Tailings Backfill for Optimizing Pit Lake Water Quality

Miloš Novotny
DHI Water & Environment, Inc., Lakewood, Colorado, USA

Brent Johnson
Hydrogeologica, Inc., Golden, Colorado, USA

Devin Castendyk
Hatch Consultants, Inc., Lakewood, Colorado, USA

ABSTRACT

A prefeasibility-level mine closure study of the Metates open pit, gold and silver project in Mexico was recently completed that involved optimized partial backfill of tailings into the pit. The study considered several treatment options to improve pit lake water quality including mixing of lime with the upper horizons of tailings backfill in order to neutralize acidity in the tailings pore water and pit lake. Models of groundwater flow, water balance and pit lake geochemistry were used to predict and optimize the pit lake water quality. Results highlighted trade-offs between the treatment options and were used to manage the overall project cost and risk.

BACKGROUND

Backfilling of underground mine workings has historically been used as an engineering measure to stabilize the mine rock mass in order to prevent mine collapse and land subsidence as well as an alternative disposal location when potential surface disposal areas are constrained. More recently, backfilling strategies have included the selective disposal of more highly-reactive mine wastes into workings below the water table in order to eliminate waste oxidation and mitigate potential environmental impacts of surface storage. These strategies have been investigated and/or applied at a limited number of open pit mines (e.g., Wickham, Johnson and Johnson 2004) and fewer yet in early, pre-development phases of project feasibility.

Large and small mines have the potential to cause severe environmental degradation from impacts including acid mine drainage and water consumption during both operation and closure (or abandonment). Reclamation and closure have become greater issues in mine planning and development because of the recognition of environmental value (e.g., ecosystem services, community impacts, and landscape protection), increased requirements for cash bonding, and corporate stewardship programs. When considered early in the planning phases, addressing environmental concerns has the potential to positively affect mine permitting, development and operation with little additional upfront cost to the project and potentially significant cost savings during operation, reclamation and closure. The potential impacts are similar at many mines but each project requires a unique plan in order to take advantage of that site's specific hydrology and geochemistry.

Project and Site

The Metates Project (Project) mine site (Site) is located in the northwestern portion of the state of Durango, Mexico, approximately 160 kilometers (km) northwest of the city of Durango and 175 km north of the coastal resort city of Mazatlán, Sinaloa, Mexico. The Site is located in the Sierra Madre Occidental Mountains of western Mexico. Terrain is steep and rugged with mountains exceeding 2,000 meters above mean sea level (masl) near the Site. Climate is temperate and arid with monsoonal precipitation patterns characteristic of the region.

The mine will have milling and sulfide flotation operations on Site with planned milling rates ranging between 30,000 and 90,000 tonnes per day depending upon the phased plant configuration (M3, 2016). During the 30 years of open-pit mining, low-grade ore will be stockpiled while the processed, higher-grade ore tailings and waste rock will be placed in the Integrated Tailings and Waste Rock Storage Facility (ISF) located in the steep, narrow drainage to the southwest of the open pit (Figure 1). Process water will be recovered and recycled into the process by filter-press of the sulfide flotation tailings. Following mining of the open pit, the low-grade stockpile will be processed over a period of 10 years. A lake is anticipated to form in the the post-closure pit.

A number of challenges exist for the development of the Project which were addressed early in the Feasibility process including water supply and closure planning. For instance, while the tailings are expected to be mostly inert, much of the waste rock generated during mining, as well as some of the rock exposed in the pit walls, will be potentially acid generating. In order to minimize potential environmental impacts associated with the waste rock, a unique placement configuration was developed for the ISF whereby oxidation of the acid-generating materials is minimized by layering of waste rock and tailings. Other closure challenges for the Site include limited space for surface facilities in the steep terrain, degradation of water quality from acid-generating materials in pit walls, and reclamation and closure of the ISF. The current Metates closure plan includes provisions for long-term operation of a water treatment plant for a minimal quantity of ISF seepage located at the toe of the ISF.

A plan was developed to backfill the tailings into the pit during processing of the the low-grade stockpile in final 10 years of mine operation in order to address these other closure challenges and to minimize costs associated with reclamation (Interralogic 2013). Direct benefits of the plan include rapid covering of the acid-generating lower pit walls by tailings deposition and diversion of surface water; reducing the ISF footprint by utilizing the open pit storage volume; and the ability to reclaim the ISF more rapidly and concurrently during operations, while the Project is still generating revenue and equipment and personnel are at site. To evaluate the plan feasibility including the potential downgradient movement of impacted pit lake water to the environment, a pit lake model was developed for the partially-backfilled pit.

