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ARTICLE

Analyzing variation of the water table level with three-dimensional numerical simulations to assess reclamation techniques for an acidic tailings impoundment

Stefan Broda, Marie-Pier Éthier, Daniela Blessent, Michel Aubertin, Abdelkabir Maqsoud, and Bruno Bussière

Abstract: Tailings with sulphide minerals exposed to oxygen and water can oxidize and produce acid mine drainage (AMD). This study evaluated the impact of natural conditions and of a thin cover deposition on the water table level, with respect to selecting the reclamation technique to control AMD on the elevated portion of an abandoned tailings impoundment. The reactive tailings were partly covered with alkaline tailings transported as a pulp from a nearby mine. A three-dimensional numerical variably saturated groundwater flow model of the tailings impoundment and its surrounding area was built. The simulation results reproduced well the field observations before, during, and after the deposition of a thin layer of tailings. The calibrated model was then used to forecast the evolution of the water table position for the next 100 years under various site conditions, including a period of 5 years with dry summers. The results show that the water table levels are on average several metres below the interface between the reactive tailings and the cover, thus failing to meet the target criterion to control the production of AMD determined from previous column tests. The results are analyzed and discussed in terms of the site configuration and atmospheric recharge.

Key words: acid mine drainage (AMD), tailings, reclamation, elevated water table (ETW).

Résumé : Les résidus miniers sulfureux exposés à l'oxygène et à l'eau peuvent engendrer la production de drainage minier acide (DMA). Cette étude évalue l'impact de la déposition d'une couverture sur l'établissement d'une nappe phréatique surélevée (NPS) comme méthode de contrôle du DMA sur un parc à résidus miniers abandonné. Les résidus réactifs ont été recouverts partiellement par des résidus alcalins sous forme de pulpe provenant d'une mine voisine. Un modèle numérique tridimensionnel d'écoulement souterrain à saturation variable du parc à résidus et ses environs a été construit. Les résultats de ces simulations reproduisent bien les niveaux phréatiques observés avant, durant et après la déposition des résidus. Le modèle calibré a ensuite été utilisé pour prédire l'évolution du niveau phréatique pour les 100 prochaines années et dans le cas de périodes estivales plus sèches. Les résultats ont montré que la nappe phréatique serait en moyenne plusieurs mètres sous l'interface entre les résidus réactifs et le recouvrement, soit nettement sous la cible permettant de contrôler la production de DMA selon des essais antérieurs. Les résultats sont analysés et discutés selon la configuration du site et la recharge atmosphérique.

Mots-clés : drainage minier acide (DMA), résidus miniers, restauration, nappe phréatique surélevée (NPS).

1. Introduction

Sulphidic mine tailings exposed to water and oxygen can oxidize and produce acid mine drainage (AMD), which may adversely impact water quality on and beyond the disposal site. Different reclamation techniques can be applied on such tailings impoundments to control and prevent the generation of AMD. The applicability of the available techniques is closely related to climatic conditions (e.g., Aubertin et al. 2002, 2016).

Water infiltration barriers, which serve to prevent water inflow in the reactive tailings, are mostly efficient in arid to semi-arid climates. Water percolation can be prevented by adding low-permeability materials, such as compacted clay layers, geomembranes, and geosynthetic clay liners, on the surface.

An oxygen barrier is preferably adopted in humid climates (Aubertin et al. 2002, 2016). The cover design can then take advantage of the low oxygen diffusion coefficient in water or nearly saturated porous media to limit oxygen ingress to the tailings (Mbonimpa et al. 2003). Installation of water covers or covers with capillary barrier effects as well as maintaining an elevated water table (EWT) are the main techniques available to impede transport of oxygen to reactive tailings. Water covers have been applied in the past, but their use is generally decreasing, in part because of the serious concerns regarding the long term-behavior

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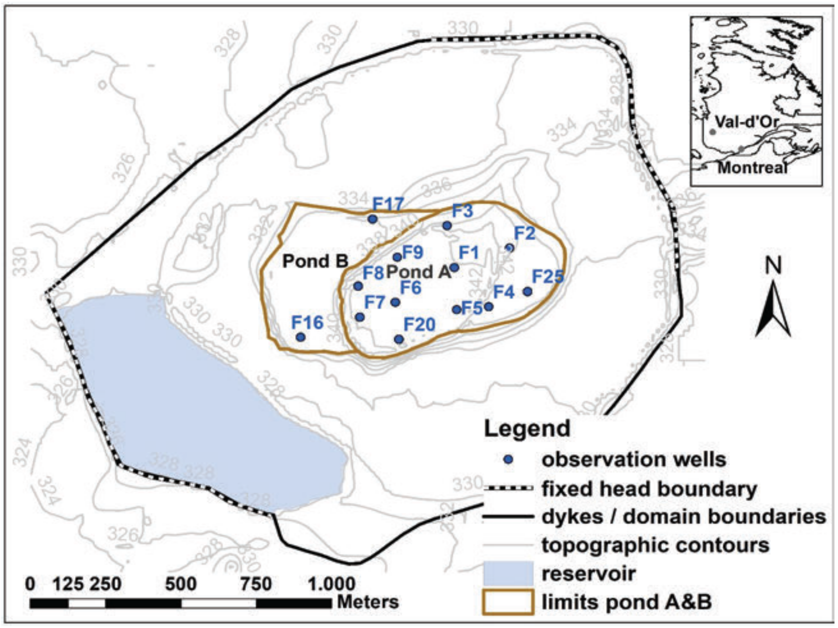
Fig. 1. General location within the province of Quebec (inset) and surface map of Manitou tailings site, with location of monitoring wells used in this study and model boundaries. (Figure was created using ArcMap version 9.2 and assembled from the following data sources (shapefiles): observation wells (Bussière et al. 2009*c*); dykes/domain boundaries, topographic contours, reservoir (Agnico Eagle Mines Ltd.); base map (NGA 2001).) [Color online.]



and stability of the retaining dykes needed to maintain the tailings in a submerged condition (e.g., Aubertin et al. 1997, 2011, 2016; Kossoff et al. 2014). Other problems related to water covers include tailings resuspension and oxygen mixing that can enhance the production of sulphide oxidation and, consequently, the production of AMD (e.g., Catalan et al. 2000; Adu-Wusu et al. 2001; Awoh et al. 2014).

