The Value of Holistic Water Quality Assessment to Support Pit Lake Closure Decisions

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Abstract

Decisions relating to pit lake closure can exert basin-scale influence on surface water and groundwater systems. This was evaluated in a water-stressed region where a flow-through pit lake system was proposed as a community water resource. The integrated assessment considered climate, hydrology, groundwater and waste-rock seepage to test both lake viability and regional hydrological effects. The results show that closure decisions can change materially when pit lakes are assessed as part of the wider hydrological system, in-line with water stewardship principles.

Keywords: Pit lake, mine closure, water stewardship

Background and issue

Pit lakes can often act as control on the surrounding post closure water system, with potential wider impacts on water resources than just the quality of the pit lake itself. The lake will typically act as a contaminant sink or source for the immediate surrounding hydrological system to some extent, but influences can be wider reaching where pit closure involves river diversions or changes in groundwater flow regime. Under such circumstances, the pit lake interacts directly with wider hydrological pathways, and an isolated assessment of the pit lake would not capture the basin scale consequences of closure choices.

This was the case at a gold mine in sub Saharan West Africa, where rainfall is highly seasonal, evaporation greatly exceeds precipitation, and water resources are limited and strongly contested among closure objectives, local and downstream users and the broader environment. The final landform comprised three pit voids, and the closure planning concept involved diverting part of the adjacent ephemeral river through the three pits to accelerate filling and create a post closure lake resource for the benefit of local communities.

Earlier assessments had explored this closure concept, which stemmed from the original Environmental Impact Assessment for the mine. They focused on pit lake recovery and concentrations of substances in the pit lake. However, they did not evaluate the broader interaction between the pit lakes and regional groundwater and river resources. Upon review, the previous work also omitted several inputs, such as waste rock seepage and pit wall reactivity, and relied on assumed values for other inputs that appeared to be controlling the results, where dedicated parameterisation studies were needed. As a result, confidence in their conclusions was not sufficient to make updated closure decisions.

The mine was also adopting a water framework based on International Council on Mining and Metals (ICMM) water accounting/reporting and Alliance for Water Stewardship (AWS) catchment water-stewardship principles, so closure decisions needed to consider catchment-level impacts rather than only site outcomes. Given the uncertainties, it was clear a broader integrated study was needed to reassess long-term pit lake behaviour and regional water-resource consequences.

Aim

The aim of the project was to assess the long term hydrological and geochemical behaviour of the proposed pit lake system and its wider impacts, under two closure scenarios:

1. diversion of part of the river through the pits to accelerate filling and sustain higher lake levels near surface for community use [“with river scenario”], and

2. no river diversion, with pit lake levels driven by groundwater rebound, direct rainfall and runoff from adjacent waste rock dumps, where water quality was likely to be poor (Figure 1).

The study needed to provide conclusions sufficient to support closure decision making and advance the water management plan.

Approach

The assessment combined climate analysis, catchment runoff analysis, river hydrology modelling, groundwater modelling, waste rock seepage evaluation, pit wall geochemistry and a water and solute load model for the pit. A single integrated team worked across these linked components, ensuring consistent assumptions and enabling feedback between disciplines.

Climate

Climate sensitivities in this arid region would influence all parts of the assessment, particularly with the potential effects of successive dry years that had already occurred in the past and long-future climate change with potential for more intense but shorter wet seasons. Historical climate inputs were derived from regional and site rainfall gauges, site weather station data and A pan evaporation records and fitted to a climate model to fill data gaps and extend the time series, producing a daily long-term record for calibration and climate change modelling.

The site was represented by a mean annual precipitation of approximately 460 mm/year with an evaporation of around 3,500 mm/year reflecting the strongly negative climatic water balance at the site.

River flow

The ephemeral river adjacent to the mine is a regional drainage system with a catchment of over 2,500 km2 . In the wet season, flood occurs as a flashy flood of the channel and surrounding area due to the intense rains. The river passes over two shallow dams next to the mine that the mines raw water as well as water supply for the adjacent town and farmers, with the residual downstream flow supplying communities. To accurately model the function of the diversion channel, its flow into the pit lake and the lakes impact to the downstream river catchment the river diversion assessment needed to be able to mimic the wet season run-off, storm surge, and how this might change in the future.

