Mine Closure 2023 - Behrooz Abbasi, Jeff Parshley, Andy Fourie & Mark Tibbett (eds)
ISBN 978-0-6450938-7-2
doi:10.36487/ACG_repo/2315_057

Closure modelling of the Eagle Ni-Cu mine, Michigan: Part 1. Hydrogeology and water quality of the underground mine pool

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Abstract

The Eagle underground Ni-Cu mine on the Upper Peninsula of Michigan, owned by Eagle Mine LLC (Eagle), a subsidiary of Lundin Mining, began operations in 2014. Ore is trucked 80 miles to the Humboldt Mill (see Part 2) whereas waste rock is stockpiled at the surface and returned underground as cemented and uncemented rockfill. After mining concludes, one possible reclamation plan involves flooding the underground workings with deep, saline groundwater plus fresh water pumped from the overlying Quaternary aquifer and reclaiming the surface footprint as a greenfield property. The mine pool must not deteriorate water quality in the Quaternary aquifer or the nearest downgradient surface water receptor, the Salmon-Trout River, located 1.5 miles north of the mine. To assess closure costs, timeframe, and risk associated with this reclamation plan, Eagle developed a four-part closure study in 2021 that calculated the time to flood the mine pool, estimated the vertical components of the hydraulic gradient post-flooding, predicted the water quality of the mine pool, estimated the travel time to the Salmon-Trout River, and predicted the water quality in both the downgradient Quaternary aquifer and river.

The multi-disciplinary modelling approach presented herein provides several insights for predicting the closure of underground mines: (1) Where steady-state vertical components of the hydraulic gradient are downward, groundwater is likely to flow downward from the shallow aquifer into the mine pool, but not from the mine pool into the shallow aquifer; the mine pool can be expected to have little to no influence on water quality in the overlying aquifer. (2) For mines with low bedrock hydraulic conductivity and downward hydraulic gradients, the addition of bulkheads between different mine workings at different depths may direct flow from the flooded mine workings towards the surface. (3) Underground mines with low bedrock hydraulic conductivity and low steady-state flowthrough rates (Q) may generate low mass loading (M) to downgradient aquifers, regardless of mine pool concentrations (C), where M=Q×C; a small load addition from a mine pool to a large aquifer may generate a steady-state water quality in the aquifer that is indiscernible from background water quality. (4) The representation of backfill pore space water in both water balance and geochemical models can influence geochemical predictions, especially where cemented backfill and weathered, uncemented waste rock are used. (5) The reaction time specified for the release of mass from wall rocks and backfill to mine pool water influences the predicted water chemistry of the mine pool.

Keywords: *FEFLOW, GoldSim, PHREEQC, bulkheads, case study*

1 Introduction

The Eagle Mine is an underground nickel-copper mine located below the Yellow Dog Flats on the Upper Peninsula (UP) of Michigan (Figure 1). The mine is owned and operated by Eagle Mine LLC. (Eagle), a subsidiary of Lundin Mining Company, Vancouver, Canada. Eagle recovers nickel and copper from semi-massive and massive sulfide ore zones surrounded by siltstone and peridotite country rock. At the time of this investigation (2021) there were two deposits under development which were connected by a long decline: the shallower Eagle Deposit and the deeper Eagle East Deposit. In 2022, a third deposit was added to the life of mine, the Eagle East extension, which lies along the same lineament.