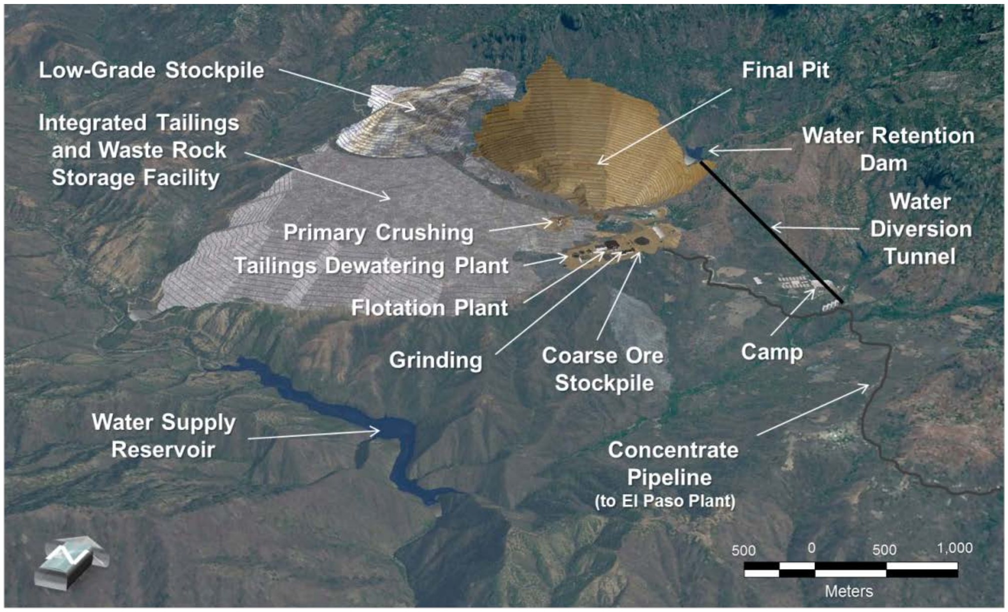

Figure 1. Operational site layout

MODEL

A pit lake model (Model) was developed to predict the filling rate, ultimate water level, and water quality expected for the lake that will form in the pit and to evaluate pit lake management options (Hatch 2016). The model simulates four pit lake closure alternatives used to evaluate the overall pit-closure strategy. The alternatives considered engineering measures to manage pit lake water level and groundwater discharge as well as the addition of lime amendment to the tailings backfill to manage water quality in the pit lake. The four Model alternatives developed are:

1. Managed lake elevation 837m, no lime amendment.
2. Managed lake elevation 837m, lime amendment.
3. Managed lake elevation 880m, no lime amendment.
4. Managed lake elevation 880m, lime amendment.

The Model employs the GoldSim dynamic systems modeling software (GoldSim Technology Group 2014) for its water balance and the PHREEQC (Parkhurst and Appelo 2013) geochemical speciation model for predicting water quality. The Model also uses the Monte Carlo method to predict a distribution of potential water balance results using uncertainty distributions developed during the evaluation of the water-balance inputs. While the results of this analysis are outside the scope of this write-up, the approach was important for not only recognizing total uncertainty in the closure plan, but to guide collection of additional data to constrain the model inputs and decrease uncertainty-based risk of the Project closure plan

The Model required inputs including climate (precipitation and evaporation), surface water runoff, groundwater inflow and outflow, geochemistry and ambient water quality, all of which were evaluated specifically for the Site, as well as aspects of the mine plan including mine infrastructure, tailings moisture content and surface water diversion. A conceptual model of the Metates pit water balance is shown in Figure 2.

Climate

The climate at the site is the largest single driver of the pit lake water balance as it contributes to the surface water inflows as well as the balance of precipitation to, and evaporation from, the pit lake surface. On an average-annual basis, the site is evaporation-positive; rainfall at the proposed plant site shown in Figure 1 is approximately 1020 mm and potential evaporation is greater than 2050 mm. A thorough review of climate characteristics and statistical analysis of seasonal precipitation and evaporation rates were undertaken in order to constrain the climate inputs.