The basic principles and effectiveness of covers with capillary barrier effects (CCBE) acting as an oxygen barrier to control oxidation of sulphidic tailings were investigated by Rasmusson and Erikson (1986), Nicholson et al. (1989), Barbour (1990), Yanful (1993), Yanful et al. (1993*a*, 1993*b*), and Aubertin et al. (1994, 1995). Numerical simulations, large-scale laboratory experiments, and field observations have confirmed the potential efficiency of CCBE while also highlighting the impact of site-specific factors such as the major effect of a sloping surface on the performance of layered cover systems (Aubertin et al. 1997; Ricard et al. 1997, 1999; Bussière et al. 2002, 2003, 2006; 2009*a*; Maqsoud et al. 2009, 2011). These investigations have shown that properly designed and constructed covers can be quite efficient. Accordingly, these have become commonly applied for the control and reclamation of reactive tailings impoundments under humid climatic conditions (Dagenais et al. 2005; Aubertin et al. 2006, 2016; Bussière 2007). However, CCBEs often raise significant challenges, such as materials availability, long-term performance, maintenance, and vegetation impact.

An effective and economic alternative for the closure of tailings ponds under humid climatic conditions is the EWT technique (MEND 1996; Aubertin et al. 1999; Dagenais 2005; Dagenais et al. 2006; Ouangrawa et al. 2006, 2010; Pabst 2011; Ethier et al. 2018*a*, 2018*b*; Pabst et al. 2018). The goal of this method is to raise or maintain the water table at a position allowing the reactive tailings to stay at a sufficiently high degree of saturation (S_r) to prevent sulphide oxidation. Tailings are saturated below the water table and can be maintained at a high degree of saturation in the lower part of the capillary fringe to effectively limit oxygen diffusion. These processes can be observed in natural systems as well (Hendry et al. 1986).

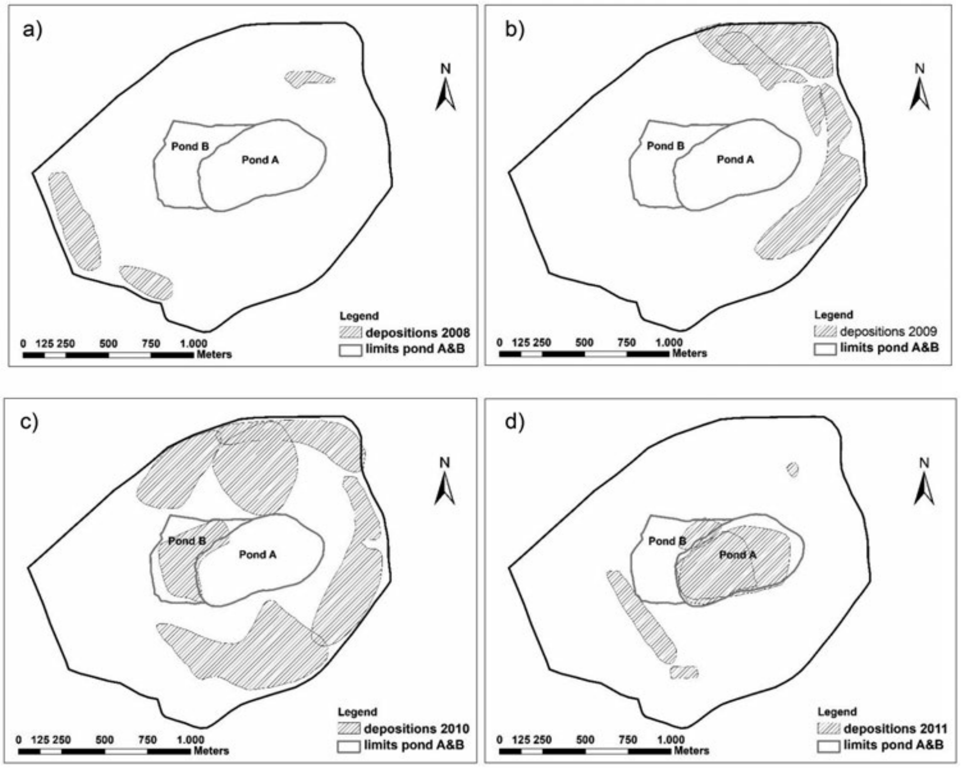
Three basic approaches have been identified to raise the elevation of the water table and increase the capillary rise within tailings (MEND 1996): (*i*) modifying the water balance of the impoundment (i.e., increasing water input to or decreasing water losses from the tailings), (*ii*) enhancing the water-retention ability of the tailings (i.e., enhancing physical characteristics of the tailings to increase their air-entry value (AEV)), and (*iii*) constructing groundwater flow barriers within the tailings (i.e., reducing horizontal and often preferential downgradient flow within the tailings) to limit the outflow.

In recent years, the EWT technique has been investigated through a series of laboratory column tests to assess its potential regarding the control of AMD. For instance, Dagenais (2005) showed that a high degree of saturation could be obtained and maintained during dry periods of up to 60 days when the tailings are placed under a single layer of coarse-grained material. Ouangrawa et al. (2006, 2010) conducted long-term (500 days) column tests on unoxidized (fresh) tailings, which showed that the EWT technique leads to maximum efficiency when the water table depth below the reactive tailings remains less than about one-half of the tailings' AEV. These tests and associated numerical simulations further showed that the performance of the EWT technique can be improved by lowering the saturated conductivity of the tailings and increasing their AEV (Ouangrawa et al. 2009). The importance of the cover material added on top of the tailings to favor water infiltration and limit evaporation during dry spells was also shown from the results of studies by Dagenais et al. (2006) and Cosset and Aubertin (2010).

The specific study described in this paper was conducted to systematically evaluate if the EWT technique was appropriate for the most elevated areas of the abandoned Manitou tailings disposal site. Simulations were conducted at the field-scale using a three-dimensional (3D) numerical variably saturated groundwater flow model. The results presented here were part of the analysis conducted to help select the reclamation technique for the specific area of the Manitou tailings site.

An agreement was made between the site owner and the nearby operating Goldex mine so that the slightly alkaline Goldex tailings

Fig. 2. Goldex tailings zones of deposition between (*a*) 2008, (*b*) 2009, (*c*) 2010, (*d*) 2011 and approximated affected surfaces.



could be deposited as a slurry (with process water) on the old Manitou site. Deposition events of Goldex tailings took place between 2008 and 2011. The 3D numerical model was constructed and calibrated with (rarely available) monitoring data collected before, during, and shortly after deposition events (which include seasonal variations). The simulations to assess the position of the water table in the long term (100 years) were performed using two different sets of material properties and four precipitation scenarios, based on the characteristics of Manitou tailings sampled in the field and on regional climatic parameters. The simulated water level position was compared with the elevation target developed from large-scale laboratory column tests, to prevent the production of AMD in the Manitou tailings.

