USE OF A CONCEPTUAL MODEL IN ADVANCE OF NUMERICAL SIMULATIONS TO DEMONSTRATE AN UNDERSTANDING OF LOADING FROM A RECLAIMED WASTE ROCK PILE

C. Bradley[1], G. Meiers[1], D.Mayich[2], M. O'Kane[3], J.Shea[4]

[1]O'Kane Consultants Inc., Fredericton, New Brunswick, Canada

[2]David Mayich Consulting, Sydney, Nova Scotia, Canada

[3]O'Kane Consultants Inc., Calgary, Alberta, Canada

[4]Public Works and Governments Services Canada, Sydney, Nova Scotia, Canada

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ABSTRACT

A conceptual model is an initial step in demonstrating an understanding of site conditions to inform on long-term impacts from waste storage facilities. This understanding provides the basis for additional work, including numerical simulations should they be required, and identifies appropriate objectives. In conjunction with numerical simulations, a representative conceptual model establishes a high degree of confidence in simulated results. A conceptual model also serves as a delivery mechanism for conveying information to site personnel or management who may not have the technical knowledge or time required to interpret results. Although developing a conceptual model may seem like an unnecessary step, it is an instrumental skill which needs to be cultivated.

The Victoria Junction waste rock pile was reclaimed with an engineered cover system that includes a geomembrane layer and is presented as a case study. The waste rock pile is located on Cape Breton Island near Sydney, N.S., Canada, and was reclaimed in 2006. Using site information, a conceptual model was developed to include physical, flow, and geochemical components for predicting loading and long-term impacts to the receiving environment. The case study details the conceptual model and methodology employed, and highlights the importance of implementing a monitoring program to ensure sufficient information is collected to adequately inform the conceptual model. It was demonstrated through the conceptual model that a drain-down seepage analysis was required, while rigorous groundwater flow and contaminant transport modeling was not. The conceptual model identified that long-term acid loading from the waste rock pile will be limited to levels that allow for closure objectives to be achieved. Consideration may be required in long-term planning given that the longevity of geomembranes are in the order of 500 to 1,000 years and that stored and potential acidity will remain for ~580,000 years.

Net present value and a representative conceptual model were used to demonstrate the financial and environmental benefit of the reclaimed waste rock pile compared to the

collection and treatment of basal seepage in perpetuity. While the net present value was similar for both alternatives the conceptual model demonstrated that further improvement in surface and groundwater quality was observed through the reclaimed scenario that would not have been realized through collection and treatment.

1. INTRODUCTION

A representative conceptual model captures something real and in its simplest form is an analytical tool used to organize site information and ideas. A site conceptual model for mine waste management facilities includes supporting physical, flow and geochemistry components. The physical component of the model describes the waste storage facility and surrounding landform, and the flow component describes the movement of water through the physical component, both above and below the ground surface. Waste material is characterized in the geochemistry component and source terms are tested for accuracy when coupled with the physical and flow components. Combined, these three components demonstrate an initial understanding of site conditions and may inform on long-term trends such as impacts to the receiving environment.

A functional conceptual model must remain flexible and evolve as new site information becomes available and context for the site is established. A conceptual model that is inclusive but yet simple and demonstrates site processes serves as tool for the engagement of management / site personnel in a forum of active collaboration. A collaborative effort that occurs throughout the project allows for continuous refinement of the conceptual model through intimate site knowledge which may or may not be included in reports.

The conceptual model is a holistic approach that ultimately informs management on decisions regarding site practices in effort to meet closure objectives. It also provides the basis for additional work to support the model and identifies appropriate objectives. Should numerical simulations be required, a conceptual model establishes an understanding for anticipated outcomes for simulations before they are completed, hence a high degree of confidence is established in the results.

This paper presents a case study in which a conceptual model was developed to assess and predict long term performance (i.e. loading to the receiving environment) of the reclaimed Victoria Junction (VJ) waste rock pile (WRP) located in Cape Breton, Nova Scotia, Canada. The conceptual model demonstrates that seepage numerical modeling was required to inform on drain-down from the WRP but groundwater flow and contaminant transport numerical modeling was not. All too often there is a desire to proceed to numerical simulation before a representative conceptual model has been developed.

The VJ WRP was reclaimed with an engineered cover system that includes a geomembrane layer (high-density polyethylene) with the objective of limiting the ingress of meteoric water and oxygen to the underlying waste material. Reduced loads to the receiving environment have been observed and are expected to continue provided cover system performance is maintained, which is largely dependent on the geomembrane, as well as the overlying layers and overall stability of the landform. The conceptual model indicates that stored and potential acidity will be leached from the reclaimed WRP for ~200,000 years, while the longevity of geomembranes is estimated to be upwards of 1,000 years (Rowe, 2005). Studies conducted by Benson et al (2010) estimate the minimum lifespan of geomembranes used in cover systems is on the order of 55 to 125 years.

While it is perceived that any leakage through a geomembrane constitutes a failure from their traditional use as a liner, it may not be the case for meeting closure objectives for waste storage facilities in the mining industry. Although there is a considerable range in the estimates of geomembrane lifespan, it is conceivable that a geomembrane will performing satisfactory as a barrier beyond this period as long as appropriate design considerations are included in the cover system. The key is adequate information to inform on long term performance and to develop an understanding of risk for impacts to the receiving environment.

