ABSTRACT
The elevated water table (EWT) technique can be an advantageous method for the management and closure of reactive mine tailings impoundments. The principle consists of maintaining by submersion or capillarity a high degree of saturation within the tailings in order to inhibit sulphidic mineral oxidation. Its potentially high efficiency is due to the low rate of oxygen diffusion under nearly saturated conditions. The effectiveness of an elevated water table in preventing acid mine drainage (AMD) can be quantified using numerical simulations of water flow, oxygen diffusion, sulphide oxidation and geochemical transport. In this study, the reactive transport model MIN3P (Mayer, 1999) is applied to simulate several laboratory columns with different water table elevations. Each column contained reactive tailings overlain by a sand layer and was subjected to transient recharge and drainage (fifteen 30-70 day cycles for 502 days). A free-draining control column without a sand layer was also used. The numerical results were generally consistent with the observed experimental data, which showed more neutral pH and lower SO$_4$ and Fe concentrations as the water table elevation was increased. The results highlight the conditions under which EW Ts can significantly reduce AMD generation.

RÉSUMÉ
La technique de la nappe phréatique surélevée (NPS) peut constituer une méthode avantageuse pour la gestion et la fermeture de parcs à résidus miniers réactifs. Le principe consiste à maintenir les résidus à un degré de saturation élevé par submersion ou par capillarité afin d’empêcher l’oxydation des minéraux sulfureux. La technique repose sur le faible taux de diffusion de l’oxygène en milieu quasi saturé. Cette efficacité à empêcher le drainage minier acide (DMA) peut être estimée à partir de simulations numériques de l’écoulement de l’eau, de la diffusion de l’oxygène, de l’oxydation des sulfures et du transport géochimique. Dans cette étude, le modèle de transport réactif MIN3P (Mayer, 1999) est utilisé pour simuler des essais en colonnes avec différentes positions de la nappe. Chaque colonne comporte des résidus sulfureux surmontés par une couche de sable. On y applique une recharge avec drainage (15 cycles de 30-70 jours pendant 502 jours). Une colonne témoin avec un drainage contrôlé et sans couche de sable a été également utilisée. Les résultats numériques sont généralement conformes aux données expérimentales observées qui montrent que plus le niveau de la nappe est élevé dans les résidus, plus le pH est élevé et les concentrations en sulfates et en fer sont faibles. Ces résultats montrent les conditions requises pour que la technique de la NPS puisse réduire la production de DMA de manière significative.

1 INTRODUCTION
The Canadian mining industry is of critical importance to the country’s economy. However, ore processing produces significant volumes of potentially reactive waste tailings, which must be carefully managed to prevent environmental impacts including acid mine drainage (AMD). Mine tailings are usually deposited in surface impoundments surrounded by dykes and dams. In such environments, and when sulphidic minerals are present in the tailings, water covers (or underwater disposal) are often used to prevent AMD. The use of water covers for controlling AMD has been well documented over the years (e.g. David and Nicholson, 1995; Li et al., 1997; Amyot et Vezina, 1997; Catalan et al., 2000; Adu-Wusu et al., 2001; Vigneault et al., 2001; Peacey and Yanful, 2003; Mian and Yanful, 2003). Although effective, water covers can be expensive to maintain and can lead to geotechnical instability (Aubertin et al. 1997).

Over the last decade, the elevated water table (EWT) technique has received increasing interest as a possible option for management and closure of reactive tailings impoundments (MEND, 1996). The principle of the technique consists of maintaining a high degree of saturation within the tailings by submersion and/or capillary rise in order to inhibit sulphide oxidation. Its efficiency is based on the low rate of oxygen diffusion in saturated or near-saturated conditions. Oxygen diffusion rates through highly saturated porous media, for example, can be several orders of magnitude less than under relatively dry conditions (Nicholson and Tibble 1995; Aubertin et al., 1995; 2000; Mbonimpa et al. 2003; Aachib et al., 2004). The effectiveness of the EWT technique depends on many factors including the capillary retention properties of the waste material, climatic conditions, water balance of the impoundment, as well as the tailings mineralogy and buffering capacity (Ouangrawa et al.
2 MATERIALS AND LABORATORY SET-UP

