Coal waste storage facilities reclaimed with engineered geosynthetic cover systems – Performance based on three years of field monitoring

G. Meiers
O'Kane Consultants, Fredericton, NB, Canada

C. Bradley
O'Kane Consultants, Fredericton, NB, Canada

L. Barbour
University of Saskatchewan, Saskatoon, SK, Canada

ABSTRACT: Detailed closure plans for legacy coal waste storage facilities in Atlantic Canada were developed by Public Works and Government Services Canada. Two of the engineered cover system designs include a growth medium for vegetation underlain by a geomembrane to restrict net percolation; however, only one of these designs includes a drainage layer above the geomembrane. Field monitoring of the performance of these cover systems has enabled a side-by-side comparison of their performance and validation of the designs.

An interesting aspect of the performance comparison has been the role and importance of a drainage layer in limiting net percolation through the geomembrane. The total leakage through holes in the geomembrane is estimated to be much lower for the cover system that included a drainage layer (estimated to be less than 1 mm per year, < 0.1% of precipitation). The presence of the drainage layer ensured rapid lateral drainage of water ponded on the geomembrane thereby reducing the potential for prolonged leakage through holes. Comparatively, the estimated leakage was approximately 20 mm for the cover system without a drainage layer. Monitored performance also highlighted the unique water balance associated with the presence or absence of a drainage layer, and consequently the importance of various design elements, such as the bedding material, growth medium, surface water management and lateral drainage capacity, on long term performance.

1 INTRODUCTION

The use of a geomembrane as a hydraulic barrier layer in cover system applications is becoming more common in the mining industry. This is due, in part, to more stringent regulatory requirements for very low rates of net percolation. At other sites, the use of a geomembrane might be driven by site limitations such as the lack of clay mineral soils to serve as a low permeability layer, or by the need for very low net percolation rates to meet closure objectives or to meet stakeholder's expectations. A cost analysis for a legacy waste rock pile (WRP) reclaimed by Public Works and Government Services Canada (PWGSC) demonstrated that a lower net present value (NPV) was attained for a geomembrane cover system as compared to collection and treatment of basal seepage in perpetuity (Bradley et al. 2016). The cost comparison in this case is somewhat unique due to the very low prescribed rates of net percolation, the relatively small size of the pile, and the short time frames for both drain-down and the reduction in basal seepage following geomembrane placement. In addition reduction in basal seepage allowed for the receiving environment to recover, which would not have occurred under water collection and treatment.

Typical design elements for cover systems with a geomembrane layer include a growth medium, a drainage layer, a geotextile separator fabric, and bedding material or other geotextile protector fabrics. For waste rock facilities a bedding material or geotextile fabric is required to protect the geomembrane from the coarse textured waste. Sand is commonly used as a bedding material since it is relatively easy to spread and compact into a thin uniform lift. Cartaud et al. (2005) reported that it is common practice in France to install a geotextile beneath the geomembrane because of concerns of geomembrane puncture from below. It is also common to use a protector fabric in composite cover systems between the geomembrane and geosynthetic clay layer (GCL) or compacted clay layer (CCL).

The rate of water movement through an intact geomembrane is extremely low (on the order of 10^{-14} to 10^{-17} m/s) and consequently the primary source of leakage are holes in the geomembrane (Giroud and Bonaparte 1989). The transmissivity (hydraulic conductivity multiplied by thickness) of the bedding material and the layer above the geomembrane as well as the quality of the contact between the underlying material and geomembrane influence leakage through the geomembane and subsequently the realized cover system performance. Wrinkles or waves in the geomembrane, smoothness of the bedding layer, smoothness of the underlying waste rock on which the protection layer is placed, as well as the geotextile protector layer itself, all contribute to the quality of contact. Cartaud et al. (2005) studied the effects of leakage rates through holes for different geotextiles placed between the geomembrane and CCL. The geotextiles reduced the effectiveness of the CCL in minimizing leakage with not only the thickness of the fabric but also the type of geotextile.

Contact with the bedding layer can also be influenced by traffic ruts, grooves from the compactor, and stones, all of which can result in a lack of contact. Poor contact can also occur from folds or wrinkles in the geomembrane. Giroud & Wallace (2016) demonstrated that the performance of a geomembrane in a composite liner system (with 5 holes per hectare each having an area of 1 cm^2) is only slightly better than the performance of the underlying CCL itself when the geomembrane is wrinkled.

Much of the learnings described above apply equally to geomembranes used as pond liners (e.g. continuously ponded water) as well as geomembranes used in covers. However; in the case of cover design it is important to consider the temporal variation of the head above the geomembrane that drives water flow through holes. In this application, the duration and magnitude of the ponded water will be dependent on soil-cover atmosphere transfers (e.g. water balance), cover slope and aspect, as well as the thickness and texture of materials placed above geomembrane. In many cases, it is critical to provide lateral drainage to mitigate a prolonged buildup of ponded conditions on the geomembrane.

In this paper leakage rates, or net percolation, is estimated from empirical equations for two different geomembrane cover systems. The measured transient head of water that formed above the geomembrane was used to simulate net percolation and evaluate the influence of the saturated hydraulic conductivity of the bedding material, quality of the contact, and a hole on a wrinkle of the geomembrane.

2 BACKGROUND

PWGSC funded the reclamation of historic coal mines located near Sydney, Nova Scotia, Canada. Waste rock was consolidated into piles and reclaimed with engineered cover systems at seven sites. Local engineering consulting firms, through standing offer agreements with PWGSC, were engaged to develop detailed closure plans for the WRPs.

This paper focusses on the reclaimed Scotchtown Summit (Summit) and Victoria Junction (VJ) WRPs. The WRP cover system at Summit consists of a high-density polyethylene (HDPE) geomembrane overlain by a geotextile separator fabric and a till growth medium, while the cover system at VJ consists of a granular drainage layer (GRDL) placed between the HDPE and the till growth medium layer. The bedding for the geomembrane at Summit and VJ is a 0.15 m sand layer. Figure 1 provides a schematic of the cover system profiles.