2. Site description

The Manitou mine site is located about 15 km east of the city of Val-d'Or in the Abitibi-Témiscamingue region of the province of Quebec, Canada (Fig. 1). This zinc, copper, gold, and silver mine (which was abandoned in 1979) produced nearly 11 million tonnes of tailings, which were deposited in ponds that ended up covering up to 191 ha (including uncontrolled deposition and spilling areas). Due to their significant sulphide content, these tailings are highly acid-generating (Aubertin et al. 1999; Pabst 2011) and have had a strong impact on surface water, groundwater, and local ecosystems.

Following an agreement with the Ministry of Natural Resources (MRN) of the province, which manages this abandoned mine site, neutral tailings from the Goldex mine (Agnico Eagle) were deposited on the acid-generating Manitou tailings (Émond et al. 2011). New dykes were also constructed around the site to retain the freshly deposited tailings (and water). One of the goals was to raise the water table near or above the neutral–reactive tailings interface to inhibit sulphide oxidation.

Various laboratory tests were performed on the reactive Manitou tailings (both unaltered and already oxidized by years of exposure) and non-reactive Goldex tailings (produced at a new mine). The column tests included in the experimental program aimed at evaluating different reclamation scenarios indicated that the water table must be located very close to the surface of the Manitou tailings, under a layer of Goldex tailings, to progressively improve effluent quality (Demers et al. 2013). Pabst (2011) also showed that a monolayer cover may be ineffective in limiting sulphide oxidation when the water table is located below the Manitou–Goldex tailings interface (see also Pabst et al. 2014). The higher water table target for Manitou tailings, compared with other sites (e.g., Dagenais et al. 2006; Ouangrawa et al. 2010; Rey et al. 2020), can be related to the pre-oxidation and past contamination at the site and to the very high reactivity of the sulphidic tailings after decades of exposure.

At the field scale, the efficiency of the EWT technique is evaluated by means of hydrogeological and geochemical monitoring programs. A study of a mono-layer cover of Goldex tailings added on a lower portion of the Manitou tailings site showed good performance with respect to controlling AMD production. The water table levels on this section of the site, with a lower elevation, generally reached the target elevation, i.e., the interface between the Manitou and Goldex tailings, so the oxygen flux is well controlled (Bussière et al. 2011; Ethier et al. 2013, 2018*a*, 2018*b*).

The work presented here focussed specifically on the most elevated part of the tailings disposal facility, near the center of the domain (Ponds A and B in Fig. 1), to evaluate the long-term position of the water table and assess if it could be raised sufficiently and maintained at the targeted elevation in the long term. During the preliminary phase of the project, some of the reactive tailings were covered by neutral tailings from the Goldex gold mine, which were transported hydraulically (with a pulp density of about 50% solids) through a 24 km long pipeline system to the Manitou site and deposited by single point discharge or spigots. Thirty observation wells were installed within the tailings ponds and the surrounding environment in 2008 and 2009 to monitor

Fig. 3. Atmospheric precipitation and tailings-induced water recharge on the elevated tailings area. [Color online.]

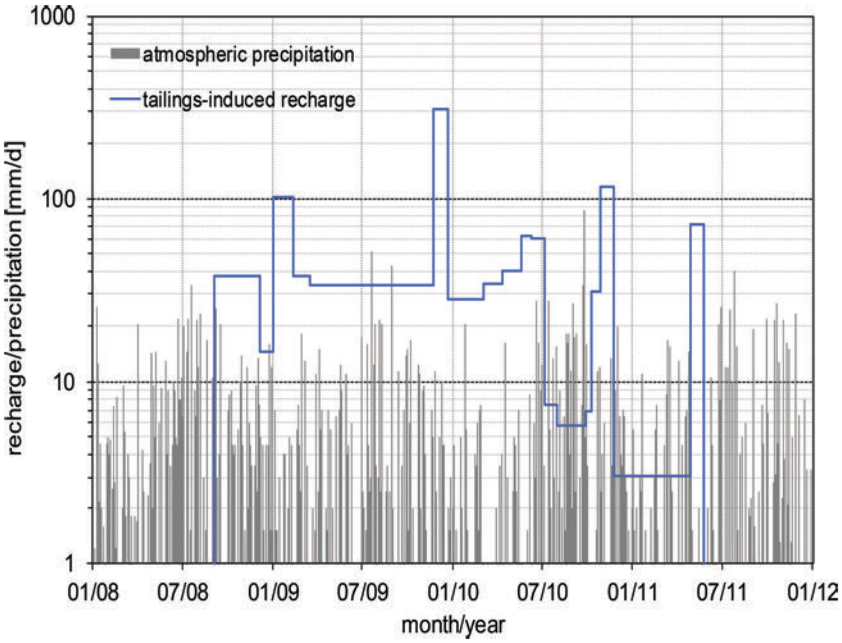
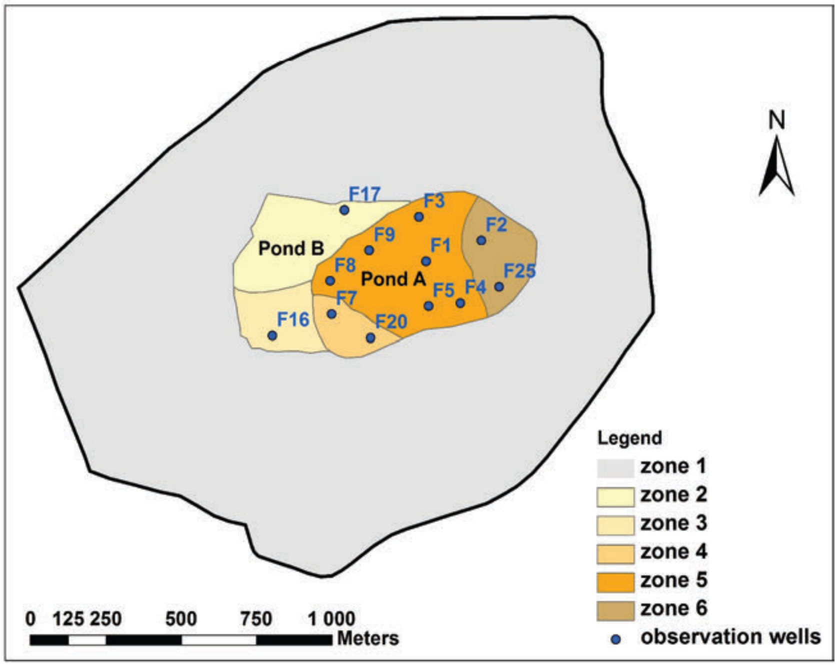


Fig. 4. Identification of the different hydraulic conductivity zones in the calibrated model for the elevated tailings area. [Color online.]



the pore-water pressure heads over time (Bussière et al. 2009*b*; Maqsoud et al. 2016). Groundwater levels in the observation wells were logged at 6 h intervals with Micro Divers (Schlumberger). In total, 12 observation wells installed in the elevated area of the impoundment (Ponds A and B, covering an area of 42 ha) were considered for this study (Fig. 1). The period between 2009 and 2012 provided the field monitoring data used here.