River flows were modelled via a catchment scale hydrological and hydraulic modelling workflow. The catchment runoff was represented using a lumped basin soil moisture accounting model in HEC HMS and was calibrated against dam water level gauges. The flow intensity from the runoff was simulated using a 2D HEC RAS hydraulic model of the adjacent river corridor. The model was calibrated against the large, short duration flood events using the 15 minute spillway record that was available for the dam

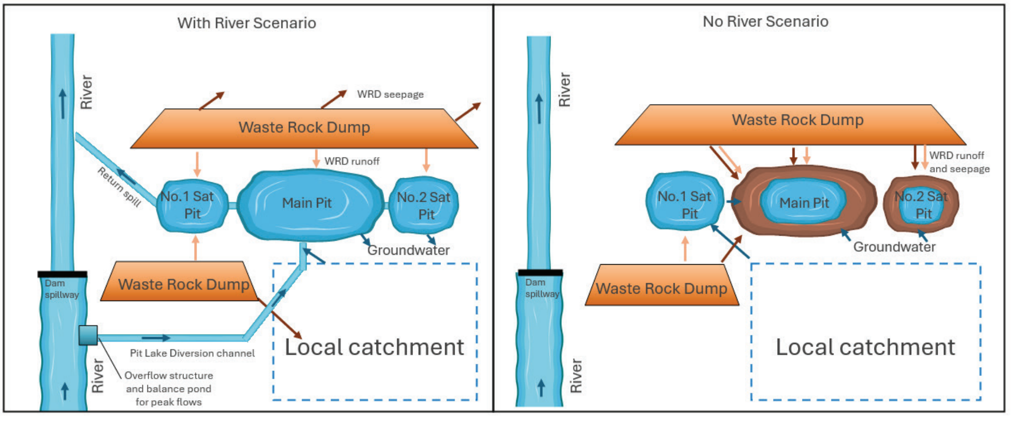

Figure 1 Simplified conceptual model of pit lake inflows and outflows under the two closure scenarios.

to capture the flashy hydrograph shape that is not resolved in daily simulations and also observed flood extents from satellite imagery. The proposed pit-lake diversion channel alignment was designed iterating cross section dimensions into the terrain to convey the design event without spilling.

Groundwater

In the river diversion scenario rapid filling of the pits would quickly exceed the local depressed groundwater levels. This would create outflow from the pit to the wider groundwater system, increasing the volumes of river water required to compensate for groundwater storage recovery and once the levels were near surface as intended in the closure design, permanent outflow from the lake to the wider groundwater system would occur. Conversely the no river scenario would represent constant loss from the groundwater system to the lakes and water level reduction in the aquifer and act as a sink for contaminant issues relating to the mine infrastructure. SRK had previously developed a regional scale 3D groundwater model in FEFLOW (Diersch, 2005) as part of a separate project for the mine. For this project, the regional model was cropped to the vicinity of the pit to estimate transient stage-dependent inflow and outflow relationships for the pits under variable lake conditions to use in the lake water balance simulations. Because groundwater was both a lake inflow and a potential receptor, the regional model was also used to simulate how both scenarios effected long-term groundwater levels, flow directions and the potential migration of seepage from the mine facilities

Waste Dump Seepage

The mine has a number of laterally extensive waste-rock dumps (WRD), known to readily leach metals, in particular arsenic. In dry climates, waste-rock dumps can remain under-saturated with respect to equilibrium moisture contents for years to decades, with wetting fronts progressing slowly and chemistry evolving as deeper oxidised materials are progressively wetted. Prior assessments had not taken account of this seepage source, focussing on observed solute loading from WRD runoff only. This seepage source that would potentially be released post closure was likely to be a sensitive input into the model, therefore it was decided to constrain the seepage rates and timing using unsaturated flow modelling in HYDRUS (Šimůnek, 2013). The model incorporated WRD geometry, deposition history, particle-size distribution and representative soil–water characteristic curves, with parameters adjusted to account for the coarse fraction that contributes little to storage. Residence-time analysis confirmed that downward wetting through the WRD matrix component would be slow compared to rapid macropore infiltration events, with quasi-equilibrium moisture conditions in the matrix predicted to occur well after mine closure and solute migration further delayed by the saprolite below the WRD footprints. Once quasi-equilibrium moisture conditions were reached post-closure, percolation from the WRD was estimated at around 5% of annual rainfall, based on a combined representation of long-term cover including areas of sparse shallow- and deep-rooting vegetation as per restoration plans, together with unvegetated areas where only sandy wind-blown cover was assumed to have developed.