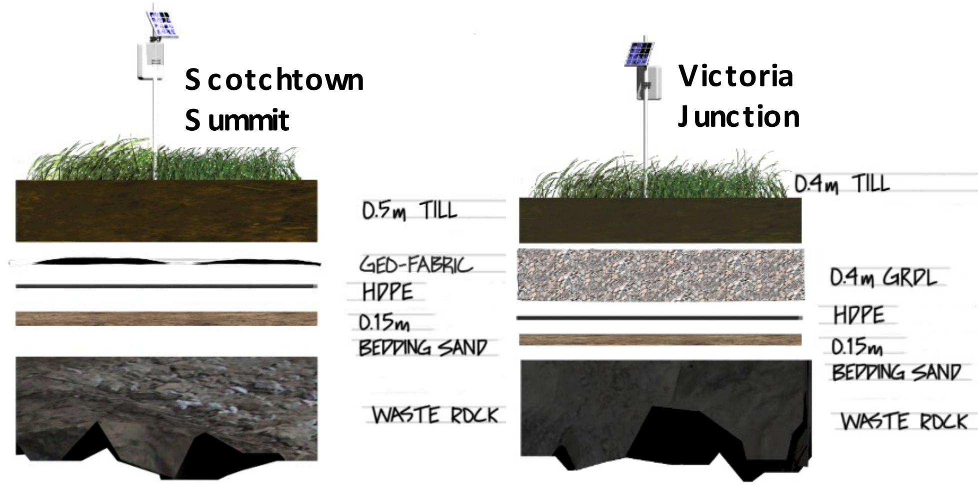

Figure 1. Schematic of the Summit and VJ WRP cover systems.

The Summit WRP covers an area of approximately 44 ha and the thickness varies from 1.5 to 10 m with the thickest deposits near the center. The WRP plateau has a surface grade of approximately 2 to 3% and side slopes of 7:1 (H:V). VJ has a footprint of approximately 26 ha and height of 40 m. The WRP plateau has a grade of 7% and 3:1 side slopes.

The texture of the till growth medium material is similar for both cover systems, consisting of approximately 35% cobbles and gravel, 45% sand, and 20% silt and clay-size particles, based on the Unified Soil Classification System. The till is classified as a material with slight to medium plasticity with a plasticity index of 5. The saturated hydraulic conductivity (k_{sat}) measured with a Guelph permeameter provided an arithmetic mean of 1 x 10^{-6} m/s. The GRDL consists of approximately 70% gravel and 30% sand, with less than 10% passing the No. 10 sieve size (2 mm). The estimated k_{sat} is in the range of 1 x 10^{-3} to 1 x 10^{-2} m/s. The bedding sand is a 18 mm minus with less than 15% passing the #200 sieve (0.075 mm), with and estimated k_{sat} of 5 x 10^{-7} to 5 x 10^{-6} m/s.

Sydney, Nova Scotia is seasonally humid and classified as humid continental under the Köppen climate classification. Mean annual precipitation (PPT) and potential evaporation (PE) are approximately 1,500 mm and 650 mm, respectively. Less PPT occurs during the summer (May to September) with approximately 97 mm of rainfall per month compared to 145 mm for the rest of the year. Relatively equal proportions of rainfall and snowfall occur in the winter (December to March). The atmospheric demand for moisture during the winter is low, typically less than 20 mm of PE per month, which increases to greater than 100 mm per month in the summer.

3 FIELD PERFORMANCE MONITORING DATA

This section presents monitored volumetric water content and pore-water pressure data from the two cover system profiles to highlight the temporal variation of ponded conditions on the geomembrane and to provide the basis for estimating net percolation rates through the geomembrane.

3.1 *Volumetric Water Content*

Figures 2 and 3 are isopleth contour plots of the volumetric water contents within the covers at the VJ and Summit sites, respectively. Changes in volumetric water content in response to atmospheric forcing (i.e. rainfall and evaporation) was observed throughout the monitoring period at both sites. The volumetric water contents within the growth medium remains relatively high during the late autumn and early winter, a period in which the PE is low. The volumetric water contents are generally lower and more dynamic in the spring, summer and early autumn as water stored within the cover are taken up by evapotranspiration. The volumetric water contents within the GRDL at VJ remain low throughout the year, although there are wetting and drying cycles occurring. It is estimated that approximately 25% of PPT (i.e. 385 mm) passes through the drainage layer at VJ while only 3% of PPT (i.e. 46 mm) is drained laterally at Summit. This is reflected in the higher water contents in the cover profile at Summit from late autumn through to early spring. The observed difference in water dynamics between the two cover systems are primarily attributed to lateral drainage capacity.

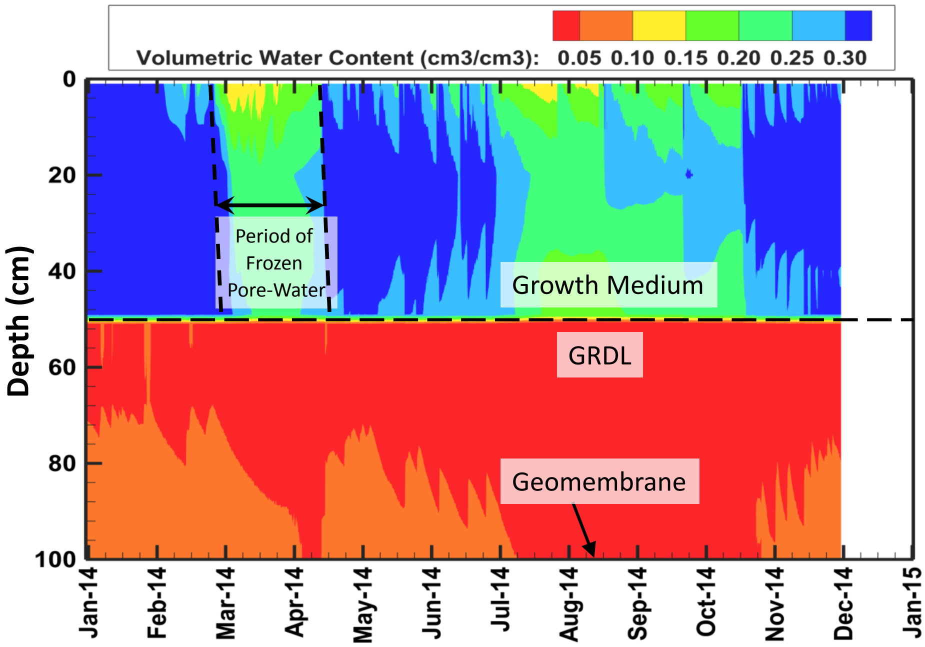

Figure 2. 1-D isopleth contour of the VJ cover system volumetric water content profile depicting adequate lateral drainage capacity in the GRDL. Note: 'drying' in the growth medium layer in the winter (i.e. February and March) is artificial and is due to a change in the dielectric constant of pore-water when it freezes.

