Mine Closure 2023 - Behrooz Abbasi, Jeff Parshley, Andy Fourie & Mark Tibbett (eds)
© 2023 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-7-2
doi:10.36487/ACG_repo/2315_058

Closure modeling of the Eagle Ni-Cu mine, Michigan: Part 2. Limnology and water quality of the Humboldt Tailings Disposal Facility, a pit lake used for sub-aqueous tailings disposal

E Evans *WSP USA Inc, USA*

D Castendyk *WSP USA Inc, USA*

R Verburg *WSP USA Inc, USA*

J Nutini *Eagle Mine LLC, USA*

A Matznick *Eagle Mine LLC, USA*

L Cavalieri *Eagle Mine LLC, USA*

Abstract

Water quality models are an important tool to predict and manage risks and determine the best operational strategies and long-term solutions for mine waste and water management. Eagle Mine LLC (Eagle), a subsidiary of Lundin Mining, uses a hydrodynamic model to predict stratification and water quality in the Humboldt Tailings Disposal Facility (HTDF) during operations and closure. Ore from the Eagle underground Ni-Cu mine is processed at the Humboldt Mill in Champion, Michigan, and a sulfide-rich tailings slurry is sub-aqueously disposed in the HTDF, a meromictic pit lake which formed in the 1950s. A water treatment plant (WTP) treats effluent prior to discharge through a reverse osmosis system that returns a brine to the bottom of the HTDF. After operations conclude in approximately 2027, the WTP will continue to operate until water quality meets discharge criteria.

In 2022, Eagle generated a 34 year, 2D hydrodynamic and water quality model of the HTDF in CE-QUAL-W2. The model included a novel code that adjusted bathymetry over time as a function of tailings deposition and simulated profiles of water temperature and concentrations of several constituents of interest from 2019 to 2053.The modeling was conducted in five parts. Part 1 (Calibration) predicted conditions from 2019 to 2020 and adjusted input variables to match predicted and observed conditions. Part 2 (Validation) assessed the accuracy of the prediction using observed data from 2021 to 2022. Strong agreement between predicted and observed physical and chemical conditions provided confidence in the model and enabled its use in water and tailings management decisions. Part 3 (Operations) extended the model to the end of operations and quantified the impact of specific tailings and water management decisions on water quality, including tailings production rates, tailings deposition plans, minimum depths of tailings injection, start dates for new water treatment equipment, and composition of various inflows. Part 4 (Remediation) predicted the WTP would need to run for approximately 3.5 years (mid-2027 to 2030) after operations to meet closure criteria and this finding was used to estimate closure costs. Part 5 (Post-Closure) predicted conditions during the first two decades of passive discharge (2030 to 2053). The HTDF was expected to remain vertically stratified until approximately 2040 and discharge water quality was predicted to meet required limits. The model is routinely updated as new tailings production and water management plans are generated. Models such as the one described in this paper are reliable and valuable tools for supporting mine waste and mine water management decisions throughout the life of mine.

Keywords: *closure modeling, pit lakes, CE-QUAL-W2, subaqueous tailings deposition*

1 Introduction

Eagle Mine LLC (Eagle) is evaluating the operational water treatment requirements and closure plans for the Humboldt Tailings Disposal Facility (HTDF). The HTDF is a meromictic (layers do not mix), iron-ore, pit lake located in Champion, Michigan, USA, that Eagle uses for the disposal of a slurry containing sulfidic tailings produced by the Humboldt Mill (the Mill). WSP USA Inc. (WSP) designed and executed a CE-QUAL-W2 (Wells 2021) hydrodynamic model to predict the physical stratification and water quality of the HTDF during Operations, Reclamation, and Post-Closure periods. CE-QUAL-W2 has been used to evaluate pit lake water column stability and chemistry in a variety of settings (Colarusso et al. 2003, Paulsson & Widerlund 2022).

The water column of the HTDF is perennially density stratified into a Surface Layer, Middle Layer, Chemocline, Deep Layer, Pycnocline, and Brine Layer (Figure 1). Vertical mixing occurs within the Surface, the Middle, and Deep Layer, however, complete mixing between subjacent layers or across the entire water column has not been observed since the start of monitoring in 2014. The Chemocline separates the Middle and Deep Layers, while the Deep and Brine Layers are separated by the density gradient across the Pycnocline.

During the Operations period (present to 2027), a tailings slurry is added to the HTDF from the Mill and a water treatment plant (WTP) is used to treat water effluent from the HTDF until it complies with water quality discharge criteria specified by the Michigan Department of Environment, Great Lakes, and Energy (EGLE 2022). Treated effluent is discharged to the Middle Branch of the Escanaba River, a tributary of Lake Michigan. The WTP process includes: (1) a plug flow reactor (PFR) which drives a Fenton’s reaction to oxidize WTP influent; (2) a pH adjustment tank; (3) reaction tanks where a polymer is added to remove metals; (4) a clarifier system to remove hardness; (5) an ultra-filtration system; and (6) a reverse osmosis (RO) system. Various WTP wastes, including off specification water from the PFR and filter cleaning solutions, are returned to the HTDF via an Off Spec line. RO brine is returned to the bottom of the HTDF. Due to vertical differences in water density, this management approach has created a stratified lake system with a fresh (i.e., low total dissolved solids [TDS] concentration) Surface Layer and a saline (i.e., high TDS) Brine Layer at the bottom of the HTDF separated by several layers of intermediate composition (Figure 1). The WTP plays a critical role in the containment of mine-impacted waters within the HTDF by controlling the water surface elevation, and thus, maintaining an inward hydraulic gradient towards the HTDF.

At the time of modeling, Eagle planned to bring a Zero Liquid Discharge (ZLD) system online in October 2023. The ZLD is a key asset in the reclamation plan and would pump water from the Brine Layer and Pycnocline, pre-concentrate the liquid, and evaporate until salts precipitate as a crystalline solid. This solid will be disposed and a small volume of purified water will be returned to the HTDF, recycled internally through the WTP, or added to plant discharge water. The ZLD system will operate until at least the cessation of Operations.

