Performance evaluation of the Quemont 2 mine reclamation techniques using a three-dimensional groundwater model

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ABSTRACT
The Quemont 2 mine site, located near the Rouyn-Noranda city, covers an area of 119 hectares and its reclamation should be performed during the next few years after tailings storage facilities (TSF) closure. To select the appropriate reclamation technic for controlling acid mine drainage (AMD), three-dimensional numerical groundwater was built and calibrated with the objective to simulate the hydrogeological behavior of the mine site after TSF closure. After model calibrations, the model was completed by considering the impact of climate change on water resources of the TSF. In these last simulations, the effect of climate change in Quemont 2 will be the increase of the groundwater level due to the precipitation increase. These results will be used in the next step to evaluate the cover performance placed on the TSF of the Quemont 2 mine site.

RÉSUMÉ
Le site minier Quemont 2, situé près de la ville de Rouyn-Noranda, couvre une superficie de 119 hectares et sa réhabilitation devrait être effectuée au cours des prochaines années après la fermeture des installations de ce parc. Afin de sélectionner la technique de réhabilitation appropriée pour contrôler le drainage minier acide (DMA), un modèle numérique tridimensionnel des eaux souterraines a été élaboré et calibré dans le but de simuler le comportement hydrogéologique du site minier. Après ces calibrations, le modèle a été complété en considérant l'impact du changement climatique sur les ressources en eau de ce site. Dans ces dernières simulations, l'effet du changement climatique sur le Quemont 2 sera l'augmentation du niveau des eaux souterraines due principalement à l'augmentation des précipitations. Ces résultats seront utilisés dans la prochaine étape pour évaluer la performance de la couverture mise en place sur l'ISR du site minier Quemont 2.

1 INTRODUCTION

In the presence of oxygen and water, sulphide minerals in mine tailings can oxidise, allowing to produce acid mine drainage (AMD). In situ AMD generation can last for hundreds to thousands of years and is exceedingly harmful to the ecosystem.

The REGENERE Chair's research program aims to identify the best reclamation scenario for the Quemont-2 tailings storage facility (TSF), which will reach its maximum capacity between 2022 and 2024 (WSP 2019a). This site was targeted for its proximity to the urban center (Rouyn-Noranda city) and to the Dufault Lake. The effective reclamation of the TSF aims to protect the environment and requires an assessment of the local hydrogeological and geochemical framework to support the selection of the most appropriate technique of reclamation.

In these techniques one can find cover with capillary barrier effect (CCBE), hydraulic barrier, monolayer cover combined with an elevated water table (EWT). Indeed, we will choose an effective and economical technique to limit AMD generation from tailings, particularly under humid climatic conditions.

The Quemont 2 mine site has been extensively examined in recent years in order to identify the hydrogeological behaviour of this site (El Mrabet 2021; Kahlaoui 2022, WSP 2019a, WSP 2019b). Also, field and laboratory tests were performed to test different mine site reclamation (see Merzouk et al. 2022; Granados et al. 2022).

Indeed, it's important to analyse the impact of TSF reclamation on the hydrological and hydrochemical behaviour of the Quemont 2 mine site. This analysis can be performed by hydrogeological modeling of this site, which constitute the goal of this paper.

2 SITE DESCRIPTION

The Quemont 2 TSF, owned by Glencore Fonderie Horne, is located north of the urban perimeter of Rouyn-Noranda city (Abitibi-Témiscamingue, Québec) between latitudes, 48°278' and 48°266' and between longitudes, West 79°001' and 78°975' (Figure 1).

The TSF, which covers an area of around 119 hectares (ha), poses unique environmental challenges due to the nature of its mine waste, as well as its proximity to Rouyn-Noranda's metropolitan border. This region borders the:

- Dufault Lake, which is the main source of drinking water for the Rouyn-Noranda city;
- Osisko Lake, which has been contaminated in the past by smeller activities, mine tailings ponds and municipal wastewater.

The regional hydrogeological context of the Quemont-2 site is defined by a bedrock generally outcropping, otherwise covered by unconsolidated deposits of glaciolacustrine origin.

The tailings pond was used successively for the deposition of sulfide tailings, and the co-deposition of tailings (sludge and slag). These releases in co-deposition are composed of fresh slag generated following the flotation of residual copper in the Horne smelter concentrator and treatment sludge from the weak-acid treatment unit (El Mrabet 2021). These materials can generate contaminated water and are therefore likely to pose a risk to the health and safety of the population of the Rouyn-Noranda city and to affect the quality of the surrounding environment.