Geochemical sources

Source terms for waste rock seepage and runoff, and pit wall inundation were derived to provide solute loading inputs into the integrated model. The derivation was based on a static and kinetic test work dataset for site lithologies including humidity cell tests (HCTs). Materials were classified as non PAG, but metal-leaching. Arsenic leaching at near neutral pH was the principal long term source concern. For WRDs, runoff source terms were developed for the exposed surface mix (typically dominated by lower risk lithologies) and calibrated to monitored WRD runoff collection pond chemistry. WRD seepage used internal dump lithologies, the long initial oxidation period and expected leaching dynamics, with evaluation in PHREEQC (Parkhurst and Appelo, 2013) to constrain oversaturated mineral phases. For pit walls, runoff contact water and first submergence flushing were treated separately;

reactive mass was estimated from 3D pit wall areas by lithology from the site's geology model. Submergence release was coupled with assumptions regarding fracture release based on fracture zone thickness, density and an oxidised rind in addition to contributions from talus on benches.

Pit lake load model

A 2D laterally averaged hydrodynamic model (CE QUAL W2) was initially planned for use in the gap analysis phase, consistent with the first of the prior assessments that suggested river inflows could generate temperature stratification. However, scoping simulations of seasonal inflows into the main pit lake were tested in 3D in TUFLOW (BMT, 2019) to check if this assumption was correct, and this indicated that persistent stratification in the main pit lake was unlikely. As a first pass, the hydrological and geochemical inputs were combined in a GoldSim (Kossik and Van Kuiken, 2006) water and solute balance model for the three pits to simulate long term water levels, solute loads and bulk concentration behaviour, with screening for oversaturation of solute in the lake using PHREEQC. GoldSim's complete mixing assumption was adopted for options appraisal because sustained stratification was not expected to be a control on long term outcomes. The model used equations to balance the flow between the lakes during river inflow events. The GoldSim approach was taken with the recommendation that if river diversion is progressed to design, lake hydrodynamics should be revisited using a 3D model once inlet/outlet structures and operating controls were better defined, particularly to understand the extent of mixing in the No2. Satellite Pit. The outputs of the pit lake model were fed back into the river and groundwater models to understand the linked effects to these systems.

Results

The results showed that both the long term behaviour of the pit lakes and closure water system was controlled by a relatively small number of dominant processes: strong evaporative loss, delayed but increasingly strengthening WRD seepage, the seasonal influx from the river (for the with river scenario) and the direction of groundwater flow as water levels changed.

No river diversion scenario

Under the no river scenario, the Main Pit and No.2 satellite pit acted as terminal evaporative basins that only partially refilled to approximately one third of the pit depths over decades. Water quality deteriorated over time through evapoconcentration and progressive loading, particularly for arsenic. The No. 1 satellite pit performed more favourably if the local catchment was directed to that pit only providing some, albeit volumetrically reduced, potential for beneficial community use post-closure. However, with this scenario inward groundwater gradients were maintained to the main pit. This contained poorer quality mine waters within the former mine site which were present from seepage in the TSF area and would be developed post closure from the WRDs situated adjacent to the pits, once full seepage potential was reached, thus limiting regional risk.

The with river diversion scenario

Under the river-diversion scenario, the main pit completed rebound to near surface in around a quarter of the time of the no river scenario, before overflowing through the linked pit system, then to the river. During filling, the diverted river inflow diluted concentrations and improved predicted water quality considerably relative to the terminal scenario. These improved outcomes were contingent on sustained throughflow for the lake back to the river. Because topography prevented direct diversion-channel connection to the No.2 satellite pit, it relied on a single connection to the Main Pit and lacked throughflow; its water quality therefore did not meet standards and continued to worsen after lake connection. Whilst the Main Pit lake quality was greatly improved compared to the no river scenario, initially achieving standards after filling, a slow gradual decline in quality was predicted over decades as continued loading outweighed dilution, meaning some water quality standards were exceeded long-term. Although water quality not achieving standards might have limited use of the river augmented pit lake, predicted concentrations remained much better than the terminal evaporative pit lakes in the no river scenario.

