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TECHNICAL ARTICLE

20 Years of Evapotranspiration Cover Performance of the Leach Pads at Richmond Hill Mine

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Abstract

The Richmond Hill Mine heap leach pads (HLP 1&2, and HLP 3) were reclaimed in 1996 using a three-layer evapotranspiration (ET) cover designed to limit percolation of precipitation through the facilities. HLP seepage outflow rates have been measured on an approximately weekly basis. Large seasonal and wet/dry outflow cycles have been observed. Several years after the cover system installation, increased HLP drainage rates were observed, which could be due to increased permeability of the compacted layer in response to pedogenic processes such as wetting/drying, freeze/thaw, and root development. The estimated net infiltration rate during the monitoring period is about 34% of precipitation. To evaluate the cover system efficiency, a monthly time-step, spreadsheet based water balance model was created. The model considers close inter-relation between precipitation, ET, and cover net infiltration on a monthly scale and continuous feedback of water movement in the soil-plant-atmosphere continuum. The model accurately reproduced the recorded seepage rates for the monitoring period after pedogenic processes reach a stable condition.

Keywords Store-and-release cover · ET cover · Mine closure · Mine reclamation

Introduction

LAC Minerals operated the approximately 162 ha (400 acre) Richmond Hill mine in the northern Black Hills, 6.4 km (4 mi) northwest of Lead, South Dakota. The mine facilities were located at an elevation between 1676 and 1829 m (5500 and 6000 ft) above mean sea level in an area of relatively rugged terrain. Active mining occurred from 1988 to 1993 using conventional heap leach technology. Ore was crushed to ¾” (2 cm) minus and placed on the leach pads in 6 m (20 ft) lifts. LAC Minerals began reclamation actions on closure in 1994.

The Richmond Hill Mine heap leach pads (HLP 1&2 and HLP 3) were reclaimed in 1996. Reclamation consisted of grading slopes to 2.5:1 (H:V) and placing a multi-layer evapotranspiration (ET) cover designed to limit percolation of precipitation through the facilities (Fig. 1). The ET cover design consisted of, from bottom up, (1) 0.3 m (1 ft) of compacted spent ore amended with bentonite (amended soil liner) with a minimum of 7% bentonite by dry weight; (2) 1.2 m (4 ft) of thermal barrier/drainage layer material with a minimum of 18% by weight passing > 4.75 mm and a maximum of 8% <0.15 mm, and (3) 0.15 m (0.5 ft) of stockpiled topsoil.

To control subsurface drainage from the drainage layer, the amended soil liner was extended past the geomembrane liner that exists below the HLP and a minimum 0.30 m (1.0 ft) deep drainage trench was cut into the original ground surface to collect subsurface water flow from the drainage layer (Fig. 2). The drainage collection trenches were sloped to drain to perimeter drainage channels. To control surface water drainage, a series of drainage benches were constructed within the HLP, which were graded to divert water towards perimeter drainage channels.

The ET cover surfaces were reclaimed with a grass seed mix, and deep rooting vegetation (i.e. trees and shrubs) were removed by hand to prevent their establishment on the ET cover. The HLP 1&2 and HLP 3 ET cover areas are nearly identical at about 10.5 ha (26 acres) each. Of this area,

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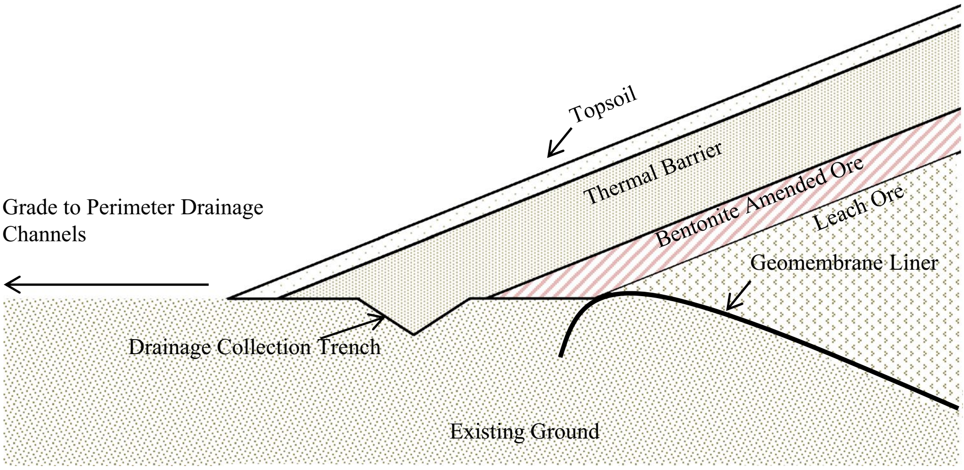
Fig. 1 Richmond Hill mine heap leach pad 1&2 and heap leach pad 3