Precipitation data were retrieved from the Val-d'Or meteorological station located 7 km from the site (Environment Canada 2013). The average yearly precipitation amounts to 914 mm, which are proportionally lower in the winter months, while the yearly potential evaporation amounts to 490 mm. The minimum and maximum average daily temperatures are −17 °C (January) and +17 °C (July), respectively.

3. Model setup and calibration

The evaluation of the water table position over time was conducted using the HydroGeoSphere code (Therrien et al. 2010), a fully-integrated 3D finite element subsurface and surface flow and transport model based on the Richards' equation to represent variably saturated groundwater flow (Therrien and Sudicky 1996).

The finite element numerical domain, covering 260 ha, was discretized into, on average, 10–20 m in the *x*- and *y*-directions.

Vertically, the domain was made of 13 layers of variable thicknesses, increasing gradually from 0.1 m at the soil–atmosphere interface to 20 m at the base of the model. This resulted in a mesh with 69 062 nodes and 125 866 prismatic elements.

Along the northeast and southwest domain boundary, a fixed-head condition, located 0.5 m below the surface, was applied (black and white dashed line in Fig. 1) to reproduce the observed regional groundwater level and hydraulic gradient. The remaining domain boundary, i.e., perimeter dykes in the real world, was defined as impermeable. Furthermore, the reservoir was represented as a fixed-head boundary condition set to an elevation of 327.5 meters above sea level (masl). The domain topography was based on a survey conducted in the summer of 2013; it thus included some of the Goldex tailings deposited over the previous years.

The base of the model domain was at 300 masl while the maximum elevation is at 343 masl (around observation well F1 in Pond A). The domain contained layers of rock, till, clay, and reactive tailings, each having a variable thickness ranging from 1 to 40 m, 0 to 6 m, 0 to 3 m, and 0.1 to 15 m, respectively.

The deposition of the neutral Goldex gold mine tailings began in September 2008 and was interrupted from November 2011 to October 2013 due to operational issues. The impact of the subsequent depositions, after October 2013, is not considered in this study. In total, 19 deposition events recorded within the model domain between 2008 and 2011 were implemented, at different locations and times. The final affected surface and the total tailings discharge is approximately known for each deposition event (see Fig. 2), so a tailings-induced water recharge per unit area can be calculated. The tailings discharge rate is assumed to remain constant throughout each individual deposition period for this calculation.

Figure 3 shows the atmospheric rainfall observed at the Val-d'Or meteorological station and the calculated tailings-induced recharge, highlighting the significance of the latter. While atmospheric precipitation is mostly below 10 mm/day, the water recharge originating from the tailings depositions (albeit on limited areas) can be an order of magnitude larger (or more) and long lasting (up to several weeks). All recorded precipitations have been converted to daily recharge, adopting a typical recharge/precipitation ratio of 30% for tailings in this region (Ricard et al. 1999; Nastev and Aubertin 2000; Leblanc 2010; Ethier et al. 2018*b*). The high elevation of the site favors wind erosion so there is little snow cover locally; the spring snowmelt has thus been neglected in the simulations (as is the presence of a frozen surface in the winter).

The saturated hydraulic conductivities of the tailings and soils were calibrated using the field data. One of the principal aims of the model calibration was to avoid overly complex material zonation and distribution. As a result, the rock, till, and clay layers have been considered homogeneous and isotropic throughout the domain. The tailings outside Ponds A and B were also considered homogenous and isotropic. Inside, a zonation was applied, with three zones in Pond A and two zones in Pond B, based on field observations (i.e., characterization tests performed on samples recovered during installation of the observation wells) and typical disposal methods. The central zone 5 (in Fig. 4), defined as anisotropic (see Table 1), corresponds largely to the most elevated area of the tailings pond.

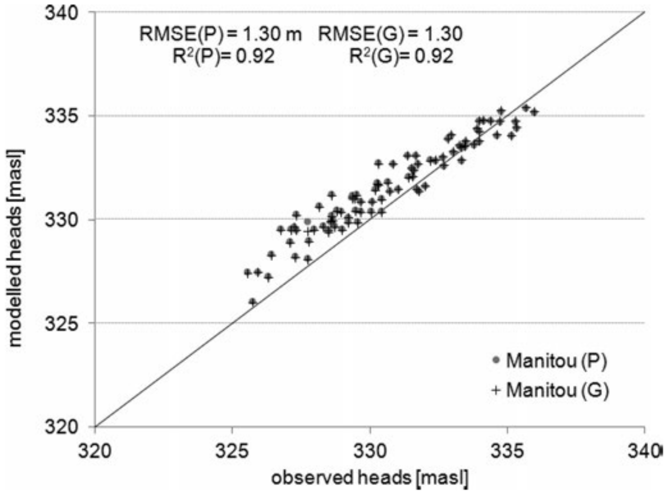
The numerical model parameters were calibrated manually for a (pseudo) steady-state condition using 90 piezometric head measurements taken at different periods over several years. For this calibration, an average constant recharge rate of 262 mm/year was applied, based on 30% of the average yearly precipitation, as indicated above. The results lead to a satisfactorily match, with similar statistical parameters for both Manitou tailings unsaturated zone characteristics (root mean squared error, RMSE = 1.30 m for the head, with coefficient of determination, $R^2 = 0.92$, see Fig. 5). The modelled heads are somewhat overestimated for the lower portion of the domain and correspond best to the observations at the higher elevations (the most critical locations for this study). Dispersion of the data can be attributed to the nature of the field measurements used for calibration (local measurements at various times, including dry and wet periods).

