Final Results of the Cover System Test Panel Trials at the Pierina Mine

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Abstract

The Minera Barrick Misquichilca Pierina Mine near Huaraz, Peru is located at 4100 m elevation and is characterized by bi-modal precipitation with wet and dry seasons. Annual precipitation and pan evaporation rates are 1250 mm and 930 mm, respectively. In late 2005, Pierina initiated a testing program to evaluate the efficiency of two different cover systems in controlling net percolation. Two large-scale test panels (20m X 55m) were constructed at a closed area of the heap leach facility to test different clay layer construction methods. In one panel, approximately 35 cm of clay/silt material was placed and roller-compacted to approximately 90% of maximum density. In the other panel, approximately 55 cm of clay/silt material was placed and compacted only by equipment traffic. Approximately 30 cm of topsoil was then placed over both test panels to serve as growth media. In addition, every 10 meters along the slope, suction breaks were installed in the topsoil to depressurize the topsoil material during the rainy season.

Cover performance monitoring stations were established in each panel. Precipitation, evaporation, stormwater runoff, water content, soil water potential, and direct percolation data were collected from 2006 through 2009 followed by a decommissioning and field hydraulic property testing program. Cover system performance monitoring data indicate that net percolation into the leach ore increased over time, especially in the compacted clay test panel. The post-test data showed that the hydraulic conductivity of both clay liners had increased to similar ranges and that rooting of grass species was significant in both panels up to depths exceeding 1.5 meters. Roots were generally larger, more abundant and penetrated deeper in the uncompacted clay test panel. Based on these data, there appears to be no long-term advantage to compacting the clay liner. Testing program results indicate that net percolation rates approach 25% of precipitation for both test panels. Surface water runoff decreased with the establishment of vegetation and also appeared to decrease over time from the compacted clay Panel 3 side-slope, possibly due to increased infiltration and net percolation through the clay liner. The average surface runoff between both panels was around 14% of precipitation and can be modelled using the SCS equation with a CN of 91,

1 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 2013. In 2006, in an effort to support closure planning, test panels were constructed over spent heap leach ore to evaluate the efficiency of two different types of multi-layer cover systems in controlling infiltration (net percolation) into the spent heap leach material. The test panels cover system design consisted of the following:

1) 35 cm of compacted clay and 30 cm of topsoil in panel 3

2) 55 cm of uncompacted clay and 30 cm of topsoil in panel 4

Four cover performance monitoring stations recorded data for 3.5 years on climate, stormwater runoff, water content, soil water potential, and direct percolation into the leach ore. Vegetation was seeded and plant growth established in 2006. In January 2010, test pits were constructed in the test panels to remove instrumentation, conduct rooting surveys and perform in-situ testing of the clay liner hydraulic properties.

1.1 Site Conditions

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 6.0°C. Average annual precipitation from 1998 through 2009 was about 1250 mm with most precipitation received as afternoon thunderstorms. Precipitation and pan evaporation data is collected on site. The reference crop evapotranspiration from a well-watered grass (ETo) was calculated using the Penman-Monteith equation (Allen et al., 1998) and the modified Blaney-Criddle method (Zhan and Shelp, 2009). The recorded average annual precipitation during 2006 to 2009 monitoring period was approximately 1290 mm; recorded pan evaporation and estimated ETo were approximately 930 mm and 740 mm, respectively (Figure 1). Average annual precipitation exceeds pan evaporation and estimated ETo by approximately 300 and 550 mm per year.
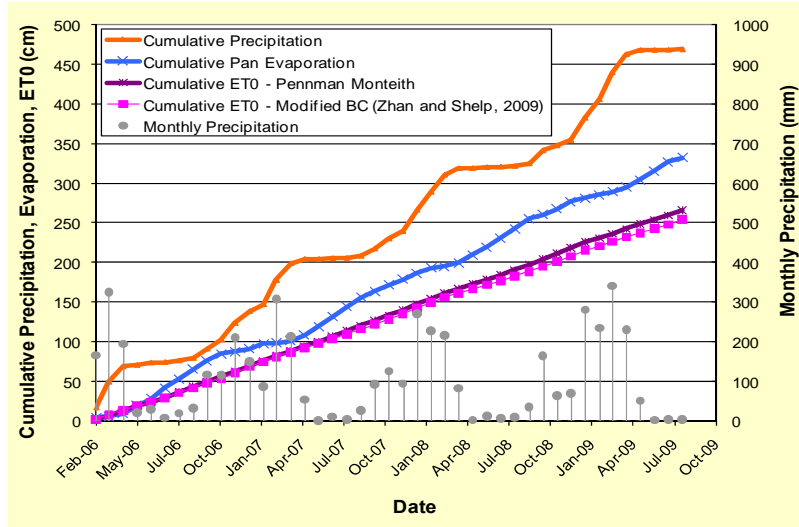
Figure 1. Estimated test panel precipitation, pan evaporation and reference crop evapotranspiration (ETo)

1.2 Test panel design

Because precipitation exceeds the potential evapotranspiration, a cover system which reduces infiltration and deep percolation cannot rely solely on evapotranspiration. Previous research indicates that the geometry of a cover system affects the movement of water and oxygen fluxes (Aubertin et al., 1997, 2006; Bussière et al., 2002, 2003). Moisture that builds up above an interface between coarse- (i.e. topsoil) and fine-grained (clay/silt) materials can flow along a sloped interface. Because the Pierina heap leach and waste rock facilities have extensive side-slope areas there is an opportunity to manipulate subsurface flow through side-slope covers and reduce deep percolation. However, cover system side-slope effects have been investigated using only laboratory or modelling approaches. Consequently, the Pierina cover system test panel design was developed to evaluate side-slope effects in the field and to monitor cover system performance in terms of reducing net percolation into heap leach and mine waste material.

The basic cover system design consists of a clay/silt layer emplaced on top of the waste with a topsoil cover to support vegetation. To exploit the potential for subsurface flow along the topsoil/clay interface, the Pierina cover system used "suction breaks". The suction breaks consist of a network of drainage pipes placed at regular intervals in the topsoil layer. These drains serve to reduce the pore pressure in the topsoil material, thereby increasing topsoil stability and also reducing the potential for deep percolation. They also block lateral flow along the sloped interface between the topsoil and clay/silt layer.