The laboratory study included a total of 15 short cylindrical experimental columns (0.4 m long) with different tailings material and/or negative (suction) pressures at the base. In this paper, the authors will consider only four of these test columns (columns 1, 4 & 12), which were prepared using tailings sampled from the Louvicourt mine site, located near Val-d’Or, Quebec, Canada. Larger columns (1.5 m to 2 m long) were also tested but will not be considered here.

The general set-up for the short column tests is represented in Figure 1. Each column included 15 cm of consolidated tailings and 20 cm of sand (acting as an evaporative barrier). At the top, the columns were open to the atmosphere. A removable TDR probe was used to measure volumetric water content in the sand. A removable sensor fixed to a cap was also used to measure oxygen consumption in the columns which were temporarily closed after three weeks of drainage; however, the oxygen-consumption test results are not presented here (see Ouangrawa 2007 for details). At the base, the columns were equipped with a ceramic porous plate. The water table position was adjusted by applying suction through a port connected to a U-shape plastic tube. The tube was also used to collect leachate for chemical analyses.

This study focuses on hydrogeochemical analyses and numerical modelling to evaluate the effectiveness of an elevated water table for controlling acid mine drainage from sulphidic mine tailings. The laboratory experiments used columns of tailings from the Louvicourt mine in Quebec, Canada. The columns had different water table elevations and were subjected to transient recharge. Water flow, oxygen consumption, and chemistry of the drainage water were monitored to establish the hydrological and geochemical conditions which control system behaviour. The observed behaviour is compared with numerical reactive transport simulations. The latter are used to evaluate how an EWT may be effective in preventing the production of AMD. More details on this study can be found in Ouangrawa (2007).

The initially unoxidized Louvicourt mine tailings are composed primarily of silt and fine sand size particles with a percentage passing 80 µm of about 90% (and 80% passing 40 µm). Characteristic grain diameters, corresponding to 10% (D10), 50% (D50), and 60% (D60) passing on the cumulative grain size distribution curve, are 2 µm, 17 µm and 24 µm, respectively.

The main observed silicate minerals are quartz (19 wt. %), chlorite (11 wt. %), feldspars (1.5 wt. %) and muscovite (11 wt. %). Pyrite (38 wt. %) is the main sulphide mineral with small amounts of chalcopyrite and sphalerite. The main carbonates are dolomite (3 wt. %) and siderite (7 wt. %). The saturated hydraulic conductivity of the tailings is in the range 10\(^{-6}\) - 10\(^{-5}\) cm/s at a void ratio of 0.5 - 0.7, and the Air Entry Value (AEV) is approximately 300-350 cm H\(_2\)O.

The chemical composition of the tailings was determined by Inductively Coupled Plasma analysis (ICP-AES) after acid-Bromine digestion. Dilute HCl was used to extract sulphates and the resultant solution was analyzed by ICP-AES. The silica content was determined by ICP-AES analysis following a Na\(_2\)O\(_2\)/NaOH fusion. The results show that the Louvicourt mine tailings are rich in Fe (27.3 wt.%), chlorite (11 wt. %), feldspars and pyrite (38 wt. %) with small amounts of chalcopyrite and sphalerite. The main carbonates are dolomite (3 wt. %) and siderite (7 wt. %). Total sulphur and total inorganic carbon were obtained with the LECO CS-400 Carbon/Sulphur Series apparatus. The results were consistent with the ICP-AES analyses.

The Louvicourt mine tailings were selected partly because of their high acid generating potential. Acid-base accounting (ABA) tests (Lawrence et Wang, 1997) showed that the tailings net neutralization potential (NNP) is approximately -558 kg CaCO\(_3\)/tonne and the acid generation potential (AP) is 599 kg CaCO\(_3\)/tonne.