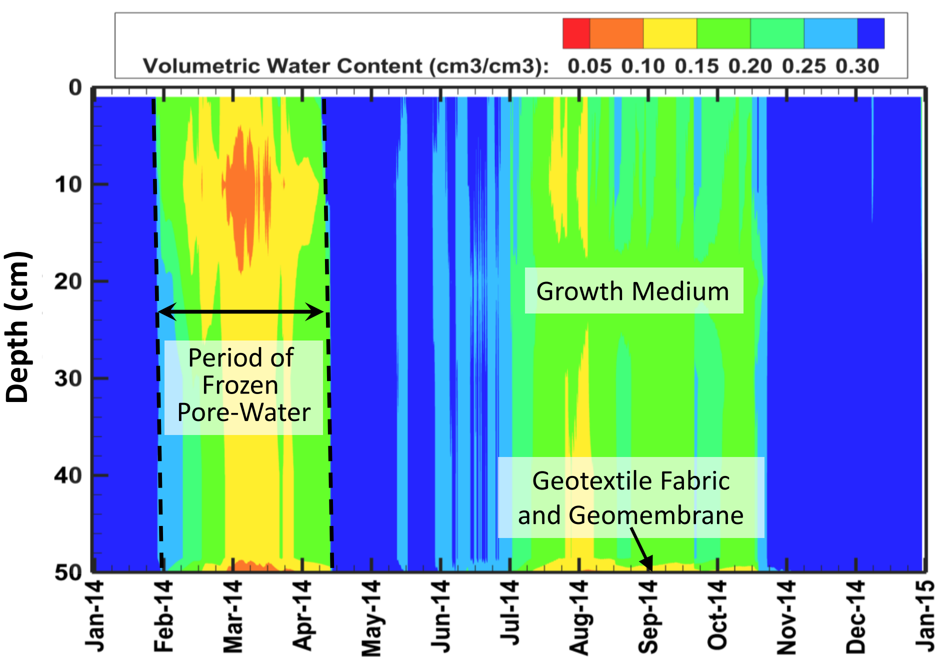

Figure 3. 1-D isopleth contour of the Summit cover system volumetric water content profile depicting limited lateral drainage capacity in the growth medium. Note: 'drying' of the growth medium layer in the winter (i.e. February and March) is artificial and is due to a change in the dielectric constant of pore-water when it freezes.

3.2 *Pressure Head on Geomembrane*

The pressure head above the geomembrane for VJ and Summit in the 2012 to 2014 monitoring period is illustrated in Figure 4. In late autumn and early winter, the head of water at Summit is maintained at approximately 500 mm, equal to the full depth of the cover profile. For comparative purposes the maximum recommended head of water above a geomembrane liner for municipal waste storage facilities is 300 mm (Giroud et al. 2000). While liner performance is primarily attributed to the transmissivity of the drainage layer and slope along the base, the design of drainage layers in covers systems should incorporate landform designs which support surface water management and lateral drainage capacity. Thus cover systems with drainage layers have design options not available to liner systems.

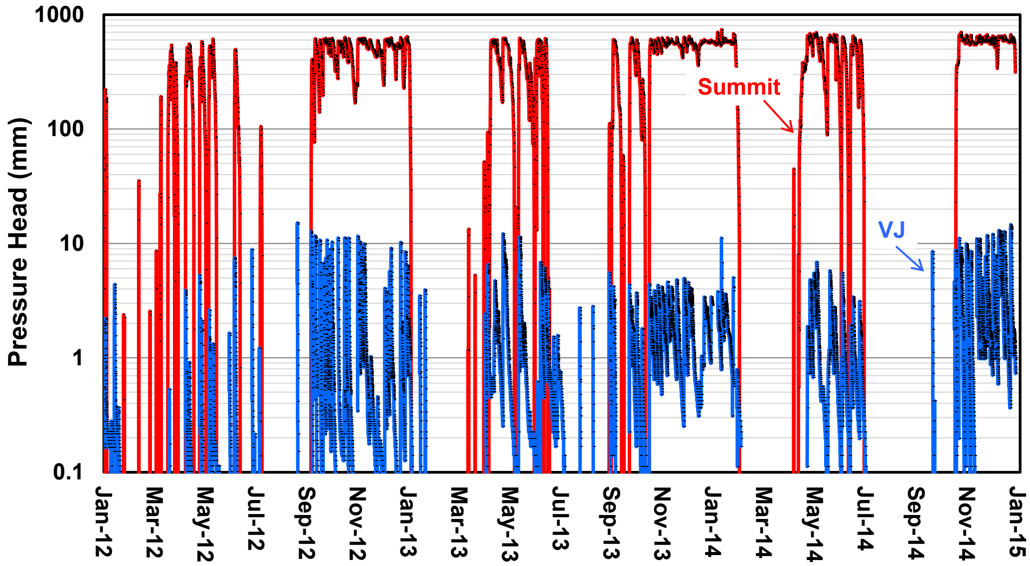

Figure 4. Hydraulic head above the geomembrane at Summit and VJ over the 2012 to 2014 monitoring period.

The covers freeze to their full depth by late winter. In the spring, the head of water is highly variable as the cover accepts snow melt infiltration followed by increasing AET (actual evapotranspiration). AET in the summer is adequate to draw the head of water down. The pressure head above the geomembrane at VJ fluctuates between 0 and 12 mm. The observed hydraulic head is highly transient and quickly dissipates to 1 mm or less. The influence of seasonal or inter-annual variability in climatic conditions is observed in the monitored performance.

Figure 5 compares rainfall to the flux of water to the GRDL in the last half of 2014 for VJ, where the flux of water is taken as the measured interflow volume. Rainfall intensity is generally less than 2 mm/hr but numerous events are greater than 6 mm/hr. The flux of water to the drainage layer reached highs of approximately 0.25 mm/hr in the autumn and 0.35 mm/hr in early winter. The higher rates of water ingress in winter are due to lower PE.