Borrow material property characterization, the design of the Pierina test panels, and the results of in-situ hydraulic property testing were previously discussed (Zhan et al., 2007). In brief, two test panels, each approximately 20 m by 55 m were constructed on a 2.5H:1V slope heap leach pad to test different clay layer construction methods. Each test panel had clay/silt borrow material placed over the waste, with topsoil material placement for vegetative growth. The clay/silt material in Panel 3 was roller compacted to

approximately 90% of maximum Proctor density (2.07 g/cm3) after placement to a final approximate thickness of 35 cm. In Panel 4, only equipment traffic compaction occurred on the clay/silt material resulting in a final approximate thickness of 55 cm. Approximately 30 cm of topsoil were placed over Panels 3 and 4, respectively, and suction breaks were installed 10 m apart on the side-slopes.

Test panels were installed in December, 2005 with subsequent seeding with a mix of native and non-native grasses and sedges. After plant establishment, vegetative ground and canopy cover generally approached or exceeded 100%. A cover performance monitoring system was installed and brought on-line in February 2006 to develop a better understanding of the capability of the cover systems to minimize deep percolation into the heap leach material after closure.
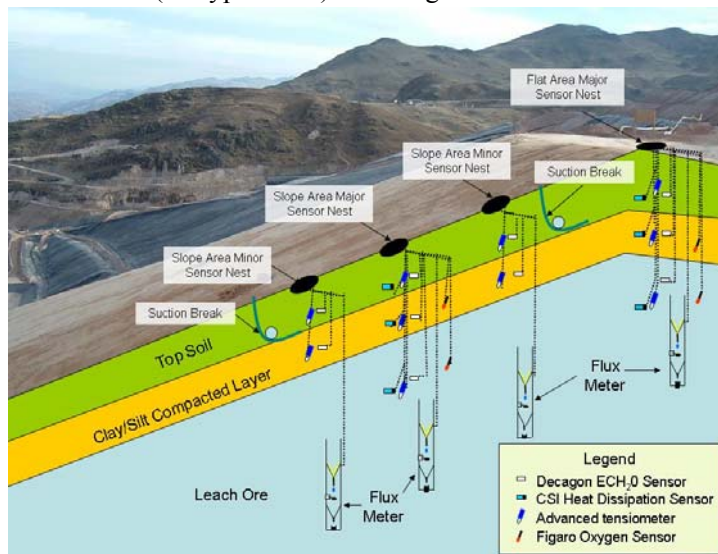
2 Cover System Performance Monitoring

2.1 Monitoring System

The monitoring system was installed to evaluate long-term cover performance in the two test panels at two different topographic locations (flat areas versus sloped areas) and above and below the suction breaks. Four sites were selected for each panel. One site was on an upper bench and the other three sites were on the side slope located between the second and third suction breaks.

Monitoring system sensor types included soil water potential sensors (heat dissipation sensors or HDS, and advanced tensiometers, or AT); soil moisture content sensors (ECH2O); water flux meters (WFM); oxygen content sensors (Figaro KE50); and surface water flumes (H-Type flume). Drainage from the suction breaks was monitored manually on a daily basis. A representative cross-section of the sensor types and burial depths is presented in Figure 2. Soil water potential (HDS and AT) and water content (ECH2O) sensors monitor the wetness of the soil cover and the removal of water through drainage and evapotranspiration. Water flux meter (WFM) measurements provide a small-scale point measurement of deep flux at each location. Oxygen sensors monitor the efficiency of the clay/silt layer in minimizing oxygen flux into the leach ore. Finally, the H-flumes provide a very precise measurement of surface water runoff. A more detailed discussion of the sensors and installation procedures are presented in Zhan et al. (2007).

Figure 2. Cross-section of monitoring nest installation

2.1 Conceptual Model of Cover System Performance

The cover system design relies on three components to minimize net percolation into the leached ore. Net percolation is defined as infiltration that is not removed by evapotranspiration or by subsurface down-slope flow before percolating into the leach ore material:

1) The low conductivity clay barrier restricts net percolation flux and can also cause water to move down the slope in overlying topsoil material with removal via the suction break system.

2) Vegetation maximizes evapotranspiration which reduces the net percolation.

3) A sloped cover system enhances surface water runoff and reduces the amount of precipitation that can infiltrate into the cover system.

These components affect the rate of infiltration of precipitation or enhance removal of soil water from the soil profile and subsequently net percolation through the cover system.

Wetting due to precipitation in the rainy season is observed in the uppermost topsoil sensors and then the lower sensors as the wetting front advances. In order for water to percolate into the coarser-grained leach ore material, water contents must reach or approach saturation in the clayey layer. That is, the leach ore will act as a capillary barrier and minimize the downward vertical movement of water. Variations in this sequence of progressive wetting (i.e. if a deeper sensor shows wetting prior to overlying shallower sensors) may be caused by preferential flow or lateral movement of water. For example, excessive fluxes measured by the WFMs may result from preferential flow along roots or other flow paths, and textural layering or bulk density differences may cause water to flow laterally and bypass sensors.