Table 1. Calibrated values for the horizontal hydraulic conductivity, K_h, and anisotropy ratio, K_h/K_v (where K_v is the vertical hydraulic conductivity); and porosity, *n*, of the soils and tailings (see Fig. 4).

	K_h (m/s)	K_h/K_v	n^*
Goldex tailings	7×10^{-07}	1.0	0.42
Manitou tailings			
Zone 1	2×10^{-6}	1.0	$0.45^P/0.35^G$
Zone 2	5×10^{-7}	1.0	$0.45^P/0.35^G$
Zone 3	9×10^{-6}	1.0	$0.45^P/0.35^G$
Zone 4	8×10^{-6}	1.0	$0.45^P/0.35^G$
Zone 5	4×10^{-6}	4.0	$0.45^P/0.35^G$
Zone 6	8×10^{-6}	1.0	$0.45^P/0.35^G$
Clay	1×10^{-8}	1.0	0.50
Till	1×10^{-5}	1.0	0.32
Rock	2×10^{-6}	1.0	0.02

*Superscript “P” refers to data from Pabst et al. (2014) and superscript “G” to data from Gosselin (2007) for the Manitou tailings.

Fig. 5. Calibrated steady state heads for the case with fine Manitou tailings (dots; P) and the coarser Manitou tailings (crosses; G), and corresponding root mean squared errors and correlation coefficients.



The calibrated saturated hydraulic conductivities are listed in Table 1. These calibrated values, used in other simulations, agree with typical properties of tailings (e.g., Bussière 2007) and of the corresponding soils (e.g., Chapuis and Aubertin 2003). To represent the on-site variability of the tailings grain-size distribution, two estimated sets of unsaturated zone characteristics, based on the van Genuchten (1980) hydraulic functions, have been used for the Manitou tailings (Fig. 6). One represents a finer grain size based on experimental data from Pabst (2011), hereafter identified as “P”, with an AEV of about 9 m; the other has a coarser grain size distribution, with an AEV of 2.2 m, based on data presented in Gosselin (2007), indicated by “G”.

Table 2 gives the material parameters for the water retention curves (WRCs) expressed through the van Genuchten (1980) equation. These parameters are in line with those of similar tailings (Bussière 2007). As the foundation materials layers (clay, till, and rock) remain saturated for most of the domain, their respective

Fig. 6. Water retention curves expressed using the van Genuchten (1980) equation for the Goldex tailings (dotted line), fine Manitou tailings (solid line; P) and coarser Manitou tailings (dashed line; G); the Manitou water retention curves are applied for all calibrated Manitou tailings zones.

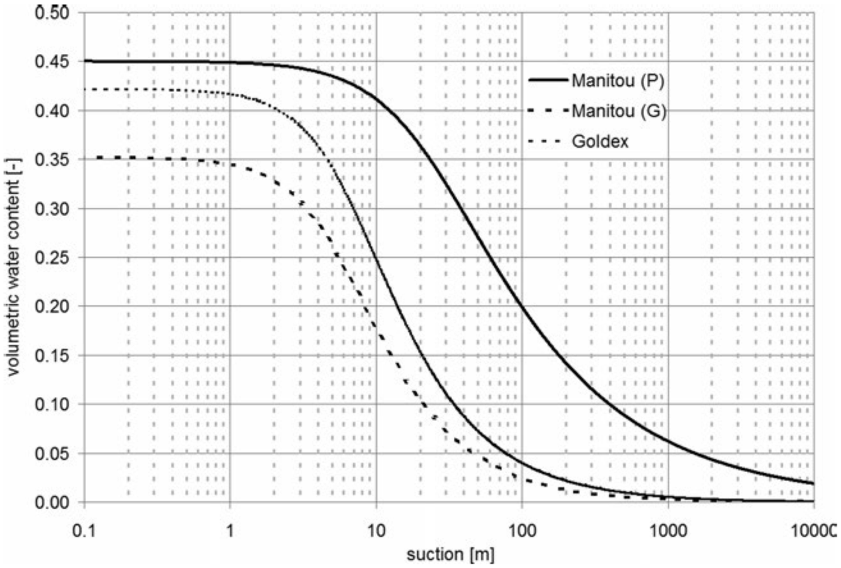


Table 2. Parameters of the van Genuchten WRC equation for the Manitou tailings (after Pabst et al. 2014 (P) and Gosselin 2007 (G)) and Goldex tailings.

	Manitou (P)	Manitou (G)	Goldex
θ_r	0.00	0.00	0.00
θ_s	0.45	0.35	0.42
α (m^{-1})	0.045	0.188	0.15
β	1.52	1.89	1.87
AEV* (m)	9.0	2.2	3.0

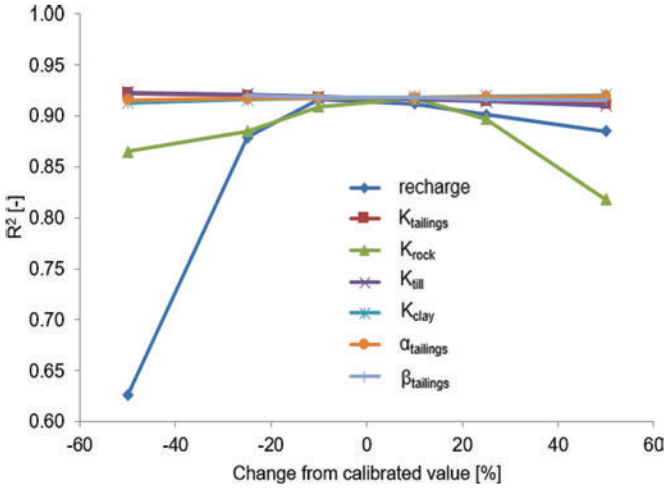
Note: θ_r, residual water content; θ_s, saturated water content; α and β, van Genuchten WRC model fitting parameters.
*AEV retrieved with tangent method.

water retention characteristics were not explicitly defined and the default setting of the HydroGeoSphere model was used.

A sensitivity analysis was conducted for the main calibrated parameters with the steady-state model to better understand and assess the impact of parameter variations on the calculated hydraulic heads, using R^2. Parameter values were modified from the parameter set of Tables 1 and 2. The values for each individual parameter were changed from −50% to +50% of the respective value of the calibrated model.

