Effect of climate change on the performance of a monolayer cover combined with an elevated water table to prevent acid mine drainage

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ABSTRACT
The chemical reaction of sulfides contained in mine tailings with water and oxygen can generate acid mine drainage (AMD). Reclamation methods must be considered, such as monolayer cover combined with elevated water table (EWT). This method consists in maintaining the tailings close to saturation, which limits the flow of oxygen and AMD generation. The performance of the technique is strongly related to precipitations that can influence the water table position within the tailings. In the context of climate change, the evolution of the future precipitation regime must be considered to ensure the efficiency of the reclamation over the long term. A monolayer cover combined with a EWT is considered to reclaim the Doyon-Westwood (Québec) mine site tailing ponds. Experimental cells installed on the site since 2015 were simulated numerically to evaluate the performance of the method. Average annual weather conditions up to year 2100 and extreme drought events were then incorporated into the model.

RÉSUMÉ
La réaction chimique des sulfures contenus dans les rejets miniers avec l'eau et l'oxygène est responsable du drainage minier acide (DMA). Une méthode de restauration comme la technique du recouvrement monocouche avec nappe phréatique surélevée (NPS), doit alors être envisagée. Cette méthode, permettant de maintenir les résidus saturés, limite le flux d'oxygène et ralentit fortement la génération de DMA. L'efficacité de cette méthode est liée aux précipitations qui vont influencer le niveau de la NPS. Dans un contexte de changements climatiques, il est important d'intégrer l'évolution du régime des précipitations futures afin de s'assurer de l'efficacité de la technique sur le long terme. Cette méthode de restauration sera mise en place au site minier Doyon-Westwood (Québec). Afin d'évaluer la performance de la méthode, une modélisation numérique de cellules expérimentales, présentes sur le site depuis 2015, est réalisée. Les conditions climatiques annuelles moyennes jusqu'en 2100 et les événements de sécheresse extrêmes sont intégrés au modèle.

1 INTRODUCTION

Gold and base metals are often associated with sulphide minerals. Mining operations generate various waste materials that can contain significant concentrations of sulphides. These sulphides can chemically react with oxygen and water. The products of this reaction, called acid mining drainage (AMD), are characterized by low pH and high concentrations of dissolved metals and sulphates (Blowes et al., 2014; Nordstrom et al., 2015).

Tailings are produced during ore processing, and are usually stored in tailings ponds. Reclamation is required to limit AMD generation from sulphidic tailings. Reclamation methods usually aim to limit the chemical reactions involving sulphides, oxygen and water, and act as a barrier limiting the access towards the taillings of one of the two main reagents (oxygen or water).

Oxygen barriers are often suggested in temperate climates. Water covers (MEND, 2001) are an efficient oxygen barrier. Indeed, the oxygen diffusion coefficient (D_e) in water is 10000 times lower than in air (Aachib et al., 2004). The concentration of oxygen migrating towards the tailings is therefore strongly limited. Although an efficient, technique water cover presents geotechnical instability risks of the containment infrastructures (Aubertin et al., 2011; Aubertin et al., 2016; Aubertin et al., 1997).

An alternative method using this concept is the monolayer cover combined with elevated water table (EWT). This reclamation method associates two techniques, which when jointly established, allow maximization of the efficiency of the method. This method consists of maintaining the water table level at an optimal depth within the tailing ponds by the control of the water budget and the capillary rise (Cosset, 2009; Dagenais, 2005; Dagenais et al., 2006; Demers, 2008; Demers et al., 2007; Ethier et al., 2014; Ethier et al., 2013; Ethier et al., 2018; Ouangrawa, 2007; Ouangrawa et al., 2010; Ouangrawa et al., 2009; Ouangrawa et al., 2006; Pabst et al., 2014; Senes, 1996). In a material close to full water saturation, the oxygen flow is proportional to D_e and varies according to the degree of saturation (S_r), and becomes similar to the D_e of a water cover at a degree of saturation above 85% (Dagenais, 2005). Because of the capillary rise, a thickness of taillings situated over the water table stays close to saturation (Cosset, 2009). The finer the material is, the more important the capillary rise will be. The particle size distribution of typical tailings is similar to that of a silt (Aubertin et al., 2002), which facilitates the implementation of the EWT in tailings. The height of the capillary rise is relative to the air entry value (AEV) of the material, which can be determined by the water retention curve (WRC).