The k_{sat} of the till growth medium is 1 x 10^{-6} m/s (~3.6 mm/hr), or approximately one order of magnitude greater than the maximum water ingress rate to the GRDL. The drainage of surface infiltration through the growth medium to the GDRL is attenuated by changes in storage within the growth medium resulting in the fluxes to the GDRL being delayed and dampened relative to infiltration into the growth medium. The attenuated water ingress and delayed release minimizes the head of water that develops above the geomembrane and highlights the importance of the consideration of the growth medium material in the design of a cover system with a drainage layer.

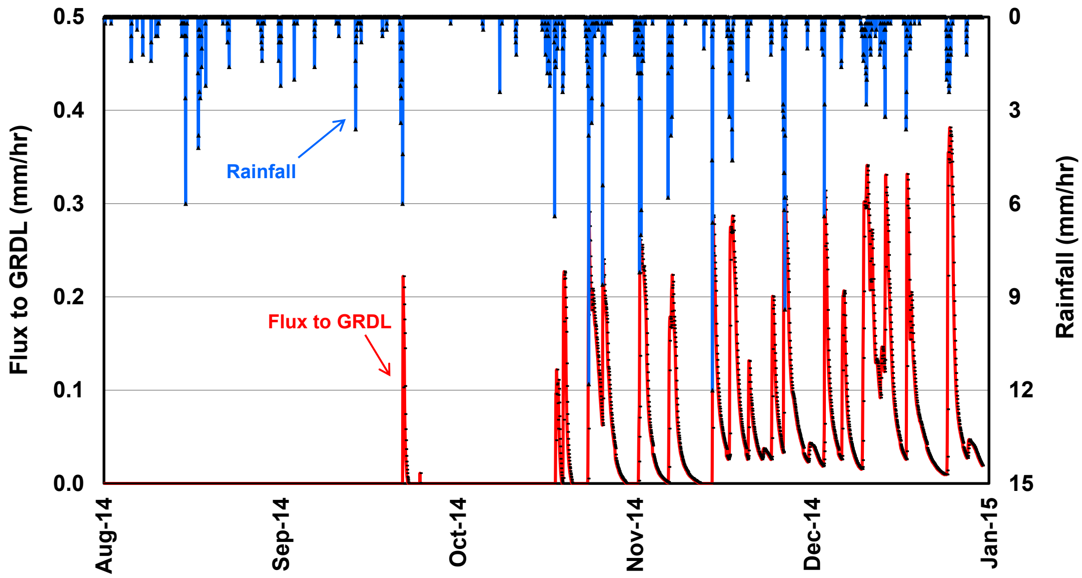

Figure 5. Rainfall and water ingress to the GRDL for the JV cover system.

4 NET PERCOLATION

Conceptual and interpretative models of cover system performance have been developed for Summit and VJ based on the observed water dynamics. The following section developed an understanding for the risk of net percolation using a range of potential rates, and applies analytical methods to reduce uncertainty in the simulated rates when the range is unacceptable or not informative.

4.1 *Simulated Net Percolation*

Net percolation was simulated for a range of scenarios representing a variety of potential field conditions (Table 1). Leakage through a geomembrane is influenced by the hydraulic head, size and number of the holes, and hydraulic conductivity of the underlying material and quality of the contact with the geomembrane. Analytical solutions after Giroud et al. (1989) were used to simulate leakage through defects for good and poor contact and determined as follows:

$$Q = 1.15A^{0.1}h^{0.9}k_{sat}{}^{0.74} \tag{1}$$

where: Q is the leakage rate (m^3/s); 1.15 is the contact parameter (0.21 for good and 1.15 for poor); A is the area of the defect (m^2); h is the hydraulic head (m); and k_{sat} is the saturated hydraulic conductivity of the underlying material (m/s). Equation 2, after Giroud & Wallace (2016) was used to simulate the leakage through a defect located on a fold or wrinkle:

$$Q_w = L_w \left[W_w k_{sat} \left(\frac{h}{H}\right) 2h \sqrt{\frac{k_{sat}\,\theta}{H}} \right] \tag{2}$$

where: Q_w is the leakage associated with the wrinkle (m^3/s); L_w is the length of the wrinkle (m); W_w is the width of the wrinkle (m); H is the thickness of the layer under the geomembrane (m); h is the hydraulic head over the flat portion of the geomembrane (m); and Θ is the transmissivity of the interface between the geomembrane and underlying material (m^2/s). The calculated leakage is considered a maximum as it is assumed that flow through the defect does not diminish the head of water at the bedding sand across the surface area of the wrinkle.

Table 1. Scenarios to reflect field conditions for simulating net percolation.

Scenario	Holes/ha	Geomembrane Contact	k_{sat} (m/s)
1	13	Good	$5x10^{-7}$
2	13	25% poor	$5x10^{-7}$
3	13	25% poor with one hole on fold	$5x10^{-7}$
4	13	Good	$5x10^{-6}$
5	13	25% poor	$5x10^{-6}$
6	13	25% poor with one hole on fold	$5x10^{-6}$

The transient ponded pressure conditions presented in the previous section were used in the analysis. The simulation uses 13 holes per/ha with a diameter of 10 mm, which is approximately the average cited in the literature (Forget et. al. 2005, Barroso et al. 2006, Nosko and Touze-Foltz 2000 and Needham et al. 2004a). The number of holes were not varied in the analysis. The focus of the analyses is on the influence of the pressure head, transmissivity of the bedding material, and quality of the contact on net percolation. The analyses framework might also be used to estimate geomembrane hole frequency/size if net percolation was defined.

A range of k_{sat} values for the bedding sand ($5x10^{-7}$ and $5x10^{-6}$ m/s) were estimated using SVSoils (2016). The contact between the geomembrane and bedding sand was varied from good to 25% poor contact and then 25% poor contact with one defect on a fold of the geomembrane. The surface area of the fold is 0.1 m^2. It is anticipated that 25% poor contact would be a conservative estimate based on inspections of the bedding sand. Figure 6a and 6b show the exposed bedding sand at Summit and VJ following removal of the growth medium and geomembrane, respectively.