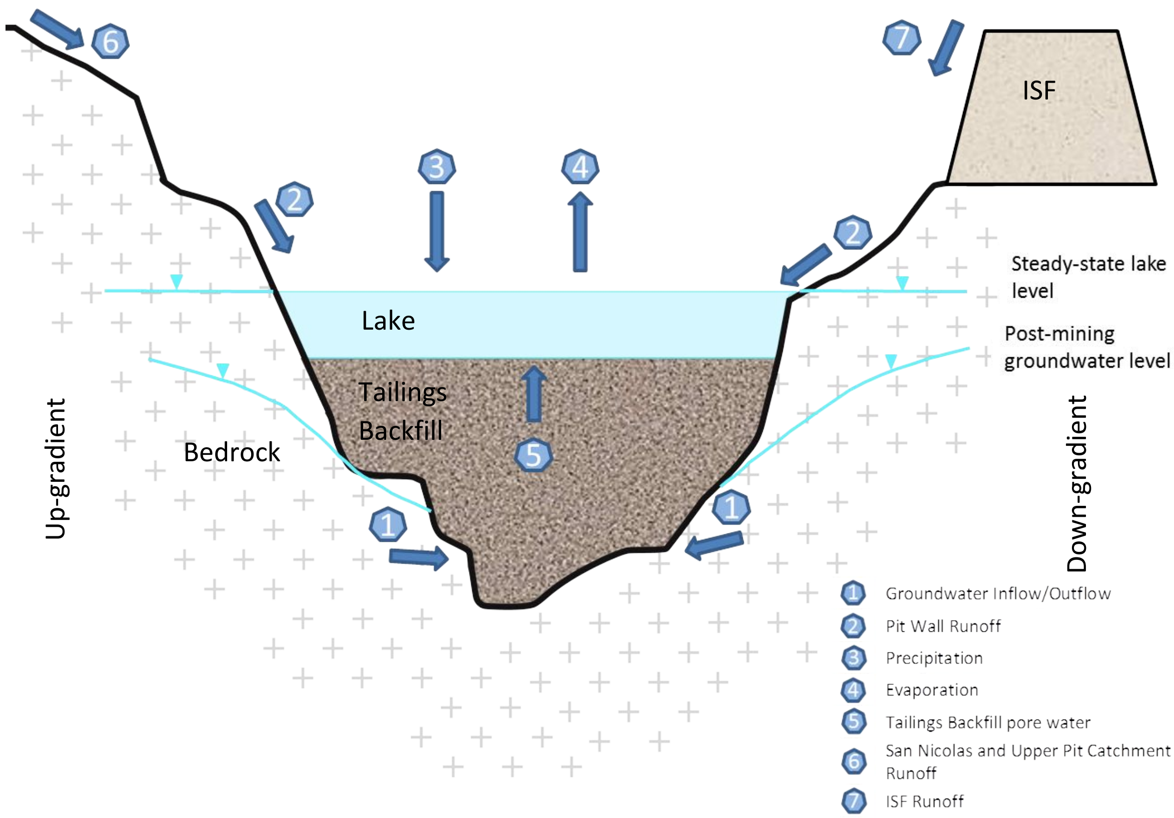

Figure 2. Conceptual water balance cross-section of partially backfilled pit

With only four full years of weather station data available from one location at the Site, statistics calculated from regional datasets were used to characterize Site variability in time and space. Highly variable (orographic and elevation effects) and seasonal climate occurs regionally with a dry season occuring from October to May and a rainy season occurring from June to September. During the rainy season, two main types of storms exist: cyclonic and convective, each having distinct precipitation characteristics. Cyclonic storms, related to large tropical depressions, are infrequent, generally widespread, and high-intensity. These storms produce large amounts of precipitation and occur in the late summer to winter. Convective storms tend to be frequent and localized, occurring during the summer months with low intensity and producing variable amounts of precipitation. During the dry season, evaporation rates are highest. For instance, in the four years of Site precipitation data available, no precipitation was recorded in the driest month (April).

An orographic precipitation effect is present in the Sierra Madre foothills with a positive correlation between rainfall depth and elevation present at both the Site and regional scales. Because of the large range of elevations at the Site, precipitation was adjusted by applying a linear correction factor to the mean elevation within each Model area.

Surface Water Runoff

Surface water runoff is the largest source of water to the open pit in the long term and includes runoff from pit walls, reclaimed surfaces and upstream catchments, and diversion of surface water to enhance submergence-rate of the tailings and for potential pit lake water-level maintenance. Review of Site and regional data indicate runoff rates that vary seasonally with a greater proportion of rainfall resulting in runoff during the dry season, when infrequent-but-large, cyclonic storm events and minimal vegetation coincide. In contrast, during the rainy season vegetation is at a maximum, convective storms tend to have lower duration and canopy interception is greater. Runoff rates of the undisturbed vegetation and reclaimed Model areas are specified as 7% and 14% for the rainy and dry seasons, respectively. Runoff from the un-reclaimed pit walls is specified as 35%.

Surface water will be diverted into the pit from the ISF and upstream catchment during the closure period in order to rapidly fill the pit. In post-closure, these sources will be diverted away from the pit except as required to maintain a given pit-lake level.