The monolayer cover, placed on the surface of tailings, can facilitate the rise of the water table in the tailings. A cover made of a relatively coarse-grained materiel allows reduction of evaporation from the tailings and to favor infiltration (Dagenais et al., 2006; Ouangrawa et al., 2010; Ouangrawa et al., 2009). In the case of a cover material as fine as or finer than the tailings, the cover material can make use of its own capillary rise to maintain an elevated water table level (Ethier et al., 2014; Ethier et al., 2013; Ethier et al., 2018; Nicholson et al., 1988). Finally, the use of weakly reactive or desulfurized taillings (i.e. non-acid generating) as cover material can provide an oxygen sink by consumption through oxidation, and decrease the oxygen concentration which could migrate towards the tailings (Demers et al., 2007; Demers et al., 2009; Dobchuk et al., 2013; Mbonimpa et al., 2003; Romano et al., 2003; Sjoberg et al., 2001).

The performance of the technique is strongly related to the amount of precipitation that will influence the water budget, and particularly the water table level within the tailing ponds. In the context of climate change, it is important to integrate the evolution of the future precipitation regime in the design of cover systems to ensure the efficiency of the technique to limit AMD over the long term. While the increase of precipitation would have a positive impact on this technique, it is the drought events that would be an issue. To represent the conditions of extreme drought, most of the studies used a period of two months without precipitation (Bussiere et al., 1999). Although this period seems realistic, it comes from no systematic analysis of meteorological data. In a context of climate change, this approach could underestimate intensity and period of drought, as well as its effect on cover performance. A new approach is being prepared to take adequately take these changes into account (Bresson et al., 2018) and will be used in this study to evaluate the impact of climate change on the performance of a monolayer cover with EWT.

2 SITE DESCRIPTION

2.1 Location and previous investigation

The Doyon-Westwood site, property of Iamgold Corp., is located approximately forty kilometers east of Rouyn-Noranda (Quebec). Gold from the Doyon deposit has been mined and processed between 1978 and 2010. The tailings generated by this operation were stored in tailings ponds. These tailings contain 2 to 4% sulphides, mainly as pyrite, and a low neutralization potential; therefore they are acid-generating. Underground mining of the Westwood deposit, located to two kilometers at the east of the Doyon mine, began in 2014.

The reclamation method initially chosen for tailings ponds #2 and #3 was a water cover. The capacity of pond #2 having more quickly been reached than planned, the operator tried to find an alternative reclamation method to increase the pond capacity. The monolayer cover combined with EWT, having several advantages in this case, was then selected as an alternative. First, it increased the storage capacity of ponds without need to raise the dikes. Second, it improved the geotechnical stability of the dikes, since the interstitial pressure exerted on the dikes was lowered in the case of a soil cover than water (Demers, 2008). Furthermore, this method also allowed to study the possibility of using desulfurized tailings as cover material, as expressed by the «integrated tailings management» approach (Bussière et al., 1995). This approach encourages the re-use of acid-generating tailings and reduces the volume of tailings to store in the ponds (Benzaazoua et al., 2008).

The reclamation method was first tested in the laboratory with experimental columns to test various parameters such as water level, residual sulphide content of tailings used as cover, and cover thickness (Demers et al., 2007). This investigation allowed demonstrating the efficiency of the method. The subsequent numerical modelling allowed to determine the optimal configuration of the cover as being one meter thick, containing 0.8% of sulphide and with a water level located at the interface between Doyon tailings and the cover (Demers, 2008; Demers et al., 2007).

2.2 Experimental field cells

Although the closure of the Doyon mine occurred before reclamation of Ponds #2 and #3 began, the «integrated tailings management» concept was maintained with the commissioning of the Westwood mine, which uses the Doyon mineral processing facilities. The performance of a monolayer cover made of desulfurized tailings coupled with an EWT was therefore further tested. To assess the reclamation method in the field, three experimental cells, with different configurations (one being shown in Figure 1), were installed on the site in 2015 (Rey et al., 2016, 2017).

