A 3D numerical model to assess the performance of the reclamation measures for an abandoned mine site

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Abstract

Acid mine drainage (AMD) production by mine tailings can be mitigated with a monolayer cover and an elevated water table. This reclamation technique, which aims at using water saturation to limit the diffusion of oxygen, was implemented at the tailings storage facility 2 (TSF 2) of the Manitou abandoned mine site (Québec, Canada). It was observed through physical modeling of this reclamation technique with the Manitou tailings that a key criterion to stop AMD production is the water table level. A hydrogeological numerical model of the site was built to complement laboratory and field data and assess the reclamation performance according to different scenarios. This paper presents the setup and calibration of the 3D model of the Manitou TSF 2 site. Data was gathered from the 38 ha TSF through geophysical, geospatial, and drilling monitoring. A 3D hydrogeological model was built to perform simulations with a numerical variably-saturated groundwater flow model. The steady-state calibration and determination of the main parameters was achieved by comparing the hydraulic heads to average field measurements. A three year transient state analysis is presented here and compared to hydraulic heads measured at 13 field stations. The results are consistent with the field measurements.

Key words: Acid mine drainage, hydrogeological modeling, abandoned mine site, elevated water table, monolayer cover

Introduction

Mine tailings sometimes contain sulphide minerals that can oxidize in the presence of oxygen and water, and produce acid mine drainage (AMD). The AMD production may last hundreds to thousands of years in situ and can be very harmful to the environment.

An effective and economical technique to limit AMD production from tailings, notably under humid climatic conditions, is the implementation of an elevated water table (EWT) with a monolayer cover (SENES, 1996; Aubertin et al., 1999). This method consists of raising or maintaining the water table to an elevated position that will allow the reactive tailings to stay at a high degree of saturation, preventing sulphide oxidation because of the low solubility and low effective diffusion coefficient of oxygen in (nearly) saturated porous media. This reclamation technique has been investigated in the laboratory and numerical models (Dagenais, 2005; Ouangrawa, 2007; Demers et al., 2008; Ouangrawa et al., 2010; Pabst, 2011), but little field work has been conducted to assess the performance of this method.

In the last 25 years, the Manitou site has been studied extensively in order to find a viable and cost-effective reclamation technique that would stop the production of AMD (Aachib, 1997; Aubertin et al., 1999; Molson et al., 2008; Demers et al., 2009; Bussière et al., 2011; Émond et al., 2011; Demers et al., 2013; Pabst et al., 2014). Laboratory column tests were part of a recent experimental program to evaluate different reclamation scenarios. Their interpretation indicated that a water table located close to the surface of the Manitou tailings can progressively improve effluent quality (Pabst, 2011; Demers et al., 2013; Pabst et al., 2014). A field investigation was undertaken at the Manitou tailings storage facility 2 (TSF 2) abandoned mine site to evaluate the performance of the EWT reclamation technique (Ethier et al., 2013); the preliminary results are generally positive (Ethier et al., 2014).

One limitation of field monitoring is that it can only be performed on an implemented design under the prevailing climatic conditions at a site and over a tested period. In order to assess the TSF 2 cover's performance over a broader range of potential conditions, it is important to investigate the influence of factors, such as cover thickness, material properties, and changes in climatic variables, that cannot necessarily be directly evaluated through field monitoring. A numerical model simulating the hydrogeological behavior of the Manitou TSF 2 was developed for this purpose. This paper presents the site description, field monitoring data, numerical model setup and calibrations performed to evaluate the hydrogeological behavior of the Manitou TSF 2 reclamation scenario.

Site description and field monitoring data

Zinc and copper were produced at the Manitou mine between 1942 and 1979. During the operation, nearly 11 million tons of acid-generating tailings were deposited in poorly-confined ponds that cover up to 191 ha. The AMD generated over several decades has had a severe impact on the surrounding environment. TSF 2 is a 38 ha spilling area at the Manitou site. The technique selected to reclaim TSF 2 is an elevated water table with a monolayer cover made of tailings from the nearby Goldex mine. The deposition of Goldex tailings on TSF 2 was carried out in 2009; the fine-grained Goldex tailings are non acid-generating and slightly alkaline, and their thickness varies from 1.2 to 2.1 m.

A map of TSF 2 is shown in Fig. 1. The surface elevation of the cover decreases from 327.5 to 321.7 meters above sea level (masl) in the east-west direction. Thirteen observation stations were installed within the TSF 2. At these stations, from August 2012 to August 2015, groundwater levels were measured at six hour intervals using Mini-Diver pressure sensors (Schlumberger Inc.) in wellpoints. Volumetric water content and suction were also monitored at two different depths in the cover; i.e., at 20 cm from the top and 20 cm from the base of the cover (see Ethier et al., 2014 for details).