Fig. 2 Evapotranspiration cover and drainage collection trench



approximately 20% of the HLP 1&2 surface and 42% of the HLP 3 surface has a shallow grade (i.e. less than 5% slope).

Recorded leachate outflow overtime from the HLP 1&2 and HLP 3 are nearly identical with a combined flow of 0.094 m^3/min (25 gpm), or 13 million gall a year. The water from the Richmond Hill Leach Pad sites goes through both a biological plant and a reverse osmosis (RO) plant.

Climate

Precipitation has been measured at the Richmond Hill Mine weather station with a heated rain gauge (rain gauge precision equals 0.025 cm). Recorded annual precipitation ranges from 0.30 to 1.12 m (12–44 in), with an average of about 0.73 m (29 in). Average monthly precipitation ranges from a low of 2.64 cm (1.04 in) in December to a high of 11.99 cm (4.72 in) in June. Snowpack accumulates during the months of December, January, February, and March, and melts during the months of April, May and June.

Potential evapotranspiration (PET) is not directly measured and instead was estimated from temperature data using the Hargreaves equation (Hargreaves and Samani 1985). Estimated annual PET ranges from 0.84 to 1.02 m (33–40 in), with an average of about 0.90 m (36 in). Average monthly PET ranges from a low of 1.52 cm (0.60 in) in December to a high of 16.33 cm (6.43 in) in July.

Average monthly temperatures range from a low of − 5 °C (23 °F) in January to a high of 20 °C (68 °F) in July, with an average over the year of 7 °C (44 °F). As indicated on Fig. 3, most precipitation falls in the April to June time frame, coincident with the snowmelt period, before significant evapotranspiration occurs at the site. This climate pattern causes > 20% of the precipitation to infiltrate into the cover system during periods of low evapotranspiration and subsequently percolate into the leach pads.