Cover materials begin to dry in May through September during four months of little to no precipitation, when ground and air temperatures begin to rise and available water evapotranspires from the ground surface. In addition, the zero flux plane, the depth at which water is moving neither up nor down, will move deeper as water is extracted via deeper roots. This drying occurs most rapidly at depth intervals where plant roots are concentrated. This often is the upper portion of the cover materials, as root concentration and water extraction rates typically decrease with depth. Variations in root growth may occur as a result of variable clay compaction or material heterogeneity.
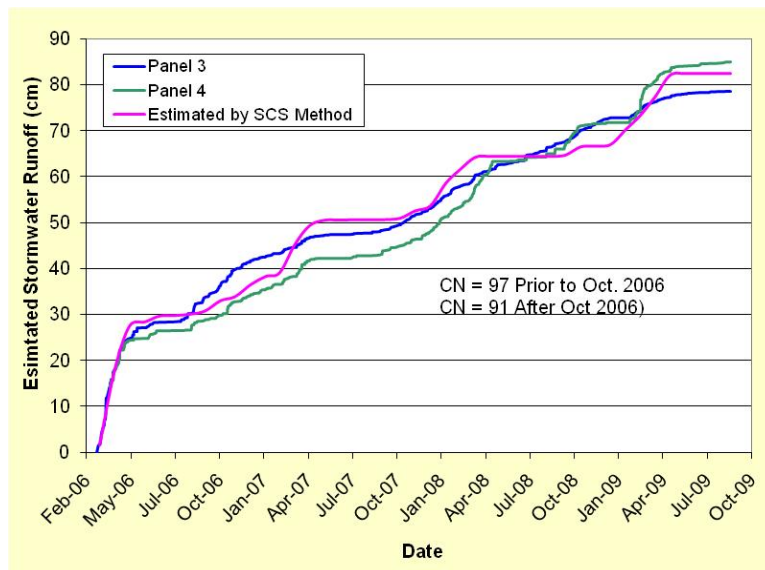
2.3   Cover system performance monitoring results

The monitoring system was fully operational from February 15, 2006 to August 15, 2009. The lowest precipitation rates were observed in July. Consequently, the hydrologic water year is defined as the 12-month period from July 1st to June 30th. The hydrologic water year is designated by the calendar year in which it ends and includes six of the twelve months of the calendar year. For example, the hydrologic water year ending June 30th, 2009 is called "Water Year 2009".

2.3.1 Precipitation, surface water runoff and suction break data

Water year precipitation from 2006 to 2009 ranged from 1149 to 1480 mm with an average of 1294 mm over the monitoring period. Stormwater runoff rates generated from the two panels were similar, though decreasing volumes from Panel 3 were observed over time. During the first rainy season, stormwater runoff averaged approximately 40% of the total precipitation whereas by the second rainy season, it had decreased to approximately 15% of precipitation (Figure 3). It was also observed that in subsequent rainy seasons the amount of siltation (from erosion) that was observed in the flumes decreased significantly due to the emergence of mature vegetation on the test panels.

As indicated on Figure 3, the observed stormwater runoff can be simulated by Soil Conservation Service (SCS) model (SCS, 1986) to estimate the approximate amount of runoff from a rainfall event in a defined area. A curve number (CN) value of 97 was observed to provide the best fit for the first rainy season; a lower CN of 91 during subsequent rainy seasons reflects the development of mature vegetation. Both CNs are much greater than what would be estimated using standard assumptions for hydrologic soil type and vegetative cover in the SCS method. These data indicate that stormwater runoff estimates using SCS CNs in these types of climate should be adjusted upwards to account for steep slopes.

Figure 3. Simulated and observed stormwater runoff

Only minor amounts of drainage were recorded from the suction breaks at both panels (1% or less of total precipitation). High topsoil and clay water content values were observed in the monitoring data; however,

soil saturation is required for significant seepage from the suction breaks to occur. Low topsoil or high clay hydraulic conductivities could have reduced suction break efficiency. In addition, rooting around, and into the geotextile material surrounding the suction break pipe could have resulted in reduced efficiency.

2.3.2 Water flux meter data

Table 1 shows the annual net percolation flux measured at each of the eight WFMs in Panels 3 and 4. During the first year, the highest net percolation fluxes were observed at the flat monitoring nests (P3-S1-T and P4-S1-T). Because the measured flux was greater than the total precipitation during the first year, it is believed that ground settlement around the sensor nests resulted in a topographical depression where stormwater could accumulate. These depressions were filled with topsoil during the 2006 dry season after which the measured flux was greatly reduced. WFMs in both flat areas and in three of the six side-slope areas stopped measuring flux between March and October 2007, possibly due to sensor failure, or, at least in the case of P4-S1-T, interference from roots growing into the device (Section 3.2).

In water year 2006, WFMs located on the side-slope areas showed average net percolation flux of 8.8 and 12.2 cm (14% and 19% of total precipitation) for Panels 3 and 4 respectively (Table 1). In general, for WFMs on the side-slopes, no flux was observed from October to January. Of the three WFMs working after 2007, the Panel 3 below-suction-break WFM showed the highest flux rate, the Panel 3 mid-slope WFM had an intermediate rate, and the Panel 4 mid-slope WFM had the lowest flux rate (Table 1). The functioning WFMs indicated generally stable flux rates for the Panel 4 mid-slope (P4-L1-T) station while the Panel 3 mid-slope (P3-L1-T) and Panel 3 below-suction-break (P3-L1-M) WFMs generally showed increasing fluxes over time.

Table 1. Measured net percolation (flux) and precipitation ratios for WFM locations

