Simulated Mining, Backfilling, and Artificial Recharge of the Corani Open Pit

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Abstract The Corani mine will produce 160 million tons of silver-lead-zinc ore from an open pit over 18 years. To prevent formation of an acid pit lake at the end of mining, a decision was made to backfill the pit with Potentially Acid-Generating (PAG) waste. At closure, the backfilled waste will be artificially recharged to saturate it as quickly as possible, then capped with an evapotranspiration cover to limit infiltration and surface water/groundwater interactions. A MODFLOW Surfact model was constructed to simulate mine groundwater impacts during a complex operational and closure history.

Keywords Acid rock drainage, MODFLOW Surfact, artificial recharge

Introduction

The Corani epithermal silver-lead-zinc deposit in southeastern Peru will produce 160 Mt of ore from an open pit over a projected mine life of 18 years. The project site is in the High Andes 150 km southeast of Cusco, at an elevation of 5000 m. The deposit's sulfide mineralogy ensures that Acid Rock Drainage (ARD) will be produced where water comes into contact with mineralized pit walls and waste rock.

A MODFLOW-Surfact flow model was constructed to predict mine-related groundwater impacts. Modeling goals included predicting groundwater inflow rates to the pit, estimating impacts in the enclosing watershed, predicting postclosure ARD water volumes requiring treatment, and guiding the design of mine elements to minimize ARD water production.

The mine plan calls for backfilling of the pit with Potentially Acid Generating (PAG) waste rock beginning in the later years of mining. Backfilling of the pit will prevent formation of a pit lake, and modeling suggests that this will reduce the volume of ARD water requiring long-term treatment by about 90 %.

Geology

Mineralization is hosted by Miocene volcanic tuffs, which are sandwiched between underlying Paleozoic mudstone and overlying younger unmineralized tuffs (Prado 2008). Mineralization is closely associated with faults, but the host rocks are otherwise largely flat-lying and undeformed.

Glaciation has produced broad-floored valleys blanketed with 20 to 40 m of sand, gravel, clay, and peat. The low-relief valley bottoms are poorly drained, and occupied by expanses of verdant wetlands called bofedals. These consist of islands of grass-covered peat separated by a mesh-like network of streams and ponds. Uplands slopes bordering the valleys extend to the high ridgelines bounding the watershed, and are irregularly mantled with tuff-derived windblown sand.

Mine Project Elements

Mine Parameters Fig. 1 shows the domain of the numerical model and the mine facilities inside the domain. Mineralization is localized in three areas, Corani Este, Minas, and Main. The horseshoe-shaped pit produced after 18

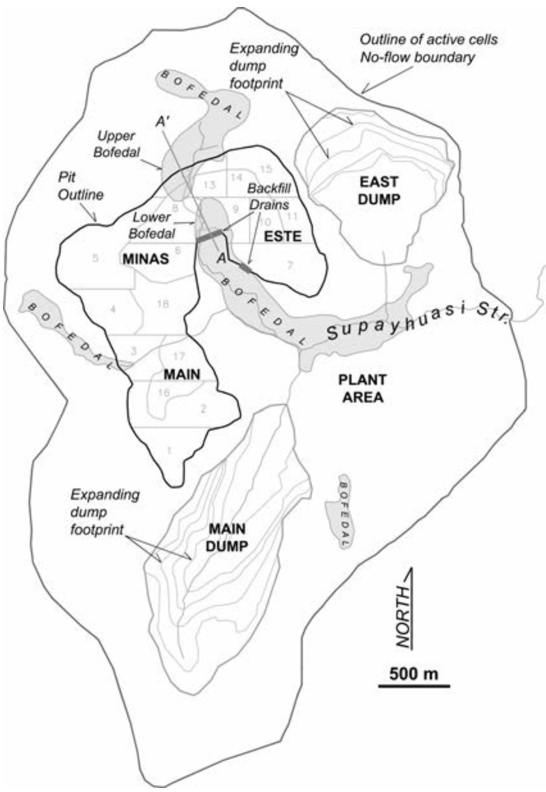

Fig. 1 *Mine elements and model domain.*

years of mining will occupy 190 ha, and will have maximum relief of 375 m. Ore will be trucked from the pit to a processing plant to the east. Slurried tailings will be pumped from there to an impoundment 5 km to the south.