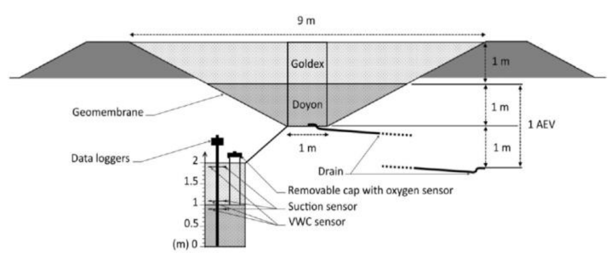

Figure 1. Configuration and instrumentation of field cell #1 (Rey et al., 2017)

The cells are shaped as truncated inverted pyramids. Cell #1 is filled with one meter of sulphidic Doyon tailings. and the cover of the desulfurized tailings is one meter thick (Rey et al., 2016). During the implementation of cells, the Westwood treatment plant was not yet operational, so a similar material, from the Goldex mine (Val-d'Or, Agnico Eagle Mines Ltd), was used as a replacement for the cover material.

Drains equipped with flowmeters were installed on the base of cells to set the water table level. The drains were located 1 meter below the cover-tailings interface for cell #1, theoretically equivalent to ½ AEV of the Doyon tailings.

Cells were also instrumented to monitor various parameters over several years (2015-2017), such as the volumetric water content (VWC) measured with Decagon 5TM sensors and suction with Watermark sensors (Figure 1). Probes were installed 10 cm below the surface of the desulfurized tailings, 10 cm above the cover-tailings interface and 10 cm below this interface.

2.3 Climate change projections for Abitibi region

In Quebec, important variations of temperatures and annual average precipitation are expected within the next century. Also, this region should expect an increase in the frequency and intensity of extreme events (Desjarlais and Blondlot, 2010; Plummer et al., 2006).

A prediction of the changes expected for the Abitibi region was performed in a synthesis study of climate change for six mining regions in Quebec (Roy, 2015). This study was based on a set of climatic simulations resulting from the project CMIP5 «Coupled Models Intercomparison Phase 5» (Taylor et al., 2012) and each simulation was based on Representative Concentration Pathway (RCP) radiative scenarios (Moss et al., 2010). These scenarios represent the possible evolutions of greenhouse gases concentration in the atmosphere according to the global socioeconomic evolution during the next decades (Taylor et al., 2012). In this study, two scenarios were considered: RCP4.5 and RCP8.5. The first one corresponds to a scenario where actions would be currently initiated to limit greenhouse effect gas emission and the second corresponds to a case where no or little changes would be achieved (Riahi et al., 2011; Thomson et al., 2011).

As for the rest of Quebec the region of Abitibi (where the study site is situated) should observe an increase of temperatures and of annual and extreme precipitation at the horizon 2080. The return periods for the extreme events would decrease from 20 years to 15-17.5 years. The snowmelt period would occur approximately one month earlier than during the historical period of 1971-2000. Also, the maximal accumulation of snow would be lower (Roy, 2015). Table 1 presents the climatic indicators related to precipitation, the predictions obtained by this study for the Abitibi region.

Table 1. Evolution of the climatic parameters of precipitation for three temporal horizons and two RCP scenarios for the region of Abitibi compared to 1971-2000 data (Roy, 2015).