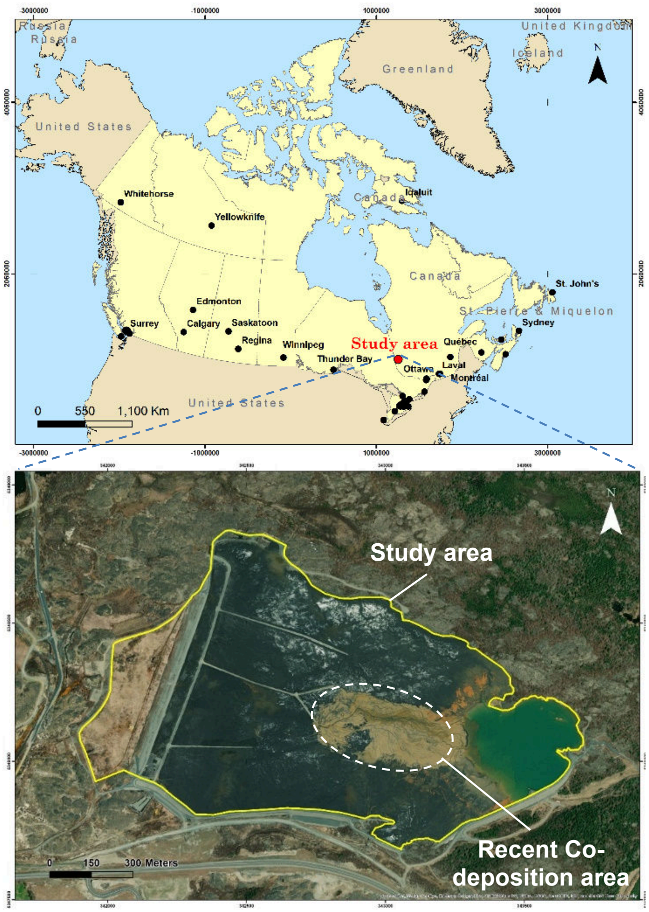


Figure 1. Location map of the study area (Esri map available on ArcGIS software).

3 METHODOLOGY

A hydrogeological database and numerical model have been developed to characterize and to simulate the hydrogeological behaviour of the Quemont 2 TSF. All required data (relevant technical reports and climate data related to datasets and outputs of the study region) was processed for this purpose, and the following results were obtained: (i) climate data, (ii) hydrogeological database and settings, and (iii) numerical model setup calibrations used to assess the hydrogeological behaviour of the Quemont 2 TSF.

3.1 Climate data

The Rouyn meteorological station provided climatic data (Environment Canada 2020). The average annual precipitation is 882.8 mm, the average minimum and maximum monthly temperatures are -17°C (in February) and 26°C (in July).

A combination of regional climate modelling projections data generated from the Government of Canada website (https://climate-scenarios.canada.ca/?page=statistical-downscaling) and a collection of local observation datasets for precipitation (P) and temperature (T) for our study area were used in this assessment. This section is based on extracting time series of P and T variables from 2006 to 2100. MATLAB software was used to extract time series of P and T variables from NetCDF (Network Common Data Form: www.unidata.ucar.edu/software/netcdf) files (.nc) for the entire time period from 2006 to 2100. We extract data for a specified set of latitude and longitude coordinates.

Time series plots, based on the climatic data, that summarise and display the most up-to-date knowledge on the climatology of our study area are presented in the Figure 2a and 2b. These figures show the evolution of predicted P and T for the Coupled Model Intercomparison Project 5 (CMIP5) climate model with several scenarios used to study future impact of climate change (Representative Concentration Pathway (RCP) 2.6, 4.5 and 8.5), which we have displayed and edited.