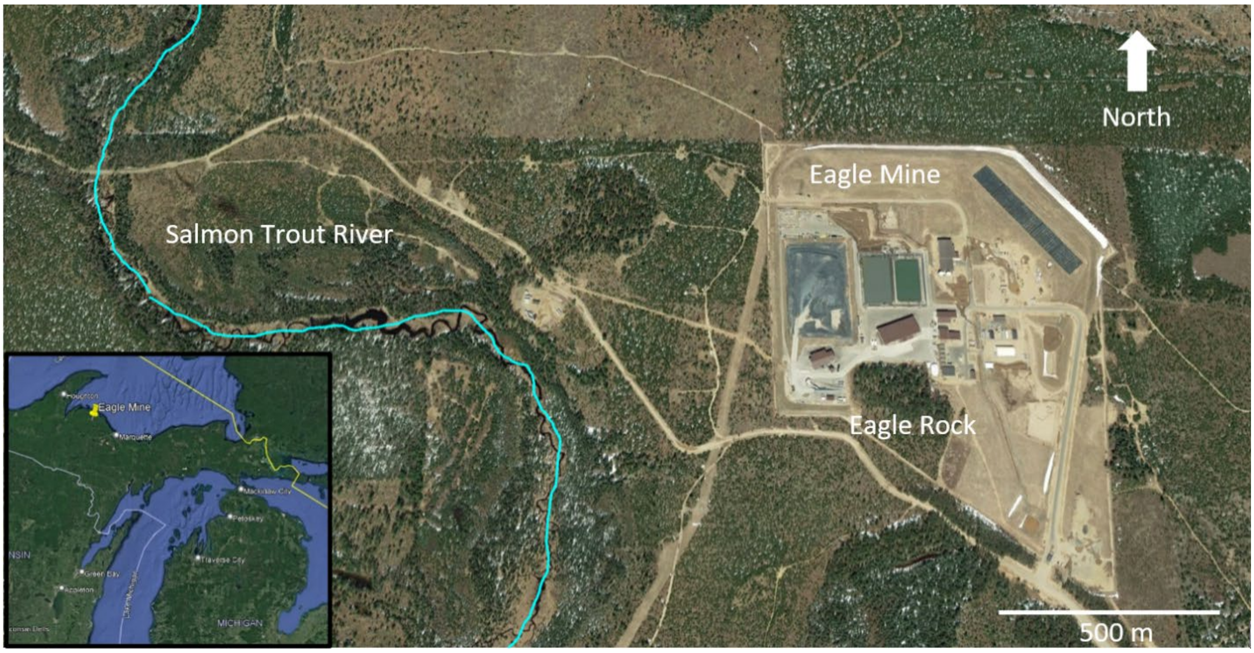

Figure 1 **Aerial view of Eagle Mine surface footprint and Salmon Trout River (flows to north)**

Waste rock from underground is stockpiled in the temporary development rock storage area (TDRSA) at the surface for uses in cemented and uncemented rockfill. Pentlandite and chalcopyrite ores are trucked approximately 60 miles southeast to the Humboldt Mill in Champion, Michigan for processing. In Part 2 of this study, Evans et al. (2023) discuss the hydrodynamic model used to simulate the sub-aqueous disposal of the tailings slurry in a pit lake called the Humboldt Tailings Disposal Facility (HTDF), and the predicted water quality at closure.

Successful closure is a priority for Lundin, Eagle, and the local community for the following reasons:

- Eagle plans to demolish the surface structures at the mine, return the surface to a greenfield property for use in forestry, and receive release from future liability from the Michigan Department of Environment, Great Lakes and Energy (EGLE). To achieve this goal, the water quality of the overlying Quaternary aquifer must remain suitable for drinking water purposes in the future, and there should be no adverse impacts to the aquatic habitat in downgradient streams.
- The Keweenaw Bay Indian Community (KBIC) of the Lake Superior Band of Chippewa Indians is located approximately 65 miles north of Marquette, Michigan in the L'Anse/Baraga area, and has land on both sides of the Keweenaw Bay Peninsula in Baraga County. Their area includes the reservation as well as members in Ontonagon, Gogebic, Marquette, Houghton and Keweenaw Counties. The L'Anse Reservation is both the oldest and the largest reservation in Michigan. KBIC recognizes Eagle Rock, a prominent topographic feature at the mine site and the location of the underground mine portal, as a sacred native place of worship. Since the start of operations, Eagle has worked with KBIC to provide periodic access to Eagle Rock for ceremonies, and will preserve Eagle Rock during closure activities.
- Eagle was the first sulfide mine approved in Michigan under the Part 632 of the Natural Resources and Environmental Protection Act of 1994, titled "Nonferrous Metallic Mineral Mining" (Michigan Legislature 2023). Meeting closure objectives will provide a strong demonstration that future

> sulfide mining on the UP (plus Minnesota and Wisconsin) can be safely developed, operated and closed without causing harm to the environment. This will showcase Eagle and Lundin's commitment to the community and leave a positive legacy for both entities.