Groundwater

Depending upon the pit lake water level, a pit lake may act as a hydrologic sink, where the lake is the terminus for the Site groundwater system or the pit may have flow-through characteristics and discharge to a down-gradient area. A 3-dimensional numerical groundwater flow model (groundwater model) was developed for the area including the Rio San Juan de Camarones and several nearby drainages to determine the groundwater regime of the pit from mine development through post-closure (Hatch 2015). The hydrogeologic model, which forms the basis of the groundwater model, explicitly represents basement geology, later intrusives, several volcanic units, massive talus units, alluvium, and faults and fracture zones with offsetting of hydrogeologic units where present. The groundwater model was developed to answer several specific questions related to groundwater flow at the pit including:

- What rates of pumping will be required to dewater the pit?
- What rates of groundwater inflow will occur pit dewatering ceases and it begins to fill with water?
- Will there be outflow of pit lake water to the surrounding groundwater system once equilibrium is reached?
- What are the effects of engineering measures that might be used to manage the pit lake in the closure period?

The groundwater model predicts dewatering requirements of approximately 1,000 m3/day at the end of mining, when the pit bottom has reached an elevation of 472.5 masl.

For closure, the effectiveness of two different engineering measures for limiting outflow from the pit were evaluated for the entire range of possible pit lake levels. One measure considers the placement of a clay liner (‘Clay Plug’) on the pit walls and ISF at the downgradient side of the pit. The other measure considers collecting rainfall during the rainy season to enhance recharge (‘Focused Recharge’) in the same area, effectively creating a hydraulic barrier in the groundwater system that prevents discharge from the pit lake. As well, the combination of the two measures (‘All Engineering’), and a base case with no engineering, were simulated. Results show that with no engineering measures, discharge from the pit will begin at an elevation above 820 masl, increasing to approximately 20 m^3/day at a lake level of 840 masl (Figure 3). The two engineering measures both have an effect of decreasing the discharge, with the combination of the two providing the greatest decrease at higher pit lake levels.

Water Quality

Water quality for the various sources was estimated from Site and regional sample data. Ground water quality was estimated using the average from monitoring well samples collected at the Site. Precipitation and non-disturbed surface runoff water quality was estimated from regional water quality sample analysis data. Tailings process water quality was estimated using a synthetic precipitation leaching procedure on tailings generated during the process pilot study. The water quality associated with the pit walls and leaching of wall rock were characterized using field barrel tests of the geologic materials present in the pit walls and waste rock. These materials included each of the two volcanic units as well as the ore-hosting metasedimentary bedrock sub-categorized by percentage of contained sulfur. The barrels were exposed to ambient conditions at the Site and allowed to fully drain into collection vessels. Periodically, collection vessels were emptied then sampled at the next precipitation event including the first event of the rainy season when accumulated chemical residues are flushed.

The sources of water and solute were mixed fully during each model time step and allowed to equilibrate. The resulting equilibrium solution was then mixed with the input sources in the next time step.