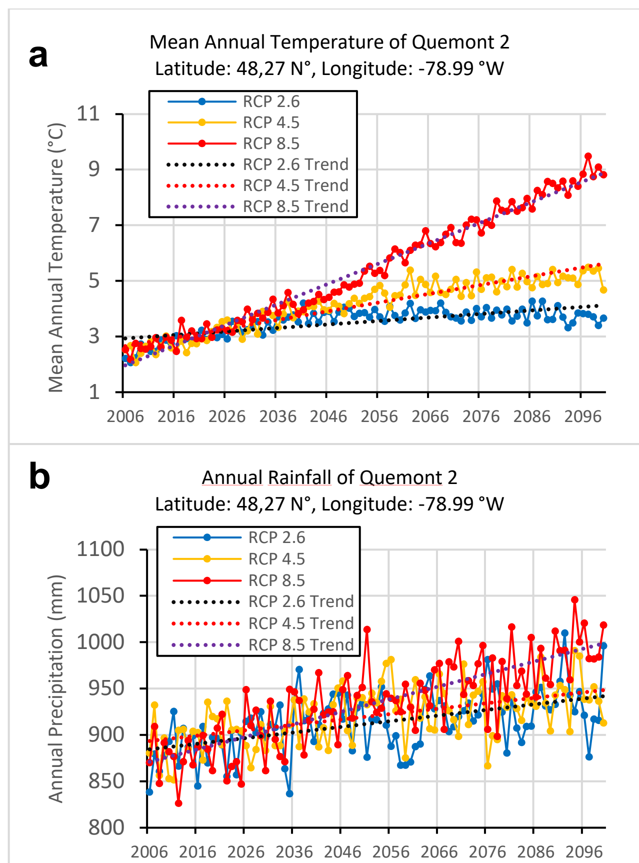


Figure 2: Temperatures (a) and Precipitations (b) over time (2006-2100) in the study area for RCP 2.6, RCP 4.5 and RCP8.5.

For three scenarios, these graphs show clearly that temperatures and precipitations are primarily increasing.

3.2 Hydrogeological Database

A Geodatabase has been designed based on data collected from various organizations and studies which describes the surface water and groundwater resources (geology, piezometry, geometry, quality, etc.) (Figure 3) to produce decisional thematic maps and diagrams. The obtained thematic layers were organized according to the needs of managers and decision makers. This action facilitates consultation, customization and duplication of information in relation to the various aspects of water resources.

The conceptual model of the study area has been also integrated into this database (Figure 3).

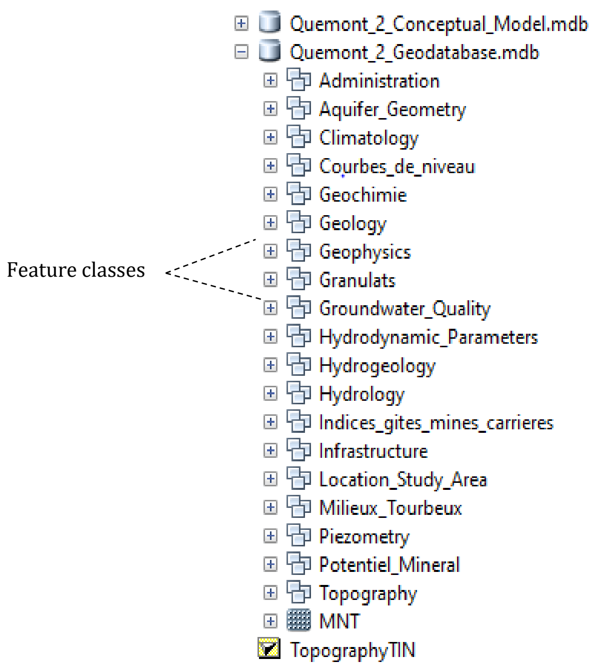


Figure 3. Hydrogeological Geodatabase Structure of the Quemont 2 TSF under GIS

3.3 Hydrogeological setting

The hydrostratigraphic units presented in this section were established from all the boreholes logs of previous studies (Geocon 1988, Envirotecheau 1993, SNC-Lavalin 2007) obtained from WSP report (WSP,2019a), as well as those from the survey campaign conducted by WSP in 2017 and 2018 (WSP 2019a). Seventeen drill holes going 4 to 41 m deep were used throughout the Quemont 2 TSF.

Within the Quemont 2 TSF, four piezometers were equipped with data logger for continuous monitoring of groundwater levels from November 5th, 2020 to February 5th, 2021.

A tridimensional (3D) model was developed using the available information on the non-reactive sludge and slag tailings, Quemont-2 tailings, and underground unit structure (Roc and Glacio-Lacustre Deposits) (Figure 4).

The Quemont 2 TSF is dominated and formed mainly, from the bottom to the surface, by four hydrogeological units:

3.3.1 Unit 1 (Roc)

The rock unit is relatively homogeneous on the Quemont-2 site. According to observations made during drilling, the roc under the pond consists mainly by basalt and andesite with different alterations.

The till unit has not been considered in this research because it appears outside of the study area.