In columns 1 and 4, suctions of 209 cm and 130 cm H\(_2\)O, respectively, were applied to the base. These different suctions represent different water table depths below the tailings surface. Column 12, used for control, had neither
a ceramic plate nor a sand cover; the tailings were underlain by a geotextile. The equivalent suction in column 12 was zero from 0-322 days (cycle 1-8) and then was increased to about 10 m (according to the WRC) from 322-502 days (cycle 9-15) by opening the base to free drainage.

Once a month, each column was wetted with approximately 570 cm$^3$ of demineralised water (pH~6) added at the upper surface. The columns were then allowed to drain. A total of 15 drainage cycles were completed, each lasting approximately 30 days (cycle 1 lasted 70 days). The pH and redox potential of the leachate were measured after each cycle, while the different concentrations (SO$_4$, Mg, Mn, Ca, Zn, Cu, Fe…) in the leachate were determined by atomic absorption spectroscopy.

3 NUMERICAL MODELLING

3.1 MIN3P code

The reactive transport simulations were conducted using the MIN3P code (Mayer, 1999; Mayer et al. 2002). MIN3P is a finite volume based numerical model for simulating 3D variably-saturated flow, advective-dispersive transport in the water phase, diffusive gas transport, sulphide mineral oxidation, and multi-component kinetic or equilibrium controlled geochemical reactions including mineral buffering. The model is based on a system of nonlinear equations for coupled flow and mass transfer in soil, and has been used extensively in previous studies of reactive mine wastes, including those by Bain et al. (2001), Mayer et al. (2002), Jurjovec et al. (2004), and Molson et al. (2004, 2007).

3.2 Modelling methodology

Physical and hydro-geochemical material characteristics determined from the laboratory (Table 1) were used as input data to the MIN3P model to simulate the experiments. The numerical model considers three layers (from the bottom to the top): the ceramic plate (0.6 cm), the tailings (15 cm), and the sand (20 cm) as shown in Figure 1. The van Genuchten (1980) model parameters ($\alpha$, and $n_v$) were determined using the RETC code according to van Genuchten et al. (1991). A $k_{sat}$ of 10$^{-7}$ m/s and an AEV of 3.50 m of water were used in the simulations. The AEV and the residual volumetric water content ($\theta_r$) were also measured and determined with the modified Kovacs (MK) model (Aubertin et al. 2003). At the base of each column, suction were applied which corresponded to those used in the laboratory experiment. The hydraulic characteristics (AEV and $k_{sat}$) used for the ceramic plate are given by the manufacturer (Soilmoisture Equipment Corp, 2002).

Each column was simulated for a 502 day period, with time steps varying from a minimum of 2x10$^{-4}$ s to a maximum of 0.8 days.

The initial mineralogy and aqueous phase chemistry of the tailings were based on observed laboratory data (see Section 2). The secondary minerals which were allowed to precipitate in the model were: siderite, gibbsite, gypsum, ferrhydrite, and jarosite. Sixteen primary aqueous components (Ca$^{2+}$, K$^+$, Cl$^-$, H$_2$SiO$_4$, Al$^{3+}$, CO$_3$$^2$-, H$^+$, O$_2$(aq), Fe$^{2+}$, SO$_4$$^{2-}$, Fe$^{3+}$, HS$^{-}$, Mg$^{2+}$, Zn$^{2+}$, Cu$^{2+}$, and 38 secondary aqueous species were included in each simulation. A dispersivity of 0.5 mm was assumed for all simulations and the materials in the columns were considered initially fully saturated ($S_w = 100\%$). Execution times were typically on the order of 3 hours to 2-3 days on a Pentium IV, 2GHz machine.

