaw in late May. Approximately 17 mm of net percolation was predicted through the conventional store-and-release cover system during the spring period, while only 9 mm was predicted to flow through the enhanced store-and-release cover. The summer months produced a net upward movement of moisture from the underlying waste material into the cover system. A smaller amount of upward moisture movement occurred in the enhanced store-and-release cover system; the same thin layer of material that restricts downward flow also limits upward flow in comparison to the conventional store-and-release cover system. An additional 31 mm of net percolation produced a total of 54 mm of net percolation through the conventional 1.0 m store-and-release cover system for the simulation period. A total of 32 mm of net percolation was predicted for the 1.0 m enhanced store-and-release cover system for the same period.
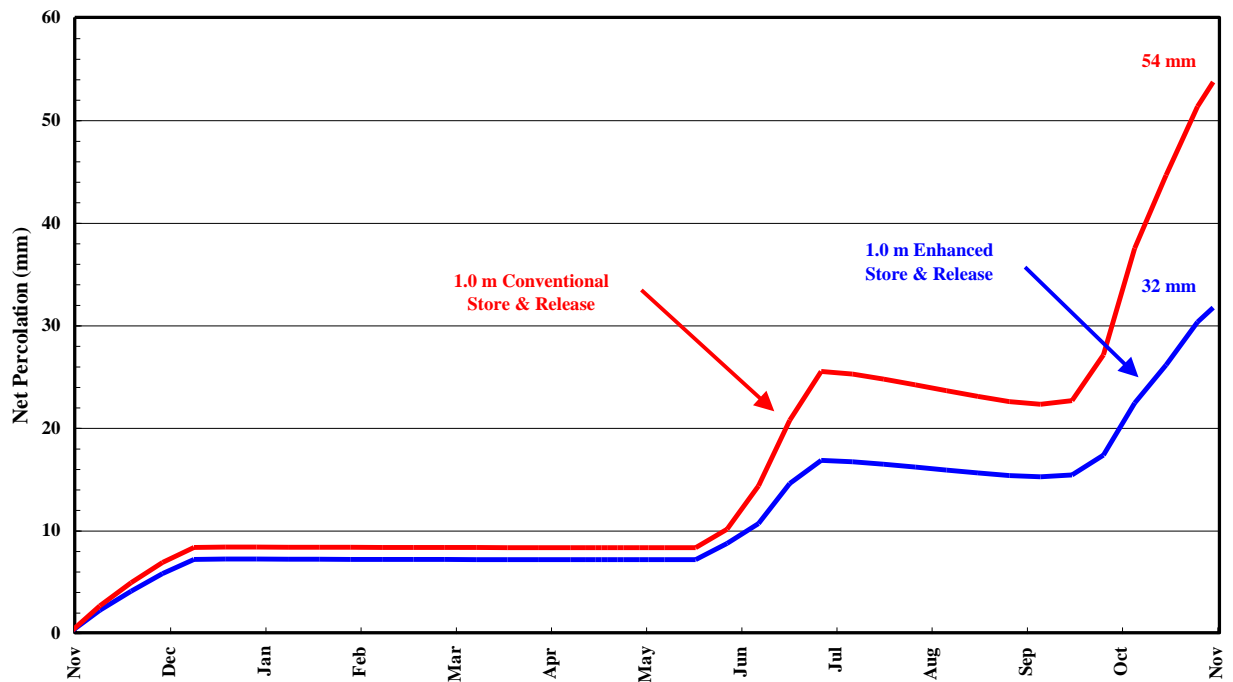
Figure 2. Cumulative net percolation predicted for the 1.0 m store-and-release cover systems at the Canadian site.

Fig. 3 shows the predicted net percolation for a conventional and enhanced 1.0 m store-and-release cover system for an above average climate year (in terms of rainfall) at the Australian site. The results are similar to the Canadian site in that the predicted net percolation for the enhanced store-and-release cover system is significantly lower. The cumulative rainfall displayed on Figure 3 shows that the moisture storage capability of the 1.0 m cover system was able to "absorb" the rainfall of December and early January without allowing significant net percolation. However, the storage capability of the cover system is depleted by the large rainfall events in early February when approximately 210 mm of rain fell in a period of two weeks.