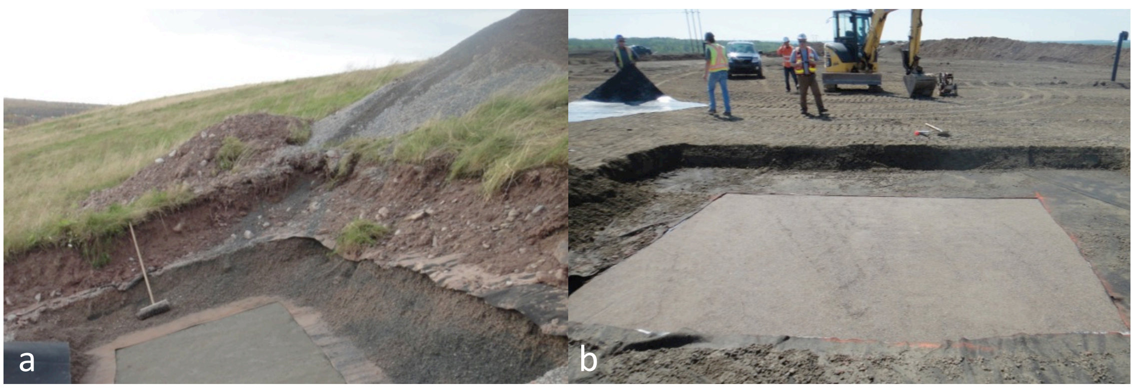

Figure 6. Exposed bedding sand at VJ (a) and Summit (b).

Figure 7 summarizes the simulated average annual net percolation from 2012 through 2014. The analysis highlights the influence of the ponded pressure head, hydraulic conductivity of the bedding material, and characteristics of the defects on net percolation. Net percolation is approximately one to two orders of magnitude greater for Summit, which has inadequate lateral drainage capacity and prolong periods of ponding, than for VJ.

The simulated net percolation for the reclaimed VJ WRP is less than 6 mm or 0.4% of PPT for all scenarios. The risk for net percolation was widely accepted by stakeholders. Since installation of the cover system in 2006, treatment of seepage has transitioned from active to passive treatment and with annual costs reduced from approximately C$212,000 to C$1,800 per year (Meiers et al. 2015).

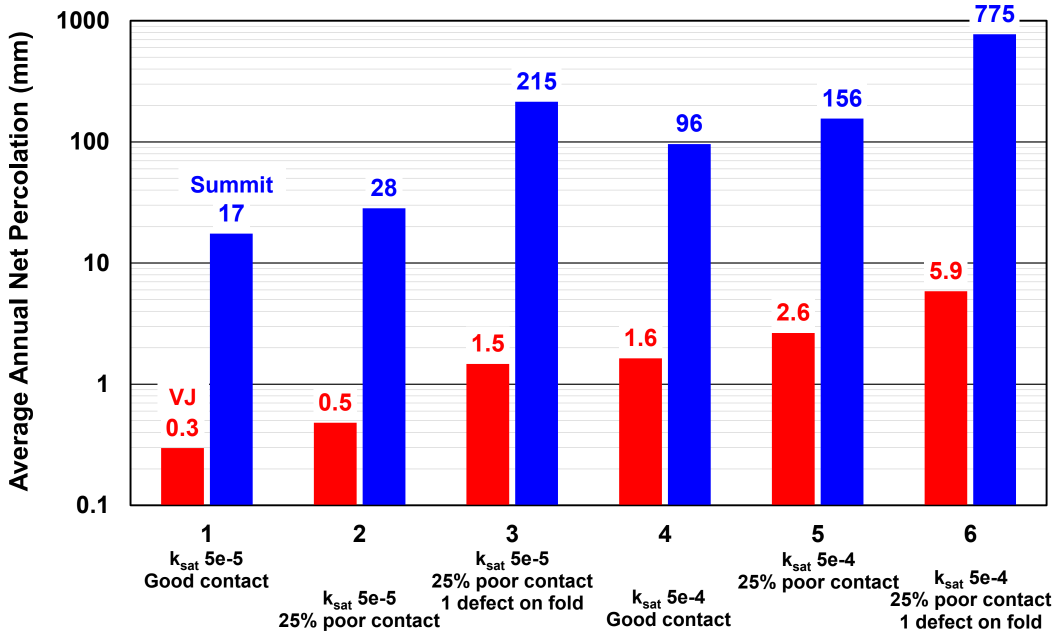

Figure 7. Simulated average net percolation over the 2012 to 2014 period based on the six scenarios.

While the simulated net percolation exceeded 100 mm for Summit under three scenarios, it is likely that the estimated net percolation values are high due to the following factors. First, the higher the net percolation rates the more rapidly the pressure heads on the geomembrane will decrease. This coupling between pressure head and net percolation was not incorporated into this analyses, but rather the observed pressure heads were assumed to exist independent of the estimated values of net percolation. Second, the limited transmissivity of the geotextile protector fabric and growth medium would likely result in lateral ‘drawdown’ as flow progresses towards the hole, reducing the pressure driving leakage. Nevertheless, the simulated results highlight the risk of net percolation for cover systems that are exposed to prolong periods of ponding.

Including 25% poor contact almost doubles the simulated net percolation. Comparatively the detrimental effect of only one hole located on a fold is apparent in the analysis, providing an increase in the range of one order of magnitude from the good contact scenario. The realized increase was greater for Summit than VJ, to some extent, due to the geometry of the simulated wrinkle and location of the hole. In the analysis it was assumed that the hole is located on a wrinkle 4 mm above the ‘flat’ surface of the geomembrane due to the fold; hence, at ponded water level less than 4 mm it is a barrier to flow reducing its ability to convey water.

An increase in the k_{sat} of the bedding material by one order of magnitude resulted in an increase in the simulated net percolation by four to five times. The results highlight the importance of selecting a bedding sand that considers protecting the barrier, as well as the influence of leakage through holes. Thus a “clean wash sand” may be less desirable than a well-graded sand with a fines content. Construction quality control is also key to provide a uniform layer for placement of the geomembrane and minimizing wrinkles during installation.

4.2 *Impact of Net Percolation on Changes in Stored Water*

The sensitivity study highlights that the net percolation from the Summit site is likely to be much higher than that for the VJ site. A water balance was completed for the Summit WRP from October 24th to November 13th (Fig. 8). This period was selected since potential evaporation is a small component of the water balance, the volume of water in the cover profile is relatively constant, and limited storage capacity is available. This reduces potential errors that inherently occur in site water balances. For example, PE in the period is ~19 mm. Based on Eddy Covariance system measurements and monitored water contents, an average AET to PE ratio of 0.8 is used in the analysis and considered reasonably accurate and conservative. Nevertheless, if the ratio was increased from 0.8 to 0.9 the error would be approximately 2 mm.