Specific information on the site geology and material properties was gathered through trenches, drillings, geospatial data, and results from previous studies (Bussière et al., 2011; Pabst, 2011). Twelve drill holes going 4 to 16 m deep were created throughout the TSF. In addition, 13 trenches were dug to gain more information on the cover's characteristics. The topography was determined from a survey conducted in the summer of 2012. A geophysical study was performed using electrical resistivity imaging (ERI) to gather complementary information on the in situ conditions. The electrical resistivity of soils depends upon effective porosity, degree of saturation, and resistivity of the water (Lesmes and Friedman, 2005). Such measurements give a more global picture (instead of a local view) of the site conditions including water distribution in the different strata, without disturbance. The geophysical data were collected using a Lund Imaging SAS4000 (ABEM Instrument) with dipole–dipole and Wenner protocols, using 5 m as the electrode spacing. Two pseudo-sections (i.e., 2D areas under the apparatus and where resistivity is measured) were analyzed (see Fig. 1) and the results allowed for differentiation between the bedrock, till, and clayey soils. More information on these tests results can be found in Ethier (2016). A 3D geological model was developed with GOCAD using the available information on the non-reactive Goldex tailings, Manitou tailings, and underground soil structure.

Precipitation data were retrieved from the Val D'Or meteorological station (Environment Canada, 2015). The average yearly precipitation amounts to 914 mm; the yearly potential evaporation is 490 mm; the average minimum and maximum daily temperatures are -17°C (in January) and 17°C (in July) respectively.

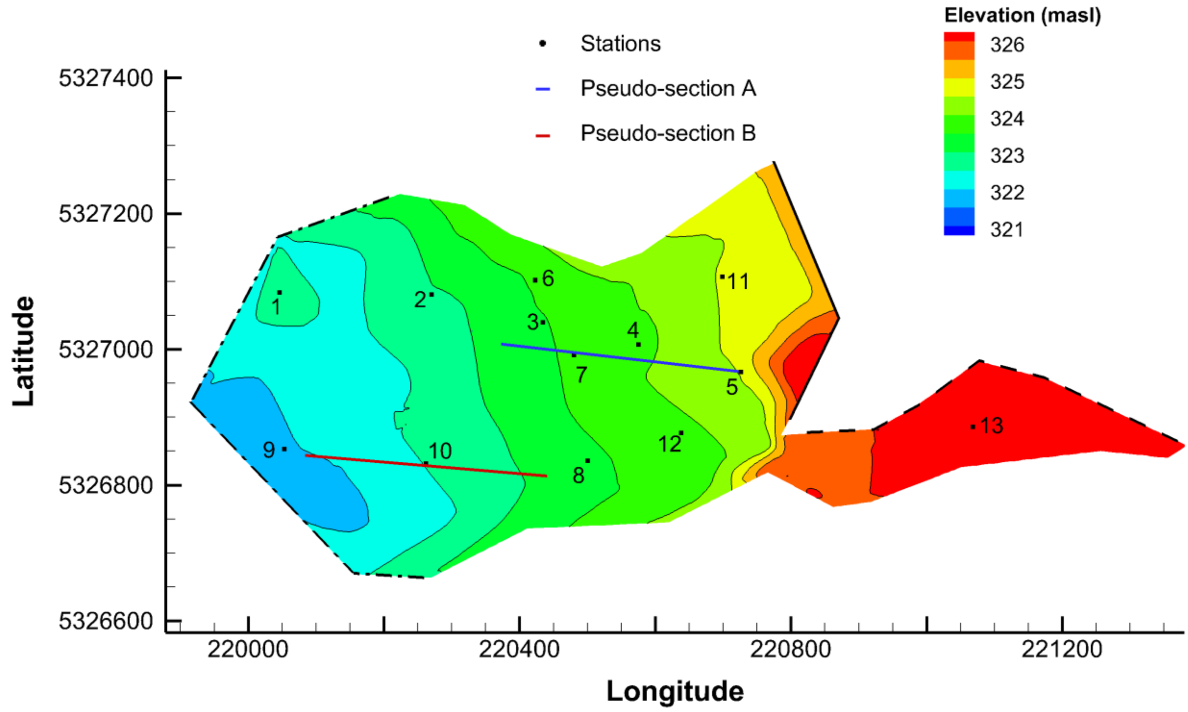


Figure 1 *Model configuration of the Manitou TSF 2 site, with the 13 measurement stations, the pseudo-sections for the geophysical surveys and the boundary conditions at 319 masl (dash-dotted line), 322.5 masl (thick plain line), and 323.5 m (dashed line).*