2. VICTORIA JUNCTION

2.1 PHYSICAL MODEL

The reclaimed VJ WRP is located on the site of a historic coal preparation plant approximately 5 km northeast of Sydney and has a footprint of approximately 26 ha and a height of 40 m. The WRP is located in a topographic low and thought to be constructed on the edge of a post-glacial lake created by a large depression in bedrock. Geology generally consists glacial till over sedimentary bedrock. There is a sand deposit in the wetland immediately north of the WRP, along with a peat layer that encompasses the wetland.

The VJ site has evolved over many years to accommodate operational changes to the coal preparation plant and as part of the remediation activities post-closure of the facility. The coal preparation plant operated from the mid 1970’s to 2000. During operations, the coal preparation plant washed up to 4 million tonnes of raw coal per year, of which 15–20% was placed into the WRP and 3% into tailings ponds. Two coal tailings ponds were constructed as required by processing and storage demands, and were eventually relocated within the WRP and encapsulated with waste rock. Three additional tailings ponds were constructed within the confinements of the WRP. It was general procedure to keep the coal tailing ponds covered with supernatant water to prevent oxidation from occurring. Upwards of 10 million tonnes of potentially acid forming (PAF) waste was placed in the WRP.

In 1987 a 1 m thick bentonite wall was constructed along the north and east toe of the WRP to reduce acid rock drainage and metal leaching (ARD/ML) moving through shallow overburden into the wetland. A toe-drain collected upwelling seeps that were treated through an active treatment plant. The toe-drain was upgraded to the leachate collection system (LCS) in 2006 during construction of the cover system, and encompassed the entire perimeter of the WRP. A basic lime slurry addition water treatment plant was located adjacent to the WRP for the collection and treatment of ARD/ML-affected runoff. This was replaced in 1994 with another lime slurry water treatment plant that included various surge, settling and polishing ponds before discharging into Smiths Brook east of the pile. In 2003, six pump-and-treat wells were installed into bedrock to the north of the WRP to intercept deeper impacted groundwater. A wet well was installed north of the lower surge pond to intercept ARD/ML impacted water percolating through the base / lining of the lower surge pond. The lower surge pond received water from the pump-and-treat wells, the LCS, and the wet well through a series of pumps. Fig.1 shows key landform features and remediation measures.

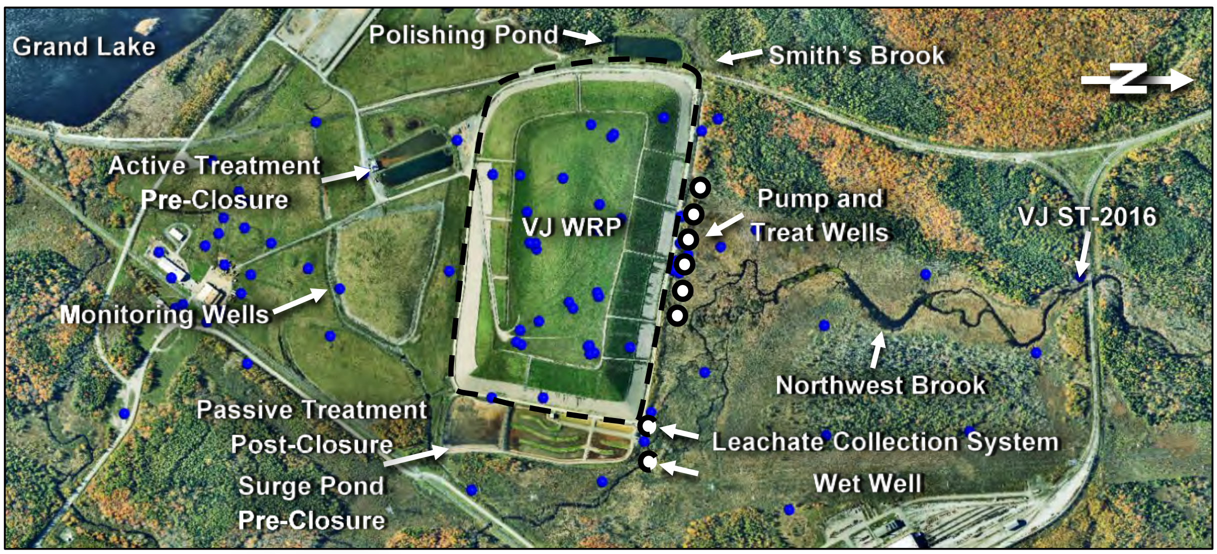

Figure 1. Victoria Junction WRP and site features. Photo taken post-closure with passive treatment.

An engineered cover system was implemented as part of the closure plan for the WRP in 2006. The cover system was designed based on several closure objectives:

- providing a measurable positive effect on the environment compared to the impact pre-closure;
- minimizing the impact to wetlands connected through Northwest Brook; and
- site aesthetics in accordance with industry standards and public expectations.

The cover system comprises a till growth medium layer placed over a granular drainage layer and a 60 mil HDPE geomembrane. The cover system was designed to limit the ingress of meteoric water and oxygen, thus limiting the transport of stored acidity and generation of potential acidity. In 2013, the active water treatment plant was decommissioned and a passive water treatment system constructed in the lower surge pond to the east of the WRP, as shown in Fig. 1. The passive treatment system is recharged with lime and polymer, and ARD/ML impacted water is actively pumped from the LCS into the treatment system.

