Assessment of the Process of Pit Lake Formation and Associated Geochemistry in Open Pits – Mupane Gold Mine, Botswana

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Abstract Open pit gold mining began in 2004 at Mupane's Tau Pit in Botswana and has since extended to a total of four pits, including Tholo, Kwena and Tawana. Tau and Tholo are currently not operational and pit lakes have formed in them. The two lakes are completely different hydrogeochemically in spite of being located within the same geological stratigraphy and located only 1 km apart. The Tau pit lake has a pH of 7—8 with elevated total arsenic concentrations exceeding the World Health Organisation (WHO) limits of 0.01 mg/L. The Tholo pit lake is highly acidic with a pH of 2—3 and high total metals including lead, zinc, iron and manganese, although arsenic is lower at 0.009 mg/L. Due to the arid climate and shortage of accessible surface water in the area, an understanding of the formation of the pit lakes on closure of the mine and the predictive long term water quality is required so that adequate mitigation measures can be undertaken to minimize the risks to the local ecology, currently using the lakes as a drinking water supply.Numerical groundwater flow modelling, a water balance, hydrogeochemical analysis including stable isotopes of groundwater, and modelling of the reactant rocks using PHREEQC indicate that there is sufficient buffering capacity in the groundwater to neutralize acid generated in the Tau pit. Conversely, the chemistry of the Tholo pit lake appears to be the result of extreme rainfall events rinsing precipitated efflorescent salts from the highwalls; and there is insufficient groundwater inflow into the pit to neutralize it.Mitigation measures could include addition of lime to raise the pH, and/or addition of organic carbon to enhance sulfate reduction. The depth of the pits should be taken into consideration to allow sufficient groundwater inflows to buffer the acidic runoff. Backfilling of the pits to the static water table depth could be considered to restrict access by fauna to the pit lakes.

Key Words surface water groundwater filling, pit lake chemistry, groundwater modelling, ecology, mitigation

Introduction

Mupane Gold Mine is located in the eastern part of Botswana, 30 km south east of Francistown and is owned by IAMGOLD Corporation. Open pit gold mining began in 2004 at Tau Pit and has since extended to a total of four pits, including Tholo, Kwena and Tawana as shown in Figure 1. The pits vary in depth between 70 to 170 m and currently only Kwena is operational. Pit lakes have formed within Tholo and Tau with distinctly different chemistry, Tholo pit being highly acidic (pH of 2—3) whereas Tau pit is circa neutral (pH 7—8). The Tau pit has total arsenic concentrations on average of 0.02 - 0.04 mg/L (exceeding the WHO Guideline Limits of 0.01 mg/L for Drinking Water and the Canadian WQG Ecological Benchmark of 0.005 mg/L) whereas Tholo Pit lake has lower arsenic concentrations (0.009 mg/L) but higher sulfate (5000 mg/L) and iron (approximately 200 mg/L) concentrations.

Botswana is a dry land locked country which receives around 400 mm of rainfall annually and an estimated 75% of its domestic and livestock water needs are sourced from boreholes. Due to the arid climate and shortage of accessible surface water in the area, the local fauna (including leopard, hyena, etc.) are using the pit lakes as a drinking water supply which could impact on the health of these animals.

An understanding of the formation of the pit lakes and predictive long term water quality on closure of the mine is required so that adequate mitigation measures can be undertaken to minimize the risks to groundwater users and the local ecology.

Background

The general topography is relativley flat at an elevation of 980 mamsl sloping in a southwesterly direction towards the Tati River. The annual precipitation in the Mupane Mine area is about 450 mm with most precipitation occurring between November and April, usually as high intensity storm events. The annual open-pan evaporation is 2000 mm, exceeding precipitation and resulting in a water deficit throughout the year. Recharge to the groundwater is estimated to be less than 1% of the mean annual rainfall.

The Mupane mine is located within the Tati Greenstone Belt which comprise a NNW striking group of Archaean metavolcanic, metasedimentary and igneous rocks over a 65 km strike length and up to 20 km width. The rocks have been metamorphosed to lower-mid amphibolites facies