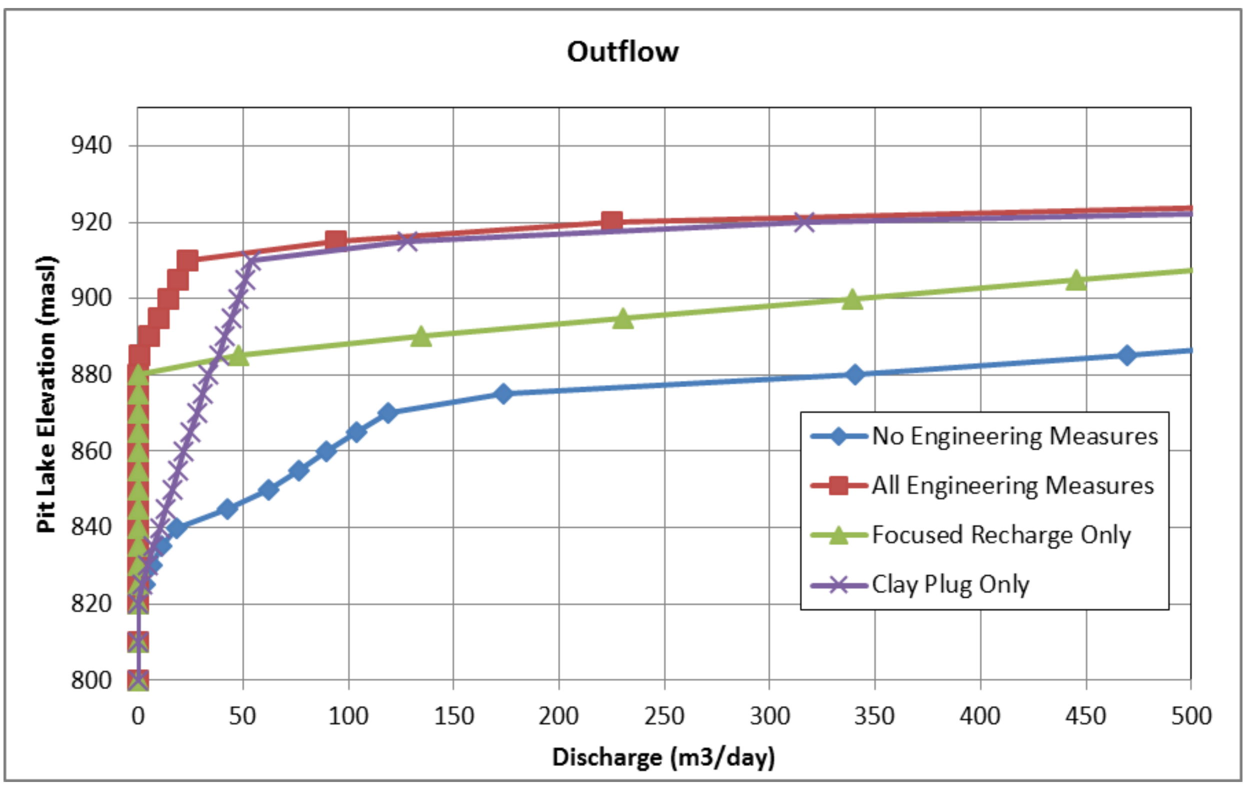

Figure 3. Predicted discharge rate to groundwater from the Metates pit

RESULTS

Water Balance

The water balance for the closure was run considering the Site-specific inputs described above using monthly time steps. The general concept of the closure is that following the end of open-pit mining, the low-grade ore stockpile will be processed and the tailings (including retained process water) will be conveyed into the pit; at a rate of 49,000 m^3/day; this is by far the largest source in the pit-filling (Figure 4). During the filling period, surface water will also be diverted from the upstream drainage and ISF into the pit.

During backfilling, the backfill pore-water level remains below the top of the backfill and the backfill will be graded and placed by mechanized equipment (Figure 4). After approximately 7.5 years, backfilling ends at an elevation of 817 masl. The backfill water level continues to rise above the tailings surface having a final freeboard of 20m above the backfill.

It is predicted that the tailings will be fully-saturated and a pit lake will form after a period of approximately 20 years. Under alternatives 1 & 2, surface water diversion continues until it reaches a hydrologic equilibrium of 837 masl. Under alternatives 3 & 4, surface water diversion continues until it reaches the 880-masl level at which point the level is maintained through periodic diversion.