2.2 FLOW MODEL

The VJ WRP is located within the Northwest Brook watershed. Northwest Brook flows from Grand Lake, located approximately 100 m south of the site, around the east side of the WRP and through the wetland into the Atlantic Ocean approximately 6 km north of the site. Two sampling locations upstream of the WRP provide water quality prior to mixing with ARD/ML and one sampling location downstream of the WRP (VJ ST-2016) is a receptor for ARD/ML and used to evaluate load to the receiving environment. Smith's Brook is a small tributary flowing into Northwest Brook northwest of the WRP and provides alkalinity to the wetland from an open limestone channel constructed within the lower portion of the brook. There are also alkalinity contributions to the system from the active / passive treatment discharge water, two limestone pools imbedded within a surface runoff collection ditch, and natural alkalinity in flows from Grand Lake and groundwater.

Groundwater elevations in the vicinity of the WRP are relatively shallow, approximately 1-5 m below the ground surface, and flows are generally towards the north-northeast. Groundwater discharges north of the WRP, supported by the vertical hydraulic gradients, presence of the wetland, and artesian flow in some of the monitoring wells. Recharge is anticipated to occur to the west and east of the WRP based on the topography. Flow contours were generated for the site from monitoring wells and extended to encompass the landform by interpreting groundwater elevations from topography and water elevations in local water bodies. Contours indicate flow is focused towards VJ ST-2016 (see Fig. 2) and supports the use of this location as a receptor of ARD/ML in the geochemistry model.

Figure 2. Groundwater contours in the vicinity of the VJ WRP.

In general there are strong downward hydraulic gradients below the WRP and weak upward hydraulic gradients in the wetland north of the WRP. The upward hydraulic gradients in the wetland are attributed to the topographic highs surrounding the site and are anticipated to have existed prior to placement of the WRP. The strong downward hydraulic gradients are likely the result of the large hydraulic heads within the WRP caused by maintaining a supernatant water cover over the coal tailings ponds and the high ingress of meteoric water into the bare waste, and have reversed the natural upward hydraulic gradient below the pile. The cover system has reduced the ingress of meteoric water from an estimated 400 mm per year to less than 1 mm per year, based on pre-cover system analysis by AMEC (2005) and estimated leakage through defects as described by Giroud et al. (2000) coupled with three years of cover system field performance monitoring data. Drain-down is expected to occur until the WRP reaches a steady state water content. A portion of drain-down has already occurred, evident by decreased water levels within the WRP following placement of the cover system in 2006. Drain-down, along with net percolation, will contribute loadings to the receiving environment through basal seepage.

There are two components to drain-down for the WRP: saturated drain-down, which will contribute greater loading over a shorter period; and unsaturated drain-down, which will occur over a longer time frame and generate a lower loading. Fig. 3 shows water levels (i.e. saturated drain-down) in two of the monitoring wells that were completed in the tailings layer one year prior to placement of the cover system and the decrease in water levels over time. The rate of decrease in water levels illustrates a more rapid drain-down shortly after placement of the cover system, followed by a gradual decrease. The trend in the rate of drain-down was extrapolated with trend lines to estimate the cessation of saturated drain-down. It is estimated that the drain-down of water perched within the pile is currently 70 mm/yr and will continue for another 10–20 years, at which time the unsaturated drain-down of water will result in a much lower rate of basal seepage. Fig. 4 presents the decrease in water levels through a cross section of the WRP over the course of reclamation.