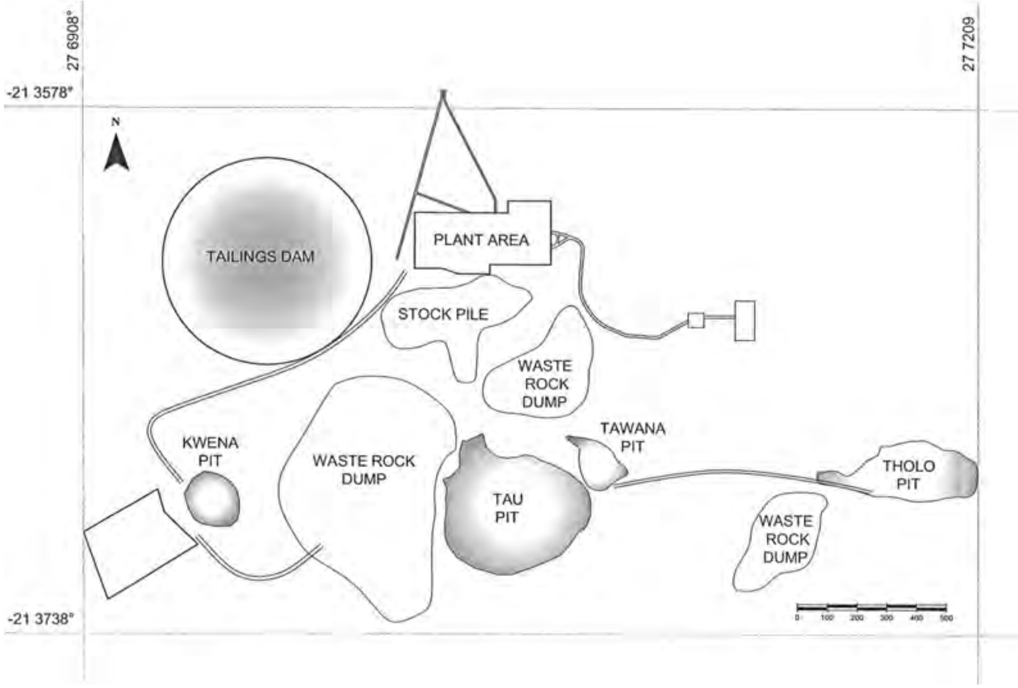

Figure 1 *General layout of Mupane Mine showing Tholo, Kwena, Tawana and Tau Pits*

throughout the belt. Several tonalite-granodiorite plutons intrude the belt and a swarm of Proterozoic dolerite dykes (Karoo dyke swarm) trends WNW across the belt.

The geology occurring within the open pits at Mupane generally consists of graphitic iron and banded siliceous formation (GIF/BIF) hosted by metasediments including coarse grained carbonate bearing conglomerates, amphibolites, marbles, and metapelites. The GIF underwent several transformations including large scale replacement by fine grained cherty silica, fine grained iron carbonate replacement, and thermal metamorphism resulting in the growth of gruneritic amphibole. Deformation and brittle ductile shearing resulted in the development of open spaces which became filled with iron rich carbonate. Continued brecciation and silica flooding with the associated precipitation of gold, arsenopyrite, pyrrhotite and minor sphalerite and galena, resulted in the mineralisation currently being exploited (Tomkinson and Putland, 2006). The thickness of the GIF/BIF varies between 10 and 90 m.

Groundwater occurs within the open fractures, joints and contact between the metamorphic rocks and dykes. The fractures and joints are generally narrow and of limited areal extent, and storage is controlled by the density and interconnection of fractures and joints. Small settlements and farmers in the area obtain their water supply from boreholes with variable yields, ranging from < 1m^3/hr to 5 m^3/hr.

Modelling

Development of Numerical Groundwater Flow Model

The water balance between the inflows into the pits (groundwater flows, precipitation) against outflows (evaporation) were evaluated using groundwater flow modelling. The first stage was to construct a detailed model to predict the steady-state pit lake levels, time of pit lake formation, and inflows. All groundwater flow modelling was conducted using the finite-element code MINEDW (Azrag *et al.*, 1998), as this code can simulate simultaneous mining of multiple pits and pit lake formation due to re-watering on closure.

The model boundary was defined along rivers in the area; Tati to the west and south and Ramokwelena on the east and north. The metasediments, metavolcanics, quartzites and schists have low permeability and were assigned hydraulic conductivities of 2.5×10^{-3} m/day whereas the dykes, which were simulated as vertical features, were assigned a higher hydraulic conductivity of 0.06 to 0.45 m/day.