In 2021, Eagle began the process of refining existing closure cost estimates based on an anticipated end-of-operations date of January 2026. The findings of the 2021 closure study were reported by Lundin Mining Corporation (2023).

The following report details the approach used to generate the 2021 closure study, provides a case study of closure predictions for an underground mine, and highlights key learnings from this exercise.

The five step approach involved: (1) using an existing FEFLOW model (Diersch 2014) to predict the groundwater inflow rate(s) to the underground mine; (2) developing a water balance for the mine during closure in GoldSim (GoldSim Technology Group, 2021); (3) predicting the water quality of the mine pool in PHREEQC (Parkhurst and Aleppo 2013); (4) predicting the flow path, travel time and discharge rate from the mine to the Salmon-Trout River in FEFLOW; and (5) mixing potential future groundwater discharge from the Quaternary aquifer (baseflow) with stream water in GoldSim and comparing results against aquatic water quality criteria. This study focuses exclusively on the 2021 closure effort and does not include updates associated with the extensions of Eagle East added to the life of mine in subsequent years (Lundin Mining Company 2023).

2 Conceptual model

Host rocks at the Eagle Mine are composed of very low-hydraulic conductivity siltstone and peridotite. There are three primary hydrogeological units (Figure 2). A thin Quaternary glacial aquifer exists at the land surface [+447 m above sea level (masl)]. An upper-bedrock hydrogeologic unit (UBHU) extends from the base of the Quaternary aquifer (+433 masl) to approximately +335 masl, and contains relatively fresh water quality with a concentration of total dissolved solids (TDS) between 100 and 300 mg/L. A lower bedrock hydrogeologic unit (LBHU) begins at +335 masl. Concentrations of TDS increase below this depth (up to 64,000 mg/L in Lower Eagle East with higher concentrations observed in some seeps) in groundwater such that, during post-closure, a continuum of water quality will exist from nearly fresh water at the top of the UBHU to saline in the deepest part of the LBHU. For modelling, two future mine pools, Upper Eagle and Upper Ramp, will exist within the UBHU, and three future mine pools, Lower Eagle, Upper Eagle East and Lower Eagle East will exist within the LBHU. Mine pools will be connected but unlikely to vertically mix due to vertical salinity and density gradients. The deepest portion of Lower Eagle East has an elevation of approximately -542 masl.