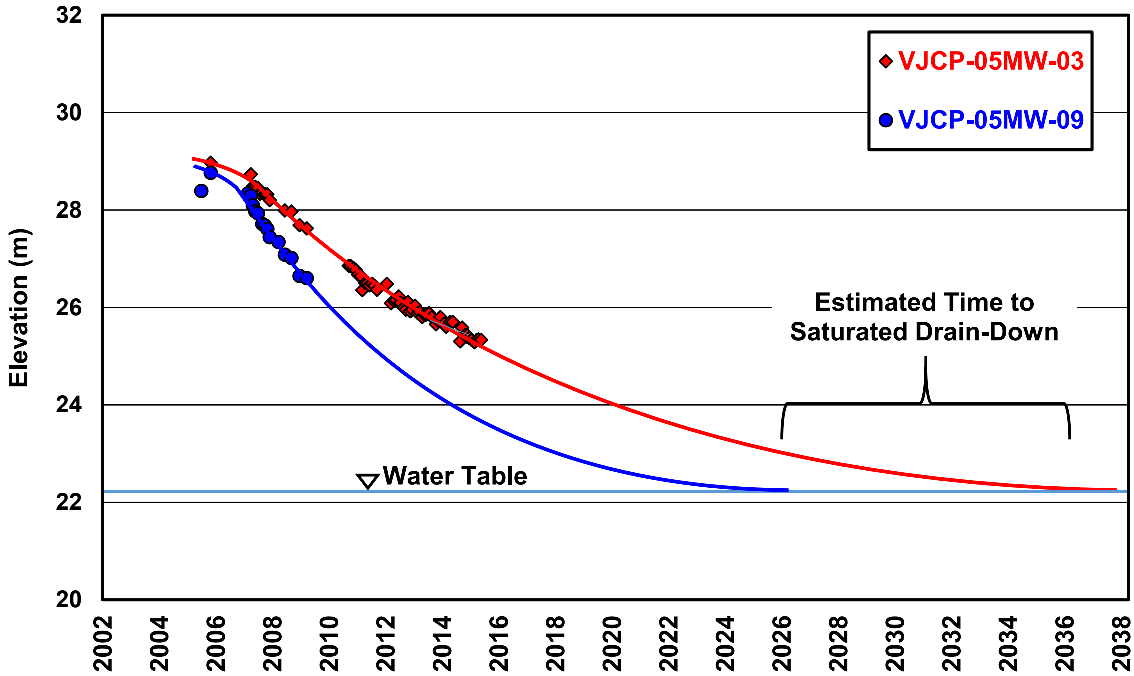

Figure 3. Estimated time to cessation of saturated drain-down in the WRP.

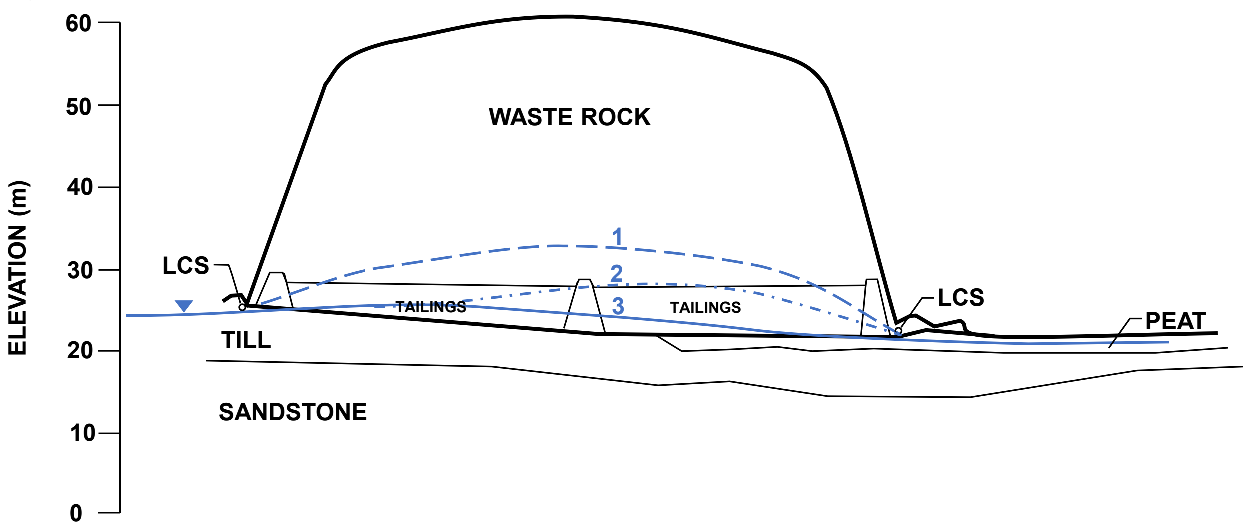

Figure 4. South-North cross section illustrating the decrease in water elevation in the WRP.

Lines 1, 2 and 3 in Fig. 4 represent the observed decrease in water levels following installation of the cover system and associated reduction in water ingress. Line 1 was generated from water levels observed prior to placement of the cover system and shows water perched to an elevation of approximately 33 m, approximately 10 m above the base of the WRP. Line 2 represents the current elevation of water levels, a decrease of approximately 5 m since 2006. The predicted water table elevation at cessation of drain-down was determined from water elevations up- and downstream of the WRP and wells within the footprint of the pile screened in underlying till. The water elevations for wells completed in the till have not changed over time and are reflective of Line 3, indicating that the final water table will likely mound within the base of the pile at approximately 3 m and diminish to near zero at the LCS. Groundwater flow through the WRP is estimated based on a cross section 3 m high and the entire width of the WRP.

2.5 GEOCHEMISTRY MODEL

Loading to the receiving environment has evolved over time and can be characterized by three distinct phases:

- Phase 1 – pre-cover system with active treatment,
- Phase 2 – post-cover system with passive treatment, and
- Phase 3 – long-term post-cover system with passive treatment.

An acid load mass balance was developed for each phase to quantify loading to the receiving environment (Figs. 5, 6 and 7, respectively), with the first two phases providing the basis for long-term predictions.

In the pre-cover system phase, two sources contribute loading to the receiving environment: basal seepage (groundwater mounding and net percolation) and runoff from the site. Sinks, or components acting to reduce this load, include the groundwater collection system (pump-and-treat and wet wells, and LCS) and the active treatment system. The source term for basal seepage was based on measured water quality at the base of the WRP and an iterative process using the acid load mass balances for Phase 1 and Phase 2. Although not necessarily required to determine loading to the receiving environment, runoff was back calculated from the other components for completeness. Grand Lake also contributes a background / natural acid load to the system and the load is essentially a result of the high flow rates observed in Northwest Brook rather than elevated concentrations. The load removed by groundwater alkalinity was calculated based on the decrease in alkalinity observed between groundwater quality up and down-gradient of the WRP.