Waste Rock Dumps Waste rock will be disposed at three sites. Unmineralized tuff, which has been determined to be Non Acid-Generating (NAG), will be trucked to the East Dump. PAG waste rock will be trucked to the Main Dump in the early years of mining. Beginning in Year 13 of mining, PAG waste rock will be used to backfill the pit, starting with the Este portion and proceeding to Minas. After mining has been completed, areas of Minas and Main will be backfilled from PAG waste stockpiles. All three waste rock disposal sites will be completed with engineered evapotranspiration covers (ET covers) that permit negligible infiltration. Because the only hydrogeologic impact of the two rock dumps is to deny recharge to the area beneath them, they are represented in the numerical model by regions of zero recharge that expand as the dump footprints grow.

Pit Backfill The pit will be backfilled to an elevation approximately even with the adjacent lower bofedal. The top surface of the PAG backfill will be slightly below the predicted lowest stabilized postclosure water table, so that when water levels have rebounded after mining, the PAG material will remain permanently saturated. A layer of unmineralized NAG waste rock will cap the PAG backfill, bringing the final ground surface above the range of postclosure stabilized water levels. The backfilled surface will be contoured so that it merges smoothly into the sloping low-relief plane of the lower bofedal.

Pit Evapotranspiration Cover The backfilled pit surface will be completed with an engineered ET cover that excludes atmospheric oxygen and infiltrating surface water from the underlying waste rock. The ET cover has an organic soil layer to facilitate vegetative growth, soil moisture storage, and evapotranspiration. Beneath the organic layer, it has a capillary break of non-reactive rock to prevent upwicking of ARD water through the cap. After closure, an expanded area of bofedal wetlands environment will develop on the ET cover, encompassing both the original lower bofedal and the backfilled surface. The stream from the upper bofedal will cross the backfilled pit surface in a lined, impermeable channel.

Backfill Artificial Recharge Program After pit backfilling is complete, it would take many years for the backfilled pit to become saturated if the water source were limited to groundwater flow, streambed leakage, and recharge from precipitation falling on the backfill surface. To minimize the time during which the PAG waste rock remains unsaturated and vulnerable to acid-generating reactions with atmospheric oxygen, the backfill will be rapidly saturated. The water source would be surface water diverted from various parts of the project site.

Postclosure ARD Discharge After the backfill is saturated and a new equilibrium water table has become established reflecting post-mining conditions, most of the groundwater that has entered the backfilled pit through the buried pit walls and flowed through the PAG backfill will be discharged to the surface at drains installed at low points on the south pit rim (Fig. 1). This water will be piped to a water treatment plant near the process plant site, treated to applicable standards, and discharged to the drainage below the plant.

Conceptual Model

Fig. 2 is a series of schematic cross sections illustrating the events simulated by the model (line of section shown on Fig. 1). Under premining conditions recharge from precipitation infiltrates fractures in the tuffs of the uplands hillslopes and the unconsolidated sediments beneath the bofedal-floored valleys (Fig. 2A). Groundwater flows downgradient to discharge points in the bed of the Supayhuasi Stream.