After Operations, the Mill site will enter a Reclamation Period when the WTP will continue to treat HTDF water, but tailings slurry will no longer be added. At the conclusion of the Reclamation Period, both the HTDF Surface Water Layer and direct lake effluent will comply with water quality criteria specified by Michigan Department of Environment, Great Lakes, and Energy (EGLE 2022), allowing the site to receive a Closure designation from EGLE. These criteria include a monthly average concentration of TDS equal to or less than 500 (mg/L) plus no acute or chronic toxicity. From a cost perspective, the shorter the duration of the Reclamation Period, the less money Eagle will spend to achieve Closure when the mine is no longer generating revenue. Minimizing the duration of the Reclamation Period will likely require more aggressive treatment of HTDF water during the Operations Period than required for discharge compliance alone, such as removing salt stored in the Brine and Pycnocline layers prior to the end of operations.

After receiving approval for Closure from EGLE, the Post-Closure period will begin. The WTP will be turned off, the water level will rise from 467 m to an engineered channel at 468 m, and the Surface Layer will decant by gravity to the adjacent wetland, and ultimately, the Middle Branch of the Escanaba River. Modeling must demonstrate that residual saline water stored in deeper lake layers will not degrade the quality of the Surface Layer above discharge limits at any time in the future.

1.1 Specific model objectives included

- Generate a robust calibration model to validate use of variable bathymetry code and input data for forward model.
- Predict water quality and lake structure (i.e., layer thicknesses and stability) through 2053.
- Test the effect of tailings deposition on Surface Layer water chemistry, including maximum allowable tailings deposition elevation.
- Test the sensitivity of layer chemistries to variations in WTP outflow and inflow rates.
- Predict the duration of the Reclamation Period (i.e., treatment time until Closure criteria are satisfied).

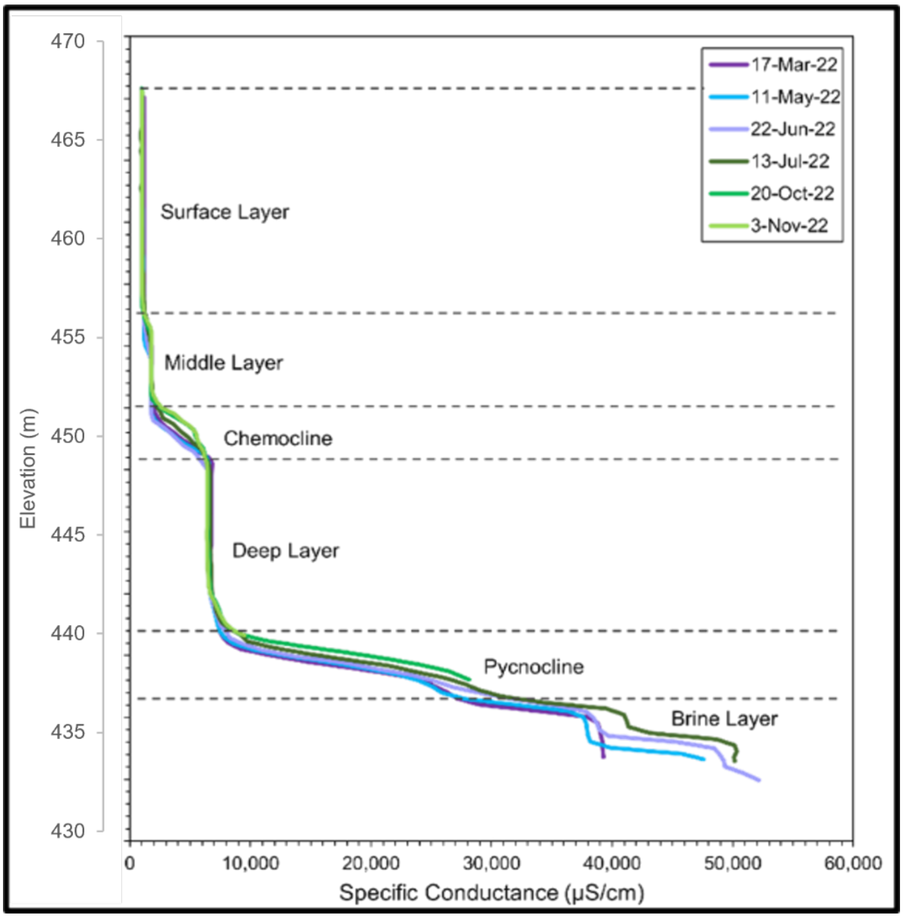

Figure 1 Observed specific conductance profiles and HTDF structure between March and November 2022

2 Approach

The modeling effort was divided into five parts: Calibration, Operations, Validation, Reclamation, and Post-Closure. This model was developed in 2021 using an updated GoldSim water balance by Barr Associates (Barr 2018), a modified CE-QUAL-W2 code that dynamically adjusts bathymetry over time, water quality monitoring data from Eagle, and the most recent (i.e., 2021) tailings deposition plan.

The Calibration model was run from 2019 to 2021 and was calibrated against in situ Conductivity-Temperature-Depth (CTD) profiles (see Figure 1 for an example) and water samples collected over this interval (e.g., WTP intake data, annual water column sampling). As part of calibration, model coefficients and source terms were evaluated and adjusted to reasonably match observed and predicted data during Calibration.

The Operations Model was run forward in daily steps for six-month periods, from July 2021 to May 2027. The first period started in April, approximately when the Surface Layer undergoes Spring turnover, and ended in October, when the Surface Layer undergoes Fall turnover. The next period began in October and continued through April of the following year. Model results were presented to Eagle at the end of each six-month modelled period, and Eagle modified WTP inflows and outflows for the subsequent model period to accommodate water treatment requirements. This process was repeated until the cessation of Operations in May 2027.