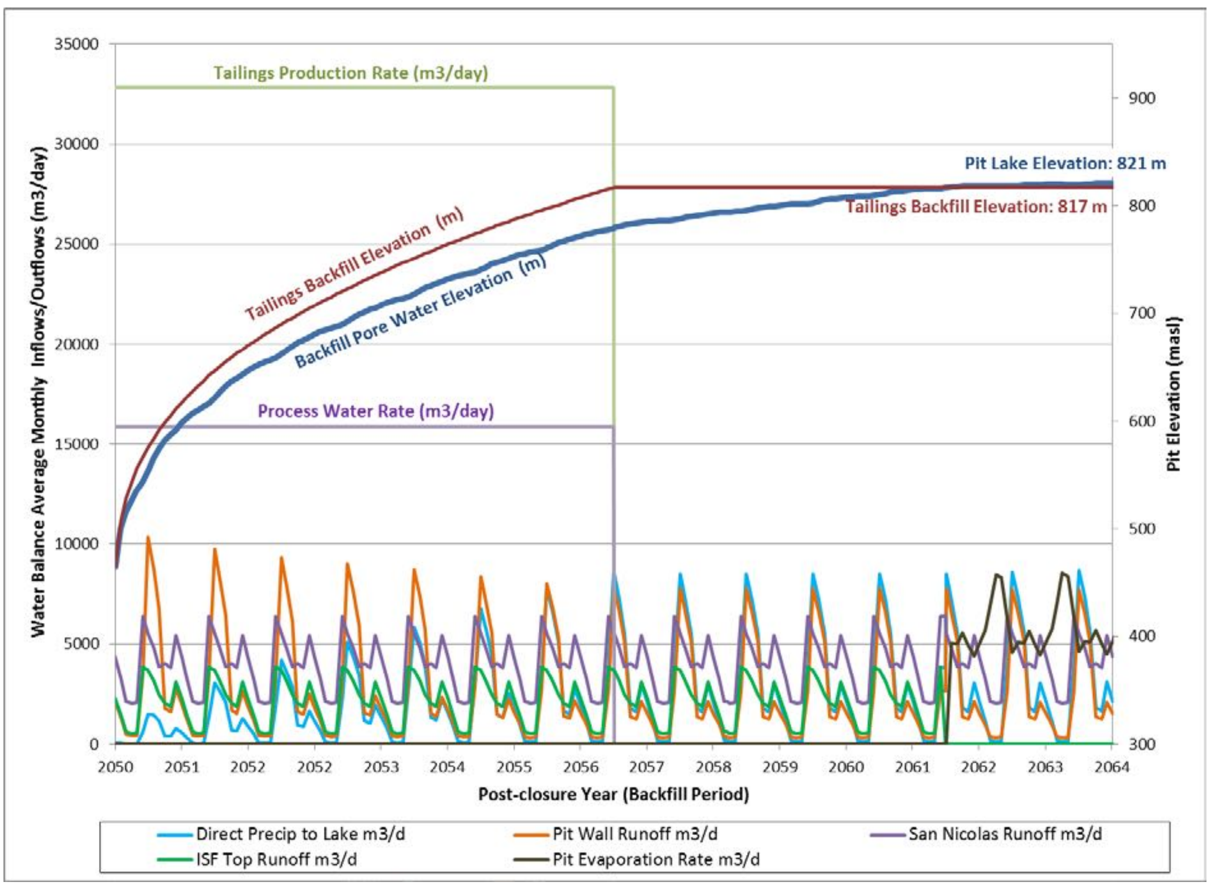

Figure 4. Early-time filling of Metates pit

Water Quality

The PHREEQC geochemical model was run to predict the resulting water quality in the pit lake using the results of the dynamic systems water balance. The geochemical model was run using time steps that correspond to key hydrologic events such as when tailings backfill stops, when the pit lake forms, etc. The geochemical model considered the chemistry of various sources in the water balance model including groundwater, tailings process water, surface water runoff from disturbed pit walls as well as undisturbed or reclaimed areas, direct precipitation on the lake, leaching of wall rock and addition of lime for alkalinity. The geochemical model includes chemical reactions such as adsorption of metals on hydrous ferric oxide (HFO), an important reaction in controlling dissolved metals concentrations.

The addition of lime within the backfilled tailings layer had a significant influence over the pH of the pit lake even though the relative amount of water flowing through the tailings into the lake was low (Figure 5). The pH of the early pit lake in the no-lime alternatives was acidic due to the low pH of the process water and pit wall runoff, whereas the lime amendment resulted in an early pit lake with a more moderate pH. When the pit lake was managed at the 880 masl level, the pH of the lake continued to increase over the 82-year filling period as a result of the contribution of higher pH surface water.