Results from this analysis, shown in Fig. 7, indicate that recharge and hydraulic conductivity of the bedrock have the most important effect on the modelled hydraulic heads. Reducing recharge by 50% caused a drop of R^2 to 0.63. However, an increase of 50% caused only a mild decrease of R^2 (0.89). Reducing the permeability of the bedrock by 50% resulted in a R^2 of 0.86 (R^2 = 0.92 in the calibration case), while increasing it caused a decrease of R^2 to 0.82. The modelled hydraulic heads appear to be much less sensitive to changes of the other tested parameters (hydraulic conductivity of the till, clay, tailings, and the van Genuchten WRC parameters).

Fig. 7. Sensitivity of the coefficient of determination to variations of the recharge, hydraulic conductivity (K) of the tailings, bedrock, till, and clay, as well as to changes of the van Genuchten WRC parameters α and β for the tailings. [Color online.]



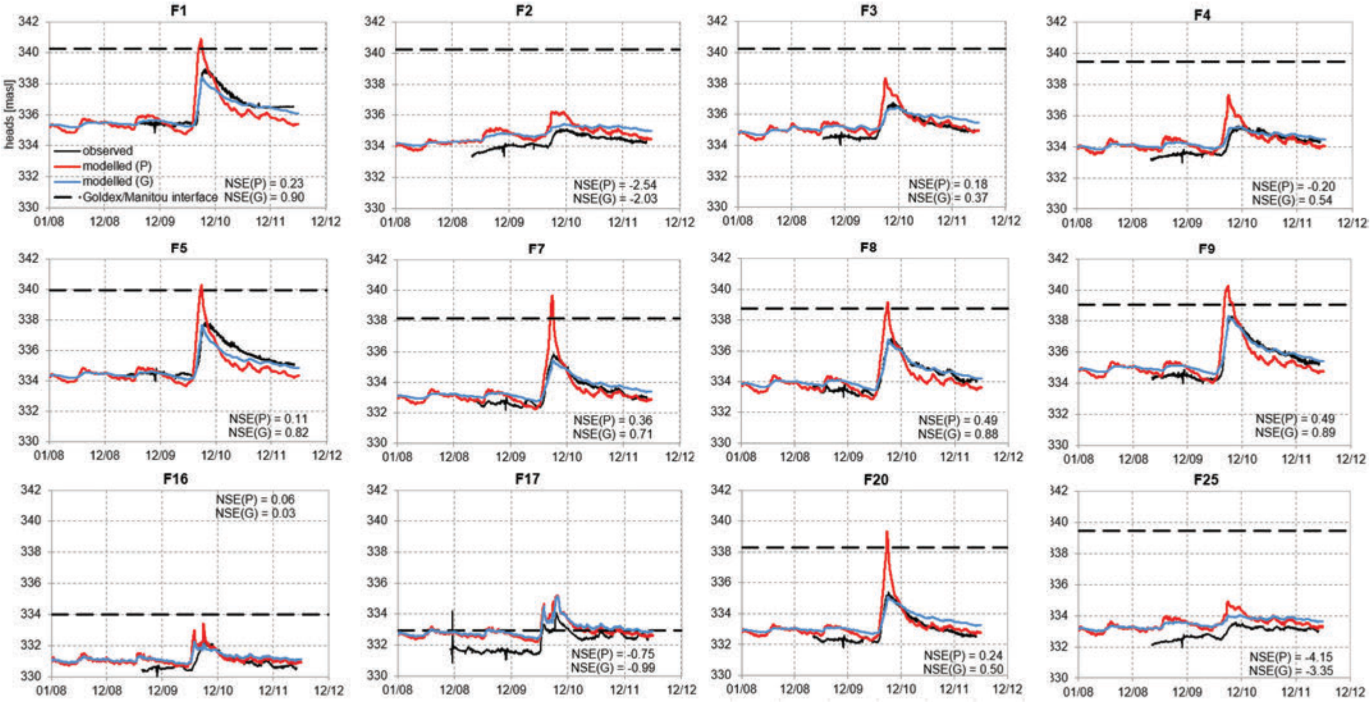
4. Transient simulation results and discussion

4.1. Comparisons with observed head variations

The model was first validated for the period going from January 2008 to June 2012 (shown in Fig. 3). The steady-state hydraulic heads obtained with the calibration runs with both sets of material parameters outlined above (Tables 1 and 2) served as the initial condition to simulate fluctuations during that time.

Overall, it was observed that the modelled piezometric heads capture the observations fairly well throughout the domain for the entire monitoring period, as seen in Fig. 8. This figure shows all 12 observation wells within the elevated tailings impoundment of Ponds A and B (with red and blue lines representing runs with van Genuchten WRC parameters for the P and G Manitou tailings based on Pabst et al. (2014) and Gosselin (2007), respectively). The results shown in Fig. 8 indicate that the fluctuations caused by atmospheric precipitation events are in the order of 10–20 cm and are best simulated with the G Manitou tailings characteristics (based on Gosselin 2007), while the run using the P tailings parameters (based on Pabst et al. 2014) lead to somewhat larger fluctuations. The generally stronger impact of the Goldex tailings deposition

Fig. 8. Observed (black line) vs. simulated (red (P) and blue (G)) piezometric heads, location of Goldex–Manitou interface at the observation wells, and Nash–Sutcliffe efficiency (NSE) for the respective modelled heads. The large peaks correspond to Goldex tailings deposition on the surface. [Color online.]



events on the groundwater head evolution is also captured quite well with both sets of simulations, with transient fluctuations of up to 4 m (head increase), particularly during the summer and fall of 2010. At all observation wells, there is an initial rise induced by the tailings deposition, which is somewhat overestimated by the model using the P tailings WRC. Each initial rise is followed by a slow decrease toward the original pre-deposition water pressure head; the modelled hydraulic heads then correspond well with the observations. Given the good match (particularly during the peak deposition period starting in late summer 2010; e.g., F3, F4, F7, F8, F9, F20) between the observations and the simulations using the G Manitou tailings WRC (for the coarser grain size), it was concluded that this model setup is representative for the Manitou tailings site. This is also supported by the Nash–Sutcliffe efficiency (NSE), commonly used to establish forecasting ability of hydrological models, which can range from a very low ($-\infty$) value up to 1 (perfect fit). NSE values below zero indicate that the mean observed value is a better predictor than the forecasting model, while the reverse is true for NSE above zero (Krause et al. 2005). Figure 8 indicates that the simulations with the P WRC for the Manitou tailings give a value of NSE > 0 at eight out of the 12 observation wells, while NSE > 0 applies for nine observation wells for runs with the G WRC. Generally, the NSE values for the simulations with the G WRC are consistently closer to 1 (except at F16 and F17) than results obtained with the P WRC. A systematic offset between simulated and observed values can be observed at some wells (e.g., F2). Using the individual offsets from the steady-state calibration to shift the modelled curves would result in an improved NSE.