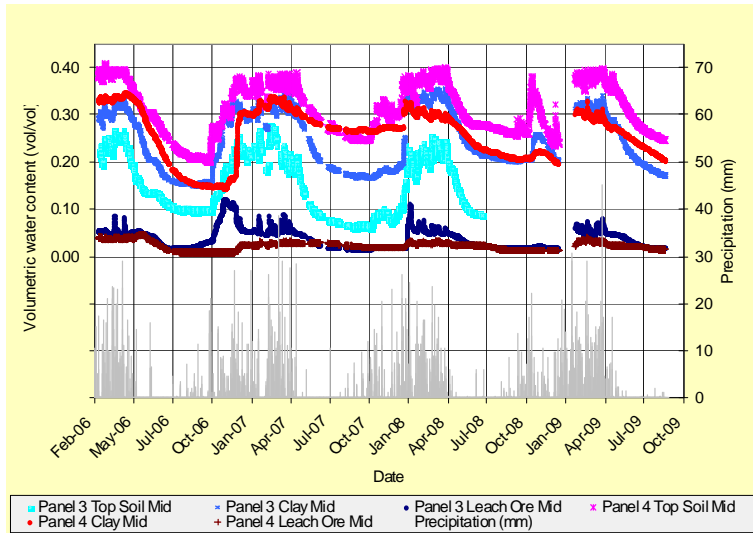| Water Year | 2006[1] | | 2007 | | 2008 | | 2009 | |
| Annual Precip (cm) | 63.87 | | 130.89 | | 115.94 | | 148 | |
Sensor Nest	Total Flux (cm)	Flux / Precip (%)	Total Flux (cm)	Flux / Precip (%)	Total Flux (cm)	Flux / Precip (%)	Total Flux (cm)	Flux / Precip (%)
P3-S1-T (flat)	75.9	119%	NA	NA	NA	NA	NA	NA
P3-L1-T (mid-slope)	8.3	13.0%	NA	NA	12.0	10.3%	24.7	16.7%
P3-L1-M (below suction break)	11.2	17.5%	36.0	27.5%	51.4	44.3%	81.4	55.0%
P3-L2-M (above suction break)	7.0	11.0%	NA	NA	NA	NA	NA	NA
Panel 3 Slope Average	**8.8**	**13.8%**	**36.0**	**27.5%**	**31.7**	**27.3%**	**53.1**	**35.8%**
P4-S1-T (flat)	119.0	186%	105.0	80.2%	NA	NA	NA	NA
P4-L1-T (mid-slope)	11.9	18.6%	12.9	9.9%	20.7	17.9%	20.9	14.12%
P4-L1-M (below suction break)	10.0	15.6%	25.4	19.4%	NA	NA	NA	NA
P4-L2-M (above suction break)	14.7	23.0%	NA	NA	NA	NA	NA	NA
Panel 4 Slope Average	**12.2**	**19.1%**	**19.1**	**14.6%**	**20.7**	**17.9%**	**20.9**	**14.1%**

1 Partial year (02/06- 06/06)

2.3.3 Water content and oxygen content data

Changes in water content with time provide an indication of how the cover responds to seasonal climatic processes (precipitation and ET) and the overall effectiveness of the cover system. Water contents increase in October in response to precipitation and decrease throughout the subsequent dry season in response to drainage and evapotranspirative demand.

At the flat area stations, Panel 3 showed consistently lower topsoil water contents than Panel 4, indicating lower available water holding capacity in the Panel 3 topsoil. Similar water content responses were observed in both the flat area clay and leach ore materials with sensors wetting in late November or December in response to the rainy season and subsequently draining (and drying) in April through October. These data indicate that similar net percolation is occurring at both locations. Of note, the top soil and clay became wetter much earlier during water year 2007 than in 2008 and 2009, most likely due to the presence of greater vegetation and ET during the latter rainy seasons.

In both the Panel 3 and 4 side-slope areas, wetting and drying occurred at all depths each season (Figures 4 and 5). The Panel 3 mid-slope topsoil showed lower water holding capacity compared to the Panel 4 mid-

Figure 4. Side-slope middle area water content sensor data

slope topsoil, whereas similar topsoil water contents were observed between the above- and below-suction break stations. Topsoil and clay layers showed water content increases of 15-20% during the wet season in both panels. The water holding capacity of the topsoil was approximately reached when the cumulative precipitation exceeded 300 mm (approximately two months into the rainy season). The clay water content sensors in Panel 3 become wet earlier than Panel 4 during the rainy season, and showed similar or greater drying in the dry season (Figure 4).

This early wetting and drying response was most likely due to the Panel 3 clay sensors being 15 cm closer to the surface than the Panel 4 sensors. During the dry season, the clayey layer significantly dried out in both panels and the ability of the clay to limit net percolation may therefore have been greater in Panel 4 due to its greater thickness. Additionally, the earlier wetting front arrival and greater water contents in the leach ore in Panel 3 during each rainy season indicates greater net percolation was occurring in Panel 3. The above suction break topsoil sensors showed lower water contents than the below suction break sensors in both panels, indicating the suction breaks were drying out the topsoil material (Figure 5). However, the above-suction-break clay sensors showed higher water content values than the below-suction-break sensors in Panel 3, whereas, the Panel 4 above- and below-suction-break sensors show the opposite trend or no trends. These data indicate that the suction breaks had a greater influence on moisture dynamics in Panel 3, possibly due to lower-permeability clay, or that the influence of the suction breaks was limited to the near surface.
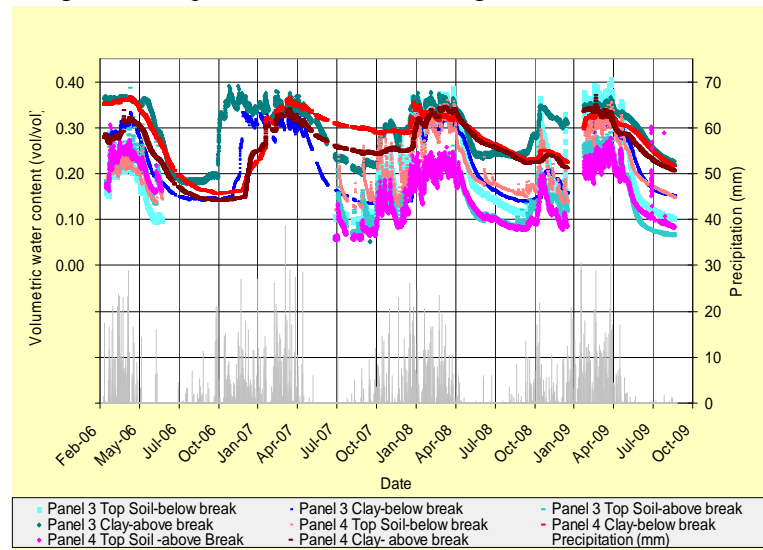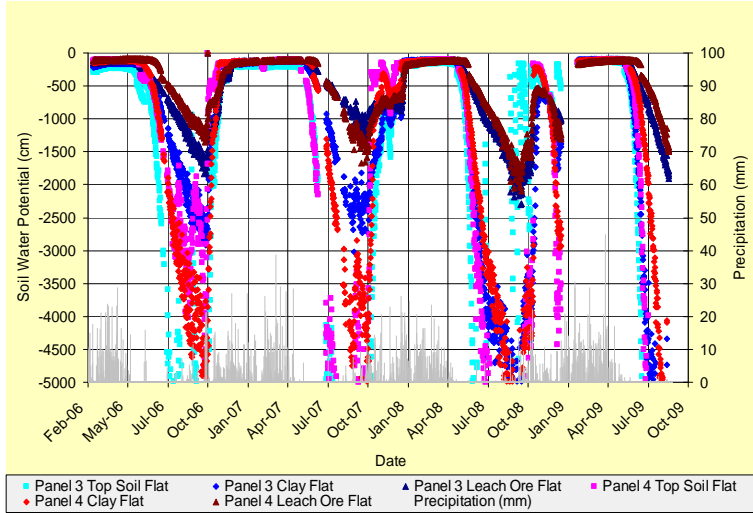