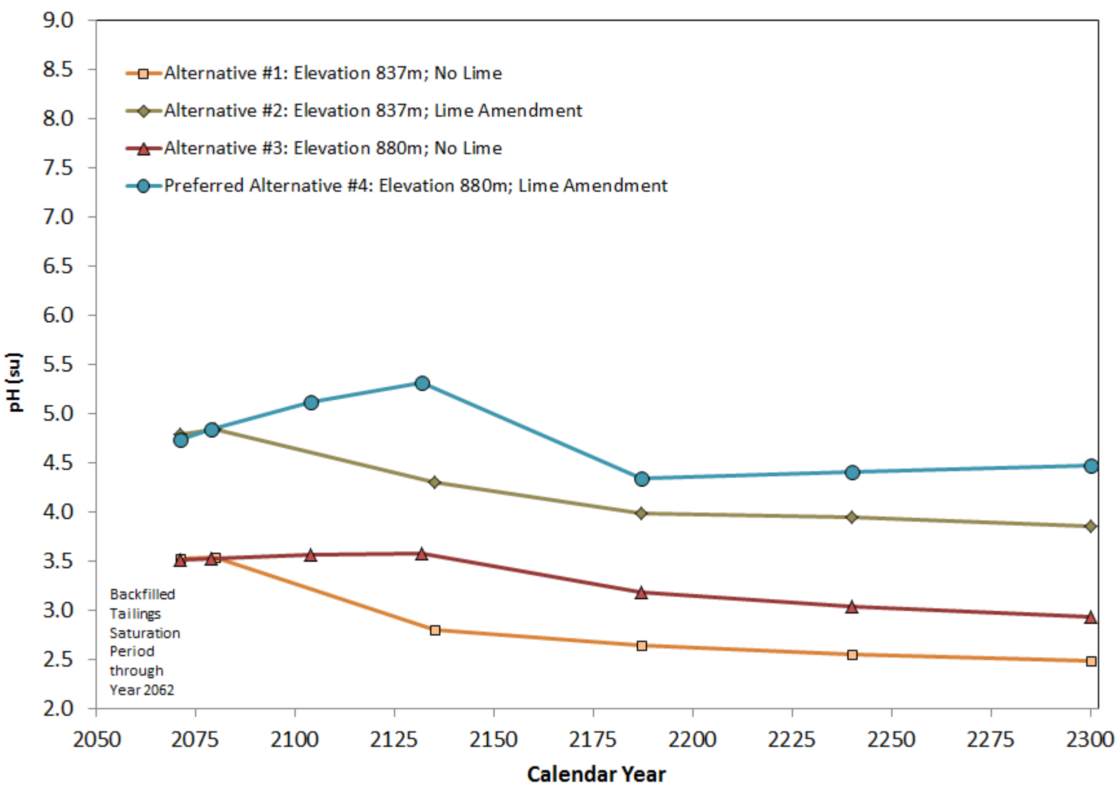

Figure 5. Pit lake water quality modeling results - pH

Total dissolved solids of the early pit lake was similar for all closure alternatives; however, continued surface water inflow from the Arroyo for the 880 masl lake resulted in lower TDS in the pit lake over time (Figure 6).

The primary sources of sulfate, iron, and metals/metalloids (i.e., arsenic, cadmium, copper, chromium, mercury, nickel, lead and zinc) to the pit lake water are tailings process water and pit wall runoff. The concentrations of these constituents in the early pit lakes were either similar (if not pH dependent), or concentrations in the lime-amended lakes were lower for constituents that tend to adsorb to HFO surfaces under moderate to slightly-acidic pH conditions (i.e., arsenic, copper, chromium and lead). Consistent with TDS, concentrations of all these constituents were much lower during filling of the 880 masl lake (compared to the 837 masl lake), as surface water provided dilution in the concentrations and the greater lake volume reduced the effect of evapoconcentration. Similarly, under steady-state conditions, constituent concentrations increased in the pit lakes as a result of evapoconcentration, but the effect was much less in the larger, 880 masl lake.