Unlike the Calibration Model, coefficient and source terms used in the Operation Model were not adjusted. As such, observations collected from the HTDF between July 2021 to and August 2022 provided a valuable opportunity to assess the accuracy of the model prediction.

The Reclamation Model was run for the time period beginning in May 2027 until October 2030, and Mill inflows and outflows (e.g., Tailings Slurry, Mill reclaim water, and Mill Vortex) were turned off. The Reclamation Period ended once the Surface Layer complied with permitted water quality requirements. Again, the model was run in six-month increments, and Eagle specified new water treatment parameters following each Spring and Fall turnover event in the Surface Layer.

The Post-Closure Model was run for approximately two decades from the end of the Reclamation Period until 2053. Over this period, the WTP was discontinued and the HTDF was permitted to discharge from an engineered spillway at 468 m.

Models were fully integrated between Calibration, Operations, Reclamation, and Post-Closure periods, with the results of the previous model period representing the initial conditions of the next model period. Conceptual model diagrams are presented in Figure 2.

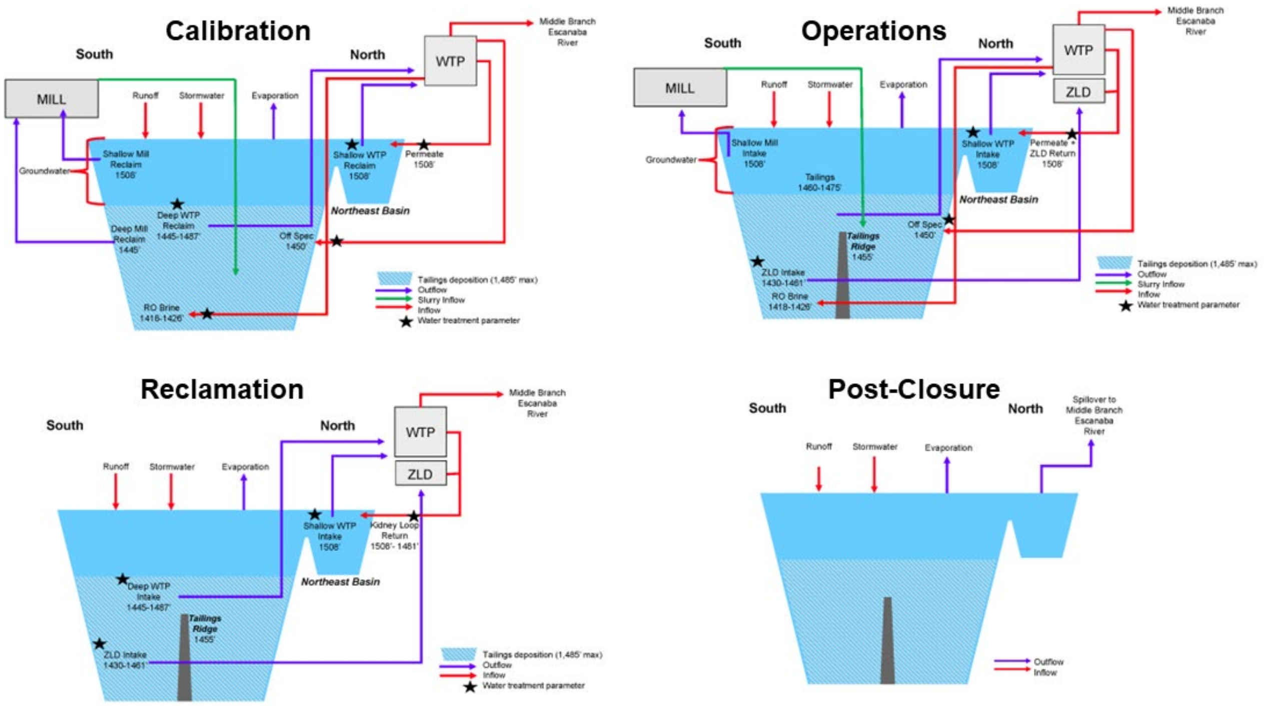

Figure 2 Conceptual diagrams of the HTDF during calibration, operations, reclamation, and post-closure

3 Model platform

The hydrodynamic model was created in the CE-QUAL-W2 software package developed by the U.S. Army Corps of Engineers (EHL 1986). The CE-QUAL-W2 program is a 2-D (profile-view: horizontal distance vs depth), laterally averaged, fluid mechanics and water quality model that has been widely used to evaluate mixing within lakes and reservoirs worldwide. Unlike one-dimensional (1-D) models, discretization in the x-direction makes CE-QUAL-W2 well-suited to model lateral changes in chemistry and temperature at a given depth which can occur in long, narrow pit lakes like the HTDF.

The model predicts TDS profiles and temperature profiles as a function of the energy balance, water balance, and mass balance equations. TDS and temperature inputs are mandatory because of the effects of these variables on water density. The program provides 2-D flow fields from which vertical mixing, and the resulting distribution of heat, momentum, and mass, can be simulated. The theoretical basis for CE-QUAL-W2 was the 2-D longitudinal-vertical transport model written by Buchak and Edinger (1984) which formed the hydrodynamic transport basis of the first version (i.e., W1) of the water quality model (Wells 2021).

The physical domain is discretised into individual grid cells that can be used by the model to iteratively calculate state variables (i.e., properties such as velocity and concentration) at all locations within the environment within each time step. The physical domain is discretised into grid segments that encompass the surface area of the waterbody (plan view, x-y directions, see Figure 3). Each segment is further discretised into depth layers (z direction). The horizontal grid spacing (e.g., 100 to 10,000 meters [m]) can be much larger than the vertical spacing (e.g., 0.2 to 5 m). The segments are used to capture the lateral movement of water through the basins and changes in bathymetry. The average widths of the grid cells are adjusted to ensure that the volume-area-elevation of the waterbody (i.e., stage-storage relationship) is accurately represented in the model.