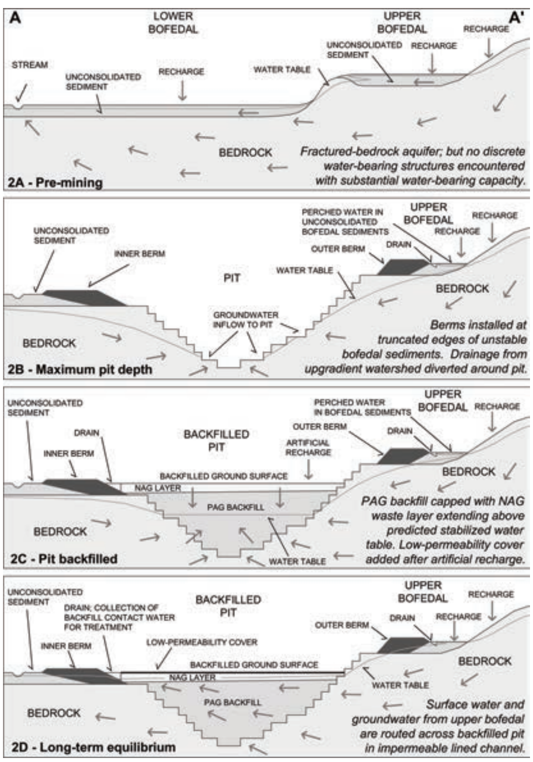

Fig. 2 *Conceptual model.*

In Fig. 2B the pit has been mined to its maximum depth. Berms have been constructed at both the north and south rims to buttress the cutbanks of unstable surficial sediments. The water table is depressed by the pit, which is a local groundwater sink. The water table falls below the streambed in the lower bofedal, and a perched water table develops in the upper bofedal. The perched-water zone shown in Figs. 2B and 2C is predicted to develop based on the stratigraphy of the upper bofedal sediments and vertical gradients observed in monitoring wells, and is not a modeled prediction. The Supayhuasi Stream is diverted around the pit.

In Fig. 2C, the pit has been backfilled with PAG waste rock, capped by a layer of NAG waste rock. A drain has been installed at the low point at the inner berm on the south pit rim. Artificial recharge of the backfill is underway, but water table rebound is incomplete.

Fig. 2D shows postclosure equilibrium conditions. The PAG backfill is fully saturated, and the water table in the backfill region is within the layer of NAG waste. The ET cover prevents surface water infiltration and minimizes the volume of water flowing through the waste (the NAG layer and low-permeability cap are not shown in the diagram). Groundwater seeps into the backfill volume through the buried pit walls, flows through the backfill, and is collected at the drain, from which it is piped to the treatment plant.

Groundwater Flow Model

Modeling Application The Corani pit was modeled using MODFLOW-Surfact (HydroGeologic Inc. 2011) and the Groundwater Vistas interface (Environmental Simulations Inc. 2012). Surfact was chosen because its adaptive time-stepping module facilitated convergence, it allowed dry cell re-wetting, and the variable properties module allowed replacement of mined-out bedrock and unconsolidated sediments with backfilled waste rock in mid-simulation.

Data Sources Data underlying the model was based on field and laboratory testing. Bedrock hydraulic conductivity (*K*) came from packer testing of 24 diamond-drilled boreholes. Pumping tests and slug tests were run in a number of wells, and two multiple-well pumping tests were carried out. Laboratory tests were run on samples representing the waste rock backfill.

The steady-state version of the model was calibrated to water levels in a network of monitoring wells and vibrating wire piezometers widely distributed around the pit. The calibration data set also included dry-season streamflow measurements, and average annual precipitation based on several years of records collected at the on-site automated weather station.

Domain The model domain is a rectangle measuring 4400 m by 5600 m with grid lines evenly spaced at 20-m intervals. The extent of the active cells generally corresponds with the boundaries of the enclosing watershed, and the watershed limit is a no-flow boundary (Fig. 1). The base of the domain is flat, at an elevation of 4700 m. The top surface is the existing pre-mining ground surface, with a maximum elevation of more than 5200 m.

The domain is divided into five layers. The form of the layer surfaces was mainly intended to facilitate representation of the pit’s complicated pattern of deepening during mining, followed by a rising ground surface during the years of backfilling. Model layering is not intended to represent bedrock stratigraphy, since observations made during drilling and packer testing suggested that aquifer properties are not substantially controlled by stratigraphy.