3.3.2 Unit 2 (Glacio-Lacustre Deposits)

The glaciolacustrine deposits unit includes clayey silt and clay units. The compilation of data in the Quemont-2 sector does not make it possible to clearly distinguish between a clay unit and an overlying unit of clayey silt. In fact, the two units have been grouped together for simplification purposes for modeling. The clay deposits are characterized by rhythmites of clay and silt, with a thickness varying from 0 to 15 m. The thickness of the clay deposit units is shown on Figure 4 (between garnet and purple raster plan).

3.3.3 Unit 3 (Mine Tailings)

Unit 3 is composed by tailings accumulated in Quemont-2 TSF. They are mainly composed by silty materials of low compactness. The thickness of the tailings is shown on Figure 4 (between garnet and Digital Elevation Model/DEM raster plan). According to the drilling data, its thickness varies from 0 m to 25 m. The greatest thickness is found in the center of the pond. This unit is omnipresent over the entire surface area of the TSF except for the northern portion of the pond, where the rock is outcropping on the surface.

3.3.4 Unit 4 (Sludge and Slag)

Mine tailings (unit 3) were then covered by a mixture of sludge and slag tailings of co-deposition treatment. According to URSTM (2009), they showed that sludge has a much finer grain size than slag, this sludge is generally less dense than slag. The average thickness of this unit is around 1,6 m and it was deduced from the difference between the digital elevation model (DEM) and the mine tailing unit.

3.4 Hydrodynamic parameters

The hydraulic conductivity values obtained by the interpretation of the slug-test method (Bouwer and Rice 1976), varies in the mine tailings unit from 3.34 x 10^{-7} m/s to 3.81 x 10^{-6} m/s for geometric mean value of 1.4 x 10^{-6} m /s (Table 1).

However, in the roc unit, it varies between 1.26 x 10^{-7} m/s and 4.42 x 10^{-6} m/s, depending on the degree of the rock fracturing, for a geometric mean value of 6.6 x 10^{-7} m/s for the rock mass in general.

In addition, pumping tests of previous studies (COOP, 1993; Richelieu, 2011; Amec, 2014) obtained from WSP report (WSP 2019a) have been obtained values for clays permeability. A typical value of around 10^{-9} m/s is generally representative to correspond the glaciolacustrine deposits unit.

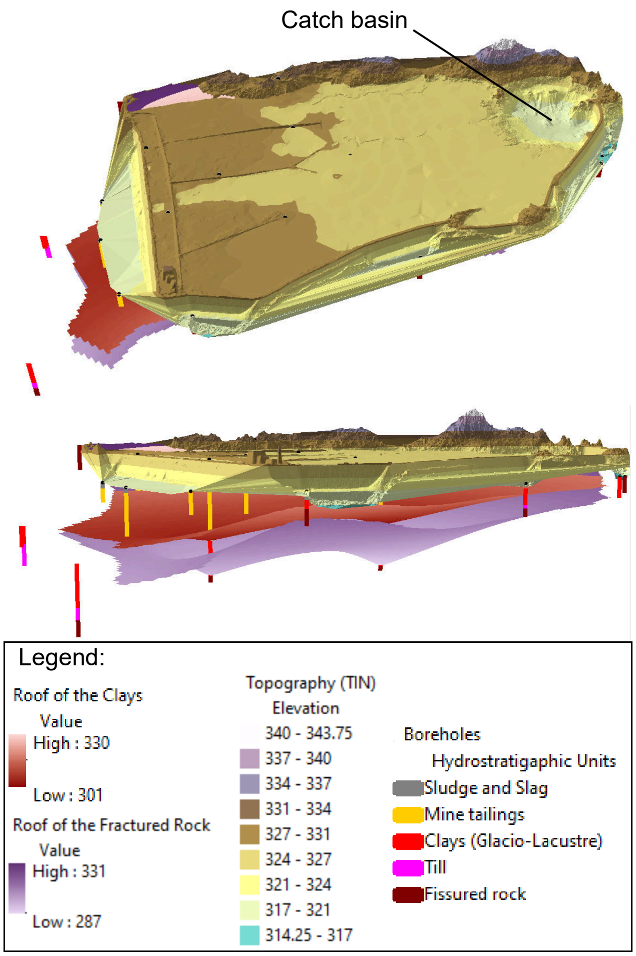


Figure 4. Tridimentionnelle (3D) model configuration of the Qemont 2 TSF.