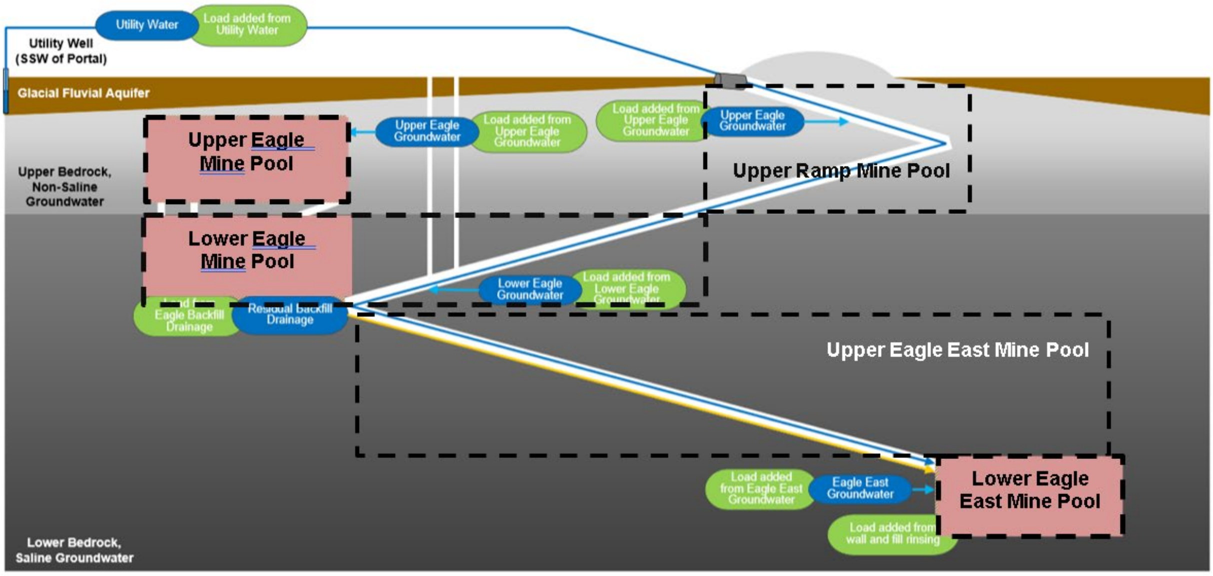

Figure 2 Schematic cross section of the Eagle Mine showing the location of each mine pool plus major sources of water (blue) and mass (green) (not to scale)

During operations, the mine uses water pumped from a utility well in the Quaternary aquifer for drilling, mucking and dust control. Groundwater inflow rates to the mine are very low but the total dissolved solids (TDS) load from LBHU groundwater is high. Cemented rock fill is a source of hardness and uncemented rock fill is a source of sulfate. These waters are either (i) captured in sumps and returned to the surface for treatment or (ii) allowed to drain into Lower Eagle East for permanent storage. As of September 2022, water had flooded the workings up to -528 masl. At the end of operations, Eagle currently plans to pump water from the utility well into the workings to accelerate flooding.

3 Groundwater inflow rates

Because previous hydrogeological assessments focused on the bedrock hydrogeologic units (Golder 2019) and given the potential usage of wells in the Quaternary aquifer to supply groundwater to flood the mine workings, a data review was conducted focusing on groundwater elevations and material properties in the Quaternary aquifer. Groundwater elevations in shallow monitoring wells completed to monitor a local wetland indicated relatively stable groundwater elevations with minor seasonal variability (+/- 0.3 m). Groundwater elevations in the Quaternary aquifer show seasonal variability of approximately 0.5 m. Groundwater elevations in the bedrock monitoring wells showed negligible influence from seasonal effects and pumping in the Quaternary aquifer. A review of pre-development groundwater elevations indicated negligible vertical hydraulic gradients existed between the UBHU and the LBHU before mine operations commenced. It was anticipated that following mine flooding a similar hydrostatic gradient will develop. As discussed in Section 5, simulated steady-state hydraulic heads were in the +428 to +430 masl range (see Figure 3), and approximately 2 m below the simulated water table in the Quaternary aquifer.

A 2019 FEFLOW (Diersch 2014) bedrock groundwater flow model (Golder 2019) was used to estimate rates of groundwater inflow to various horizons within the mine (Table 1). The combined simulated groundwater inflow rate at the end of operations was approximately 98 cubic meters per day (m^3/d)[18 US gallons per minute (US gpm)]. The simulated groundwater inflow rates reporting to the various mine horizons are reflective of the long-term steady-state conditions at the full build-out of the mine. As the water level in the mine rises (through water addition during closure and natural flooding) the hydraulic gradients in the bedrock will decrease and rates of groundwater inflow will decrease. Given the relatively low rates of natural bedrock groundwater inflow (as compared to the reflooding rate from the utility well), these values were conservatively assumed to be constant over the reflooding duration for the purposes of the water balance and geochemical assessments.

A sensitivity analysis was performed on the addition of bulkheads between mine pools during closure. Results indicated that bulkheads placed at the +335 m Level (i.e., between the fresh UBHU and the saline LBHU), directs bedrock groundwater flow towards the UBHU. Hence, the construction of bulkheads produced a less desirable closure outcome relative to a "no bulkhead" scenario. Both scenarios included a bulkhead at the mine portal and plugs at the vent raises.