For the model discussed in this paper, the CE-QUAL-W2 base code was modified to linearly interpolate between a starting and ending bathymetry over a six-month period of tailings deposition. Bathymetries are assigned a date of change, and the model interpolates the daily change in each cell over the time period of the model. As the lake shrinks, water displaced by tailings deposition moves upwards in the grid, transferring mass and energy upwards, consistent with the conceptual model.

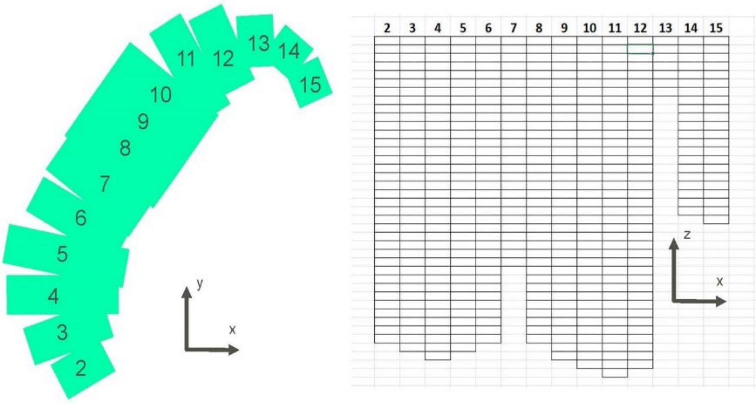

Figure 3 Example of a CE-QUAL-W2 grid discretization for the HTDF. Plan view (left) and cross section view (right) showing the bathymetry in July 2021. Each cell is 100 m long and 1 m thick

4 Model inputs

The model requires user-derived inputs to define the physical bounds of the model (bathymetry), meteorology, input parameters (temperature, inflow rate, chemistry), and outflow parameters (outflow rate). Bathymetry files were generated from the 2021 tailings deposition plan. Meteorology data were compiled from three weather stations located near the study site.

Inflow rates for the Calibration Model (2019 to 2021) were calculated from a GoldSim water balance model. The following constituents of interest (COIs) were modelled in the HTDF: TDS, nickel, calcium, magnesium, and sulfate. Suspended solids were added to the tailings slurry inflow to increase density, account for energy addition, and facilitate downward mixing in the Middle and Deep layers of the HTDF. COIs for stormwater, precipitation, wall rock runoff, Off Spec, RO Brine, and tailings slurry were assigned from Eagle's monitoring data collected between 2020 and 2021. COIs for groundwater were assigned from groundwater samples from wells installed on the south side of the HTDF in 2021. Inflow temperatures were assigned based on expected temperatures (i.e., inflows coming from the Mill or WTP are expected to be static and warmer than ambient winter air temperature).

COIs were defined by the maximum values from site data collected between 2018 and 2021. Concentrations were uniformly applied to each inflow (i.e., concentrations did not change throughout time). This approach was selected to simplify assumptions about input heterogeneity (i.e., future changes to mine plan which may impact tailings composition and flows back to the pit) and generate a conservative estimate for future lake chemistry.

4.1 Bathymetry

From previous efforts, the modeling team recognized that updating the modeling code would be beneficial for both overall model accuracy and modeling efficiency. WSP worked with the managers of the CE-QUAL-W2 model at Portland State University, Oregon, to implement modifications to the CE-QUAL-W2 software to dynamically change the bathymetry of the HTDF over time as a function of tailings slurry addition. This change allowed for uninterrupted transient modeling. This code update also included a porosity term, which allowed the user to manipulate the fraction of water which could be stored in the mass added to the model domain.

Bathymetry files were discretised into 2-D grid segments in Computer Aided Design (CAD) from the 2021 tailings deposition plan. Following the end of model period 5, bathymetric files were modified directly in Excel by removing a volume of cells at the base of the grid equivalent to the volume of tailings deposited in each period, maintaining tailings below an elevation of 452 m This approach was implemented to preserve Surface Layer water quality, which became difficult to efficiently treat once tailings deposition exceeded an elevation of 452 m.

4.2 Meteorology

The model requires the following meteorological inputs for each time step:

- Air temperature (°C)
- Precipitation (m/sec)
- Dewpoint temperature (°C)
- Wind speed and direction (m/sec; Radians)
- Cloud cover (% of sky area)
- Incident short wave radiation (W/m^2)

The meteorological input file was built using data from three National Weather Service weather stations, located between 3 and 25 km east of the HTDF.

The three-year meteorological record was used for the Calibration Model. For the Operations, Closure, Reclamation, and Post-Closure models, the 2020 to 2021 meteorological data were repeated to generate a meteorological file that extended to the end of each model interval. Climate change forecasting was not conducted.

4.2.1 Wind shelter

Wind sheltering coefficients were tested between 0.1 and 0.9 for the Calibration Model. A wind sheltering coefficient of 0.2 was selected, as it provided the closest match for the depth of surface mixing observed in monitoring CTD profiles. This coefficient means that 20% of the wind speed observed at the Negaunee Weather station impacted the surface of the HTDF.

4.2.2 Light shading

Light shading occurs where the pit walls block solar radiation from striking all or part of the pit lake surface. Shading directly influences the energy balance, which influences the predicted temperature and evaporation rates. The "shade coefficient" is a separate input file in CE-QUAL-W2. Changes to light shading had minimal impact on mixing and evaporation and, therefore, a shade coefficient of 0.9 was utilized for this model. The HTDF does not have high protected pit walls, and therefore this shading coefficient is considered appropriate. This coefficient means that 90% of the light measured at the Negaunee NWS was applied to the surface of the HTDF.