To simulate the mining activities, the end-of-mining pit configurations of each pit were modelled using time steps equal to one month, and

Table 1 *Predicted steady state pit lake levels and groundwater inflows*

Pit	Pit Bottom Elevation (mamsl)	Calculated Level of Pit Lake (mamsl)	Depth of Pit Lake (m)	Ground-Water Inflow at Steady State (m^3/day)
Tau	810	905	95	138
Tholo	920	930	10	2.5
Tawana	930	940	10	Evap exceeds inflows
Kwena	890	925	35	0.7

the elevations of the pit bottoms were assumed to change every month in the model. The monthly configurations of the pits were interpolated linearly between ground surface and final pit configuration. This special attribute of MINEDW to simulate changes in the configuration of the pit over time enables prediction of inflow and height of the seepage face most realistically. Upon completion of the simulated mining, the pit lake infilling was simulated. The numerical drain nodes which represent the ultimate pit elevation continued to simulate groundwater discharge into the pits. Water levels in the pits were calculated based on the volume of the pit per depth and accumulated water within them. After re-calculation of the water levels in the pit, the simulation continued at the new time-step with new specified heads equal to the water level in the pit. Additionally, inflows to the pit due to runoff and water losses due to evaporation from the lake surface (2,000 mm/yr) were taken into consideration for each pit.

The model simulated formation of the pit lakes for 45 years after cessation of mining in 2011 in the last open pit (i.e., until the end of 2056). Selection of this time period was based on the goal of achieving essentially "steady-state" conditions in the pit lake levels and inflow. Upon achieving steady-state conditions, three of the pit lakes — Tau, Tholo, and Kwena – are predicted to gain groundwater while the Tawana pit is predicted to lose water (and remain essentially dry) due to the evaporation rate being greater than groundwater inflow and runoff.

Table 1 shows the predicted steady state levels in the pit lakes as well as the predicted groundwater inflows into each pit following closure of each pit. It is predicted that the pits will never fill to the pre-mining water levels due to the high evaporation rates and will remain sinks to groundwater as terminal pit lakes. Groundwater flow will be towards the pits and no through-flow to the surrounding aquifer is anticipated.

Figure 2 shows a sketch of the current and predicted pit lake levels of the Tau and Tholo pit lakes.

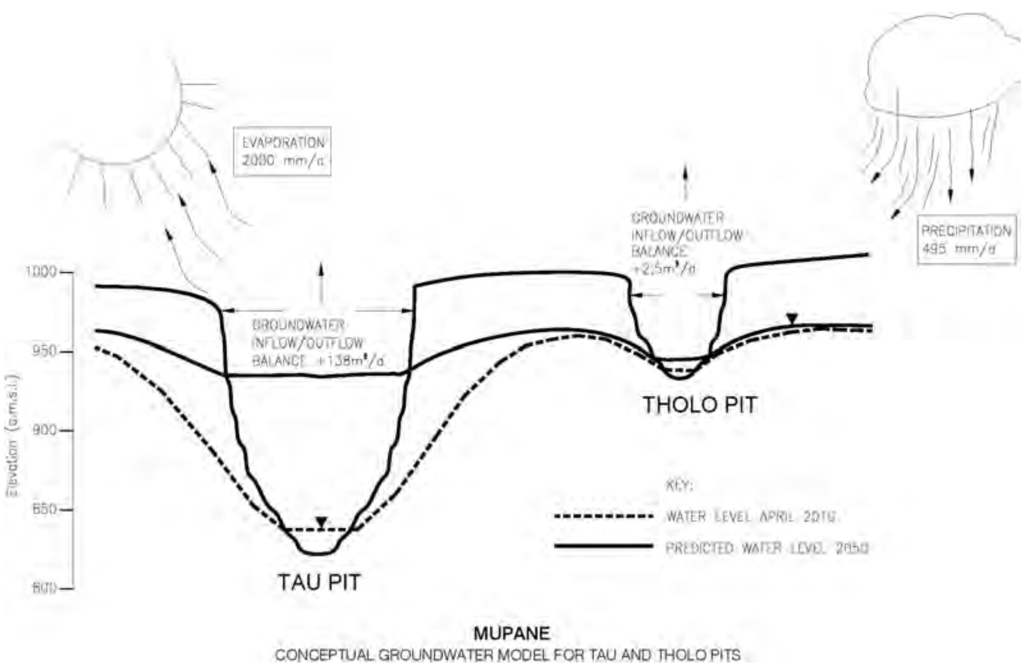

Figure 2 *Current and predicted pit lake levels for Tau and Tholo pits (not to scale horizontally)*

Rock Types	Kwena	Tawana	Tholo	Tau
BIF / GIF (ha)	1.0	0.7	2.6	3.6
Percent of Pit	31%	28%	30%	19%
Other rock types (ha)	2.2	1.8	6.4	15.1
Total area of pit (ha)	**3.2**	**2.5**	**9.0**	**18.7**

***Table 2** Summary of estimated BIF/GIF in hectares and as a percentage of the total pit surface area*

Development of Geochemical Model

An independent study was conducted in 2003 on the acid rock drainage potential for the site in which the different mineralogical aspects of the rock types were investigated. Approximately 30% of the mined materials, in particular the GIF/BIF and associated black shales, are potentially acid generating. The minerology indicates that pyrrhotite, arsenopyrite and pyrite are present as the main acid producing minerals and calcite and dolomite are the main acid neutralising minerals. The most significant element from an abundance and mobility point of view is arsenic.