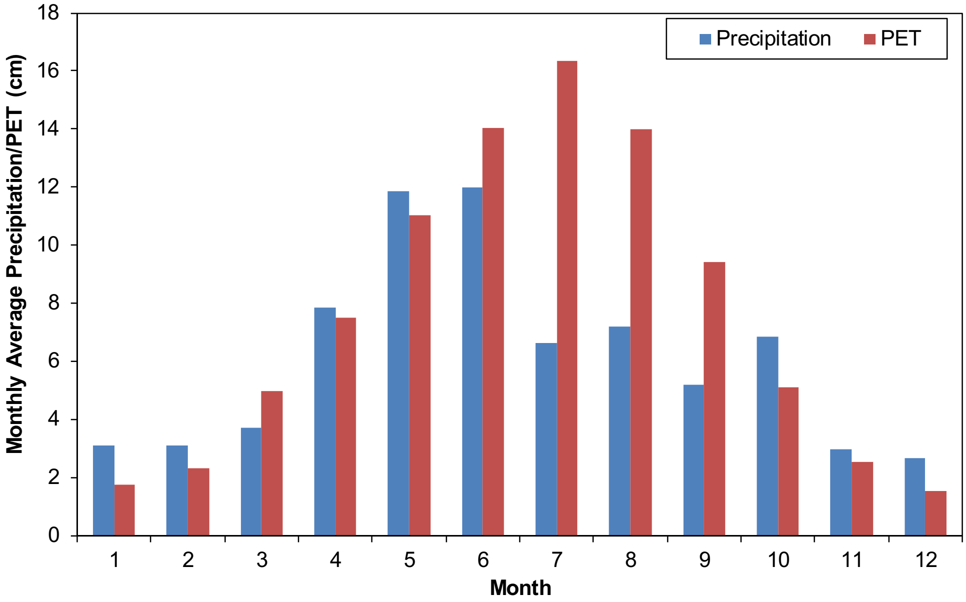
HLP Outflow Rates

HLP seepage outflow rates have been measured by the Richmond Hill mine on an approximate weekly basis from 1997 to the present. Seepage outflow is measured from manual readings of the water level in V-notch weirs installed at the HLP 1&2 sump and the HLP 3 effluent pipe. Outflow rates over time are presented on Fig. 4, in addition to water year (WY = October 1 through September 30) cumulative precipitation measured at the Richmond Hill weather station. Increased seepage outflow is generally observed during spring freshet and in response to large precipitation events. Minimum seepage outflow is typically measured in late fall and winter. The average WY seepage outflow and precipitation for the measurement record is presented in Table 1. The average annual HLP seepage outflow over this period was 32.1% of precipitation for HLP 1&2 and 31.3% of precipitation for HLP 3.

Less than 25% of the precipitation reported as seepage outflow during the initial 3 years after the installation of the cover system, even though WYs 1998 and 1999 were the wettest years on record (1.02 and 1.12 m, or 40.29 and 44.04 in). WYs 2000 through 2005 were relatively dry. Since 2006, the maximum recorded peak outflow and estimated seepage as a percent of precipitation have increased. The HLP average annual outflow rates are presented in Table 2.

The effective net percolation rates, calculated as the seepage outflow divided by the HLP surface area, are

Fig. 3 Average monthly precipitation and PET at Richmond Hill mine



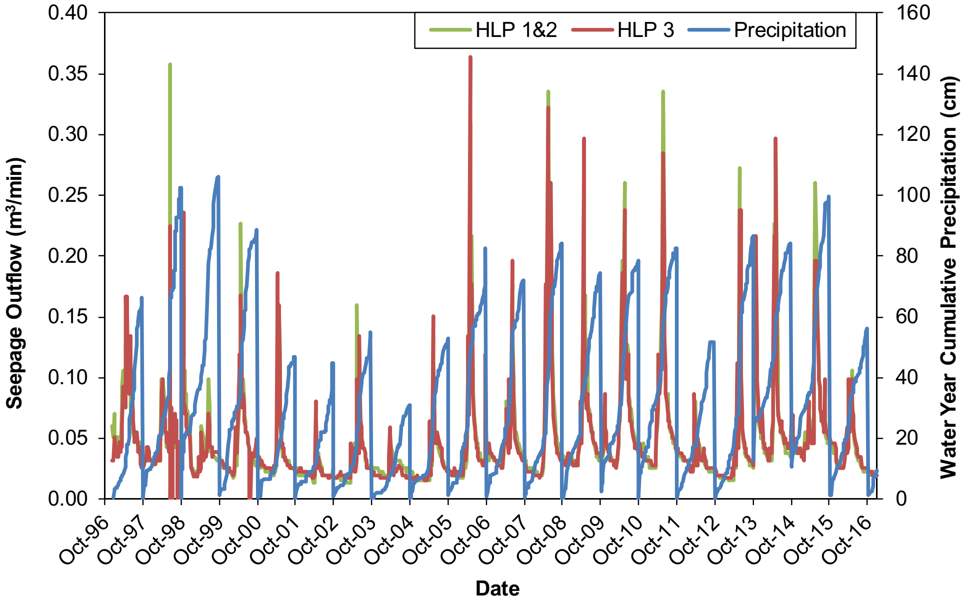


Fig. 4 Measured heap leach pad seepage outflow and water year cumulative precipitation

Table 1 Water year precipitation and seepage outflow as percent of precipitation (WY 1998–WY 2016)

	Precipitation (cm)	Pad 1&2 (%)	Pad 3 (%)
1998	102.34	23	22
1999	111.86	22	20
2000	88.49	25	25
2001	46.99	38	42
2002	44.93	25	26
2003	54.86	29	28
2004	30.78	44	37
2005	52.91	27	29
2006	82.75	30	31
2007	71.88	34	32
2008	84.15	39	34
2009	74.37	39	37
2010	78.81	43	41
2011	82.60	40	38
2012	51.77	31	31
2013	86.84	23	24
2014	84.02	41	42
2015	99.54	33	33
2016	56.21	35	37
Average All	72.95	32	31
Average 1998–2000	100.89	23	22
Average 2001–2005	46.10	32	32
Average 2006–2016	77.52	35	34

Table 2 Measured heap leach pad average annual seepage outflow rate

Water year	HLP 1&2 (m^3/min)	HLP 3 (m^3/min)
1998–2000	0.052	0.049
2001–2005	0.031	0.031
2006–2016	0.058	0.057
All	0.050	0.049

presented versus time in Table 3. The minimum effective net percolation rate is assumed to approximate the base flow from the HLPs. Seepage outflows are measured on approximately weekly so it is possible that peak seepage outflow and maximum effective net percolation rates may be greater than measured.