Figure 7. Above and below suction break water content data

Oxygen sensors from all locations showed higher oxygen values during the dry season and lower oxygen values during the rainy season. Lower oxygen contents in the rainy season are most likely due to increased soil water content with a subsequent decrease of air porosity and lack of surface communication. Oxygen sensors within the flat area clay layers frequently showed low, or zero readings after major precipitation periods, whereas the side-slope areas showed oxygen readings from 60 to 80% atmospheric oxygen during the same periods. Because oxygen levels remained high in the leach ore throughout the monitoring period, oxygen transfer through the clay/silt into the leach ore was not greatly impeded.

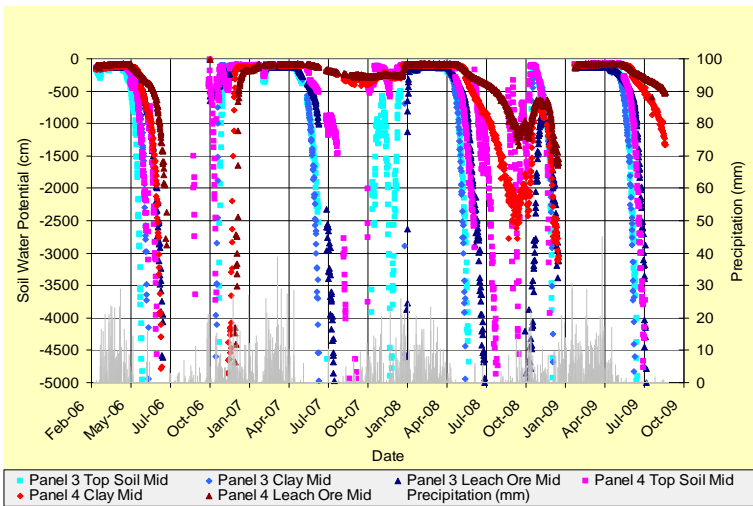### 2.3.4 Advanced tensiometer and heat dissipation data

Like changes in water content, changes in soil water potential over time provide an indication of the performance of the ET cover and its response to seasonal changes in precipitation, temperature and vegetative growth. Figures 6 and 7 present the HDS soil water potential data for the flat and side-slope areas, respectively. At the flat area stations, the Panel 4 AT soil water potential was greater (wetter) than Panel 3 in both the clay and leach ore depths in water years 2006 and 2007, whereas Panel 3 showed similar or greater water potential than Panel 4 during 2008 and 2009. The Panel 3 compacted clay layer retained greater moisture during the initial two dry seasons, but showed significant drying during subsequent dry seasons at potentials suggestive of vegetative drying (Figure 6). This shift in soil water potential indicates that the clay hydraulic conductivity changed over time. Conversely, generally lower water potentials observed in Panel 4 indicate that the net percolation flux is decreasing over time.

Figure 6. Flat area HDS data

Side-slope data (Figure 7) indicate that the mid-slope Panel 4 sensors in both the leach ore and clay remained wetter during the dry season than the Panel 3 sensors, possibly due to their location deeper in the profile relative to the surface. The observed soil water potentials also indicate vegetation-induced drying within the leach ore. During the rainy season, AT soil water potentials were generally greater in the Panel 3 mid-slope and above-suction-break stations than in Panel 4, indicating wetter conditions. The below-suction-break stations showed little difference between Panels 3 and 4.

Figure 7. Side-slope area HDS data

2.3.5 Estimated net percolation flux

Downward flux through the cover system was estimated from both direct flux WFM (Table 1) and soil water potential measurements. It should be noted, however, that the latter estimates will be revised pending the results of the test panel decommissioning test work (Section 3.1). The HDS and AT clay soil water potential data were used to approximate downward flux rates by assuming a downward unit gradient and applying the closed-form analytical solution by van Genuchten et al. (1980) to solve Darcy's law. Laboratory and field observed saturated hydraulic conductivity (Ksat), water content, and water potential relationships were combined to estimate van Genuchten parameters with a best fit. These parameters were further refined by comparing the predicted net percolation fluxes to the WFM measured data and modifying the Ksat value (within the range of field measurements) until relative agreement was achieved (Table 2). A range of Ksat values are presented in Table 2, as it was determined that multiple Ksat values were necessary to approximate the flux meter data.

Net percolation of precipitation through the cover system was estimated at each monitoring location by calculating the estimated unsaturated hydraulic conductivities from the clay water potential data and the estimated van Genuchten parameters (Table 2). Under a unit gradient assumption, the unsaturated hydraulic conductivity is equivalent to the downward net percolation rate. In actuality, upward gradients are observed through the clay in both panels from around mid-May to mid-November each year.