Model construction

The simulation of the water table position over time was conducted using the HydroGeoSphere code, a fully-integrated 3D finite element subsurface and surface flow and transport model based on Richard's equation to represent variably-saturated groundwater flow (Therrien and Sudicky, 1996; Therrien et al., 2010). This code was also used in previous studies to simulate unsaturated water flow within tailings (e.g. Carrera-Hernández et al., 2012; Broda et al., 2014; Ben Abdelghani et al., 2015). The finite element numerical x- and y- plan of the domain was discretized into 5 m wide elements. The total area is 44 ha. Vertically, the domain was made of 11 layers which gradually increased in thickness from 0.1 m at the soil-atmosphere interface to 3.33 m at the base of the model. The base of the model is at 305 masl, and the maximum elevation at the surface is 327.5 masl. This resulted in a mesh with 30 489 nodes and 60 227 prismatic elements. As illustrated in Fig. 2, the domain contains layers of rock, till, and clay soil below the Manitou tailings and the Goldex tailings cover layers.

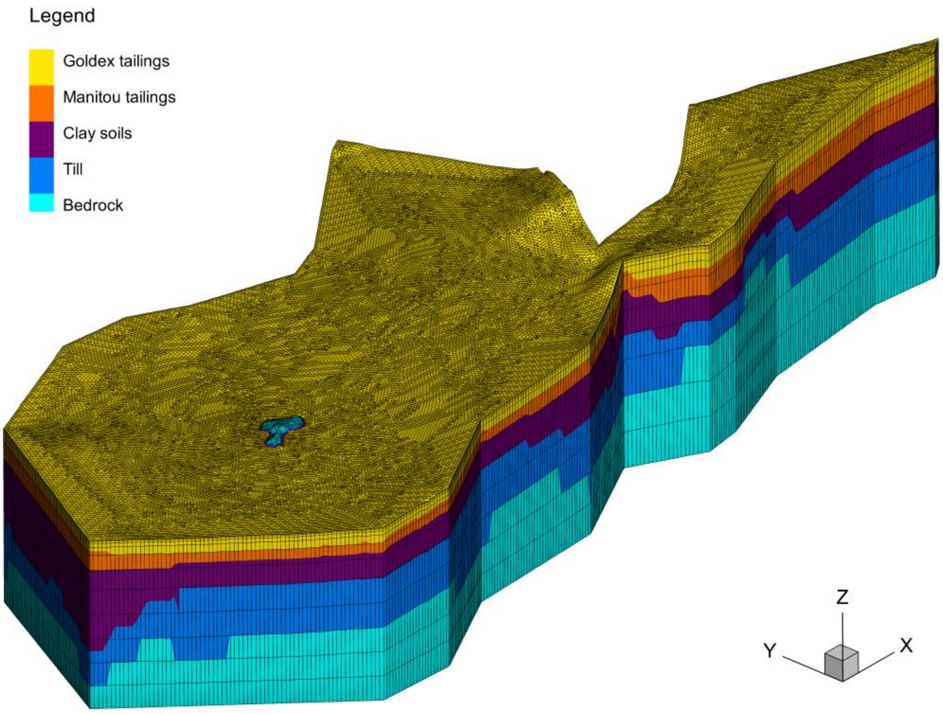


Figure 2 *Model configuration of the Manitou TSF 2 site constructed with HydroGeoSphere.*

Steady-state calibration

A calibration was performed under (pseudo) steady-state conditions, using the correspondence between simulated heads and average measured heads at each station. A recharge of 262 mm/year, which is approximately 30% of the mean annual precipitations, was applied. This ratio for recharge-precipitation is typical for tailings in this region and was used in other studies (Nastev and Aubertin, 2000; Leblanc, 2010; Broda et al., 2014).

As topographic slope is oriented East-West, flow is expected to mainly occur in this direction; domain boundaries in the North and South were defined impervious. Dirichlet type (fixed head) boundary conditions were set to an elevation of 319 masl in the West of the site, 322.5 m in the East of the site and 323.5 m at the North edge of station 13.