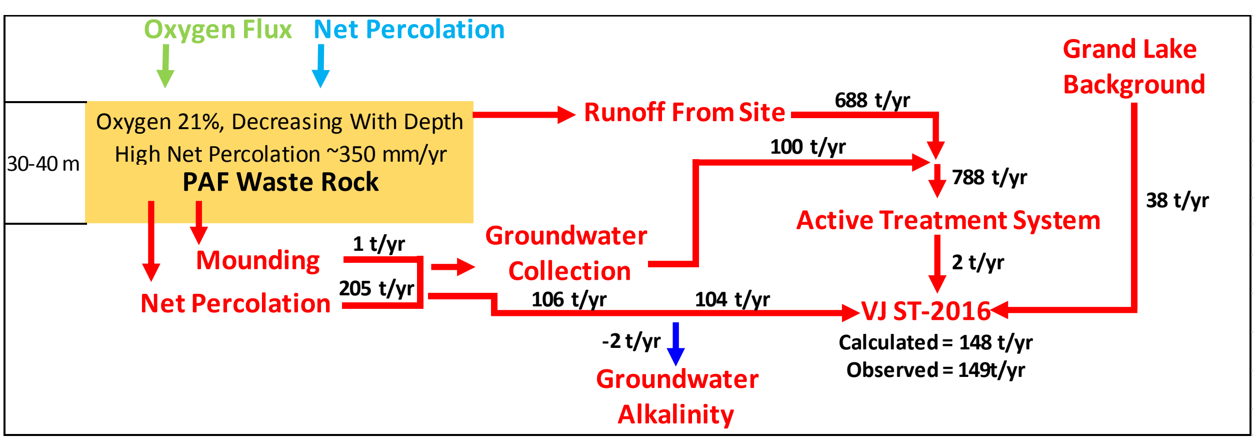

Figure 5. Phase 1 – Acid load mass balance pre-cover system.

The total calculated acid load at VJ ST-2016 is 148 t/yr, and a difference of 1 t/yr from the observed load would suggest that the flow and geochemistry models closely represent site conditions. The total acid load generated is 894 t/year, of which runoff is the largest contributor at 688 t/year. The active treatment system neutralized 788 t/year, while 2 t/year were neutralized by natural alkalinity in groundwater. In terms of basal seepage, approximately 49% is intercepted by the active treatment system, with the remaining reporting to groundwater flow, which is key in developing an understanding of loading to the receiving environment.

The mass balance changes substantially after installation of the low flux cover system and remediation of the site, both in terms of the load produced from surface runoff and basal seepage. The passive treatment system is introduced in this phase and replaces the active treatment system. A drain-down component is also introduced as a result of the decrease in net percolation. The total acid load generated from the site is reduced from 894 t/yr to 43 t/yr and clean runoff from the site represents 688 t/yr of this reduction. Approximately 23% of basal seepage is intercepted and treated before being discharged. The total calculated acid load at VJ ST-2016 is 68 t/year, compared to the current observed load of 66 t/year.

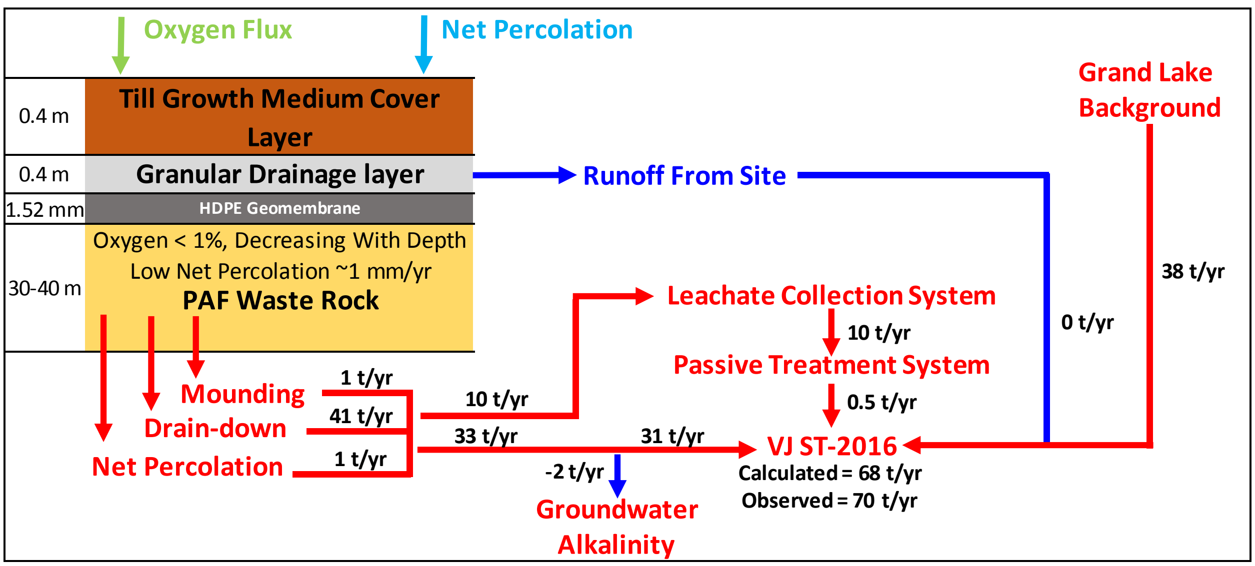

Figure 6. Phase 2 – Acid load mass balance post-cover system.