Figure 8, also shows a change in water storage back-calculated from the water balance equation using the simulated net percolation from Scenario No.1 for Summit. The calculated change in water storage provides a similar match to the measured change in water storage which would suggest that the measured components of the water balance are reflective of field conditions.

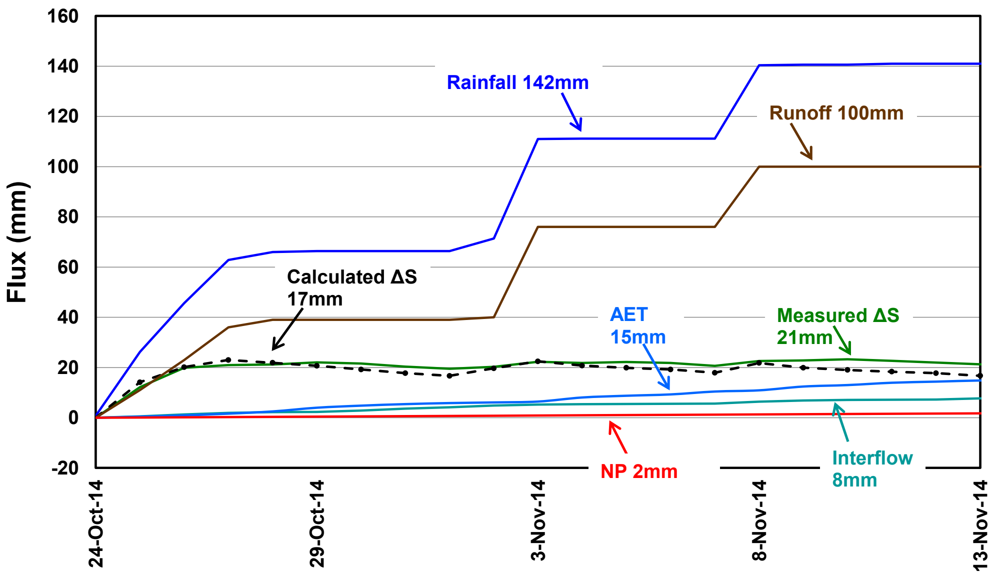

Figure 8. Water balance for the reclaimed Summit WRP and the calculated change in water storage using Scenario No. 1 (net percolation 2 mm in the period).

Using the water balance established in Figure 8, the change in water storage was recalculated using the net percolation rates generated from Scenario No.1 through No. 6 for Summit. The results of this analyses are presented in Figure 9. The decrease in water storage estimated for Scenarios No. 3 through No. 6 is more rapid than could occur based on the estimated water balance. The smaller decreases in measured water storage are assumed to be the result of lateral drainage as well as AET. The trend in the estimated stored water volumes was also observed when using water storage at the other three soil moisture monitoring stations located on the cover system.

The measured pressure head in the cover system profile is also used to provide context for the simulated net percolation. Figure 10 shows the pressure head above the geomembrane at five monitoring locations along a transect across the cover system at Summit. The maximum pressure head at each location is approximately equal to the thickness of the cover profile. In general, there are three instances in which the pressure head increased rapidly to the full height of the growth medium followed by a decrease of approximately 100 mm. Following the decrease in water levels the upper 100 mm of the cover profile would drain-down to a pressure condition of approximately 0.8 kPa at the surface and 0 kPa at a depth of 100 mm. Based on the field water retention curve for the growth medium, also illustrated in Figure 10, the volumetric water content corresponding to ~0 kPa and 0.8 kPa is 0.32 and 0.29, respectively. This would suggest that the volume of water in the upper 0.1 m of the cover profile fluctuates between 32 and 29 mm over each cycle accounting for a cumulative loss of approximately 9 mm. In addition there would also be some loss of water associated with the smaller intracycles in the period. It is estimated that the total water loss would be less than 10 or 15 mm in the period. The estimated decrease in water storage is assumed to be the result of lateral drainage and AET, similar to that observed for the water balance.

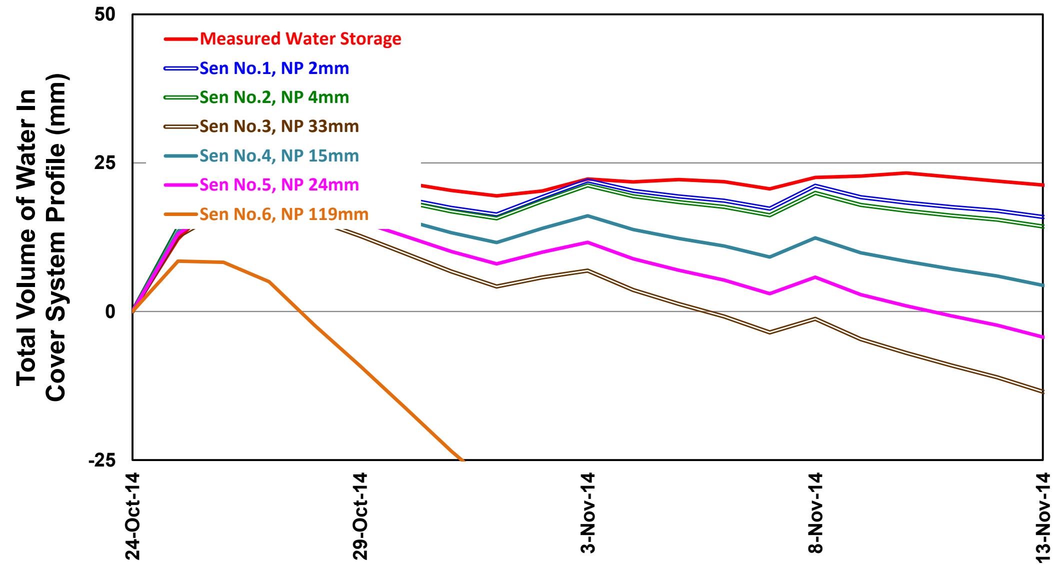

Figure 9. Calculated change in water storage in the cover profile using simulated net percolation from Scenario No.1 through No.6.