Somewhat more significant deviations exist for some of the large deposition events using the P Manitou tailings characteristics, so the latter have been deemed less representative of the overall site conditions; these are nonetheless used below (together with the G Manitou tailings) for the longer term predictions.

Various factors can explain the observed discrepancies between the field measurements and simulation results, including the uncertainty related to the actual rates (considered constant, as only the total approximated amount of deposited tailings for a given period of time is known) and extent of the deposition surfaces (also known approximately), the difficulty in representing the in situ heterogeneity of the tailings in a numerical model (Chapuis et al. 1994; Bussière 2007), and the unknown seepage (observed) flow through the dykes and in underground openings (not considered here). In addition, some of the differences could also be due to the changing model topography at the beginning and at the end of the modelled period (with the latter being used for all the simulation period).

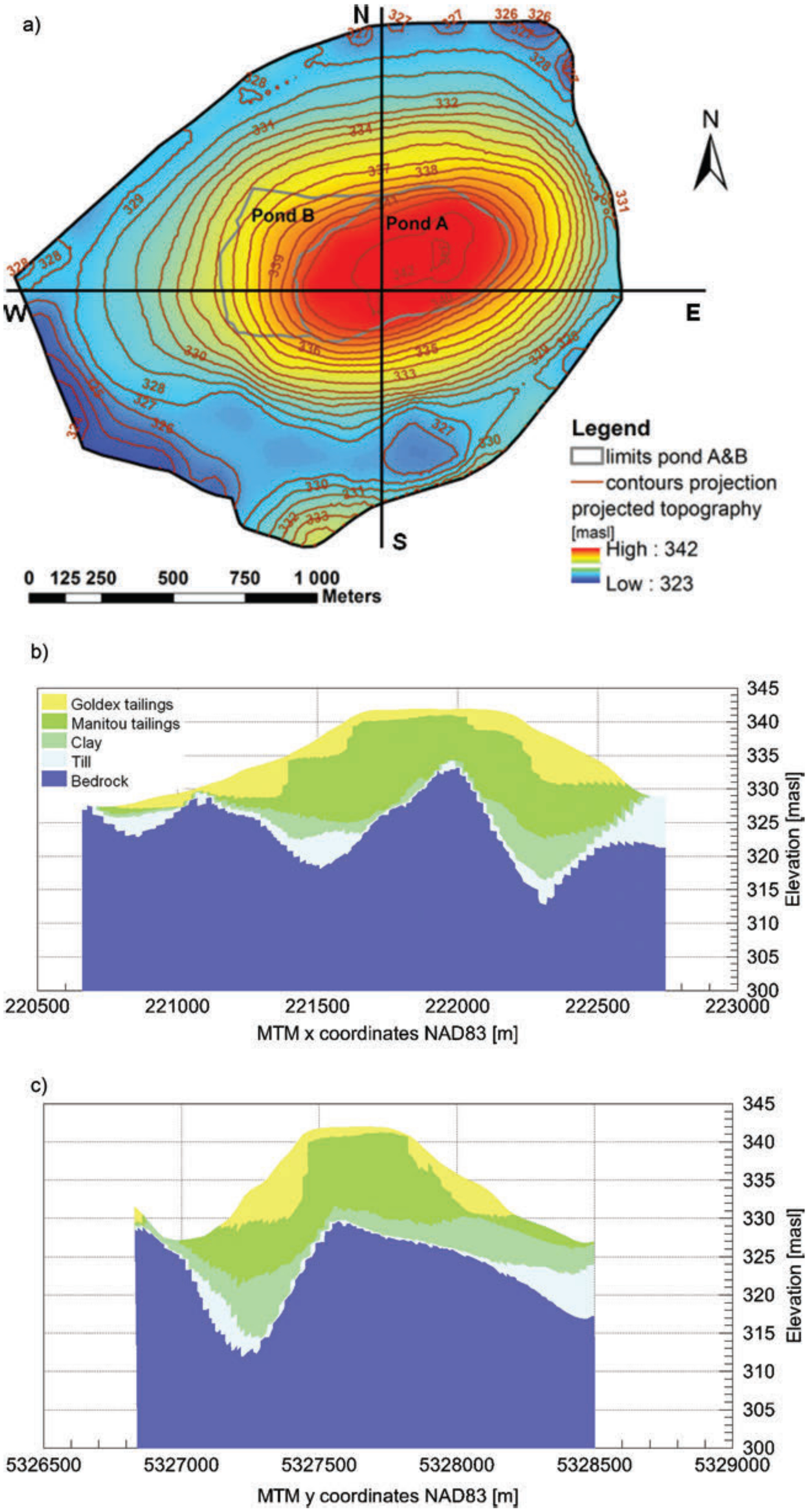
An important observation stemming from the simulations and field observations is that for most cases, the heads (before and long after the tailings deposition) are well below the Goldex–Manitou tailings interface (dashed lines in Fig. 8). The only exception is observation well F17, located at a lower elevation, where the water table remained close to the corresponding interface.

4.2. Long-term predictions

In a next step, long-term simulations were conducted. The basis for this prediction was the projected topography of the Goldex tailings on top of the Manitou tailings that was considered initially for the final stage of site reclamation (Figs. 9*a*–9*c*; based on Journeaux, Bédard et Assoc. Inc. 2004). The WRC of the Goldex tailings, with an AEV of about 3 m (see Fig. 6 and Table 2), is enveloped by the WRC of the two Manitou tailings (P and G) used in this study. Given the relatively small contrast of the tailings' WRCs, it was not expected that a monolayer cover made with Goldex tailings would induce a significant capillary barrier effect (Dagenais 2005; Pabst 2011) and the simulations conducted here confirmed this behavior.