The increase in estimated net percolation over time may be an indication that the amended soil liner saturated hydraulic conductivity (K_{sat}) has increased over time. A number of studies throughout North and South America have observed an increase in clay cover system K_{sat} and a decrease in water holding capacity due to the formation of larger pores in response to pedogenic processes such as wetting/drying, freeze/thaw, and root development (Albright et al. 2010; Benson et al. 2011; Orellana et al. 2010; Waugh 2004). Both Benson et al. (2011) and Orellana et al. (2010) observed that the largest K_{sat} increases occurred in compacted clay covers. A separate study by Benson et al. (1999) observed that the number of compacted clay covers failing to achieve their design K_{sat} increased sharply at compacted clay thicknesses less than 1.0 m. Benson et al. (2011) also reported that the long-term K_{sat} value for clay liners studied generally fell within the range of 7.5×10^{-6} cm/s to 6.0×10^{-4} cm/s. The estimated maximum effective flux rate of 6.1×10^{-6} cm/s (Table 3) is similar to this range of values.

Table 3 Heap leach pad measured effective net percolation flux rates

Water year	Effective net percolation flux rate (cm/s)					
	Average		Maximum		Minimum	
	HLP 1&2	HLP 3	HLP 1&2	HLP 3	HLP 1&2	**HLP 3**
1998–2000	8.2E−07	7.7E−07	6.0E−06	3.8E−06	2.9E−07	3.0E−07
2001–2005	4.9E−07	5.0E−07	2.7E−06	3.1E−06	2.2E−07	2.5E−07
2006–2016	9.2E−07	9.0E−07	5.6E−06	6.1E−06	2.6E−07	2.9E−07
All	7.9E−07	7.7E−07	6.0E−06	6.1E−06	2.2E−07	2.5E−07

Water Balance Model

HLP calibrated water balance models were developed using the site precipitation data and calculated PET. The calibrated models were able to predict future leach pad seepage outflow rates under normal or extreme climate conditions. The HLP water balance model was implemented in Microsoft Excel using monthly time steps for HLP inflows and outflows. The HLP water balance is based on the Vandewiele et al. (1992) model, described by:

$$S_t = S_{t-1} + P_t - R_t - Q_t \tag{1}$$

where t is time (month), S is soil–water storage, P is monthly snowmelt/rainfall, R is monthly actual evapotranspiration (AET) and subsurface runoff, and Q is monthly HLP seepage outflow. R is calculated as:

$$R_t = \min\left[E_t \times \left(1 - a_1^{\frac{W_t}{E_t}}\right), W_t\right] \tag{2}$$

where E is PET, a_1 is a positive parameter, and W is water available for evapotranspiration and subsurface runoff, calculated as:

$$W_t = P_t + S_{t-1} \tag{3}$$

Q is divided into slow seepage and fast seepage by:

$$Q_{slow} = \left[a_2 \times \left(S_{t-1}\right)^{b1}\right] \tag{4}$$

$$Q_{fast} = \left[a_3 \times S_{t-1} \times \left(P_t - E_t \times \left(1 - \exp\left(-\frac{P_t}{E_t}\right)\right)\right)\right] \tag{5}$$

where a_2, a_3, and b_1 are positive parameters. Fast seepage corresponds to seepage resulting from freshet snowmelt or large precipitation events and occurs during wet periods when water content exceeds the heap leach pad field capacity. Slow seepage corresponds to seepage from the heap leach pad soil matrix that is replenished during storms/snowmelt and drains slowly. Slow seepage is the primary source of seepage during dry periods. The precipitation and PET applied to the water balance model are presented in Fig. 5.