Table 2. Clay layer estimated van Genuchten parameters used for net percolation estimates

Location/Material Type		θ_r [1]	θ_s	N[1]	α (1/cm)[1]	L	Mean K_{sat}[2] (cm/sec)	High K_{sat} (cm/sec)[2]	Low K_{sat} (cm/sec)[2]
Panel 3	Clay	0.001	0.4	1.236	0.00162	0.5	4.90E-06	9.87E-06	2.44E-06
Panel 4	Clay	0.062	0.45	1.465	0.0106	0.5	1.30E-05	2.72E-05	7.82E-06

[1] RETC4 program fitted parameters (van Genuchten, et al., 1991)
[2] Geometric mean, high and low Ksat values from in-situ cylinder infiltrometer data (Zhan et al, 2007)

Net percolation flux estimated from the clay water potential data and mean clay Ksat value estimates for the flat area and mid-slope areas are shown in Table 3. These estimates generally matched trends in net percolation measured by the functioning WFMs (Table 1). Both side-slope WFM measurements from Panel 3 showed increasing flux over time (greater flux each year), and a better fit was provided by multiplying the mean Ksat values in water years 2008 and 2009 by a 2X and 3X factor respectively, as shown in Table 3. The observed increase in WFM flux over time in Panel 3 could be due to increasing permeability of the compacted clay with time due to natural processes such as root penetration, desiccation, thermal expansion and contraction (i.e. Albright et al., 2006; Waugh, 2004; Taylor et al., 2003; Wilson et al., 2003). This simple multiplier adequately adjusts and matches both the high clay Ksat net percolation estimate to the below-suction-break WFM and the mean clay Ksat net percolation estimate to the mid-slope WFM.

The estimated fluxes for the Panel 3 and Panel 4 flat areas were substantially different; however, the majority of the predicted net percolation in Panel 4 resulted from subsidence around the sensor nests. The side-slope estimated net percolation rates were generally similar between the panels with the greatest rates predicted for the mid-slope followed by below- and above-suction-break locations, respectively. These estimated net percolation rates average approximately 25% of the total precipitation.

Table 3. Estimated net percolation from clay soil water potential data and estimated hydraulic properties

Water Year	Precip-itation (cm)	Panel 3 Estimated Flux (cm)				Panel 4 Estimated Flux (cm)			
		Slope				Slope			
		Mid Slope[1,2]	Below Break[1,2,3]	Above Break[1,2]	Flat Area[1]	Mid Slope[1]	Below Break[1]	Above Break[1]	Flat Area[1]
2006	63.9	7.3	0.0	10.2	25.7	13.7	16.9	5.1	79.2
2007	130.9	21.1	0.0	20.7	26.3	35.7	32.1	17.4	178.9
2008	114.9	31.3	63.3	29.5	22.1	18.3	28.9	18.8	49.0
2009[4]	117.4	50.0	36.8	30.8	8.3	52.4	26.3	17.5	4.2
Total	**427.17**	**110**	**100**	**91**	**82.4**	**120**	**104**	**59**	**311.3**

[1] Calculated from soil water potential data and mean hydraulic parameters (Table 2)

[2] Mean Ksat value increased over time to reflect increasing deep percolation observed in Panel 3 WFMs (2008 Ksat*2, 2009 Ksat*3)

[3] No data for sensor before 7/2007

[4] Approximately one month of data loss in rainy season, 30.6 cm reduction from actual precipitation

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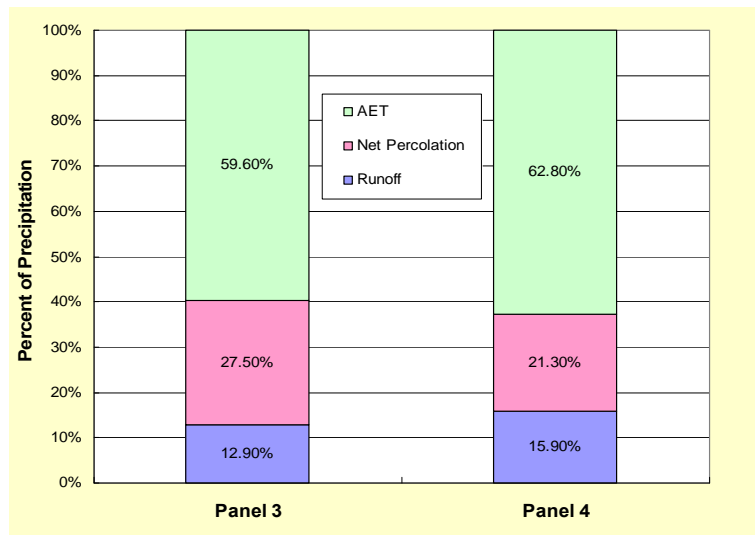
A cover system water budget can be formulated as follows:

$$R = P - SR - AET - SB - \Delta S$$

where, R is recharge (net percolation), P is precipitation, SR is surface runoff, AET is actual evapotranspiration, SB is suction break drainage and ΔS is soil storage change.

Precipitation, runoff, suction break drainage, and soil storage were monitored or calculated from sensor data. The water budget equation can be further reduced by eliminating the soil storage change term since there is no significant soil water storage change between water years. In addition, the suction break drainage was shown to be less than 1% of the precipitation and can be also removed from the water budget equation.

Figure 8 shows the Panel 3 and 4 water budget calculations using the average measured stormwater runoff, net percolation flux estimates from soil water potential data, and the resulting estimated actual evapotranspiration (AET). The ratio of calculated AET to ETo (Figure 1) ranged from 75% to 117% for both panel side-slope areas during the 3.5 years of monitoring.

Figure 8. Estimated Panel 3 and Panel 4 water budget

The average calculated AETs over the period of record were 55% and 57% of precipitation, or approximately 95% to 99% of the calculated ETo for Panel 3 and 4 respectively. The high predicted AET values indicate that test panel vegetation had sufficient soil water during the dry season and/or had higher ET rates than ETo during the growing season. It should also be noted that the development of vegetation in Panel 4 appeared to be more robust than in Panel 3, which may be related to root morphology (Section 3.2). Consequently, the Panel 4 calculated AET would be expected to be greater than Panel 3, with potentially less net percolation.

3   Test Panel Decommissioning and Hydraulic Property Testing

In January 2010, a test panel decommissioning program was conducted to: excavate monitoring instruments and check for functionality; conduct in-situ bulk density and Ksat tests;, collect cores for laboratory testing, and conduct a rooting survey to measure root density and thickness. Instruments from the topsoil layer were excavated by hand and a track mounted excavator was used to excavate instruments from the clay and heap leach material. Excavation trenches were typically two meters in depth.