Table 1 Groundwater inflows to dewatered mine from 2019 groundwater flow model

Mine pool	Elevation (masl)	Inflow rate at end operations (m^3/day)
Ramp to +335	+447 to +335	22
Upper Eagle	Top of deposit to +335	42
Lower Eagle	+335 to +10	7
Eagle East (Upper and Lower)	+10 to -539	27
		98 = Total inflow

4 Water balance and flood time

The water balance for the closure of the underground mine workings was developed using the software GoldSim™, version 12.1.3. GoldSim is a graphical, object-oriented mathematical model where input variables and functions are defined by the user and then linked together by mathematical expressions.

The model was run on a daily timestep from January 1, 2020, until January 1, 2029. The five mine pools shown in Figure 2 were represented in the model based on the geometry of the life of mine (LoM) plan available at the time of modelling. Each mine pool was modelled sequentially from the lowest to the highest as an isolated water body, assuming density gradients prevent vertical mixing. In this reclamation plan, the Lower Eagle East mine pool represented a portion of the underground mine which was flooded prior to the end of operations and constituted most of the Eagle East workings. The Upper Eagle East mine pool largely represented the dual decline between the bottom of Lower Eagle workings and the top of the Eagle East workings (Figure 2). Each mine pool was modelled as a distinct reservoir, and there was no upward transfer of water from a lower mine pool into an overlying mine pool. This assumption was based on predicted differences in salinity between the mine pools, which would limit upward transfer of water and maintain a stratified system.

Inputs and assumptions for the water balance model were as follows:

- Stage (elevation)-storage curves for each mine pool were defined by the LoM plan.
- Volumes of cemented and uncemented backfill by elevation in each mine pool, were defined by the LoM plan. Cemented rockfill was assumed to have a porosity of 20% and uncemented rockfill was assumed to have a porosity of 30%.
- Volumes of "clean" backfill in each mine pool were defined by the LoM plan. "Clean" backfill comprised material from surface demolition materials (for example, concrete) that was assumed to not impart geochemical mass and only reduced the final filling volume in the underground mine workings.
- Assumed well water (i.e., groundwater from the Quaternary aquifer) pumping rates were used. During operations, well water was added to the mine workings at a rate of 114 m3/day. After operations, well water was added to the mine workings at a rate of 1,140 m3/day.

- Projected groundwater inflow rates from the FEFLOW model were used in the GoldSim model (Table 1). At the start of closure, all groundwater discharging to the mine was assumed to drain by gravity into the Upper Eagle East mine pool. Similarly, Lower Eagle received cumulative groundwater inflow from Upper Eagle and the Upper Ramp.

The water balance results indicated that the underground mine workings should take approximately six years to fully flood under the modelled reclamation plan. This represents approximately four years of filling during operations and approximately two years of filling during closure (Figure 3).

Figure 4 illustrates the volume of water added to the mine pool from each input, expressed as a percentage of the total volume of the mine pool. For cemented and uncemented backfill, the volume added was equal to the total volume of the backfill multiplied by the porosity of the backfill. The pie diagrams shown in Figure 4 illustrate the importance of accurately predicting back fill pore water volumes and chemistries.