While an acid load of 66 t/yr was observed at VJ ST-2016, the pile contributes approximately 44% of this load. The average acidity concentration in Northwest Brook at the outlet to Grand Lake and at VJ ST-2016 is approximately 1 mg/l and 1.5 mg/l, respectively. This highlights that the acid load at VJ ST-2016 is primarily the result of the high flow rates in Northwest Brook rather than elevated concentrations. The acidity concentration of basal seepage from the WRP is approximately 2,250 mg/l, and load is attenuated as a result of the low flow rate from the pile. It is important to note that there is also an alkalinity load at VJ ST-2016 of approximately 540 t/yr, which is able provide the required buffering capacity. The natural alkalinity load from Grand Lake alone is greater than the observed acid load at VJ ST-2016 at approximately 120 t/yr. Considering the amount of alkalinity present at VJ ST-2016, there is a net negative acid load of approximately -470 t/yr.

Although the total acid load generated from the site was reduced by approximately 95% (894 to 43 t/year), the acid load at VJ ST-2016 decreased by approximately 56%. The pre-cover system and current mass balances provide context for the observed water quality at VJ ST-2016 in that a proportional decrease in loading was not observed after changes in water collection and treatment. This is primarily attributed to decommissioning the pump-and-treat wells and wet well, as well as the natural contribution from Grand Lake.

Using the mass balances and conceptual model for pre-cover system and current conditions, a mass balance was developed to predict loadings to the receiving environment 100 years post-cover system. It is estimated that saturated drain-down will be completed in another 10 to 20 years and the bulk of water from unsaturated drain-down will have occurred in 100 years; therefore, the acid load from drain-down will be negligible. The period of unsaturated drain-down is supported by numerical modeling completed for another reclaimed coal WRP with similar waste. Contributions to the LCS, and, therefore, the passive treatment system, are anticipated to decrease as drain-down completes. As a result, it is estimated that the load captured by the LCS will be negligible. Any contribution is anticipated to be from groundwater mounding and seasonal fluctuations in groundwater elevation. The mass balance closed for the 100-year period would suggest a decrease in acid load to 38 t/year, equivalent to the background load from Grand Lake.

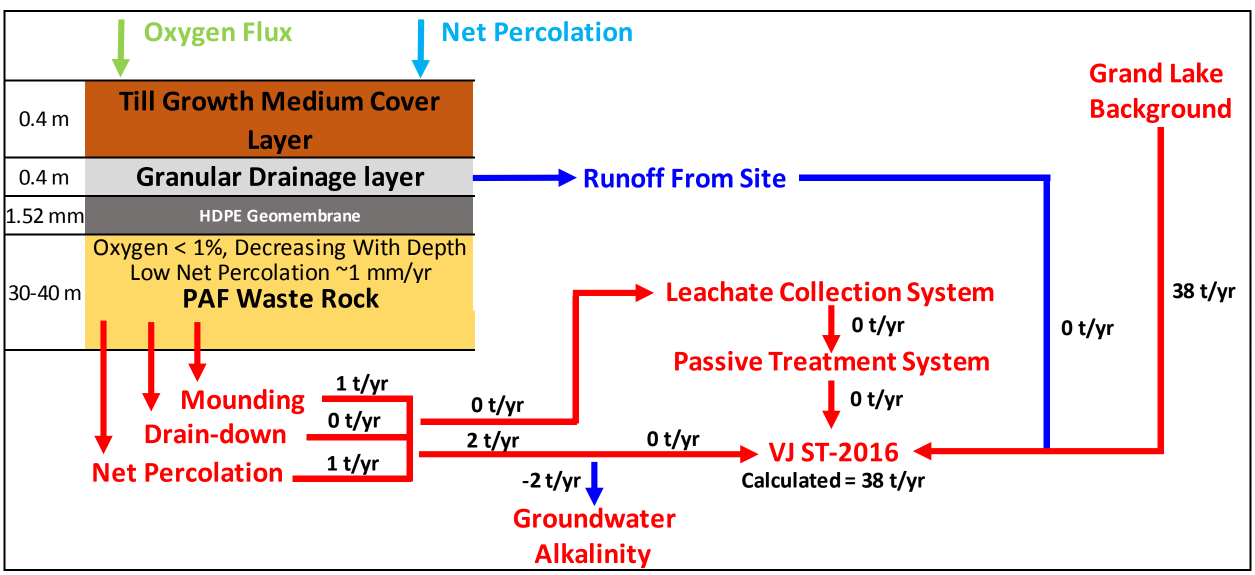

Figure 7. Phase 3 – Acid load mass balance 100 years post-cover system.

This provides context for what benefit the passive treatment system currently provides. Based on the current mass balance, it captures approximately 23% of basal seepage, reducing loading to the receiving environment from 77 t/year to 68 t/year. Loading to the receiving environment without the reduction from the passive treatment system would still be below pre-cover system loading and site closure objectives would still be met. Where the load captured by the passive treatment system is anticipated to decrease as saturated drain-down completes, a strategy for decommissioning the passive treatment system may be to maintain its operation for 10–20 years until saturated drain-down is complete and further improvements to the wetland are observed.