Table 1. Hydraulic conductivity though the Quemont 2 TSF

Unit	Borehole	Hydraulic conductivity (m/s)		
		Test 1	Test 2	Geometric Mean
Unit 1 (Roc)	01 18	9.97×10^{-7}	7.36×10^{-7}	
	02 18	2.17×10^{-7}	1.26×10^{-7}	
	03 18	4.42×10^{-6}	n/d	$\mathbf{6.6 \times 10^{-7}}$
	04 18	3.41×10^{-7}	3.25×10^{-7}	
	05 18	1.5×10^{-6}	1.54×10^{-6}	
Unit 4 (Mine Tailing)	06 18	3.5×10^{-6}	3.81×10^{-6}	
	07-18	1.2×10^{-6}	1.16×10^{-6}	
	08-18	2.7×10^{-6}	3.32×10^{-6}	$\mathbf{1.4 \times 10^{-6}}$
	09-18	3.55×10^{-7}	3.34×10^{-7}	
	10-18	9.11×10^{-7}	1.12×10^{-6}	

3.5 Model construction and boundary conditions

The hydrogeological database and the tridimensional model configuration have been used to develop a mathematical model to simulate transient groundwater flow from 2020 to 2100.

In the plan view, the domain was discretized, and the model grid consists of 190 columns and 120 rows of 10 m (NS direction) and 10 m (WE direction) wide cells (Figure 5a). Vertically, the model grid is made up by four layers that correspond to the above-mentioned Quemont 2 TSF hydro-stratigraphy layers (Figures 4 and 5b).

The total of the modeled area is 119 ha. The model's base elevation is 285 metres above sea level, with a maximum elevation of 332 metres at the surface. A mesh of 11 953 active cells was created. The domain has layers of rock, glacio-lacustre deposits, the Quemont-2 tailings and Sludge and slag tailings cover layers, as shown in Figure 5b.

The domain boundaries in the North and South were defined impervious (with no-flow condition) except the south-east portion of the pond, where Newman type boundary condition were set. Moreover, a flow boundary was established in the west of the Quemont 2 TSF based on the observed data. Dirichlet type (constant head) boundary conditions were set to an elevation of 323.5 m in the West of the site materialised by a catch basin level.

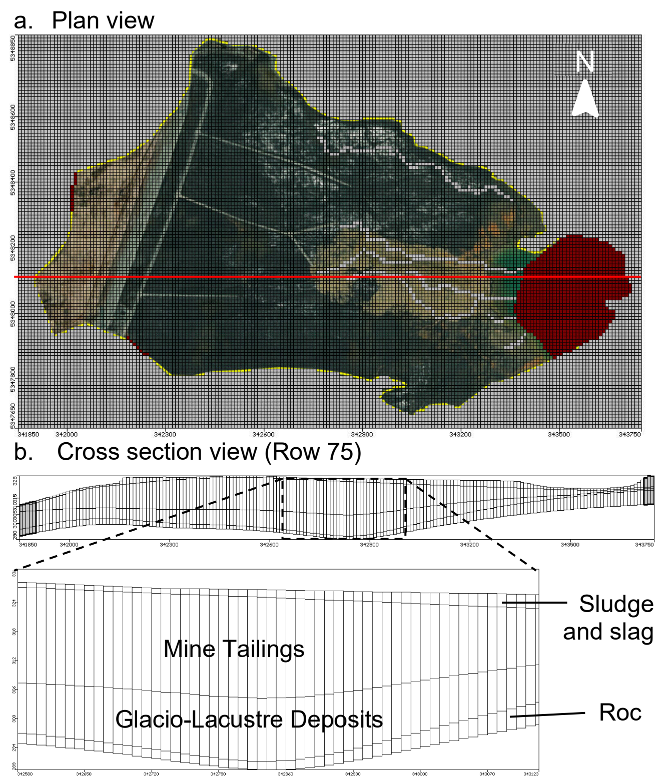


Figure 5. Discretization model of Quemont 2 TSF, showing the inactive zone (grey) and active zone.

3.6 Hydrogeological modeling

The MODFLOW code (available on the website:

https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs) a fully integrated 3D finite difference subsurface flow model based on the diffusivity equation to characterise saturated groundwater flow, was used to simulate the water table level over time.

A three-dimensional numerical groundwater flow model was calibrated under steady state and transient groundwater flow resolving Equation 1 (McDonald and Harbaugh 1988) for the period from November 5th, 2020, to February 5th, 2021. The model also predicts the hydraulic head and the concentration in the Quemont 2 TSF from the year ranging from 2021 to 2100 under three different CC scenarios (RCPs 2.6, 4.5 and 8.5), as well as the water balance within the time.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)\pm W=S_s*\frac{\partial h}{\partial t} \quad [1]$$

where K_{xx}, K_{yy}, and K_{zz} are the K-values along of the x, y, and z align directions (L/T); h is the hydraulic head (L); W is the volumetric flux per unit volume and represents sources and (or) sinks (T^{-1}); S_s is the specific storage of the porous medium (L^{-1}); and t is the time.