4 RESULTS AND DISCUSSION

4.1 Hydrogeochemical evolution (observed and simulated)

The main results obtained from the laboratory column tests and from the numerical simulations are analyzed and compared in relation to the performance of the EWT as a method to limit AMD production. Figures 2, 3 and 4 present the simulated vertical profiles of the degree of saturation $S_w$, dissolved oxygen, pH, Eh, sulphate, Ca$^{2+}$ and Fe at selected times for columns 12, 1 and 4, respectively.
In the controlled drainage case (column 12), the simulation results (Figure 2) show that when the suction applied at the base is changed from zero to about 10 m H₂O, the degree of saturation of the tailings decreases from 100% to approximately 50%. The desaturation allows oxygen to penetrate and reach the bottom of the column. As the tailings desaturate, the sulphide minerals begin to oxidize which releases acidity. This is reflected by a decrease of pH (from 7 to 3 at the end of the experiment) and an increase of Eh (from 200 mV to 1000 mV). This simulated Eh value is higher than that measured which is about 600 mV. At the same time, the simulated sulphate concentrations increased from approximately 3000 mg/L to nearly 100,000 mg/L, iron from 0.1 mg/L to about 50,000 mg/L, and calcium from less than 100 mg/L to 500 mg/L.

At the beginning of each cycle for columns 1 and 4, water drains rapidly from the sand cover, but the tailings remain close to full saturation (degree of saturation Sₑ~0.9 for column 1 and 0.95 for column 4). As the sand layer desaturates, oxygen diffuses rapidly into the column, but diffusion into the underlying tailings is limited because of its higher saturation. The limited oxygen availability allows the tailings to partially oxidize at the sand/tailings interface. The pH drops locally to about 2-3 by the end of the experiment (502 days). A limited oxygen supply (because of the higher water saturation) combined with pH buffering (by dolomite and calcite) limits the oxidation and prevents this low pH front from advancing further down the column. The pH at the base therefore remains around 6-7. The sulphate and iron concentration profiles can be correlated to the pH drop at the sand/tailings interface (see Figures 3 and 4 below).

The extent of localized oxidation is somewhat less in column 4 because the applied suction at the base of this column was less and the tailings therefore remained closer to full saturation (Sₑ~0.95). As a result, the sulphate and iron concentrations are also significantly lower.

The observed effluent data for the 15 drainage cycles (about 500 days) are compared to the simulated data in Figure 5. In column 12, the geochemical evolution of the tailings can be clearly related to the change in free drainage at 322 days. In general, similar trends are observed for the laboratory and simulated data. The pH remained between 7 and 8 for the first 322 days, and then gradually decreased to 4.5 by 500 days. The highest sulphate, iron, zinc and copper concentrations observed in control column 12 can be related to oxidation of pyrite, sphalerite and chalcopyrite.

The simulated pH in column 1 is somewhat less than the measured pH as shown in Figure 5. The simulated sulphate concentrations in column 1 remained between 2000-6000 mg/L throughout the study period, whereas the observed data are between 2000-3000 mg/L. The same observation can be made for iron, zinc and copper for which the simulated concentrations are higher than those observed (see Figure 5).
In column 4, the observed sulphate concentration gradually decreased from about 1500 mg/L to 400 mg/L after 500 days. This trend is not observed in the simulated data, which remained higher than 2000 mg/L at the end of the experiment, although the simulated concentrations of the oxidation products are somewhat higher than those observed in column 4.

Possible reasons for the differences include inherent assumptions of the shrinking core model (e.g. spherical grains), an uncertain diffusion coefficient for the solid grain cores, uncertain geochemical reaction rates, material heterogeneity in the columns, and the limited precision of the mineralogical analysis. There was also some evidence of preferential flow at the tailings/column wall interface.

The differences can also be partly attributed to the measurement time scales: while the simulated effluent chemistry is shown for every time step (generally on the order of $10^{-3} - 10^{-2}$ days, or ~1-15 min.), the observed data represent an integrated response over several hours which may not capture the rapid concentration fluctuations during drainage.