Fig. 4 further summarizes the results of the same simulation at the Australian site, comparing on the predicted net percolation, AET, and change in moisture storage from January 15th to April 1st for both the conventional and enhanced cover systems. The results for the conventional and enhanced cover systems are similar until February 15th. The increased net percolation through the conventional cover system leads to a decreased volume of moisture in storage within the cover system. A greater volume of water is held within the enhanced store-and-release cover system due to the thin, reduced hydraulic conductivity layer. The majority of net percolation is completed by March 1st for both cover systems and moisture is released back to the atmosphere resulting in a decrease in the volume of water in storage. Approximately 80 mm of net percolation and 272 mm of AET were predicted for the conventional 1.0 m store-and-release cover system during the ten week period (January 15 – April 1). In comparison, a reduced net percolation (47 mm) and increased AET (286 mm) were predicted for the enhanced 1.0 m store-and-release cover system.
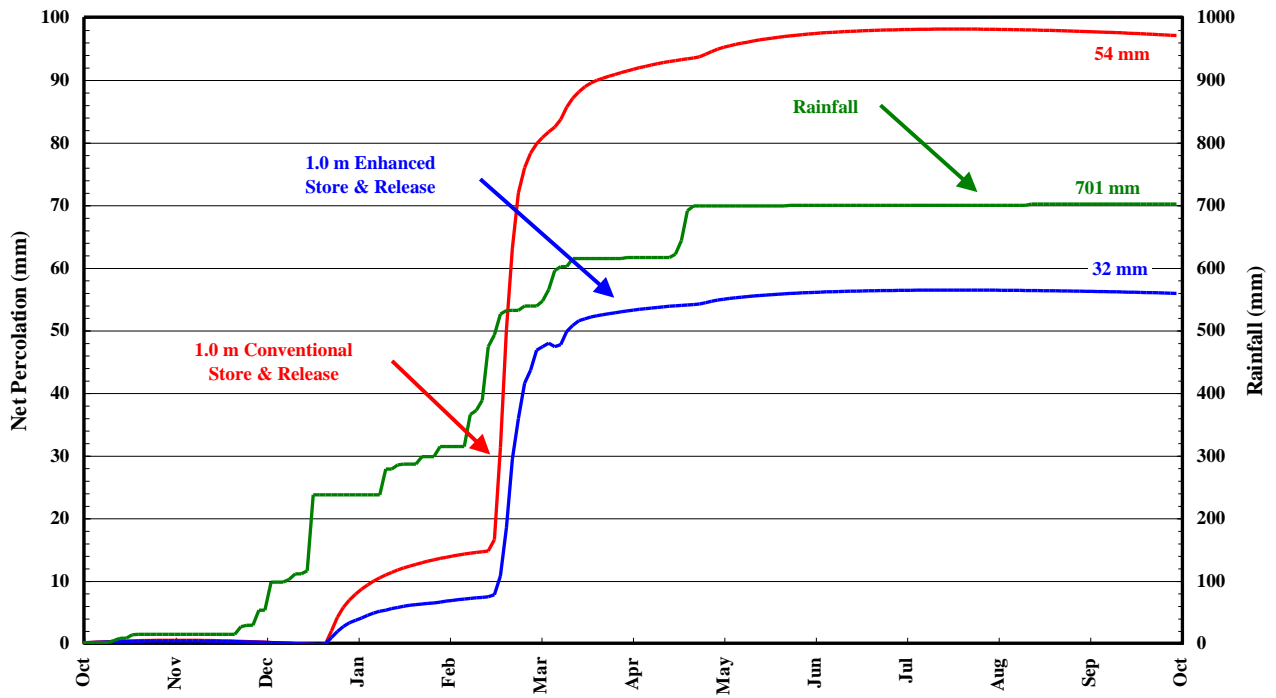
Figure 3. Cumulative net percolation predicted for the 1.0 m store-and-release cover systems at the Australian site and cumulative rainfall for the simulation period.
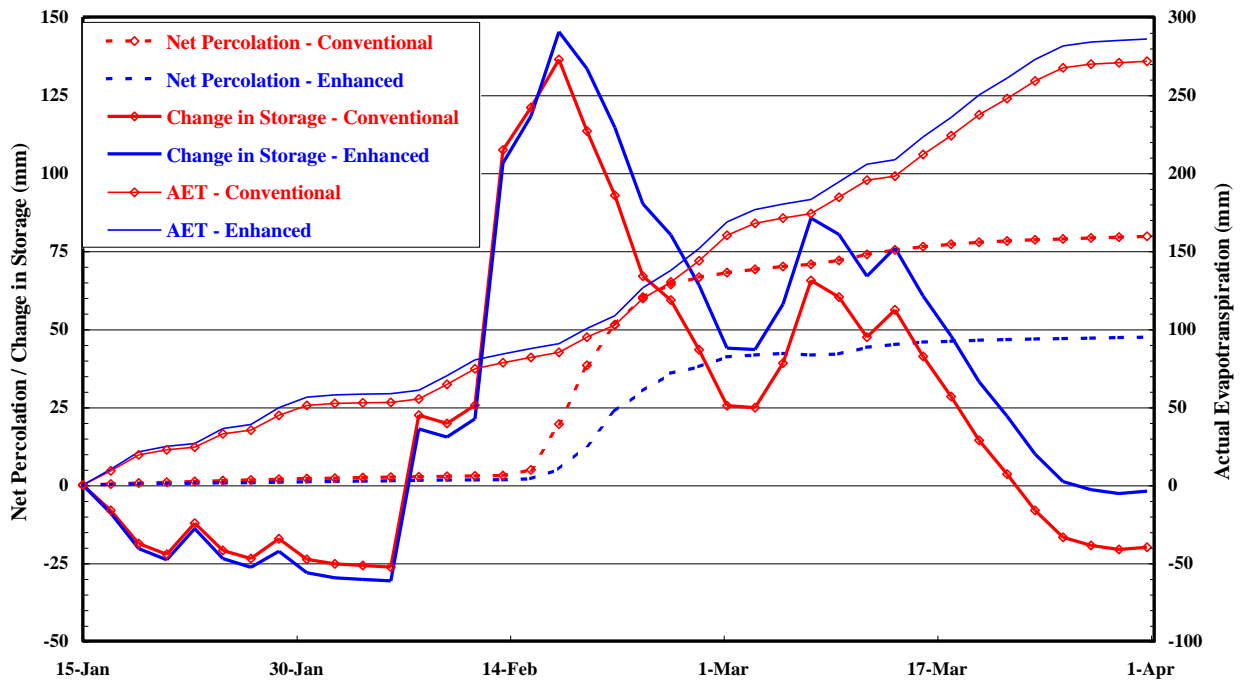