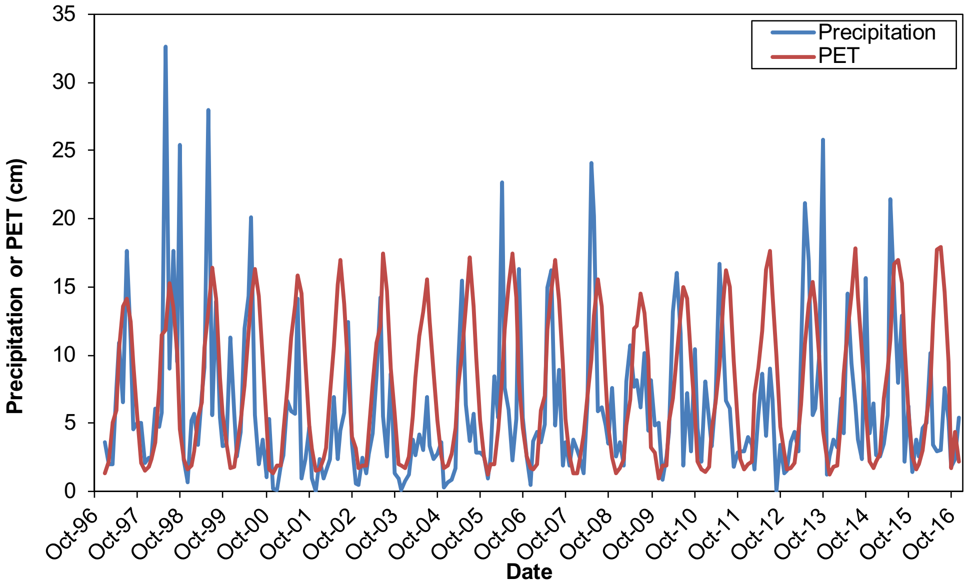


Fig. 5 Water balance model monthly applied precipitation and potential evapotranspiration

Model parameters a_1, a_2, a_3, and b_1 were calibrated to measured seepage data from January 2001 through December 2016 for HLP 1&2 and HLP 3 as a joint objective function, resulting in one set of calibrated parameters for both HLPs. Additionally, the calibration incorporated a precipitation timing correction factor to account for winter snow and spring freshet. The calibration was restricted to January 2001 and later data so as not to include early-post construction HLP conditions. Calibrated model parameters are provided in Table 4.

Model-predicted and measured seepage outflow is presented on Fig. 6a, b for HLP 1&2 and HLP 3, respectively. The model accurately represented base flow and increased seepage outflow events. Differences between model predicted and measured seepage could be partially due to the seepage outflow measurements being on a weekly basis, which were used to generate monthly average flows. The model predicted seepage outflow from HLP 1&2 and HLP 3 during the simulated period (January 2001 through December 2016) was 34% of precipitation, corresponding to measured seepage outflow of 35% of precipitation for HLP 1&2, and 34% of precipitation for HLP 3 for the same period. The remaining 66% of precipitation is predicted to be lost to evapotranspiration or subsurface runoff.