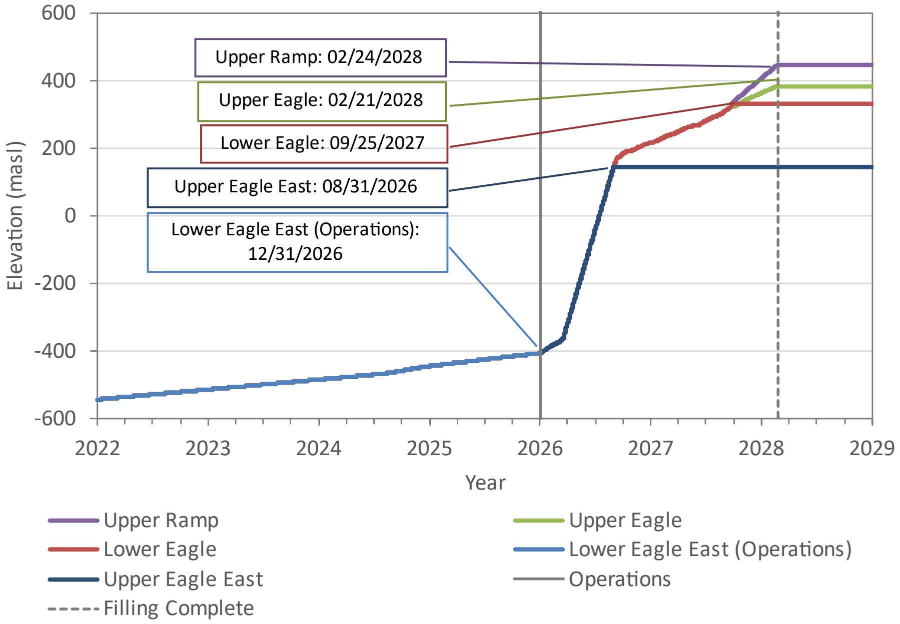

Figure 3 Stage vs time for flooding of Eagle Mine

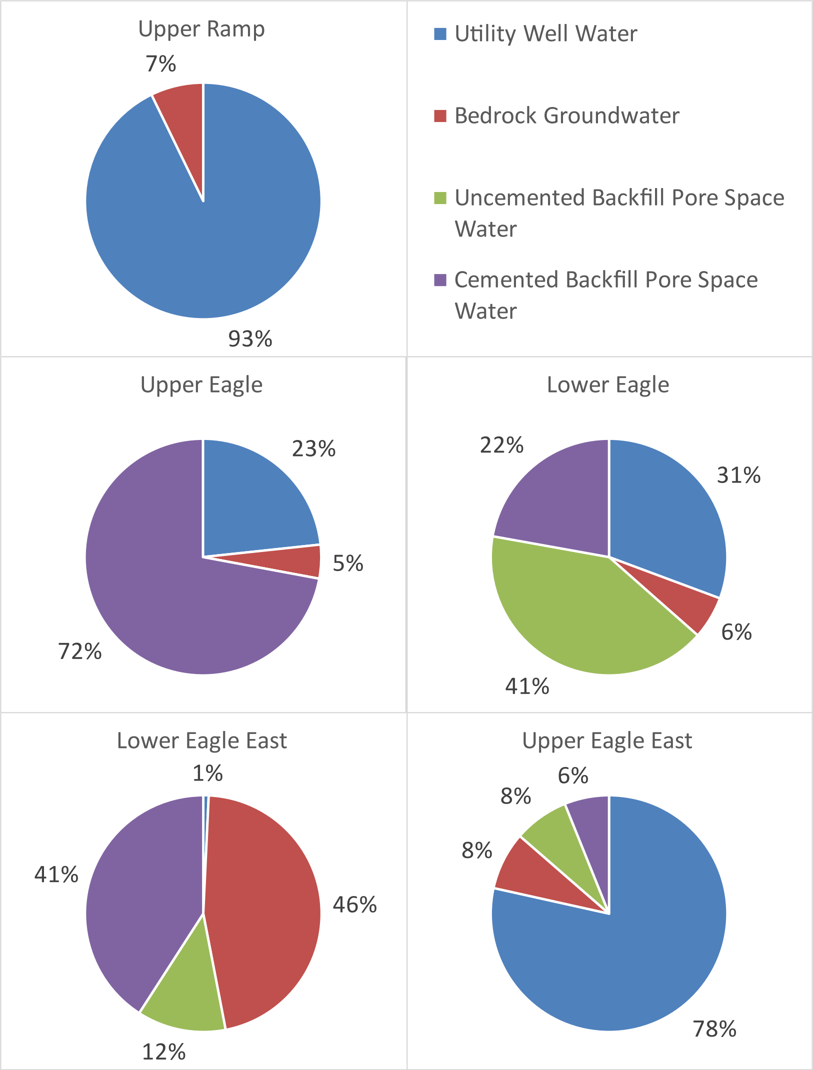

Figure 4 Water source contribution to each mine pool

5 Mine pool water chemistry

The following general approach was used to predict the water quality of each mine pool.