Steady State Calibration Pre-mining conditions were simulated with a steady state model that was calibrated to water levels measured in monitoring wells and vibrating wire piezometers, while simultaneously matching observed dry-season streamflow. Streams were represented by MODFLOW drain cells.

The calibrated model showed recharge of 8.76 mm/a for most areas underlain by bedrock and 43.8 mm/a for most areas of bofedal sediments. Bedrock *K* ranged from 1.79×10^{-7} cm/s to 5.56×10^{-5} cm/s in six zones, with no vertical anisotropy. K trends shown by the packer testing generally agreed with the bedrock *K* distribution incorporated in the calibrated model. Field work did not produce evidence of discrete large-scale water-bearing bedrock structures of the sort that might be associated with large inflows of groundwater to the pit.

Bofedal unconsolidated sediments were assigned a single horizontal hydraulic conductivity of 1.50×10^{-4} cm/s, with a 10:1 ratio of horizontal to vertical *K* (Kontis 2004). Lumping this layered sedimentary sequence into a single layer represents a considerable simplification, but is considered appropriate given the model’s purpose.

Transient Model The transient model incorporates 20 stress periods. Each of the first 19 is one year long, representing the 18-year life of the mine, plus the first year after the end of mining and backfilling. In that year, artificial recharge of the backfilled pit takes place. The final stress period is 80 years long, and tracks the gradual establishment of a new equilibrium head distribution throughout the domain in response to postclosure conditions.

Mining the Pit The Corani mining plan is a complicated one (M3 2012). Deepening of different parts of the pit follows a complex sequence over time, with the aim of achieving the best net present value for the project and balancing the ore-grade requirements of the process plant.

Pit deepening was represented in the model using drain cells. The pit was divided into 18 zones (Fig. 1). Each zone was assigned its own reach of drain cells, and the head settings of each reach were varied year by year to reflect the average pit floor elevation in that reach, controlling leakage into the pit in the zone. For example, if the deepest average pit floor elevation in Zone 10 was scheduled to be 4790 m in Year 5, simulated heads higher than that elevation would produce leakage of water into the pit.

Backfilling the Pit Backfilling of Este began in Year 13, and continued through Year 17. The model used Surfact's variable properties module (TMP1) to change the aquifer properties of the cells affected by the backfill. Cells representing bedrock or bofedal sediments in Year 12 were given the properties of backfilled waste rock in Year 13. The same drain reaches in which declining head settings had been used to show progressive deepening of the pit floor during mining were used to show the year-by-year rise in the backfilled surface during backfilling. Backfilling of Minas and Main took place entirely in Year 18.

Artificial Recharge of the Backfill The artificial recharge program was modeled by applying higher recharge rates in Year 19 to several independent recharge zones covering the backfill areas. A series of model runs were made, involving Year 19 only, to find the inflow volumes needed to saturate the backfill in a single year.

Tracking Postclosure Aquifer Trends A final 80-year stress period beginning in Year 20 was run to follow the adjustment of the aquifer to postclosure conditions. The major change from the prior stress period is that recharge applied to the backfill surface is reduced to zero, reflecting installation of the low-permeability cap. MODPATH runs were made to trace the form of pathlines through the backfilled pit, allowing adjustment of the locations of the drains collecting discharge from the backfill. Runs were made to determine the long-term stabilized volume of ARD contact water discharged from the trench drains, and the volume of water seeping through the pit walls above the elevation of the backfilled pit surface.

Results

Pit Inflow Rates Varying rates of inflow to the pit, as represented by the summed volumes discharged from the drain cells representing the 18 pit zones, vary as shown in Fig. 3. Inflow rates increase to a peak value of about 1800 m^3/d after four years of mining, and then stabilize before beginning a gradual decline that persists through the end of Year 12. Inflow rates drop sharply at the start of Year 13, when backfilling of Corani Este begins and water is no longer being pumped from the sumps in that area. Inflow briefly rises as final deepening takes place in Minas and Main, falls with expansion of backfilling to those last-mined areas, and shows a brief rise as some water applied during the artificial recharge program is lost through a few drain cells.