The conceptual model developed for the site identified groundwater mounding and drain-down as having the greatest uncertainty, and the distribution of load between these components has an impact on the predicted long-term loading. As a result seepage numerical simulations were undertaken to quantify and validate the drain-down estimates, which were then used to validate the mounding component. Results indicate that saturated and unsaturated drain-down in the post-cover system mass balance is approximately 40 mm/yr, resulting in approximately a 20 t/yr decrease in load. In order to calibrate the model the saturated hydraulic conductivity of the till underlying the WRP was increased approximately one order of magnitude to 4.0×10^{-4} cm/s, still within the range reported in the literature. Updating the conceptual model with this saturated hydraulic conductivity increased the load due to groundwater mounding by approximately 20 t/yr, which made up for the loss in loading from drain-down. Considering the changes in load from drain-down and groundwater mounding and assuming that the LCS will continue to capture 10 t/yr, the long-term load 100 years post-cover system is approximately 50 t/yr, which includes 38 t/yr from Grand Lake.

The acid load mass balances provide a strong understanding for loading to the receiving environment, and enabled long term predictions 100 years post-cover system. Coupled with the seepage numerical simulations there is a high degree of confidence in the results. The results indicate that loading has decreased substantially following placement of the cover system and will continue to decrease as drain-down diminishes. Leapfrog Hydro was used to develop groundwater plumes from monitored water quality to provide an understanding for how groundwater has evolved in conjunction with site reclamation activities.

Extensive groundwater sampling was conducted from 2002-current and permitted the generation of six 3D groundwater plume models of mean yearly sulfate concentrations to visualize groundwater plume evolution over the period (Figs. 8a-f). An improvement in groundwater quality (i.e. a decrease in the plume's extent and concentration) was observed over the monitoring period and three key phases of groundwater evolution were identified:

- significant improvement in water quality following placement of the cover system in 2006 and 7 years of active deep bedrock water treatment (Figs. 8a to 8b);
- a slight decline in water quality immediately following the decommissioning of the pump-and-treat wells (Figs. 8b to 8c); and

- steady improvement in water quality over the short term with trends that support the flow model, thus strengthening the conceptual model as a whole (Figs. 8c to 8f).

Groundwater quality improvements observed in the modelled plumes are supported by the acid load mass balance. Pockets of high concentration appear to be dissipating and there is also less impact to deep groundwater as vertical gradients in the WRP have diminished as a result of the decreased flux through the cover system

As the conceptual model demonstrates, longevity of ARD/ML is controlled by the rate of transport of acidity from the WRP, which in the long-term is controlled by groundwater mounding and net percolation. Using a simple analysis under the assumption that potential acidity will be generated at a rate greater than the mobilization of stored acidity, the longevity of ARD/ML will be a function of the loading from each component. The long-term loading rate for both groundwater mounding and net percolation is 20 t/yr and 1 t/yr, respectively. Based on the ABA analysis and the physical model, there is approximately 670,000 t of total acidity, of which 90,000 interacts with groundwater and 580,000 interacts with net percolation. Groundwater mobilizes acidity at a much greater rate than net percolation. Acidity mobilized by groundwater mounding will be lost over ~4,500 years. The acidity mobilized by net percolation will be lost over ~580,000 years.