4 MODELING RESULTS

4.1 Steady-state calibration

A calibration was made under steady state conditions at each station, using the agreement between simulated heads and measured heads (Figure 6), with an average correlation coefficient of 1, a mean error of 0.046 m, and a root mean square error of 0.052 m.

The general direction of the groundwater flow is from the North to the East with a component oriented towards the West. The vector velocities show the direction of the groundwater flow as seen in Figure 6. Figure 6a shows the simulated flow in mine tailing unit except the dry cells in the north which can be explained by the roc outcropping on the surface. Moreover, figure 6b correspond to the simulated flow in roc unit.

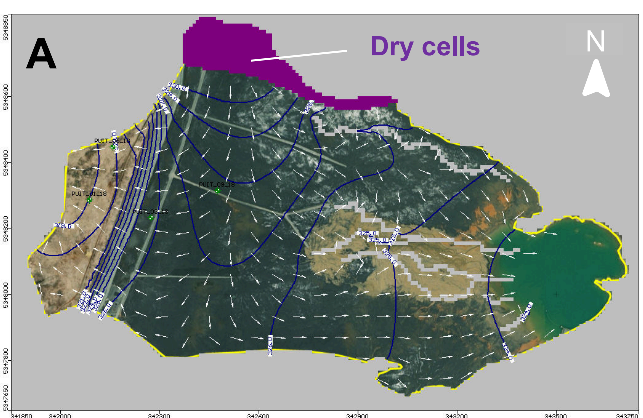
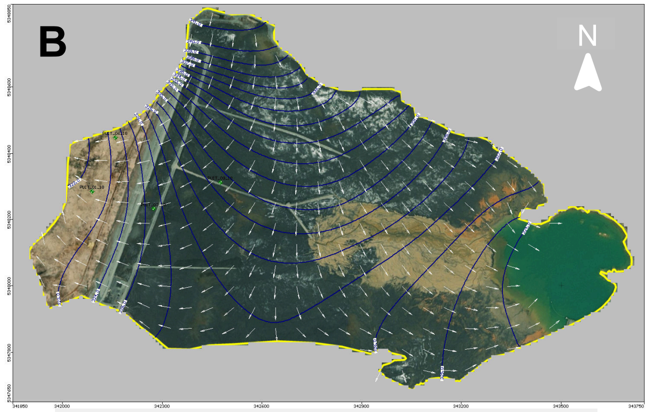
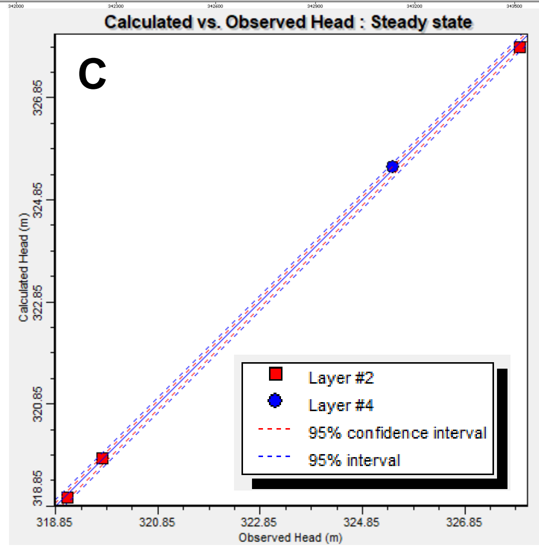


Figure 6 (Continued)





Num. of Data points: 4	Absolute Residual Mean: 0,046 m
Correlation Coefficient: 1	Root Mean Squared: 0,052 m

Figure 6. Simulated hydraulic head (m) of A mine tailing, B roc and C correlation between simulated and measured hydraulic heads for November 5th, 2020.