Climatic parameters	RCP	Time horizons		
		2020	2050	2080
Annual precipitations (%)	4.5	+4.03	+8.29	+10.70
	8.5	+4.26	+10.18	+16.13
Extreme precipitations (%)	4.5	+4.79	+11.49	+13.52
	8.5	+8.29	+16.13	+22.20
Accumulations during extreme events (%)	4.5	+7.73	+17.12	+21.48
	8.5	+9.32	+20.35	+32.37

3 NUMERICAL MODELING

Numerical modelling was performed with the software SEEP/W (Geoslope) to estimate the influence of climate change on the performance of the reclamation method. More specifically, the hydraulic behaviour of the field cells representing a case of monocover made of low-sulphide tailings combined with EWT was used as a basis for calibration and long term prediction of reclamation performance. SEEP/W allows to model the flow of groundwater in porous medium and to solve analyses in transient and steady-state conditions for saturated/unsaturated materials. Numerous boundary conditions are applicable to the model, such as the atmospheric data using the land-climate interaction (LCI) boundary condition. These boundary conditions can reflect various ground surface conditions, such as bare or snow-covered ground. It is also possible to estimate directly the functions of hydraulic conductivity and water retention curve by using integrated functions into the software (Geo-Slope International Ltd., 2017). It was successfully used in other studies to describe exchanges with the atmosphere and the water flow in non-saturated tailings (Demers et al., 2009; Ethier et al., 2018; Pabst et al., 2017).

3.1 Material characterization

The tailings used for the construction of cells were sampled for physical and hydrogeological characterizations (Rey et al, 2017).

The saturated hydraulic conductivity (k_{sat}) was measured in a rigid wall permeameter (ASTM D5856-15, 2015). The WRC was measured with a pressure cell (Tempe cell - ASTM D6836-16, 2016) and described using Van Genuchten (1980) model. AEV values were obtained using the two-tangent method (Fredlund and Xing, 1994). The characterization of materials during this study showed that Goldex tailings were slightly coarser than Westwood tailings (Table 2).

Table 2. Theoretical (Rey et al., 2017) and calibrated values of material properties

Tailings		Doyon		Goldex		Westwood
		TV	CV	TV	CV	TV
G_s	(-)	2.84	-	2.72	-	2.79
D_{10}	(mm)	6.18×10^{-3}	-	2.80×10^{-2}	-	4.29×10^{-3}
D_{60}	(mm)	4.96×10^{-2}	-	2.05×10^{-1}	-	4.36×10^{-2}
n	(-)	0.41	0.37	0.44	0.30	0.42
θ_s	(-)	0.41	0.37	0.44	0.30	0.42
θ_r	(-)	0.05	0.04	0.02	0.03	0.07
α_{vG}	(-)	0.038	0.003	0.102	0.009	0.013
n_{vG}	(-)	2.097	1.777	2.237	2.577	2.844
k_{sat}	$(m.s^{-1})$	1×10^{-6}	$3x10^{-5}$	4×10^{-6}	$1x10^{-6}$	5×10^{-7}
AEV	(kPa)	18	10	5	7	39

G_s: relative density (specific gravity) of the solid grains.
D_{10}: diameter corresponding to 10% finer in the particle-size distribution.
D_{60}: diameter corresponding to 60% finer in the particle-size distribution.
n: porosity
θ_s: saturated volumetric water content (equal to porosity n).
θ_r: residual volumetric water content.
α_{vG} and n_{vG}: van Genuchten (1980) equation parameters for the water retention curves.
k_{sat}: saturated hydraulic conductivity.

3.2 Model setup and calibration

A first numerical model representing cell#1 (1 m of Goldex tailings on 1 m of Doyon tailings) was performed in 1D. A calibration simulation was initially performed by using initial parameters of materials characterization. A first stage of calibration was applied to the model and adjusted parameters obtained are presented in Table 2. AEV calibrated values are to be confirmed in the next stages of calibration. A transient-state simulation was performed to compare the results of the simulation with those of the cells monitoring (VWC, suction and flow) for the 2015-2017 period. Tighter calibration work is still to come to confirm the material properties.

For the 2015-2017 period, weather conditions were integrated into the model as top land-climate interaction boundary condition. Climatic data from the station of Rouyn-Noranda Airport (Environment Canada) were used; the station is located only a few kilometers from the mine and is deemed representative of field conditions. Air temperature and precipitation data correspond to the daily values. For relative humidity and wind speed, a daily average was calculated from the hourly data. In the software, the solar radiation consists of two parameters. The radiation is estimated by Seep/W according to the latitude (48.25°). A daily value of albedo was defined according to the presence or not of snow on the cell surface (0.8: fresh snow; 0.5: former snow; 0.1: bare surface). The calculated evapotranspiration method is based on Penman-Wilson equation (Geo-Slope International Ltd., 2017). Flow is left free at the bottom of the model. Initial conditions were simulated under steady-state conditions with a water level at 2 m above bottom of cell to simulate the full saturation of the cell during winter. Subsequently, under transient conditions, normal climate (January 2015 to December 2017) or simplified climate change scenario (SCCS) were applied.