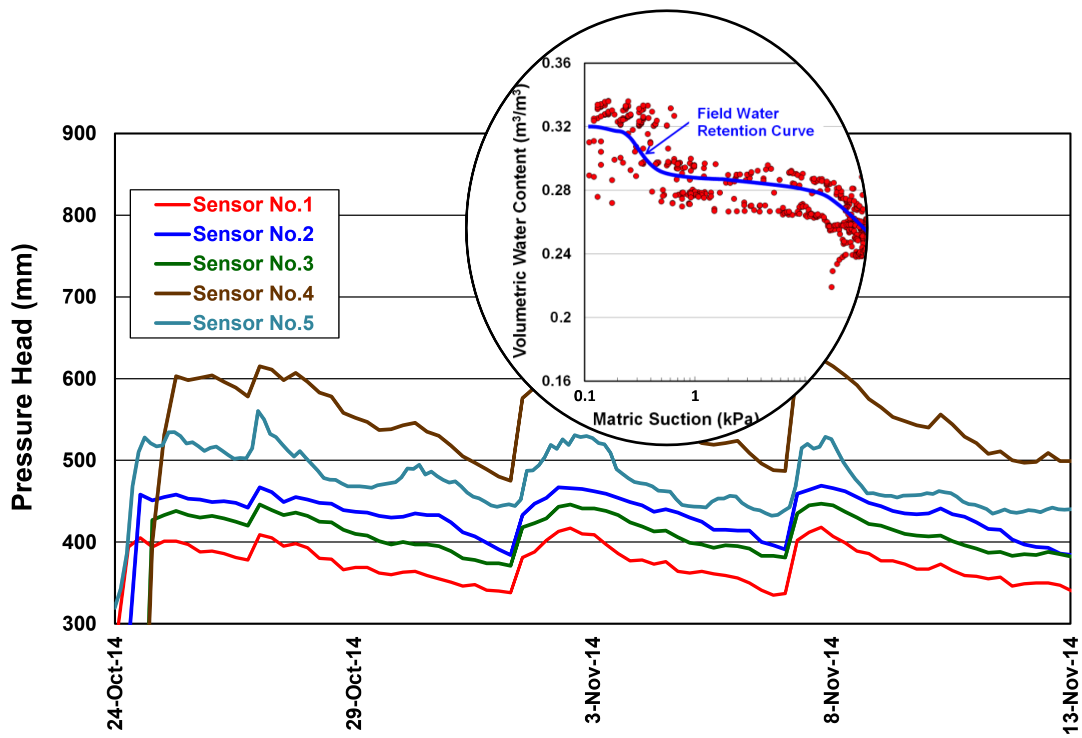

Figure 10. Pressure head measure in transect across cover system profile along with inset figure of field water retention curve based on monitored volumetric water content and suction.

Using the illustrated water balance and monitored pressure head it can be rationalized that net percolation would be in the range of a few millimeters over the period. Scaling this up to an annual net percolation, Scenario No.1 provided approximately 2 mm of net percolation over the October 25th to November 13th period and 19 mm in 2014. Subsequently field performance monitoring data would suggest that net percolation is likely much lower than the simulated values illustrated for Scenario No.3 through No.6. Depending on the risk tolerance for net percolation at Summit, additional monitoring points across the 44 ha surface could be implemented to increase confidence in the simulated performance.

5 WATER BALANCE

Figure 11 compares the various components of the average water balance for 2013, 2014, and 2015 for the two sites. The contribution of net percolation to the water balance is very small at both sites. Net percolation for VJ is estimated to be less than <0.1% of PPT with a risk of exceeding 0.3%. This very low rate of net percolation was achieved through adequate lateral drainage capacity and a delayed release of water from the growth medium limiting the magnitude and duration of water ponding above the geomembrane. Comparatively, the estimated net percolation is <2% for Summit, which is still very low but there is a risk for net percolation to be in the range of ~50%. While the upper limit is likely unrealistic given that the applied pressure head in the simulation would have decreased under such high net percolation rates and there would likely be some head loss at the hole due to the transmissivity of the geotextile protector fabric and growth medium, the risk for higher rates is apparent.

AET is similar at each site; approximately 31% of the PPT. There is a difference in runoff and interflow volumes for the two WRP. Summit has the highest runoff at approximately 64% as compared to 43% for VJ. Given the relatively low net percolation at both sites and the similarity in AET (and PPT), the relative contributions of runoff and interflow at the sites is primarily a reflection of the presence of lateral drainage.

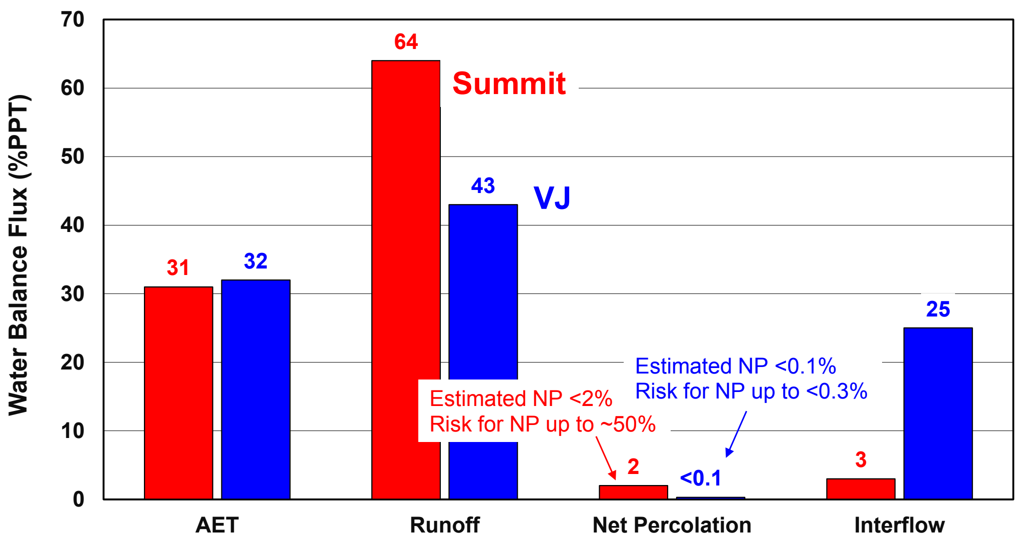

Figure 11. Water balances for VJ and Summit.

Given that physical stability of mine closure landforms (i.e. erosion, slope movements) is a common reason for failure of mine waste cover systems around the world (MEND, 2004) it is critical that surface water management strategies account for lateral drainage capacity within the cover system layer(s) placed above the geomembrane. The results shown in Fig. 11 highlight how these issues can be exacerbated in geomembrane cover systems without a drainage layer.