4.2 Transient state calibration

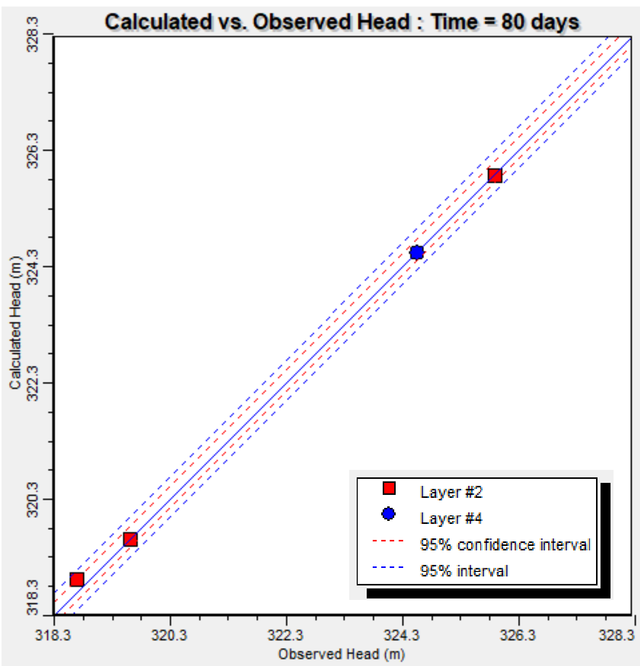
Using measured hydraulic head averages from November 5th, 2020 to February 5th, 2021, the model was calibrated in transient state. In Figure 7, the line represents the correlation of modelled and observed results. Piezometer probes of wells 1, 6, and 9 are in the mine tailings (Layer 2: red point), and for the wells 3, it is in the rock (Layer 4: blue point). The decline of hydraulic heads can be explained by drier winter season with solid precipitation (i.e., snow). With a root mean square error (RMSE) of 0.12 m for the head and an R of 1. Indeed, the results are acceptable.

The numerical model's ability to replicate the hydrogeological behaviour of the Quemont 2 TSF was demonstrated by a transient state simulation. Daily hydraulic heads were reproduced from November 5th, 2020 to February 5th, 2021. The transient analysis used boundary, Initial conditions and material parameters obtained from the steady-state calibration. Figure 8 depicts the simulation results for the relevant period.

Moreover, the simulation included the day-degree snowmelt approach to represent the drier winter season. The degree-day method is a temperature index methodology that relates the total daily melt to the difference between the mean daily temperature and a base temperature (generally 0°C); the equation is as follows:

$$M = C_M\,(T_a - T_b) \qquad [1]$$

where M is the snowmelt (mm/day), Ta is the mean daily air temperature (°C), Tb is the base temperature (°C), and C_M is the degree-day coefficient (mm/degree-day °C), This coefficient varies seasonally and spatially. Typical values are from 1.6 to 6.0 mm/degree-day °C. A value of 2.74 mm/degree-day °C was used for this study (United States Department of Agriculture 2012).



Num. of Data points: 4	Absolute Residual Mean: 0,071 m
Correlation Coefficient: 1	Root Mean Squared: 0,12 m

Figure 7. Calibrated hydraulic heads comparing estimated and observed transient state in a scatter diagram (Time = 80 days)

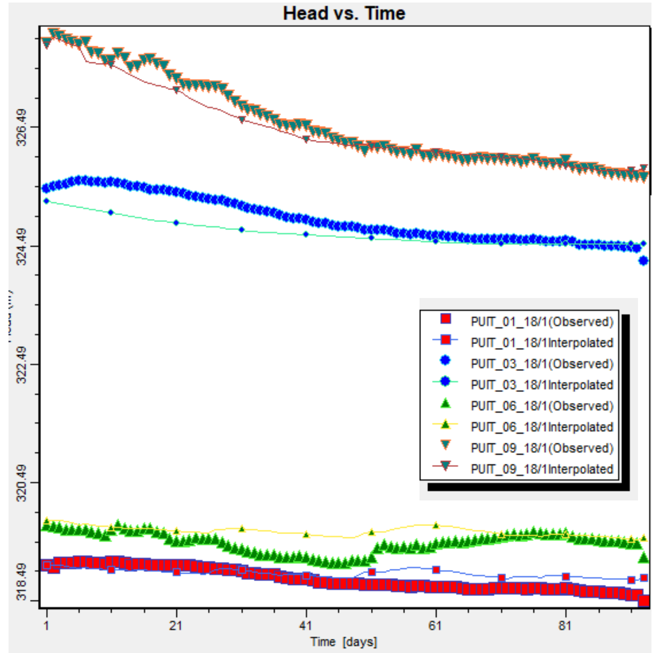


Figure 8. Simulated (spaced points) and Observed (condensed points) daily hydraulic heads at the observation wells 1, 3, 6, and 9 from November 5th, 2020, to February 5th, 2021.