The calibrated parameters are listed in Table 1. These include, for each material, the saturated hydraulic conductivities (K) and porosities (n). Parameters α and β, which are related to the AEV and shape of the WRC respectively, were calibrated only for the Manitou and Goldex tailings. The rock, till, clay soils, and Goldex tailings were considered to be homogeneous and isotropic throughout the domain. Manitou tailings were considered anisotropic with a horizontal/vertical hydraulic saturated conductivity ratio (K_h/K_v) of 10, based on typical values for tailings impoundments (Vick, 1990; L'Écuyer et al., 1992). The calibrated values agree with previous studies (Gosselin, 2007; Demers et al., 2013; Pabst et al., 2014) and with typical properties of the corresponding soils (Chapuis and Aubertin, 2003). The unsaturated properties of the two tailings were defined with the van Genuchten (1980) model and the corresponding water retention curves are displayed in Fig. 3a. The air entry values of the Manitou and Goldex tailings are 2.2 m and 1.1 m of water respectively. Since the foundation layers (rock, till, clay soils) remain saturated for most of the domain, their respective water retention characteristics were not explicitly defined, thus the default values of HydroGeoSphere were used.

Table 1 *Calibrated values for the horizontal hydraulic conductivity (K_h) and porosity (n) of each material; α and β van Genuchten WRC fitting parameters and air entry values (AEV) for Goldex and Manitou tailings.*

Material	K_h (m/s)	n [-]	α [m-1]	β [-]	AEV [m]
Rock	2.E-06	0.02	3.5237*	3.1768*	0.16*
Till	8.E-05	0.32	3.5237*	3.1768*	0.16*
Clay soils	8.E-08	0.50	3.5237*	3.1768*	0.16*
Manitou tailings	2.E-06	0.46	0.188	1.89	2.2
Goldex tailings	7.E-07	0.42	0.15	1.87	1.1

*Default values of the code (not calibrated)

The model was calibrated in (pseudo) steady-state using the measured hydraulic head averages of 2012-2014 (see Fig. 3b). The line in Fig. 3b represents equality between modeled and observed results. The dispersion of the data can be attributed in part to the local seasonal variations of the hydraulic heads. The results are acceptable, with a root mean square error (RMSE) of 0.561 m for the head and an R^2 of 0.84.

Transient state predictions

A transient state simulation was performed to demonstrate the ability of the numerical model to predict the hydrogeological behavior of the Manitou TSF 2. Hydraulic heads from September 2012 to July 2015 were reproduced. Boundary conditions and material properties selected from the steady-state calibration were applied to the transient analysis.

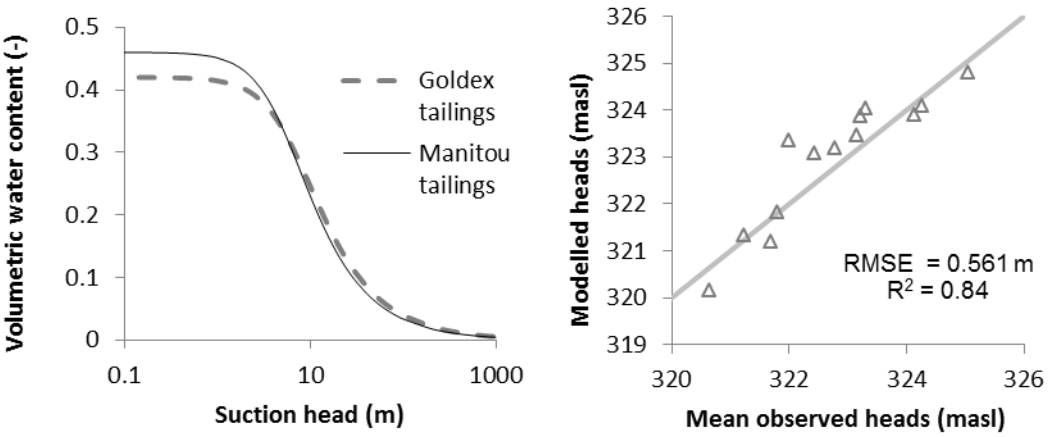
The day-degree snowmelt method was integrated into the simulation to model the dryer winter season during which solid precipitation (i.e., snow) occurs, and the spring snowmelt with a larger water supply. The degree-day method is a temperature index approach that relates the total daily melt to the difference between the mean daily temperature and a reference (freezing) temperature (in this case, 0 °C); the corresponding equation for snowmelt, M, can be expressed as follow:

$$M = C_M (T_a – T_b) \quad [1]$$

where C_M is the degree-day coefficient (mm/degree-day C), T_a is the mean daily air temperature (°C) and T_b is the base temperature (°C). The coefficient C_M varies seasonally and with the location; for this study, a typical value of 2.74 mm/degree-day Celsius was used (United States Department of Agriculture, 2012).