4.2.3 Light extinction coefficient

The light extinction coefficient is a parameter that can be adjusted to accommodate changes in water transparency and light extinction with depth. The light extinction coefficient was increased to 1.0 m^{-1} to account for the dispersion of light from suspended solids in the HTDF. Clear lakes have lower light extinction coefficients (approximately 0.2 m^{-1}) while turbid lakes have higher light extinction coefficients (greater than 1 m^{-1}). For example, Wintergreen Lake, a eutrophic lake in Kalamazoo County, Michigan, has reported light extinction coefficient values between 0.46 m^{-1} and 1.68 m^{-1} (Wetzel 1975). The HTDF has consistently had an opaque visual appearance, justifying this high light extinction coefficient, which is consistent with extinction coefficients reported in the literature (William et al. 1980, Heiskanen et al. 2015).

4.2.4 Sediment temperature

The sediment temperature is a parameter that can be adjusted to accommodate changes in sediment temperature at the base of a water body. Sediment heat was assigned a temperature of 15°C to replicate heat transfer between water and sediments. This is slightly warmer than average groundwater temperatures in Michigan (~11°C) owing to residual heat in stored in tailings. Sediment temperatures were calibrated starting at 30°C and were adjusted downward to match observed water column temperatures.

4.3 Inflows and outflows

Boundary conditions in CE-QUAL-W2 are specified as a time series of inflows and outflows into and from the waterbody. Each inflow is assigned a flow rate (m^3/sec), a TDS concentration (mg/L), and a temperature (°C).

Point source and non-point source loading can be applied (1) evenly across the lake surface (i.e., pit wall runoff), (2) evenly through the water column, (3) at a fixed x-z point for a given time step, or (4) vertically based on the density profile of the water column and the depth of neutral buoyancy relative to the inflow. A point placement was used for tailings deposition, Off Spec, RO Brine, and Permeate inflows to replicate how these inflows are piped to specific elevations and locations in the lake. Groundwater and Mill stormwater were distributed across upper layers of the HTDF in segment 2. Direct precipitation was distributed across the surface of the HTDF based on the surface area of each segment within a given layer.

5 Model calibration

The Calibration Model was run from July 2019 to July 2021 and made use of observed meteorological data and observed time-series for flows. Adjustments were made to coefficients, parameters, temperatures, and inputs to best fit observed data from Eagle. The model was calibrated by making the following adjustments:

- Lowered the sediment temperature to 15°C. Although the tailings slurry is warm (15 to 30 °C) when it enters the lake, heat is removed below the chemocline. This heat loss mechanism may be related to thermohaline convection, which transports heat to the base of the Deep Layer to the base of the Chemocline, followed by heat transfer across the Chemocline.
- Set the wind shelter coefficient to 20%, meaning only 20% of the observed wind energy measured at the Negaunee NWS (located at the old Marquette Airport) affected the water surface. The Negaunee station is in an open field closer to Lake Superior at an elevation of 429 m, approximately 30 m lower than the surface of the HTDF. Wind shelter coefficients between 0 to 100% were tested during model calibration. The wind shelter coefficient term affects:
    - The depth of shallow mixing above the Chemocline during spring and fall turnover events
    - The rate of evaporation
    - The surface water temperature
- Systematically lowered the wind shelter coefficient until a good match occurred between the observed and predicted shallow temperature profiles.
- Set tailings temperature to 18°C, Off Spec to 20°C, RO Brine to 15°C, RO Permeate to 20°C, and Groundwater to 11°C.

- Utilized the maximum TDS, nickel, calcium, magnesium, and sulfate values for the Off Spec, RO Brine, and Tailings chemistry. The model initially underpredicted COI concentrations at the Deep WTP intake and, therefore, use of maximum values was deemed appropriate.
- Set the water body type to saltwater, and use of saltwater equations of state in the model. Previous modeling efforts made use of freshwater equations of state to calculate water density. The lower layers of the pit lake have TDS solids concentrations >10,000 mg/L, with densities above 1,020 kg/m^3. Saltwater equations are better suited to simulate the density gradients associated with RO Brines observed in the HTDF.

6 Model results

6.1 Calibration Model results

During model calibration, the predicted physical and chemical properties of the HTDF were validated against measured values. After calibrating the model, predicted and observed data were compared. The following results were observed from the Calibration Model:

- Observed temperature profiles versus predicted temperature profiles for six dates between July 2019 and July 2021 displayed an average absolute error of less than 1 (Figure 4). Target absolute temperature error for this type of model is below 1 (Wells 2021).
- Observed TDS profiles versus predicted TDS profiles for six dates between July 2019 and July 2021 displayed an overall absolute error for these profile comparisons of less than 1.
- On average, the model-predicted water level was 0.5 m higher compared to observed water level between July 2019 and July 2021.
- Measured calcium, magnesium, nickel, and sulfate profiles were compared to predicted profiles on August 6, 2020 and July 13, 2021. Predicted layer structure and concentrations were within reasonable ranges relative to observed data.

The Calibration Model provided confidence that the use of the selected chemical and temperature inputs resulted in appropriate simulation of real-world conditions. The calibration results matched observed physical behavior, including the position of the Chemocline, observed water level, layer structure, and chemistry.