- Step 1: The representative water quality of each inflow in Figure 4 was defined using the median concentration of observed water quality collected by Eagle.
- Step 2: The water balance was used to define the relative percentages of water added to each mine pool from each input (Figure 4). The volumes of pore space water in cemented backfill and uncemented backfill were subtracted from the total utility water volume added to calculate the residual utility well water volume used for mixing.
- Step 3: Eagle provided the geometric area (m2) of exposed rock lithologies in mine workings as a function of mine elevation. Rock types included: Siltstone, Peridotite, Massive Sulfide Unit (MSU), and Semi-Massive Sulfide Unit (SMSU). Consistent with previous work by Geochimica (2005; 2006), the geometric areas were scaled by a factor of 100 following methods by Morin and Hutt (1997) who postulated that the total mine wall surface area is greater than the geometric surface area due to natural fractures and blasting fractures. The product provided an estimate of the total surface area of each rock type at each depth interval.

- Step 4: Prior to this study, Eagle and Geochimica (Geochimica 2005, 2006) conducted a 340-week-long (6.5 year), humidity cell test (HCT) program on 15 rock samples spanning each rock type. Samples were collected from exploration boreholes. Leachate from each cycle was tested weekly from weeks 0 to 29, and monthly from weeks 30 to 340.
- Concentrations and surface areas (derived from particle size distributions of cell materials) were used to estimate the mass of constituents added per unit surface area per time (mg/m2/week) to each mine pool from wall leaching following closure. As mine walls will generally have undergone significant exposure by the end of operations, the long-term steady state chemistry was assumed to best represent conditions at closure. Therefore, the median mass leach rate (mg/m2/week) from each rock type from HCT leachate concentrations between week 200 and 300 was used to represent long-term water-rock interactions.
- Step 5: The total rock type surface area (Step 3) was multiplied by the rock type mass leach rate (Step 4) to estimate the mass leached per time (mg/week) from each rock type. To account for uncertainty in the duration of active wall rock leaching, separate simulations were run using median mass loadings for one week, four weeks and eight weeks of leaching.
- Step 6: The mass leached from wall rock in Step 5 was added to utility well water at a volume equal to the residual utility well water from Step 2.
- Step 7: The geochemical code PHREEQC, version 3.7 (Parkhurst & Appelo 2013), was used to mix the various input solutions in the specified proportions (Figure 4), to identify likely oversaturated minerals (i.e., calcite, barite), and to calculate the final composition of each mine pool after oversaturated minerals were allowed to precipitate. PHREEQC is an equilibrium speciation and mass-transfer code developed by the United States Geological Survey, to model geochemical processes. The code has gained widespread use and acceptance by the regulatory and technical community.

The sensitivity analysis discussed in Step 5 showed increased concentrations of constituents in mine pool water as a function of reaction time. The closure study used the longest reaction time to generate a conservative estimation of future mine pool chemistry. However, the duration of wall rock leaching remains an area for further refinement which could reduce the conservativism in the model.

6 Vertical and horizonal components of hydraulic gradient

The existing FEFLOW bedrock groundwater model (Golder 2019) was updated to include the overlying Quaternary aquifer to predict the vertical components of the hydraulic gradient after flooding. A key finding was that simulated steady-state, post-closure hydraulic heads were in the +428 to +430 masl range (Figure 3), approximately 2m below the simulated water table in the overlying Quaternary aquifer. The groundwater flow model predicted that vertical components of the hydraulic gradient will be downward, therefore, Quaternary groundwater will be able to enter the flooded workings, but workings water will not migrate into the Quaternary aquifer.

Particle tracking was also used to delineate the horizontal groundwater flow paths between the mine pool and the nearest surface water receptor, the Salmon-Trout River, and to predict the groundwater travel time from the flooded mine workings to surface water. These updates involved specifying the Quaternary aquifer within the groundwater model as a fluid-transfer boundary at +433 masl. The recharge rate distribution was based on the surficial geology, with 57 mm/yr applied where the Quaternary sand unit was present on the surface and 30 mm/yr where the Quaternary till unit was present. Constant head boundaries were placed on the upper model layer at elevations specified based on topography to represent the surface water features within the model domain, including the Salmon Trout River, Yellow Dog River, and their tributaries.