A recharge equivalent to 15% of the precipitation was applied for the period from June to August, while 30% was applied to the rest of the year. The fit between the model and field data was generally good with these parameters, except for days with heavy rainfall or heavy snowmelt (> 20 mm/d). For these more extreme conditions, which occurred 28 days over the simulated three-year period, the daily recharge was reduced to 15% of precipitation instead of 30%, while recharge due to snowmelt was halved to better represent field results.

Simulation results were compared with hydraulic heads measured four times a day over a three-year period (September 2012 - August 2015). Results are presented in Fig. 4 for four stations. For three stations (i.e., stations 3, 6, and 8 in Fig. 4), the match between the simulated and measured hydraulic heads is quite good. Winter and summer decreases, as well as spring and fall hydraulic head increase, are well captured by the model. The effect of the fixed-head boundary can be observed at station 9, which is close to the limit of the model. The variations of simulated head were dampened at this station and do not well represent observations during the wet period; nonetheless, the seasonal trends are quite well reproduced. The other stations were not affected by this condition so the fit is better and deemed satisfactory for additional numerical analyses with this model.



a b

Figure 3 *a) Water retention curves defined by the van Genuchten (1980) equation for the Goldex tailings (dashed line) and the Manitou tailings (solid line). b) Modeled vs. observed hydraulic heads (triangles), root mean square errors (RMSE) and correlation coefficient R^2.*

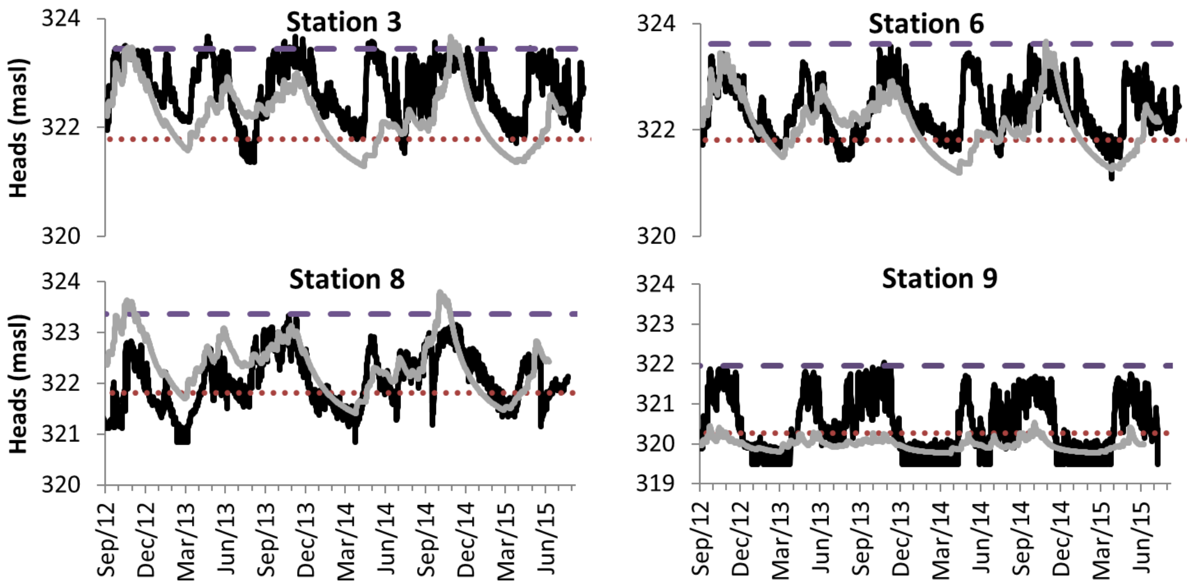


Figure 4 *Observed (black line) vs. simulated (grey line) piezometric heads and locations of Goldex/Manitou (dotted line) and Goldex/atmosphere (dashed line) interfaces at the observation wells 3, 6, 8, and 9 from September 1st, 2012, to August 31st, 2015.*

Ongoing work

This article presents the construction and calibration of a 3D numerical model that is used to evaluate the response of the reclamation technique applied at the Manitou mine site; i.e., an EWT combined with a monolayer cover. As the water budget greatly influences the efficiency of reclamation by controlling contaminant production, this 3D model will subsequently be used to evaluate the influence of several parameters on the performance of the reclaimed TSF 2. For instance, simulation using the normal climatic data shows the natural evolution of the hydraulic heads on site. Additional simulations with recurrent dry spells will assess their potential impact on AMD production at the Manitou site. A sensitivity analysis will also be performed to evaluate the model's response to changes in the main influence parameters.

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