Table 4 Heap leach pad water balance model calibrated parameters

Parameter	Calibrated value
a_1	0.70
a_2	0.10
a_3	0.0032
b_1	1

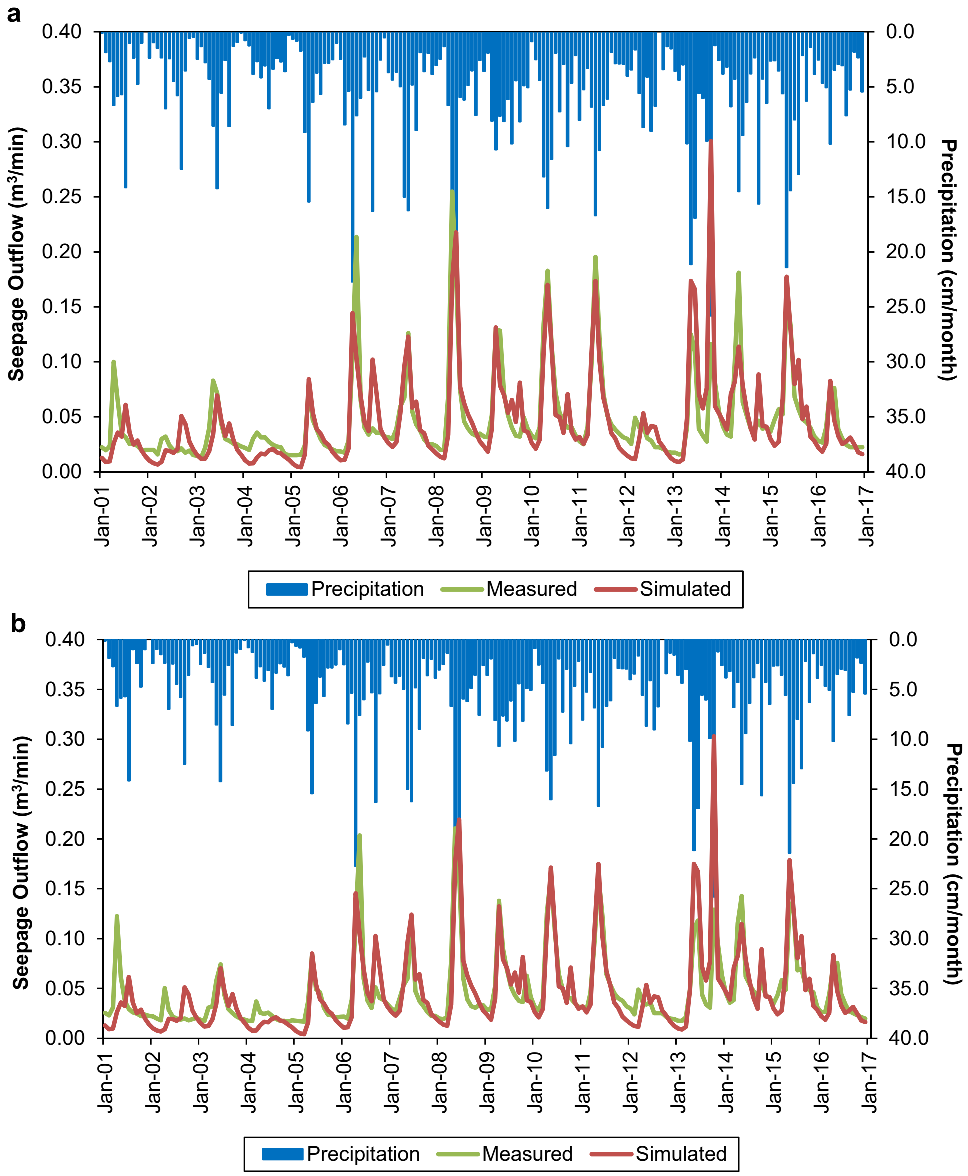
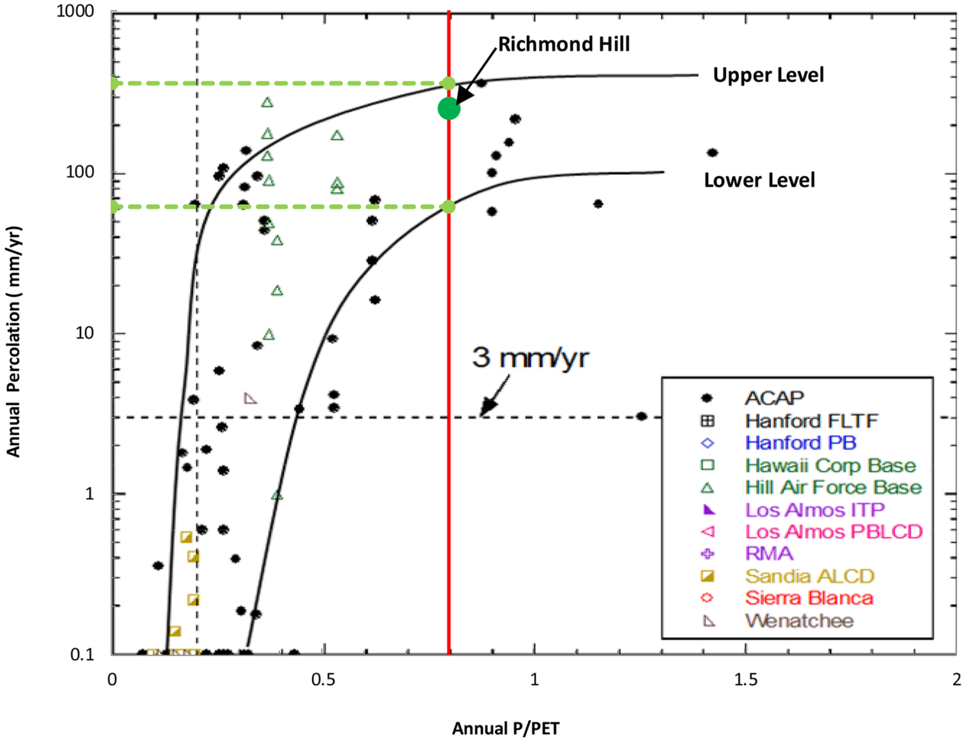