Water Levels Fig. 4 shows how water levels in different parts of the pit change over time in response to mining, backfill, and postclosure adjustments. In Corani Este, water levels fall sharply early in the mine's history, with the stair-step pattern of the decline showing close control by the annual changes in the drain head schedule. A gradual rise in water levels begins in Year 13 with the beginning of Este backfilling, and the trend terminates with a sharp water level rebound marking the artificial recharge program. The steadier stair-step decline of Corani Minas shows the even pace of pit excavation in that area. Corani Minas water levels begin rebounding when Minas is backfilled, continuing with artificial recharge in Year 19. The Corani Main graph represents a late-mined portion of Main. Significant water level declines do not begin until Year 15, and since the deepest-mined pit floor is higher than the postclosure stabilized water table, this area does not receive backfill. It is therefore not influenced by the artificial recharge

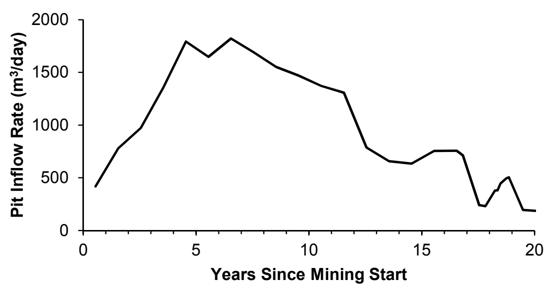

Fig. 3 *Pit inflow rates over time.*

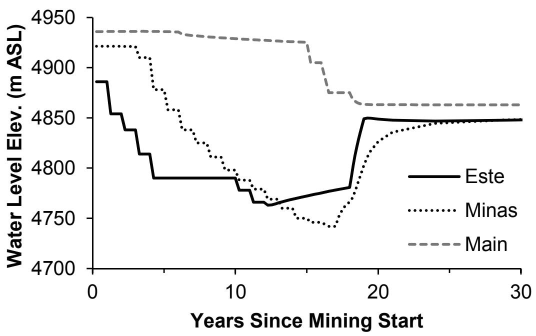

***Fig. 4** Water level variations in different parts of the pit.*

program, and water levels in this area bordering the Corani Main backfill remain permanently higher than water levels in the backfill itself.

Predicted offsite water level impacts are small, and diminish rapidly with distance from the pit. Maximum water level changes of only a few cm are predicted at a monitoring well 2 km downgradient from the pit.

Artificial Recharge Volumes Modeling indicated that it would be necessary to divert surface water at a rate of about 19,000 m^3/d to produce substantially complete saturation of the pit backfill in a single year of artificial recharge. Although flow rates approaching that value might be achievable during parts of the year, it seems more likely that accelerated saturation of the backfill would be carried out over a period of several years after the end of mining.

Postclosure ARD Water Production The model indicates that when the aquifer fully stabilizes after the end of mining, groundwater from the backfilled pit will be discharged at the drains at a rate of approximately 121 m^3/d. ARD contact water requiring long-term treatment, including seepage from the pit walls above the backfill, will total about 218 m^3/d, or 2.5 L/s.

Conclusions

Although sulfide mining projects typically host a range of potential sources of ARD water (*e.g.* waste dumps; exposed pit walls), engineering analysis indicated that the most significant ARD water source at Corani would be a flow-through pit lake, if a lake were allowed to form. The decision to backfill the Corani pit reduces the volume of ARD water that must be treated over the long term by avoiding formation of an acid pit lake. If a lake were allowed to form in the Corani pit, calculations based on standard assumptions suggest that it might produce acid water at an average rate of about 20 L/s. In contrast, the cost of long-term treatment of the predicted flow volume of 2.5 L/s appears much more manageable. Beyond that, installation of an engineered ET cover over the backfill, protected from underlying ARD water by a partially saturated layer of NAG waste rock, will allow establishment of an enlarged bofedal wetlands environment that will advance the project's long-term land use goals.

Acknowledgements

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