3.3 Influence of climatic conditions

Two climatic scenarios were used to assess the influence of climatic conditions on the model. The normal climate represents the climatic data of Environment Canada between 2015 and 2017 for the Rouyn-Noranda station. Secondly, a simplified climate change scenario (SCCS) was used to obtain preliminary results. As indicated previously (Table 1), the Abitibi region should see an increase of annual and extreme precipitations before 2080. Moreover, several climatic simulations suggest that drought periods could exceed two months in the future summers (Ouranos, 2015).

The simplified climate change scenario was built by applying daily precipitation greater to normal climate by 20 % and summer drought periods 20 % longer i.e. 74 days instead of 62 (Ethier et al., 2018). Figure 2 presents an example.

No modifications were made on the other climatic parameters (temperature, wind, relative humidity) at this stage of the study.

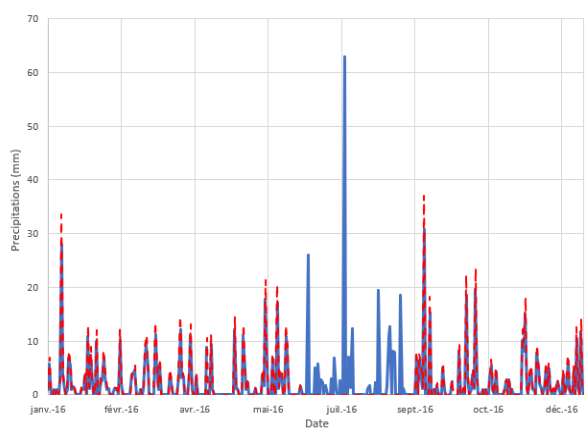

Figure 2. Precipitations in mm imposed in the model for a normal climate (year 2016; blue) and for the SCCS (red)

4 PRELIMINARY RESULTS

This paper presents preliminary results obtained for 2016 compared to the simplified climate change scenario.

The numerical model was validated by comparing field data with simulated data for VWC at 10 cm, 90 cm and 110 cm below the surface of the cell. Figure 3 shows the comparison between field data (obs.), simulated data with normal climate (sim.) and with SCCS.

Field data show that VWC remained more or less constant for two deepest measurement points, i.e. at 90 and 110 cm. VWC close to the surface (10 cm depth) was more affected by the phenomenon of evapotranspiration and showed more variation with time. The trends are respected for the 10 cm depth, meaning that the calibration of the model works well for this depth. At a depth of 90 cm the numerical model is more affected by climatic conditions than what field data showed. However, field data showed that the VWC was relatively constant over time, i.e. Goldex tailings water content remained high at this depth. At 110 cm deep, the correlation was good, VWC did not show important variations. Doyon tailings remained at high water content at this depth throughout the year.

For the simulation with SCCS, the 110 cm depth did not show significant change in VWC and the values stayed close to saturation for Doyon tailings. However, for both other depths, we observed a plateau during the dry summer.

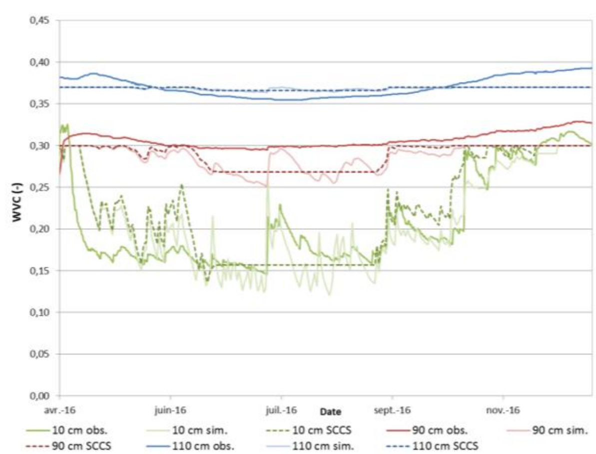

Figure 3. Comparison between measured VWC (solid line), simulated with normal climate (pale line) and simulated with SCCS (dashed line).