4.3 Climate Change

After these calibrations, the model was used to complete the simulation process until 2100 considering the impact of climate change on water resources of the TSF under three different scenarios (RCP 2.6, 4.5 and 8.5). In these last simulations, the effect of climate change in the Quemont 2 TSF will be the increase of the groundwater level due to mainly by the increase of precipitation. These hydraulic heads show clearly that the lower (Mine tailing) and upper (Roc) hydrogeological units (Figure 9). are hydraulically dependent.

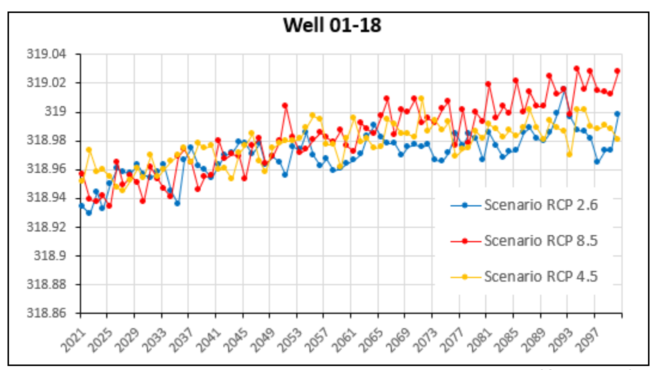


Figure 9 (Continued)

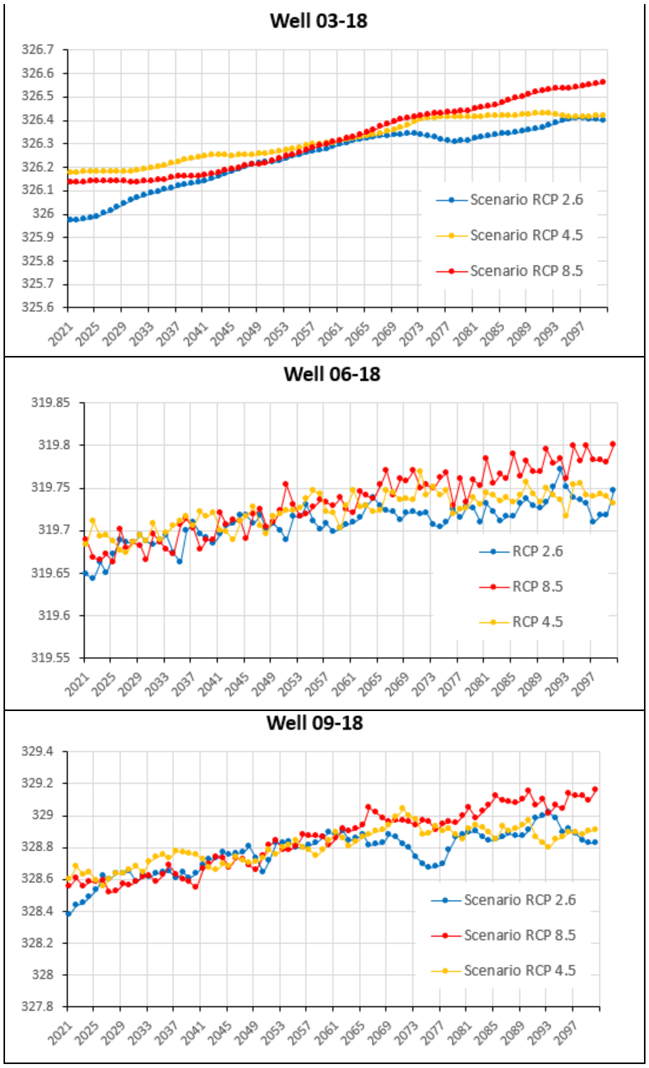


Figure 9. Time series of predicted hydraulic heads (in meters) of the Quemont 2 TSF at piezometer 01, 06 and 09 in mine tailing unit and at piezometer 03 in roc unit

5 CONCLUSION

The establishment of hydrogeological database and a groundwater model, has aided to better understand the Quemont 2 TSF hydrogeological properties and hydrodynamic performance, particularly under CC. Indeed, after calibrations of the model in steady and transient states, linking these results to a various CC scenario is critical for identifying the impacts of CC (P and T for various climate scenarios extracted from 2006 to 2100).

The effect of climate change in the Quemont 2 TSF will be an increase in groundwater level, primarily as a result of increased precipitations.

The results will be used in the next step to examine and evaluate the long-term performance, as well as identify the most appropriate reclamation technique that managers must consider while recovering the Quemont 2 TSF.

6 ACKNOWLEDGEMENTS

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