The updated groundwater flow model was calibrated using PEST (Watermark Numerical Computing 2021) parameter estimation and optimization software, which iteratively adjusts model parameters (e.g., hydraulic conductivity and recharge) within user-defined constraints until the model error, as calculated based on target data (e.g., groundwater elevations), is minimized. In this instance, PEST was implemented directly through the FEFLOW user interface. The primary focus of the model calibration was a simulation of operations conditions.

The updated groundwater model indicated that, upon closure, the Eagle Mine will fill with water and groundwater elevations will return to hydrostatic conditions reflective of the predevelopment groundwater setting. At post-closure, groundwater from the mine horizon was simulated to flow downwards, through open (water-filled) mine workings, transitioning to a deep (very low permeability) bedrock groundwater flow pathway to discharge at a location distant (generally to the north) from the mine.

7 Discussion and conclusions

In a recent NI 43-101 Technical Report on the Eagle Mine, Lundin Mining Corporation (2023) reported the following key findings of the 2021 closure study:

- *The post-closure, vertical hydrological gradient is likely to be downward. As such, water from the flooded Eagle workings is not expected to discharge to the Quaternary glacial aquifer, and the drinking water quality in the Quaternary glacial aquifer is not expected to be impacted.*
- *Water from the flooded mine workings is expected to slowly migrate to the north through the upper bedrock, hydrogeological unit. This water will ultimately discharge to the Salmon Trout River hundreds of years in the future.*
- *Due to the low mass load from the Eagle mine workings plus considerable dilution and dispersion occurring along the flow path, the discharge of water to the Salmon Trout River will have little to no impact on the drinking water quality and aquatic health of the Salmon Trout River.*
- *As such, additional treatment of the flooded mine may not be necessary to achieve permit conditions.*
- *Additional bulkheads within the Eagle Mine workings may not provide significant improvements to post-mining water quality.*

This report presented a case study of the 2021 Eagle mine closure study based on one possible reclamation scenario. The case study demonstrated the integration of groundwater, water balance and geochemical modelling applications which helped inform Eagle mine staff of future timing and potential risks associated with mine closure.

Five technical insights have been identified which may be applicable to other underground mine closure studies:

1. Where steady-state vertical components of the hydraulic gradient are downward, post-closure groundwater is likely to flow downward from the shallow aquifer into the mine pool but is unlikely to flow upwards from the mine pool into the shallow aquifer. Under this condition, the mine pool can be expected to have little to no influence on water quality in the overlying aquifer.

2. For mines with low bedrock hydraulic conductivity and downward hydraulic gradients, the addition of bulkheads between different mine workings at different depths may re-direct flow from the flooded workings towards the surface.

3. Underground mines with low bedrock hydraulic conductivity and low steady-state flowthrough rates (Q) may generate low mass loading (M) to downgradient aquifers, regardless of mine pool concentrations (C), where $M=Q \times C$. A small load addition from a mine pool to a large surface aquifer may generate a steady-state water quality in both the aquifer and streams that is almost indiscernible from background water quality and possibly within the error range of laboratory measurements.

4. The representation of backfill pore space water in both water balance and geochemical models can influence geochemical predictions, especially where cemented backfill and weathered, uncemented waste rock are used.

5. The duration of the reaction time specified for the release of mass from wall rocks and backfill to mine pool water influences the predicted water chemistry of the mine pool. This is a topic of active geochemical research not only in underground mines, but for submerged pit wall rocks and other subaqueous settings.

Acknowledgement

The authors thank Eagle for their willingness to make this study publicly available. We also wish to acknowledge Nicholas Bishop (formerly of WSP Golder Canada) and Kristina Skeries (WSP Canada) for their contributions to the closure study, plus Mark Logsdon (Geochimica Inc.) for his work on the geochemistry of the Eagle Mine.

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