The development of positive pore-water pressures within the cover profile above the geomembrane lead to reductions in effective normal stress and consequently the strength along the geomembrane interface. In a similar manner, ponding on the geomembrane can lead to cover saturation and increased runoff rates as well as the formation of localized discharge areas which will promote erosion. As a result, unlike slope instability, seepage erosion can occur along shallow slopes. Particle movement is initiated as soon as the seepage force is greater than the particle self-weight and inter particle forces (Fox et al. 2007). A seepage face may occur within a cover system at the toe of the slope or when the height of ponded water within the cover profile exceeds the elevation at the base of erosional features. Once seepage erosion is initiated, a positive feedback loop is established in that further deepening of the erosion feature leads to an increase in the hydraulic gradient to the free surface. This is further intensified by high surface runoff volumes associated with the in situ water dynamics (i.e. limited water storage capacity in the cover profile) resulting it peak runoff flows.

Figure 12 is a seepage erosion feature observed on the Summit cover system with the geotextile protector fabric above the HDPE exposed. In addition to potential erosion issues, vehicle restrictions are imposed on the cover system during periods of positive pore-water pressure due to the loss in shear strength. In essence the water dynamics dictate limits on end land-use as the cover system would be susceptible to anthropogenic damage. The Summit WRP, although it does not have a drainage layer, does typically have shallow slopes and a large surface area, except for a small section (~1.5 ha) of steeper slopes. It is expected that the exclusion of a drainage layer for the remaining WRP surface area (~42.5 ha) was attributed to the shallow slopes.

Figure 12. Seepage erosion feature on the Summit cover system exposing geotextile protector fabric and above geomembrane layer.

6 CONCLUSION

A fundamental outcome demonstrated in the comparative analysis and water balance is that the risk of net percolation is diminished when there is adequate lateral drainage capacity. In addition careful consideration is required in the selection of a bedding material and quality of the contact with the geomembrane. While there is a considerable range in the estimates of a geomembrane lifespan in the literature, it is likely that the service life of a geomembrane can be extended through the use of a drainage layer by limiting the influence of holes that may occur due to long-term degradation and service stresses. Thus a longer service life for the geomembrane at VJ is likely compared to Summit, where the service life is defined as the period that the cover system functions as an effective hydraulic barrier and not the period to antioxidant depletion as defined by Needham et al. (2004b).

The simulated net percolation was considered to be very low for the cover system with adequate lateral drainage capacity in all of the applied scenarios (i.e. bedding material, quality of contact, and wrinkle). Comparatively, there was a wide range in the simulated net percolation rates for the cover system with inadequate drainage capacity; however, through the use of field performance monitoring data, context for the simulated results were developed. Field performance monitoring of cover systems that include geosynthetic layers for the closure of mine waste storage facilities still need to evolve to account for a range of cover system designs, landforms, materials, and climatic conditions.

REFERENCES

Barroso, M. Touze-Foltz, N. von Maubeuge, K. & Pierson, P. 2006. Laboratory investigation of flow rate through composite liners consisting of a geomembrane, a GCL and a soil liner. Geotextiles and Geomembranes, 24(3), 139–155.

Bradley, C. Meiers, G. Mayich, D. & Shea, J. 2016. Use of Conceptual Models In Advance of Numerical Simulations to Demonstrate an Understanding of Loading from Reclaimed Waste Rock Piles. Presented the Canadian Land Reclamation Conference, Timmins, ON, June.

Cartaud, F. Touze-Foltz, N. & Duval, Y. 2005. Experimental investigation of the influence of a geotextile beneath the geomembrane in a composite liner on the leakage through a hole in the geomembrane. Geotextiles and Geomembranes, 23(2), 117–143.

Forget, B. Rollin, A. & Jacquelin, T. 2005. Lessons Learned from 10 Years of Leak detection Surveys on Geomembranes, Sardinia: The Tenth International Waste Management and Landfill Symposium, October 3-7, Cagliari, Italy, pp 9.

Fox, G. Chu-Agor, M. & Wilson, G. 2007. Seepage erosion: A significant mechanism of stream bank failure. In. Proc. ASCE World Environmental and Water Resources Congress, Tampa, FL, May 15-19.

Giroud, J. P. Khatami, A., & Badu-Tweneboah, K. 1989. Evaluation of the rate of leakage through composite liners. Geotextiles and Geomembranes, 8(4), 337–340.

Giroud, J.P. & Bonaparte, R. 1989. Leakage through liners constructed with geomembranes – Part 1. Geomembrane Liners, Geotextiles and Geomembranes, Elsevier Science, England, 8: 27-67.

Giroud, J. P. Zornberg, J. G. & Zhao, A. 2000. Hydraulic design of geosynthetic and granular liquid collection layers. Geosynthetics International, 7(4-6), 285–380.

Giroud, J. P. & Wallace, R. B. 2016. Quantified impact of geomembrane wrinkles on leakage through composite liners. In Proc. 3rd Pan-American regional Conference on Geosynthetics, Miami, Florida, USA, April 10-13.

Meiers, G. O'Kane, M. Mayich, D. Weber, P. Bradley, C. & Shea, J. 2015. Closure of legacy waste rock piles: can we achieve passive treatment to manage residual seepage in the short term?. In Proc. 10th International Conference on Mine Closure, Vancouver, BC, Canada, June 1-3.

MEND (Mine Environment Neutral Drainage). 2012. Cold regions cover system design technical guidance document, Canadian Mine Environment Neutral Drainage Program, Project 1.61.5c, March.

Needham, A.D. Gallagher, E.M. Smith, J.W. 2004a. Prediction of the long term generation of defects in HDPE liners. In: Proc. 3rd Eur. Conference on Geosynthetics, vol. 2, Munich, Germany, pp. 507–514

Needham, A. Gallagher, E. Peggs, I. Howe, G. & Norris, J 2004b. The likely medium to long-term generation of defects in geomembrane liners. Technical Report P1-500/1/TR, Environmental Agency, January.

Nosko, V. & Touze-Foltz, N. 2000. Geomembrane liner failure: modeling of its influence on contaminant transfer. Proc. 2nd Eur. Geosynthetics Conf., Bologna, 557–560.

Rowe, R. K. Rimal, S. & Sangam, H. 2009. Ageing of HDPE geomembrane exposed to air, water and leachate at different temperatures. Geotextiles and Geomembranes, 27(2), 137–151.

SoilVision Systems Ltd. (SVSoils) 2016. SVOFFICE 5 Help Manual. June 3.