3.1   Hydraulic property testing

In-situ hydraulic property testing was conducted in the topsoil and clay layers at each of the instrument nests. Approximately two in-situ bulk density measurements were taken from 0 to 15 cm below the surface of the clay at each instrument nest location using a modified sand cone/rubber balloon method (ASTM D 2167–08) for a total of seven and nine bulk density tests in Panel 3 and 4, respectively. Four in-situ bulk density measurements were also taken in topsoil. In-situ Ksat measurements were conducted using a Guelph permeameter (Soil Moisture Equipment Corp., Santa Barbara, CA) and a Wooding infiltrometer (Soil Measurement Systems, Tucson, AZ). Twelve and eleven in-situ Ksat measurements were collected in the upper 15 cm of the clay at the instrument nest locations in Panel 3 and Panel 4 respectively. Ksat values were derived from the Richard's equation for the Guelph permeameter data (Reynolds and Elrick, 1985) and Wooding's equation (Wooding, 1968), for the Wooding infiltrometer data. Finally, eight hand-driven core samples were collected from the clay and four from the topsoil for laboratory measurements of Ksat, bulk density and soil water characteristic curves. At this time, laboratory testing is ongoing.

In-situ bulk density results averaged 1.37 g/cm3 for Panel 3 clay material, 1.31 g/cm3 for Panel 4 clay and 1.22 g/cm3 for topsoil material. These bulk density values for the clay material are significantly lower than those measured immediately after clay material placement and roller compaction (1.60 to 1.75 g/cm3). This reduction in the bulk density could be due to daily thermal expansion and contraction, moisture related shrink and swell, and root penetration and propagation into the clay layer. Clay bulk density values were collected immediately at the surface, and bulk densities may increase at deeper depths within the clay layer.

Table 4 presents the in-situ Ksat measurements for the clay and topsoil by test panel and instrument nest location. It should be noted that the Wooding infiltrometer and Guelph permeameter tests measure slightly different soil volumes: Wooding infiltrometer

Table 4. In-situ saturated hydraulic conductivity values

Top Soils Ksat (cm/sec)				Clay Ksat (cm/sec)			
Panel 3 Location		Panel 4 Location		Panel 3 Location		Panel 4 Location	
S1T[1]	2.78E-03	S1T	1.63E-03	S1T	2.72E-05	S1T	1.45E-05
L1T	1.45E-03	L1T	2.41E-03	L1T[1]	6.05E-05	L1T[1]	8.07E-05
				L1M[1]	6.43E-05	L1M[1]	3.52E-04
				L2M[1]	1.67E-05	L2M[1]	4.83E-05
Geometric Mean	2.15E-03		1.98E-03		3.90E-05		7.67E-05

[1] Geometric mean from three or more measurements

measures the vertical Ksat from approximately 0 to 15 cm below the near surface; Guelph permeameter measures a combination of the vertical and lateral Ksat from 10 cm and below. At most locations in the clay material, the Guelph permeameter Ksat values were slightly lower than the Wooding infiltrometer Ksat results, whereas the topsoil Ksat values were generally consistent between the two methods. These differences in the clay Ksat data from the two methods indicate that Ksat may slightly decrease with depth in the clay material.

The geometric mean Ksat for Panel 4 clay is approximately double the Panel 3 clay Ksat (Table 4). The average in-situ Ksat values immediately after construction were 5 x 10-6 and 2 x 10-5 cm/sec for the compacted and uncompacted clay layer, respectively. These data indicate that within 4 years, the Ksat values have increased by 8X and 6X for the compacted and uncompacted clay, respectively. Similar and even greater increases in clay Ksat have been observed due to wetting/drying processes and root development (e.g. Albright et al., 2006; Waugh, 2004; Taylor et al., 2003; Wilson et al., 2003). Moreover, reductions in permeability gained from clay compaction were limited initially and differences in Ksat measured between the compacted and uncompacted clay appear to diminish over time.

3.2   Rooting survey

Rooting surveys were conducted in the side-slope instrument nest trenches. At the up-slope face of each trench, root size and root density distribution, and topsoil and clay layer depths were described in four replicate profiles. At each profile, root descriptions were made for 10-cm by 10-cm quadrants at depths approximating 10-20 cm below the topsoil surface; 10-20 cm below the topsoil/clay contact (within clay); 10-20 cm below the clay/heap leach contact (within heap leach), and; 70-80 cm and 120-130 cm (if the trench was deep enough) below the clay/heap leach contact. If the topsoil or clay layers were greater than 40 cm thick, additional quadrants were added, so that each profile had between 4 and 6 rooting measurements.
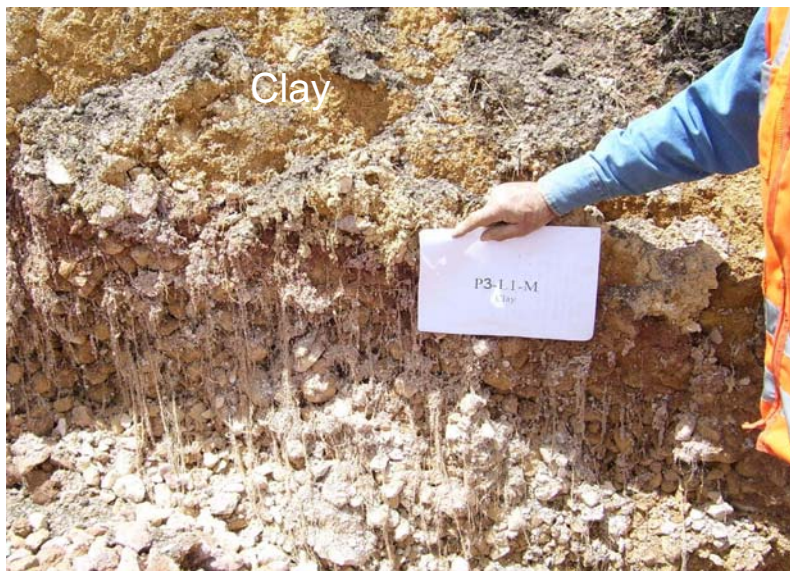

Estimated root fibre diameters were classified as: Very Fine (0 to 1 mm); Fine (1 to 2 mm) or Coarse (> 2 mm). Root density was classified in terms of number of root fibres per 1-cm by 10-cm square as: Very Few (< 10); Few (10-25); Common (25-100), and; Many (> 100).