![Figure 5. Simulated and observed evolution of column effluent quality (pH, sulphate and iron) for columns 12, 1 and 4. Showing a) pH, b) sulfate, c) total iron, d) calcium, e) zinc and f) copper.](image-url)
The efficiency of the elevated water table method was also assessed quantitatively from measured and simulated concentrations of two mobile metals: copper and zinc. Following Bussière et al. (2004) and Dagenais (2005), the % efficiency ($E_c$) is defined here as $E_c = \left(1 - \frac{C_k}{C_o}\right) \times 100$, where $C_k$ is the effluent concentration in the test column (1 and 4) and $C_o$ is the concentration in control column 12. The concentrations considered for the calculations of $E_c$ were those obtained at the end of the simulation period (502 days) at a depth of 15 cm, i.e. at the base of the tailings. Calculations show that the efficiency is approximately 92% in column 1 whereas in column 4, which had the highest water table elevation, it reached almost 100%. These values approach those measured by Dagenais (2005) (which lay between 95% and 99%) who applied the EWT technique to the same reactive tailings. The efficiencies obtained here are also comparable with those estimated for water covers (e.g. Li et al., 1997) and for covers with capillary barrier effects (CCBE) (Yanful, 1993; Aubertin et al. 1999; Bussière and al. 2004).

The observed and simulated data show that in general, higher suctions induced from a deeper water table (e.g. column 1) lead to increased oxidation (lower pH, higher SO$_4$ & Fe) relative to the lower suction case (column 4).

### 4.2 Sensitivity Analysis

Previous studies of EWTs have shown that to prevent acid mine drainage, the depth of the water table must be less than the AEV of the tailings (MEND, 1996; Ovara et al. 1997; Dagenais, 2005). In order to further understand the hydrogeochemical evolution of reactive tailings with an EWT, various additional simulations were completed using the Louvicourt tailings with the water table between 0.7 m and 6 m below the tailings surface. The simulations were based on a large column (1.70 m) of tailings overlayed with 0.20 cm of sand.

The simulated results shown in Figure 6 indicate that the lower the level of the water table, the more the tailings become desaturated. For example, for a water table at 0.7 m depth, after 396 days of simulation, the degree of saturation of the tailings is approximately 98% compared to only 75% at a depth of 6.2 m. The evolution of the pH, sulphate and iron follows the trend dictated by the degree of saturation, showing a higher degree of oxidation as the water table elevation decreases.

For example, Figure 6 shows that after 396 days, a water table located at a depth of 2xAEV within the Louvicourt tailings (-6.2 m) increases the sulphate concentrations by a factor of at least 30, and ferrous iron by a factor of 2. Copper and zinc concentrations increase by at least a factor of 10 compared to a water table depth of 1/5xAEV (-0.7 m) (not shown).
5 CONCLUSIONS

Management of reactive mine tailings is one of the most important environmental issues facing the mining industry. In this regard, water covers have been recognized as one of the most effective management techniques for controlling the production of acid mine drainage (AMD).

The elevated water table technique (EWT) constitutes a potentially effective alternative in which the tailings above the water table are maintained at a nearly saturated state by capillarity. Although this technique has recognized advantages including a rate of oxidation comparable to that found using water covers, a relatively low implementation cost, and improved geotechnical stability of the dykes, the optimal conditions and parameters are not well defined and little lab or field data exist.

The experimental and simulated results reported herein have shown that the hydrogeological state of the tailings (i.e., their degree of saturation) is critical. This state is principally controlled by the Air Entry Value (AEV). These results confirm qualitatively that if the water table is maintained at a depth less than the AEV of the tailings, an EWT works well and the effectiveness can reach 99% (similar to that of water covers and CCBEs). The simulation methodology will allow the technique to be optimized based on conditions that prevail at specific mine sites.

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