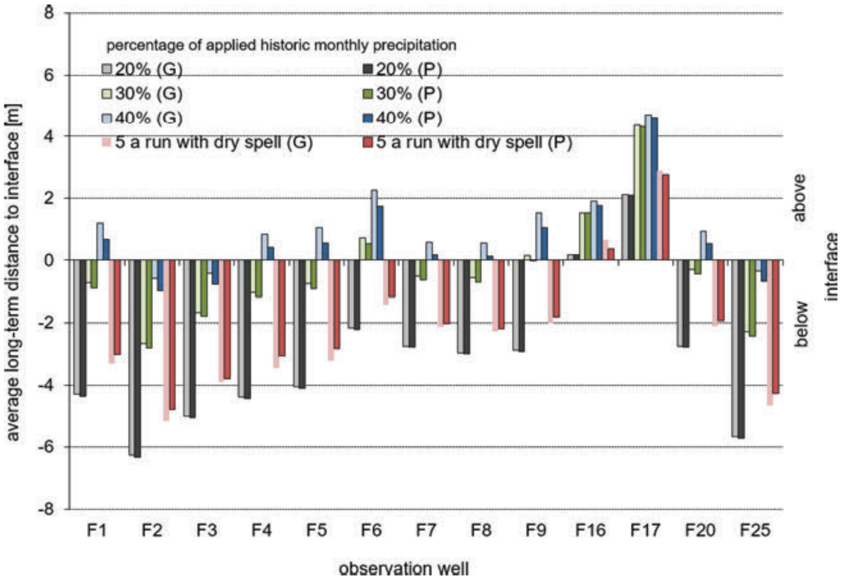
The initial hydraulic heads imposed were retrieved from the last modelling time step of the validation period (as described in the section above) using both model setups (i.e., P and G

Fig. 9. (*a*) Projected topography for site closure used for the long-term simulations; in this scenario, the Manitou tailings are covered by up to 10 m of Goldex tailings. Solid black lines indicate location of (*b*) W–E and (*c*) N–S cross sections. MTM, Modified Transverse Mercator (NAD83 / MTM zone 9). [Color online.]



Manitou tailings WRC). The model topography was however adapted according to Fig. 9. Three recharge scenarios were defined — 20%, 30%, and 40% of the monthly precipitation averages as the model input — based on the historic precipitation rates monitored at the Val-d'Or station. This resulted in three monthly recharge series for the simulations conducted over a period of 100 years. The most plausible recharge scenario is considered to be the 30% case.

Fig. 10. Average long-term distance from the water table to the Goldex–Manitou interface at all observation wells in Ponds A and B as function of the applied recharge rate (using 20%, 30%, and 40% of the monthly precipitation averages) for the simulations conducted with the fine (P) and the coarser Manitou tailings (G). [Color online.]



In addition, a 2 month dry spell in the summer was also included in one simulation (i.e., no recharge), run for a 5 year period, to investigate the effect of dryer summers.

Figure 10 shows the average predicted distance from the water table (based on simulated head) to the Goldex–Manitou tailings interface at the end of the calculations. It can be seen that for the cases with a recharge of 20% and 30% of the average precipitation applied on the model surface, the water table remains below the interface at most locations (independent of the WRC used for the Manitou tailings), with distances ranging from 0.5 m to more than 6 m. The only exceptions are observation wells F16 and F17, where the water table would remain above the interface, which is required for an acceptable performance of the EWT reclamation technique at the Manitou site (Demers et al. 2013; Pabst et al. 2014).

Increasing the percentage of precipitation reaching the aquifer would improve the situation; with a recharge of 40% of the precipitation, the water table could remain above the interface at 10 of the 12 observation wells. The use of averaged monthly precipitations in the simulations may however overshadow the effect of seasonal variations, which have been observed to reach up to 1.9 m (Ethier et al. 2014, 2018*b*); hence, even when the average pressure head reaches the interface, it can be expected that the water table could descend well below the critical level during dry spells.

This tendency was confirmed by the simulation that included 5 years without recharge during the summer (July and August) and 30% recharge for the remainder of the year (light and dark red bars in Fig. 10). It is seen that the average water table location is significantly lower, exhibiting the vulnerability of the EWT reclamation technique to dry periods for this higher topography.

5. Conclusion

In this study, the long-term position of the water table on an elevated tailings pond was evaluated by means of a 3D numerical groundwater flow model. The water retention characteristics of the Manitou tailings used here correspond to a rather fine grain size (P) and a coarser grain size (G) distribution, being representative of the typically highly variable granular composition on the Manitou site. It was shown that the numerical model was capable of reproducing field observations including periods of heavy tailings deposition, with better results obtained using the WRC of the coarser fraction of the Manitou tailings.

Predictions were executed based on a projected topography of the mine site and local climatic conditions. Albeit attractive for the lower portion of the Manitou site (not a subject of this work), the realistic scenarios considered here, including one with a 2 month long dry summer period, predicted a water table level too low to obtain a good performance of the EWT technique to control AMD production. The water table level would often be well below the interface between the Manitou and Goldex tailings, which is the condition required to control AMD production from the highly reactive and partly pre-oxidized Manitou tailings. The limitations of the EWT method for the elevated portion of the Manitou site are caused by the site configuration and limited atmospheric recharge.

This large-scale investigation of a tailings disposal site includes many original aspects including short-term simulations of deposition events of tailings and process water to assess their impact on the water table level. The use of a calibrated hydrogeological 3D model, based on field measurements, to predict the long-term response of the site with the position of the water table is also an innovative approach for evaluation of whether the EWT is applicable on this portion of the tailings disposal site. It should be noted that, despite calibration in the steady state, the model adequately represented the reality during transient runs. This work furthermore complements the paucity of studies dealing with the potential field application of the EWT reclamation technique. Such numerical hydrogeological modeling can also be applied to analyse the behavior and performance at other sites and reclamation measures upon closure.

The main outcomes from this study were considered by the owner of Manitou site, who opted for another type of reclamation technique given the poor prospect revealed for the EWT on the elevated portion of the tailings pond. Additional simulations were conducted by Pabst et al. (2018) to assess other reclamation scenarios for the elevated area of Manitou site. The combination of these numerical predictions was quite useful for suggesting a final solution. Based on these investigations, it was suggested that the most appropriate reclamation technique for the elevated area (Pond A) should involve a CCBE; in situ experimental cells confirmed the capacity of a CCBE to maintain a high degree of saturation in its moisture-retaining layer when placed on top of Pond A (see Maqsoud et al. 2017). For the other zones, located at a lower elevation, an EWT with a monolayer cover made with the non-reactive Goldex tailings will be used (Ethier et al. 2018*a*, 2018*b*).

This study illustrates the limited potential of maintaining an efficient EWT for the relatively high elevation area of the Manitou tailings site, where highly reactive tailings have produced AMD for decades. In such a case, the water table level should be maintained at or above the interface between the Manitou and non-reactive Goldex tailings, to control the production of AMD, which is more difficult to attain than the 1/2 AEV depth usually targeted for un-oxidized or less reactive tailings.

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