In general, vegetation and roots formed a dense mat at the surface in the topsoil layer. Extensive rooting was typically observed throughout the clay layer and extending below into the heap leach material (Figure 9). Roots were also seen at the maximum depth in each trench.

Figure 9. Example of roots penetrating below the compacted clay layer

Root density means from each of the three side-slope trenches (4 rooting profiles per trench) are presented in Figure 10. Rooting density was typically greater in topsoil than the underlying clay layer with a corresponding decrease in rooting diameter shown in the clay layer. Root diameters in the Panel 4 uncompacted clay layer were typically thicker than those in the Panel 3 compacted clay (fine versus very fine), although rooting densities in the clays were similar. In most trench profiles there was an observed increase in root density and root diameter as the roots transitioned from the clay into the heap leach material (Figure 10).

Whether the increase in rooting diameter and density from the clay into heap leach material is a result of rooting through cracks or preferential channels is unknown. With the exception of a few quadrants, very coarse roots in the heap material were not observed. Of note, rooting density was significant throughout the clay and heap leach material to depths of 180 cm below the ground surface. Root density was greater than 10 roots per dm2 in 88% of the Panel 3 quadrants, and 97% of the Panel 4 quadrants. Overall, Panel 4 exhibited greater root density and thicker root diameters than Panel 3 in the clay and heap leach material (Figure 9).

Finally it should be noted that average cover layer depths observed during the rooting survey were greater than the design. Specifically, Panel 3 showed approximately 40 cm of compacted clay and 30 cm of topsoil, whereas Panel 4 showed 65 cm of uncompacted clay and 45 cm of topsoil. The additional topsoil depth and increased clay depth in Panel 4 most likely contributed to the performance of the cover system.
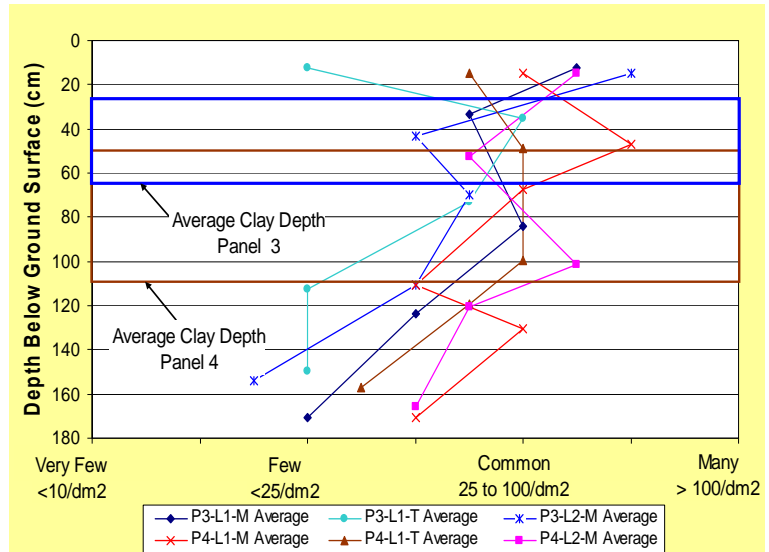

Figure 10. Mean rooting density versus depth in profile

4   Conclusions

The Pierina Mine heap leach cover test panels evaluated two types of low-permeability clay liner systems. Cover system performance monitoring data collected over 3.5 years and results from a decommissioning testing program indicate that the cover system performance is dynamic and changed over time. The following trends were observed in the monitoring data:

- The flat area in both panels showed excessive net percolation, most likely due to the accumulation of stormwater in the vicinity of the sensor nests as a result of soil subsidence. Net percolation through the side-slopes was lower than the flat areas.

- The suction breaks collected less than 1% of the total precipitation; the relatively high clay Ksat for both the clay and uncompacted clay, and the observed increase in Ksat over time appears to have reduced the effectiveness of the suction breaks.

- Net percolation through the Panel 3 side-slope clay liner appeared to increase over time, suggesting that the effect of compaction in decreasing clay permeability decreased over time.

- Surface water runoff decreased with the establishment of vegetation and also appeared to decrease over time from the Panel 3 side-slope, possibly due to increased infiltration and net percolation through the clay liner. The average surface runoff between both panels was around 15% of precipitation and can be modelled using the SCS equation with a CN of 91.

- The estimated actual ET rate was around 750 cm per year, or around 97% of ETo (57% of total precipitation).

- Based on in-situ monitoring data and a water balance approach, the long-term estimated net percolation through the Panel 3 side-slope area was approximately 33.3% of precipitation; net percolation through Panel 4 side-slope area was approximately 25.2% of precipitation.

The decommissioning tests indicate significant increases in Ksat in both the uncompacted and compacted clay liners over the four-year test period and show that Ksat differences between the clay treatments are diminishing. Rooting was extensive into the clay layers and heap leach materials to depths of at least 180 cm. The extensive rooting is most likely aided by the increase in clay Ksat and is also likely responsible for the predicted high AET rates, and predicted increases in Panel 3 net percolation.

Based on these data, there was no long-term advantage to compacting the clay liner and the suction breaks did not increase the efficiency of the cover system. Moreover, increasing the uncompacted clay layer and topsoil depths appeared significantly reduce net percolation vs the compacted clay layer cover system. Finally, considering that the estimated AET is nearly equal to the estimated ETo, it appears that the cover systems are functioning as well as practicable.

Additional data analysis will need to occur after the results of laboratory testing for hydraulic properties are complete. The observed changes in cover system performance and rooting morphology effects will also need to be evaluated in preparing for the final closure system design. Of note, the total "flat" surface area planned for closure will be minimized to reduce the potential for surface ponding and excessive infiltration.

Acknowledgements

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