The water level in the cell was not measured in the field in 2016, but it was simulated to observe the variations under normal climate and SCCS.

As seen on Figure 4, the water level remained above the value of ½ AEV for the Doyon tailings most of the time under normal climate. During summer, at three times the water level came below the ½ AEV value. With SCCS, the water level stayed underneath the ½ AEV value over the summer, however, the increase in precipitation allowed to maintain the water level higher the rest of the year.

If the water level stayed below ½ AEV of Doyon tailings during the summer, it implies that tailings did not remain completely saturated and their oxidation was possible.

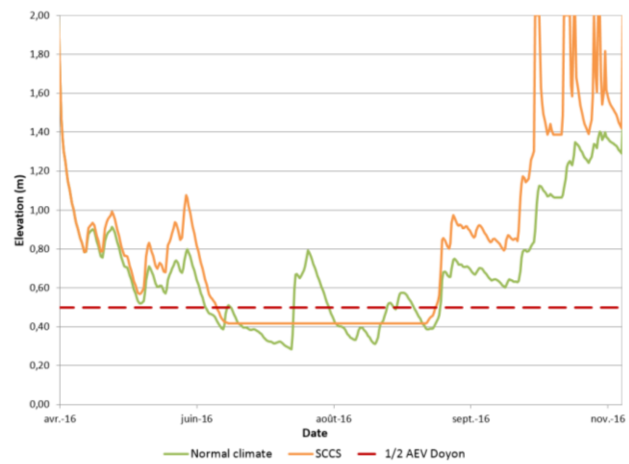

Figure 4. Simulated water level elevation (m) for the normal climate (green) and for the SCCS (orange) for year 2016 (0 m = cell bottom). Red line correspond to ½ AEV Doyon tailing value.

5 DISCUSSION

Observations made at a depth of 90 cm can be explained by the heterogeneity of the Goldex tailing properties between the top and the bottom of the layer. Indeed, variations in particle size distribution can affect hydraulic properties and behaviour under normal and climate change conditions.

For observations made at 110 cm depth, modeling results do not reflect the reality. It is expected that the VWC would keep decreasing until the end of the drought, because of effect of evapotranspiration at the surface. It is therefore necessary to continue to work on the model and on the climate boundary conditions to find the parameter which will allow taking into account better evapotranspiration.

As observed for the VWC, there is a plateau in the data during the dry summer simulated by SCCS. The water level should continue to decrease gradually till the end of the drought and should not remain constant. However, with SCCS, the increase in precipitation is beneficial to maintain the water level elevated during most of the year, including prior to the drought.

6 CONCLUSION AND UPCOMING WORK

The use of a numerical model to represent a reclamation method is an accepted process to determine the reclamation efficiency in the long term. The applicability of climatic data as boundary conditions can allow to consider the effects of climate change on the performance of the monolayer cover combined with EWT, which is strongly related to the amount of precipitation that will influence the water table level. This investigation was performed for the reclamation of the Doyon-Westwood site, where experimental field cells provide monitoring data.

The calibration of the numerical model allows reproducing the tendencies observed on the field for VWC data for year 2016. These observations will have to be confirmed with the suction data. The next stage of calibration will be made to compare all the field data i.e. from 2015 to 2017 with simulated data.

The SCCS simulation shows that the numerical model must be modified to try to better represent the effects of drought during a dry summer. Indeed, a drought cannot be only defined by lack of precipitation; it also involves evapotranspiration and water retention.

The next step of the project involves the use of real climate projections to refine the numerical model and boundary conditions. The climate projections will be defined using a set of climatic simulations resulting from the project CMIP5 and will be used to obtain more realistic climate conditions, adapted to the Doyon-Westwood mine site.

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