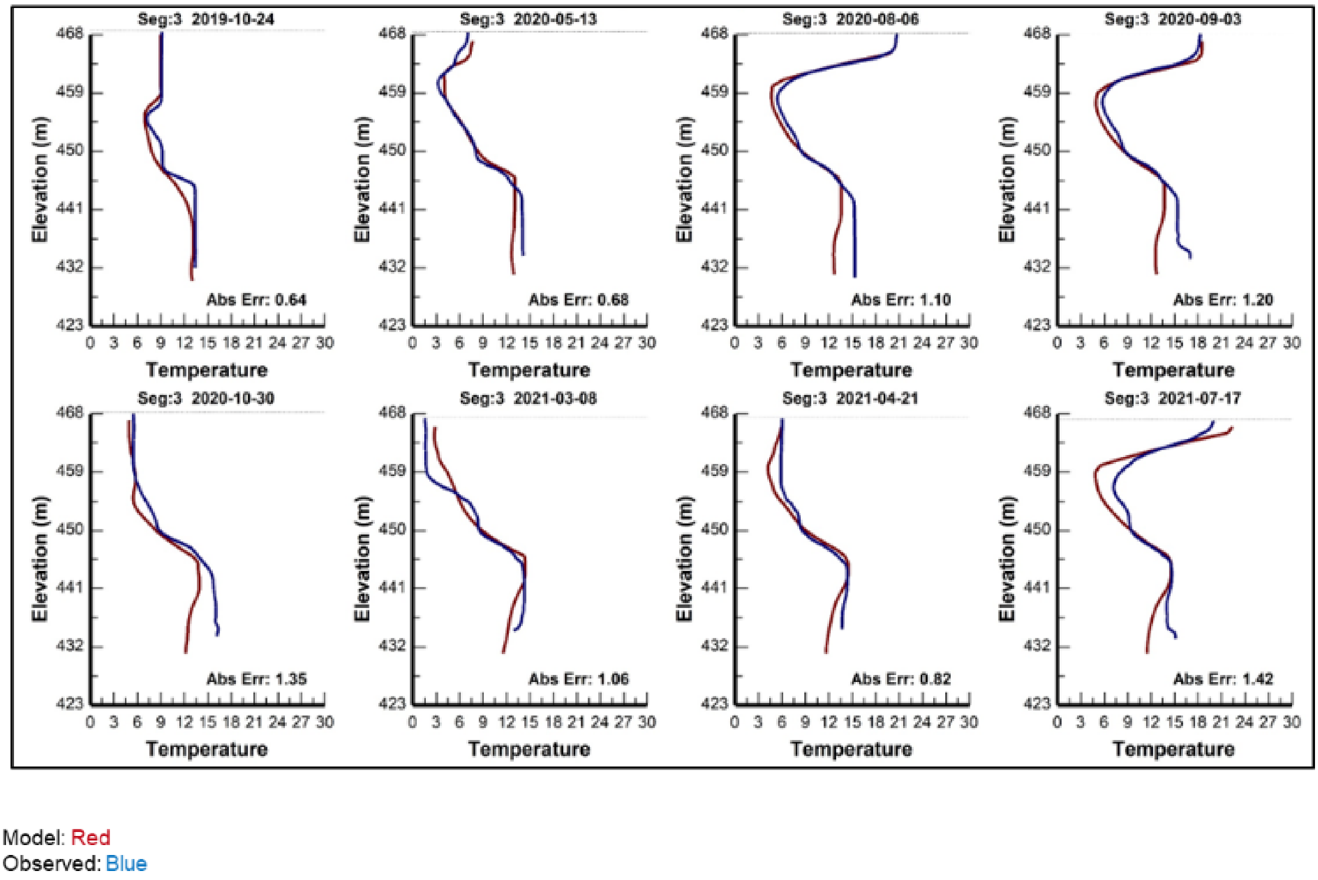

Figure 4 Temperature calibration profiles for the HTDF, 2019 to 2021

6.2 Operations Model results

The Operations Model was run from July 2021 to May 2027. Water treatment and Mill input COI concentrations were held constant across each modeling period, while runoff, precipitation, and mill storm water were input as a repeated timeseries which varied over the course of a year.

Operations Model results were compared to WTP monitoring data and CTD profiles for the interval in which the model overlapped with observed conditions (July 2021 to October 2022), providing additional confidence in the model's ability to replicate observed physical and chemical conditions.

Notable results from the Validation phase of the Operations Model include:

- Relative percent differences (RPD) between modelled and observed Deep WTP influent concentrations were 4% for hardness, 13% for TDS, 22% for sulfate, and 57% for nickel. The model is conservative with respect to average nickel and sulfate concentrations, but model results were within the observed range of WTP influent monitoring data.
- RPDs between modelled and observed Shallow WTP influent concentration were -6% for hardness, -7% for TDS, -2% for sulfate, and -6% for nickel. RPDs below 10% are considered to reflect a good model fit.
- Thermal profiles measured by CTD between 2021 and 2022 showed a strong correlation to predicted temperature profiles generated by the model. Modelled thermal profiles vary 0.3 to 2°C from observed profiles.

- TDS profiles (converted from measured specific conductance) showed a strong correlation to model predictions. Deviations of model predicted TDS relative to measured values were consistent with expected model accuracy.

Important ramifications related to water management resulting from the Operations Model include:

- Assuming an October 2023 commissioning date for the ZLD system, the HTDF remained treatable with the WTP and ZLD through the end of Operations.
- The Surface Layer was predicted to maintain a better water quality than deeper layers, which permitted the use of Surface Layer water for blending with RO permeate during Operations. Figure 5 illustrates predicted TDS in the surface intake over the course of the model.
- Treatment of the Brine Layer starting in October 2023 with the ZLD system eliminating the Brine Layer prior to the end of operations and reducing the overall mass of TDS stored in the HTDF prior to the end of operations.
- Using an unmodified version of the tailings deposition plan, tailings slurry was added above 452 m amsl in October 2023. This caused the predicted water quality of the Surface Layer to rapidly deteriorate, risking the utility of the layer for use in blending. A modified tailings deposition plan, which kept the maximum tailings deposition elevation below 452 m amsl after October 2023, significantly improved surface water quality. This modelled operational change was not a prerequisite for successful closure but was a user-selected preference during modeling.