Figure 4. Comparison of predicted net percolation, AET, and change in moisture storage for the 1.0 m store and release cover system at the Australian site.

It is likely that a thin, reduced hydraulic conductivity layer is not as effective as a barrier layer (i.e. a layer with a maximum hydraulic conductivity of 1×10^{-7} cm/s) in reducing net percolation; however, it does keep meteoric water, which has infiltrated the ground surface, within the cover system and within the zone of evaporation for an increased period of time. This increases the potential for atmospheric forcing to remove moisture through evaporation and/or transpiration and ultimately reduce net percolation to the underlying waste material. In addition, it would not be prudent to include a layer with a hydraulic conductivity in the range of 1×10^{-7} cm/s or less as part of a cover system design in a semi-arid to arid climate because this material would likely consist of clay or possess a high clay content, which could possibly result in cracking and desiccation under wet / dry cycling. MEND (2004) presented a case study in which wet/dry cycling was shown to have an effect on the long-term performance of a dry cover system.

Summary

A numerical modeling program evaluating the performance of moisture store-and-release cover systems was completed for sites in northern Canada and Australia. The purpose of the modeling program was to evaluate the effectiveness of a thin, reduced hydraulic conductivity layer in improving the performance of a moisture store-and-release cover system. Two cover system alternatives examined at each site found a decrease in the predicted annual net percolation for the enhanced store-and-release cover system. Analysis of the simulations indicates net percolation occurred during the spring after snow melt and following the autumn rainfall events at the Canadian site, and after intense rainfall events during the rainy season at the Australian site. The thin, reduced hydraulic conductivity layer improved the performance of the store-and-release cover system by holding water within the cover system for an increased period of time, allowing increased evapotranspiration in the subsequent dry periods. The reduction in moisture storage during the dry climate conditions also assists with reducing net percolation for subsequent years because this maximizes the ability to accept (and "hold") infiltration during subsequent wet climate conditions.

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