Fig. 6 Monthly measured and modelled seepage outflow for **a** heap leach pad 1&2 and **b** heap leach pad 3

Fig. 7 Annual percolation as a function of ratio of annual P/PET from Richmond cover, ACAP covers and other studies (adapted from Apiwantragoon et al. 2015)



Discussions

It appears that the K_{sat} of the amended soil liner increased in the early time between 1996 and 2000 in response to pedogenic processes. Post-construction changes in soil structure consist of decreasing density and the formation of larger pores, which may be formed by biological process such as ingress of plant roots and burrowing of worms and insects. Volume changes caused by wet-dry cycling and frost action also reduces the bulk density of soils, and can result in formation of larger pores and a broader pore size distribution. An increase in hydraulic properties is anticipated in response to these changes in soil structure.

Richmond Hill mine is located in a relative wet area with a precipitation to potential evapotranspiration (P/PET) ratio of 0.80. Based on the actual data and calibrated model results, it is estimated that 66% of the precipitation is lost to ET or subsurface runoff and 34% becomes net percolation, which results in seepage outflow from the pads.

Apiwantragoon et al. (2015) presented a comprehensive review of the field-scale performance of landfill ET covers at 12 sites across the United States. Test sections were constructed at these sites with large (10 × 20 m, 33 × 66 ft) drainage lysimeters for continuous and direct monitoring of the ET covers over a period of 3–6 years. The 12 test sites in eight states represent a broad range of geography, climates, soils, and vegetation communities. Based on the P/PET ratio, one site is arid, seven are semiarid, two are subhumid, and two are humid following definitions in UNESCO (1979). The diversity in climates is evident in the range of average annual precipitation (0.12–1.26 m, 4.72–49.61 in) and the range in P/PET (0.06–1.10). The study concluded that net percolation is very sensitive to annual P/PET ratio, and when P/PET ratio is greater than 0.2, the net percolation is generally high.

Figure 7 is adapted from Apiwantragoon et al. (2015) and shows their data (named as ACAP) and other available field data measurements. When the P/PET ratio is 0.80, such as Richmond Hill mine, the expected net percolation is in the range of 60–350 mm (2.36–13.78 in) per year (redline on Fig. 7). The simulated and measured net percolation at Richmond Hill of 248 mm (730 mm × 34%) (9.76 in) per year is well within this range (green dot on Fig. 7).

Conclusions

The revegetated and reclaimed Richmond Hill mine heap leach pads have been monitored for 20 years. A review of the monitoring data indicates that K_{sat} of the amended soil liner most likely increased in the early time between 1996 and 2000 in response to pedogenic processes. Pedogenic processes in the Richmond Hill cover system stabilized approximately 4 years after construction. It is evident that the observed HLP seepage outflow rates were well simulated by a model from 2001 to now.

HLP 1&2 and HLP 3 have nearly identical areas of about 10.5 ha (26 acres), but have 20% and 40% flat area (< 5%

slope), respectively. The observed HLP seepages from these two cells are nearly identical, indicating that the flat areas do not make a difference for the Richmond Hill HLP cover system efficiencies.

Seepage outflow rates at HLP 1&2 and HLP 3 were accurately simulated by a monthly water balance model. Simulated seepage rates are about 34% of precipitation. High seepage rates are due to the high P/PET ratio of 0.80 at the site. Expecting an ET cover to eliminate or effectively limit net percolation of precipitation at a high P/PET site (> 0.2) is not realistic, regardless of soil type, cover thickness, and cover configuration. At subhumid and humid sites, an ET cover system can reduce, but not eliminate, net percolation. Thus, the cover system at Richmond Hill HLP is considered to be functional and has met the design objective.

Results from 20 years of cover system monitoring at Richmond Hill mine provide a general review of ET cover system performance for closure of other comparable facilities, and offer guidance for ET cover system requirements in other areas with similar climate.

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