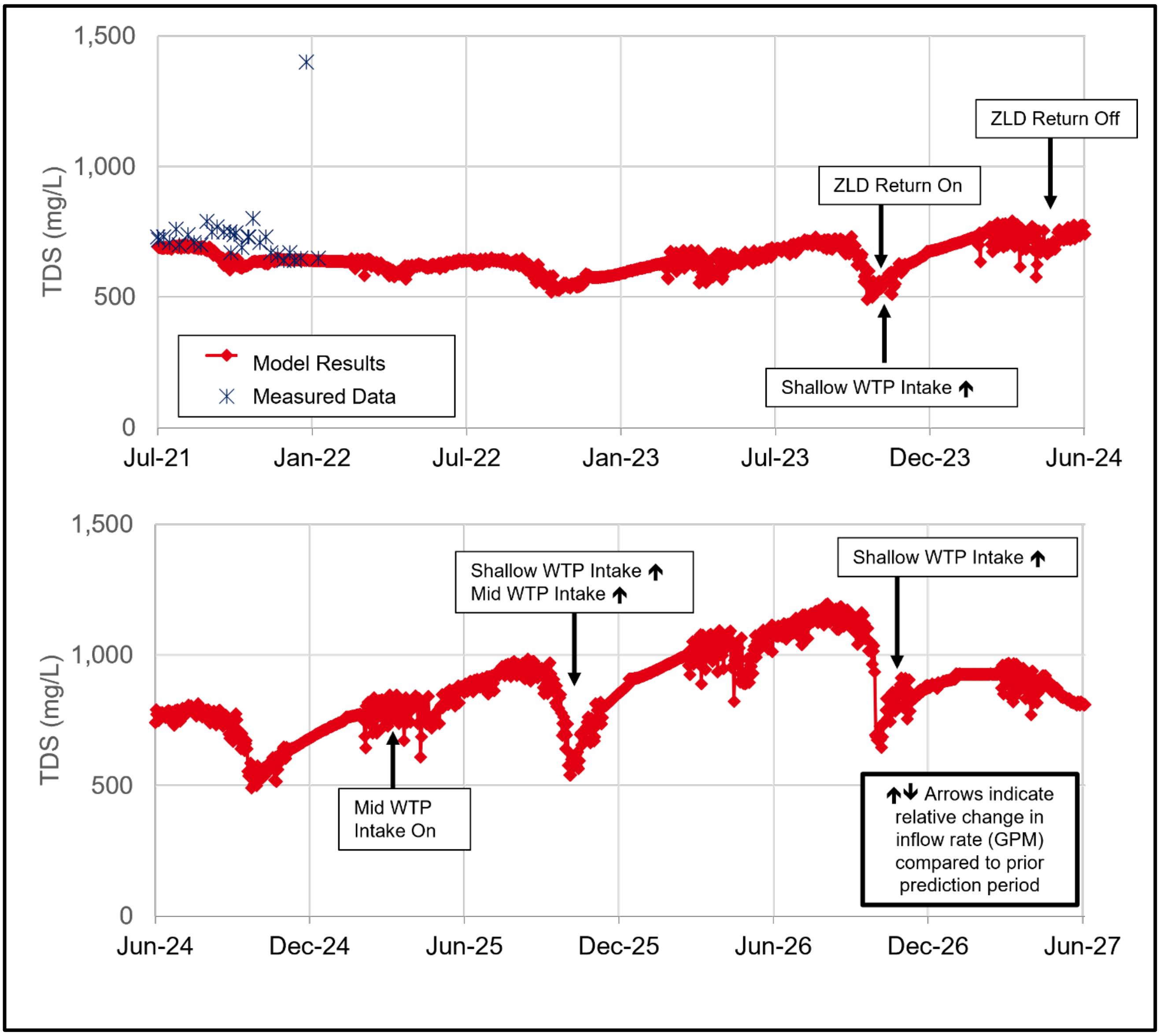

Figure 5 **Predicted and measured surface intake TDS during operations**

6.3 Reclamation Model results

Simulations in the Reclamation Model commenced in May 2027 with the goal of estimating the time required to treat the HTDF until the Surface Layer achieved permit water quality targets (TDS less than 500 mg/L) following the cessation of tailings deposition. Mill parameters (including Tailings Slurry, Mill Reclaim, and the Mill Vortex) were turned off and bathymetric change was stopped. COI concentrations in Stormwater and Pit Wall Runoff were reduced to 25% and 15% of operational concentrations, respectively. The model was run in six-month periods, with Eagle modifying water treatment parameters following each Spring and Fall turnover event in the Surface Layer.

Key findings from the Reclamation Model include the following:

- Under the assumed water management strategy, HTDF water treatment targets were achieved by October 2030, within three years of the end of operations. The Mill site is predicted to achieve Closure requirements at that time, provided all other Closure objectives are completed.

- TDS in the Surface Layer was predicted to be below 500 mg/L by the end of the Reclamation Model.
- Predicted nickel in the Surface Layer was below 25 µg/L by the end of the Reclamation Model. This is 76% lower than the 105 µg/L limit specified by EGLE (2022).
- Ongoing water treatment reduced mass from the HTDF over the course of the Reclamation Model.
- Removal of water by the ZLD lowered TDS in the Pycnocline Layer. Between 5,000 and 8,000 t of solids were predicted to be removed over each six-month period.
- Water treatment removed between 20 and 30 t of TDS per day over the course of the Reclamation Model.
- Layers present at the end of reclamation included: the Surface Layer, Deep Layer, and Pycnocline.
- Temperature profiles became more uniform at depth as heat was no longer being added with the tailings slurry.

6.4 Post-Closure Model results

The Post-Closure Model was used to evaluate the long-term structure and chemical composition of the HTDF following decommissioning of the WTP in October 2030. The Post-Closure Model was run continuously for the time period from January 2030 to 2053. The WTP was turned off, and the HTDF was permitted to discharge to a downgradient wetland via a spillway at 468 m.

The only inputs to the HTDF during Post-Closure were reclaimed Mill site stormwater (i.e., after demolition and removal of roof tops, parking lots, etc.), groundwater, pit wall runoff, and precipitation. Outflows during Post-Closure include overflow to the wetland and evaporation.