Effects to groundwater quality

With the With River scenario, as lake levels rose, groundwater gradients reversed and outward seepage became possible. The main loading from this was not from the lake water itself as this was relatively near the standard, but from the change in migration direction of seepage from WRD areas. The WRDs represented a major solute loading source and with little areal recharge in saprolitic areas, the down gradient groundwater system had little capacity for dilution beyond the water seeping from the raised pit lake itself. In simulations the WRDs developed a plume in the groundwater system migrating outside the mine site. Furthermore, a plume formed by the TSF seepage that had been migrating partially to the pit in operations, also was predicted to change direction and flow outside the mine site in long-term closure under this scenario. In the context where the groundwater is the key year round water resource for surrounding and regional communities this was a key outcome outweighing any benefit from a recovered lake for community use.

Loss of water resources from evaporation

Diverting river water through the pits reduced downstream flows by approximately 10% during the filling period and by around 4% long term due to evaporation from the new permanent water surface. These were considerable for a river of such size in a water scarce region. Cutting off the top of seasonal waters to fill the pit also had implications for the extent of the river's wet-season water migration downstream. Such river systems rely on these large-scale flood waters to reach lower reaches.

The terminal lake scenario, in contrast, gave evaporative losses for groundwater and continued drawdown from the supressed lake. However, water losses were considerably lower and largely involved groundwater already compromised by seepage from the WRDs and the TSF seepage.

Discussion

From a water stewardship perspective, the river diversion scenario provided faster filling and countered wider groundwater drawdown but introduced three regional risks: additional long term evaporative losses of the river water resource, reduced river water quality (although predicted to be marginal, highly uncertain), and the long-term potential for regionalised groundwater quality derogation driven by gradient reversal for seepage from the WRDs. Whilst lake quality was vastly improved, it did not meet all standards limiting the extent of its use and its benefit did not outweigh its risk. The terminal lake scenario avoided these wider risks and therefore despite producing lake quality and levels that removed any use, it aligned more closely with basin scale sustainability that the client was implementing in their water management framework. The effect of this boundary change is summarised in Figure 2.

These findings show two relevant points transferable to other closure water management studies. First, once the system was assessed holistically, rather than just in the context of the pit lake's water quality the preferred closure option shifted. Second, the reliability of the water and solute balance depended on whether key inputs – in this case, seepage rates and chemistry, river inflows to the lake (and mixing) and evaporative losses – had been adequately defined. And after the supporting studies were completed and integrated, the environmental impacts of the pit lake and closure options could be compared more transparently and defensibly.

Conclusion

Pit lake closure decisions, particularly in water-stressed regions, can have basin-scale impacts and can benefit from integrated assessment aligned with water-stewardship principles. At this mine, linking river hydrology, groundwater flow, long-term waste-rock seepage and pit lake formation showed that the preferred option depended on broader trade-offs, not pit lake water quality alone. The concept of a beneficial pit lake resource for local communities after mine closure was relegated when this risked regional water resource derogation. Although

Boundary	No river diversion	With river diversion	Decision implication
Pit-lake-only assessment Lake level + water quality	• Partial rebound • Terminal evaporative lakes • Evapoconcentration, poor lake quality • No beneficial use	• Rapid filling to surface • Dilution + flow-through lowers lake concentrations • Local water resource benefit (but limited by concentrations) • High lake water-quality uncertainty	**Pit-lake-only view** **With River Diversion preferred** Because lake levels and water quality improved
Regional assessment Lake + groundwater + river resources	• Pit remains hydraulic sink • Inward gradients retain WRD /facility seepage near mine • Low loss of clean water resources to evaporation • Drawdown of local groundwater	• Near-surface lake reverses groundwater gradients • Seepage toward receptors • River loss: ~10% filling /4% long term • High lake water quality uncertainty and high risk	**Holistic view** **No River Diversion preferred** Because regional water resources protected

***Figure 2** Summary of closure scenario outcomes under different assessment boundaries.*

the terminal pit lakes had poor water quality, they helped contain mine seepage, whereas the flow-through concept redirected groundwater contaminants towards local receptors and increased evaporation losses of regional water resources. The more holistic assessment therefore changed the understanding of the risks presented by the closure options and the pit lake's role at closure.

Acknowledgements

The project was a team effort from specialists of various disciplines, including, Lorenzo Bianco (climate Assessment), David Carruth, Francis Smith and Thomas Malone (catchment, river and channel design and models) Adam Bennett (groundwater modelling), Vitor Sato (WRD seepage), Mo Walter and David Tait (geochemistry), Dr. Mike Stewart (GoldSim water and load balance and TUFLOW lake model). Thanks also to contributions from Mark Raynor and the client team.

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