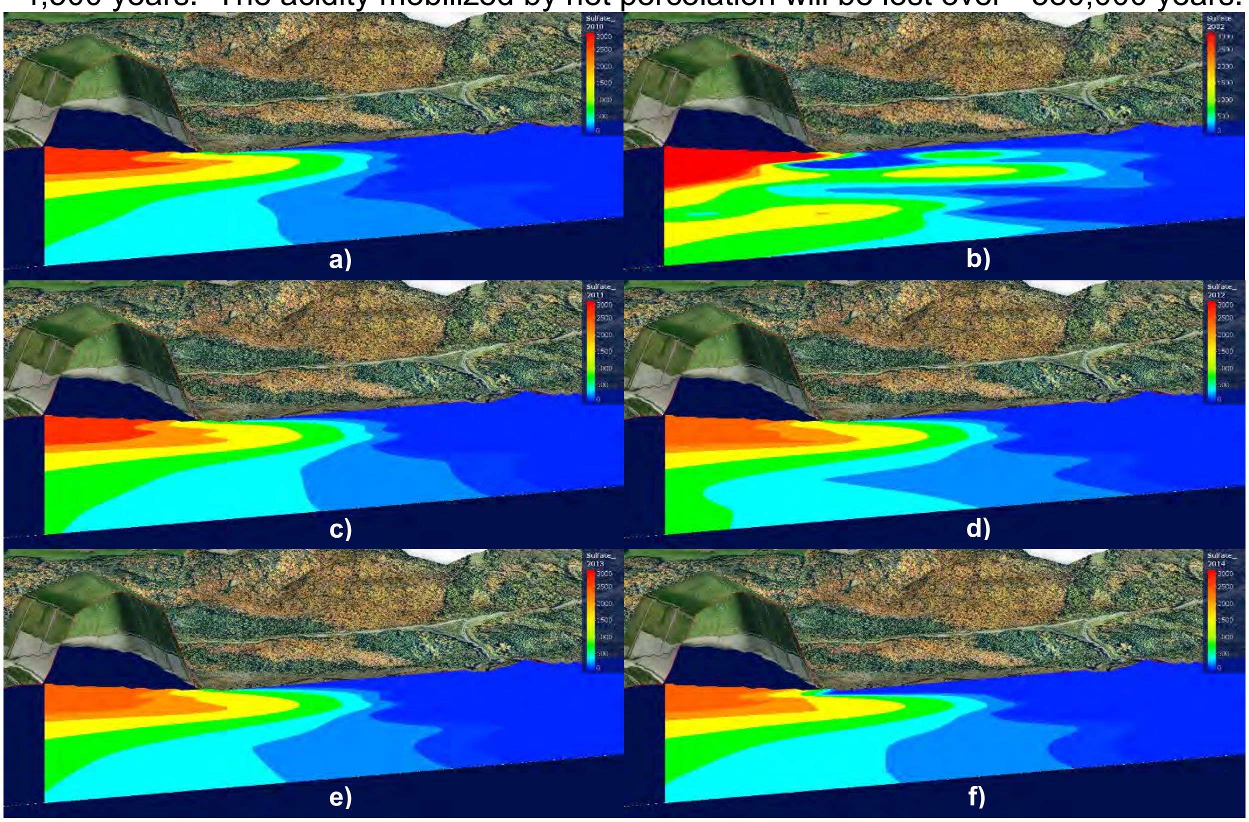

Figure 8. Groundwater sulfate plumes: a) 2002, b) 2010, c) 2011, d) 2012, e) 2013, f) 2014.

3. NET PRESENT VALUE

The mining industry is frequently challenged with the choice to either treat in perpetuity or undergo reclamation activities to manage ARD/ML generating waste. The VJ site operated with active water treatment for more than 30 years prior to reclamation and provides a unique opportunity to evaluate the decision to engage in reclamation. Comparing the two alternatives requires an analysis such as net present value (NPV), a tool often used to quantify closure costs by discounting future cash flows to a common denominator.

An NPV analysis for VJ was completed beginning in 2006 for both the treatment and reclamation alternatives for a 100 year period. Due to the time value of money, a 100 year period is essentially the same as in perpetuity (Phillip and Myers, 2003). Closure costs are typically quite difficult to forecast in the early stages of mine closure planning. Future costs for VJ for both the treatment and reclamation scenarios were based on past operating and maintenance expenditures. This provides a good estimate of future costs, although there are still many assumptions and variables such as discount rate, changes in the price of commodities, and actual improvements observed in the receiving environment. The NPV for each scenario under different discount rates is presented in Table 1. Although the treatment scenario has a lower NPV at a 4% discount rate, one must consider the risk (i.e. probability and impact) of each scenario, both from a financial and environmental stand point. For example, the load generated from the site under each scenario are significantly different, each with their own unique financial and environmental risks. In the conceptual model it was demonstrated that under active treatment approximately 49% of the basal seepage load was collected and treated. It is likely that water quality in the receiving environment would have taken a different trajectory than the cover system scenario given the acid load mass balance. The conceptual model also shows that a system failure under the treatment alternative would have a much greater impact to the receiving environment, and therefore financial impact, with an acid load generation of 894 t/yr compared to 43 t/yr in the reclaimed alternative. Although the NPV analysis has many assumptions, the decision to install the cover system was obviously not solely dependent on NPV. The goal of site closure was to minimize cost while mitigating risk.

It is also important to note that if the discount rate was reduced to say 1%, the difference between NPVs for the two scenarios would be substantially different, with the collect and treat option being substantially higher. The key point to highlight in making this comparison is that hindsight perspective for the VJ WRP closure activities provides a good argument for discount rate being an output from an NPV analysis, and to use this understanding to inform risk, rather than how discount rate is typically utilized (i.e. as an input to NPV analysis).

Table 1. Net present value for collection and treatment in perpetuity, and reclaimed WRP.

Discount Rate (%)	Treatment ($)	Reclaimed WRP ($)

1	29.5M	16.1M
2.5	17.0M	14.6M
4	11.2M	13.8M

4. CONCLUSION

An understanding for current and long-term loading to the receiving environment was developed through the use of a conceptual model. The VJ site has transitioned from active to passive treatment following placement of a low flux cover system, with continued improvements observed in the receiving environment and a reduction in loading from the WRP. Although the reclaimed WRP had a higher NPV (4% discount rate) than treating ARD/ML affected water in perpetuity, loading to the receiving environment was reduced, and environment and financial risks were mitigated.

The total acidity in the VJ WRP is estimated to be lost over 580,000 years, assuming that cover system performance can be maintained over the long-term. While there is variability in the estimated lifespan of the geomembrane layer, it is likely far less than the time required to release the total acidity in the WRP. Degradation of the geomembrane is inevitable, both in the short-term during initial placement procedures, and over the long-term due to service stresses, anthropogenic activities, animal bioturbation, and the effects of vegetation, leading to increased net percolation and therefore loading to the receiving environment. It is imperative that cover systems that incorporate a geomembrane layer are designed to consider the effects of short and long-term degradation to reduce the risk of increased load to the receiving environment.

A well-designed monitoring program is critical to the conceptual model and requires sufficient information is collected, both spatially and temporally. While groundwater flow and contaminant transport numerical modeling is commonly used in predicting long term impacts to the receiving environment, it was not required in this instance given the conceptual model and site information. This case study illustrates the importance and opportunity for using the conceptual model to communicate performance and risk, and ultimately inform management on decisions regarding site practices in order to meet closure objectives.

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