Key findings from the Post-Closure Model include:

- The HTDF was predicted to remain chemically stratified for over one decade until 2043.
- The HTDF became chemically homogenous after 2043, after which turnover extended to the base of the water column, fully mixing the HTDF biannually.
- Predicted TDS concentrations remained below the permit limit of 500 mg/L for the 23-year duration of the Post-Closure Model (Figure 6).
- Groundwater inflow ad surface runoff continued to improve the water quality of the HTDF following decommissioning of the WTP.
- The Surface Layer continued to mix biannually (Fall and Spring turnover) through 2043. After 2043, the whole lake was predicted to mix at the same seasonal intervals.
- Assuming mixing across depth, the predicted residence time of the HTDF during Post-Closure was approximately four years.

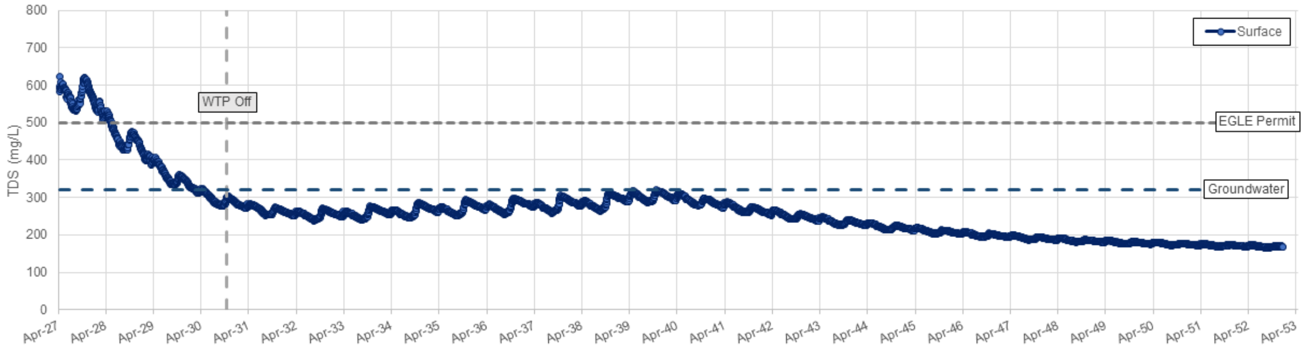

Figure 6 TDS in the Surface Layer during reclamation and post-closure

7 Conclusions

The modeling effort described in this paper represents a well-calibrated and validated hydrodynamic model of an in-pit tailings disposal facility, the HTDF at Lundin's Eagle Mine in Michigan. Under the presented base-case scenario, which assumes a 2023 date for ZLD commissioning, closure requirements for the HTDF can be achieved by 2030. Following decommissioning of the WTP, the HTDF is predicted to remain chemically stratified for one decade, after which freshening from surface runoff and groundwater inflows move the system towards chemical homogeneity.

Bathymetric code updates were thoroughly tested and validated against life of mine tailings volumes. Model input coefficients (light shade, wind shelter, and light extinction) were tested over multiple years and calibrated against observational records. Major improvements which have been implemented in this model include, but are not limited to, development of transient bathymetric code, refined COIs and temperature source terms, use of saltwater equations of state, inclusion of suspended solids in the tailings slurry, and development of a multi-year water balance. Predicted water quality and stratification showed a strong correlation and accuracy compared to observed water quality and stratification between 2019 and 2022, lending confidence to in the model predictions.

The model discussed herein represents a base-case scenario, which is routinely modified to inform Eagle's water treatment decisions and closure planning. Recommendations developed during Independent Tailings Review Board meetings have been adopted into the modeling framework and have been used to develop and test sensitivity cases. This model is a complex prediction tool used by Eagle to evaluate proactive and adaptable water management strategies, and guide evaluation of time to closure, and closure costs associated with the HTDF. Models such as these are reliable and valuable tools for supporting mine waste and mine water management decisions over the life of mine.

Acknowledgements

WSP wishes to thank Eagle for their willingness to publish these data. We also thank Scott Wells at Portland State University for his development of the dynamic bathymetry code for CE-QUAL-W2.

References

Barr. 2018. Groundwater, Surface Water, and Water Balance Model Development Report. Report prepared for Eagle Mine LLC, Champion, Michigan, from Barr, Grand Rapids, Michigan, March 2018.

Buchak, E. M. and J. E. Edinger, 1982, 'Hydrothermal Simulation of Quabbin Reservoir Using Longitudinal Vertical Hydrodynamics', Final Report, prepared for Wallace, Floyd Associates, Inc., Cambridge, MA.

Environmental and Hydraulics Laboratory. 1986. "CE-QUAL-W2: A Numerical Two-Dimensional, Laterally Averaged Model of Hydrodynamics and Water Quality; User's Manual", Instruction Rpt. E-86-5. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Environment, Great Lakes, and Energy (EGLE), 2022, 'Authorization to discharge from the Humboldt Mill, Authorization to discharge under the National Pollution Elimination Discharge System (NPEDS). Permit number MI0058649', Michigan Department of Environment, Great Lakes, and Energy, Revised permit effective June 1, 2022.

Heiskanen, J. J., Mammarella, I., Ojala, A., Stepanenko, V., Erkkilä, K.-M., Miettinen, H., Sandström, H., Eugster, W.,

Leppäranta, M., Järvinen, H., Vesala, T. and Nordbo, A 2015 Effects of water clarity on lake stratification and lake-atmospheric heat exchange, J Geophys Res-Atmos, 120.

Wells, S. 2021, 'CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 4.2; User Manual', Department of Civil and Environmental Engineering, Portland State University, Oregon.

Wetzel, R.G, 2001 'Limnology', 3rd ed., Academic Press, San Diego, CA.

Williams, D.T., Drummond, G.R., Ford, D.E., and Robey, D.L., 1980, 'Determination of Light Extinction Coefficients in Lakes and Reservoirs', Surface Water Impoundments, Proceedings of the Symposium on Surface Water Impoundments, American Society of Civil Engineers, H.G. Stefan, ed.