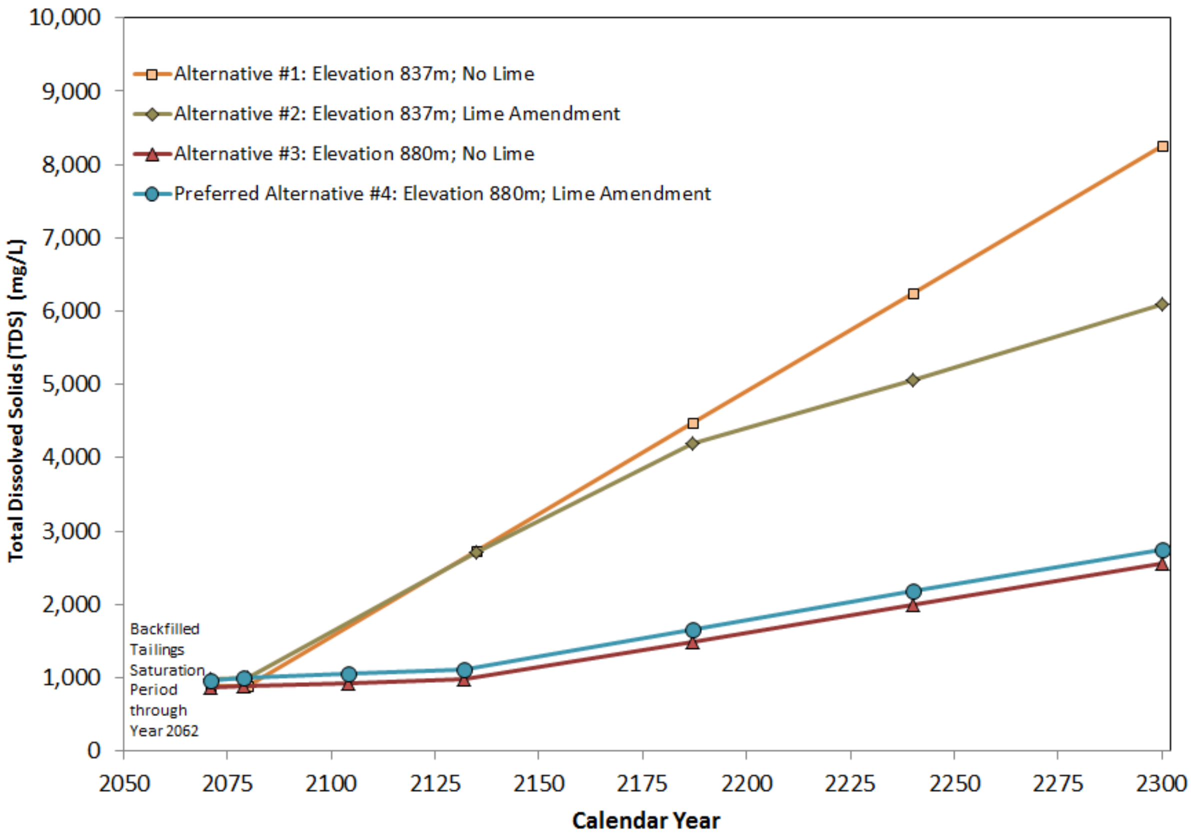

Figure 6. Pit lake water quality modeling results - TDS

CLOSURE PLAN EVALUATION

Management alternatives were developed for the Metates pit lake closure plan that took advantage of hydrologic and geochemical conditions specific to the Site. None of the alternatives use any un-tested or risk-prone technologies nor are the costs of implementing the alternatives prohibitive from a Project Feasibility standpoint.

A preferred management alternative (#4) was chosen for the current pre-Feasibility mine plan based on results from the pit lake model, including the following:

- Selective placement of clay liner on the pit walls and ISF in order to inhibit discharge to the downgradient groundwater system;
- Addition of hydrated lime to the top of the backfilled tailings as a source of alkalinity to counter acidity from the pit wall runoff and precipitate/complex dissolved metals; and

- Periodic diversion of surface water into the lake to maintain a level of 880 masl and dilute dissolved concentrations in discharging water and maintain pH.

The preferred alternative results in a relatively small flow of significantly higher-quality pit lake discharge with few maintenance requirements. Under the preferred alternative, the Metates pit lake is expected to develop with slightly-acidic conditions, elevated TDS, and some elevated metals concentrations. With the clay liner in place, the pit lake is predicted to discharge at a rate of 37 m^3/day into the downgradient groundwater system. Within the 250-year modeling period, the concentration of arsenic is predicted to exceed some Mexico water quality standards. A worst-case sensitivity analysis indicated that exceedances of cadmium, copper, mercury, nickel and zinc may be expected in the long-term. However, based on the alternatives modeling, this management alternative resulted in a better pit lake water quality in terms of pH and constituent concentrations (there are no predicted water quality exceedances of the Mexico standards for the first 175 years of the post-closure period) compared with the un-managed closure alternative.

The alternatives considered allow for flexibility in the closure plan to manage pit lake levels and water quality such as might be required for mine permitting. Further improvement on the pit lake water quality may be achieved through additional mitigation measures such as passive treatment and/or pacification of pit wall runoff and pit lake amendment. A range of possible mitigation measures exist that could be employed at closure of the Metates pit, and decisions on specific choices will be contingent on the results of further sampling and modeling as recommended for the Project as it advances to full Feasibility.

ACKNOWLEDGEMENTS

The authors would like to thank Chesapeake Gold for granting the publication of Project data and analyses and, in particular, Gary Parkison for his input to developing closure alternatives for the Site. As well, David Hoekstra of SRK Consultants was helpful in sharing thoughts on Site hydrology gained from his years of consulting experience on the Project.

REFERENCES

GoldSim Technology Group. 2014. GoldSim Dynamic Systems Modelling Software, Version 11.1.

Hatch, Inc. 2015. Ground Water Model Report, Rev. B. Fort Collins, CO. Unpublished report.

Hatch, Inc. 2016. Pit Lake Model Report. Fort Collins, CO. Unpublished report.

Interralogic, Inc. 2013. Preliminary Feasibility Study Level – Reclamation Plan, Metates Project, Mexico. Fort Collins, CO. Unpublished report.

M3 Engineering & Technology Corporation. 2016. NI-43-101 Technical Report, Metates Gold-Silver Project, Updated Preliminary Feasibility Study, Tucson, AZ. Unpublished report.

Parkhurst, D.L., and Appelo, C.A.J., 2013, Description of input and examples for PHREEQC version 3--A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Techniques and Methods, book 6, chap. A43, 497 p.

Wickham, M., B. Johnson and D. Johnson. 2004. Dynamic systems-modeling approach to evaluating hydrologic implications of backfill designs. Min. Eng. 56(1):52-56