Chemical data, in terms of water sample compositions and leachable and reactive rock compositions, were used in the preparing the detailed pit lake model. To estimate the main geological rock types in each pit, simplified geological plans were used to estimate the percentage of the most reactive rock type (BIF/GIF) shown in Table 2.

The current pit lake or sump hydrochemistry including selected metals (total) is shown in Table 3.

The pit lake model was designed to estimate the water quality compositions on an annual basis for the first 30 years of filling. The individual calculations were performed using PHREEQC (Parkhurst and Appelo, 1999). Due to the repetitive nature of the model, the various proportions used in the mixing calculations along with the reactive phase contributions and amounts of water to remove to represent evaporation were calculated in an Excel spreadsheet. The spreadsheet calculations maintain the water balance in the pit and calculates the mixing proportions annually, thus as the flow of groundwater decreases over time, the mixing proportions are recalculated. The Excel output was then utilised by the PHREEQC input file.

Contributions from leaching or oxidation of solid phases are also included in the geochemcial model. In the first year of the simulation, two different reactants contribute additional loadings to the pit lake. The first type represents easily leachable material from the non-reactive rocks present in the pit. A small contribution of this reactant is added annually. The second contribution represents the components released through sulfide mineral oxidation and acidic leaching of the reactive sulfide bearing rock. in this case the GIF/BIF was selected as representing the Reactive Rock. The Reactive Rock Leachate contribution was only added in the first year and represented components released through the oxidation of sulfide minerals in the exposed pit floor for five years prior to covering with water from the pit lake. The amount of reactive rock was estimated using a Davis Ritchie calculation (Davis and Ritchie, 1986, 1987).

The resulting solution is allowed to equilibrate with the atmosphere [CO_2(g) and O_2(g)], and with user selected possible minerals, which included calcite and ferrihydrite. In the final step, evaporation and subsequent evapoconcentration are considered. The water composition, after the evapoconcentration reactions have been completed, is defined as the composition for that specific year. That water then provides the starting composition for the next year and the cycle (except for the contribution from sulfide mineral oxidation) is repeated.

According to the model, the pH in Tau Pit remains slightly above neutral with values of about 7.8. These pH values are related to buffering reactions between calcite and carbon dioxide gas. The groundwaters used in these simulations were oversaturated with respect to calcite, so calcite is expected to precipitate. The predicted pH is similar to the pH in the sample of Tau Pit water collected in June 2010. Alkalinity values are lower in the predicted compositions due to the added acidity from the reactive leachate that will be produced by the oxidation of sulfide minerals present in the GIF/BIF material. Based on the model output, the impact of surface complexation reactions (sorption) for the Tau Pit is not seen

***Table 3** Hydrochemistry of pit lakes or sumps (2010).*

Pit	pH	EC (mS/m)	SO_4 (mg/L)	$CaCO_3$ (mg/L)	Fe (mg/L)	As (mg/L)	Pb (mg/L)	Zinc (mg/L)	Mn (mg/L)
Tau	7.8	279	1195	70	5	0.044	0.002	0.2	0.45
Tholo	2.5	656	5536	nil	377	0.009	0.03	49	282
Tawana	7.9	172	419	268	0.72	0.004	<0.001	0.07	0.6
Kwena	7.4	431	2080	312	<0.001	0.004	<0.001	<0.005	0.06

to be a significant factor.

The model predicts low arsenic concentrations on the assumption that arsenic adsorbs onto hydrous ferric oxide but the dissolved arsenic values measured in Tau pit are already at 0.04 mg/L. However, comparison of field collected samples and model predicted compositions suggest that surface complexation of arsenic onto ferrihydrite is not an active process in the Tau pit lake. In Tholo pit lake, the arsenic is an order of magnitude lower (0.004 mg/L), suggesting precipitation of arsenic with iron minerals is occurring. The arsenic behaviour in the pit lakes is not fully understood as yet.

The geochemical modeling described above, particularly the simulations that were run to assess sensitivity to different amounts of reactive rock, indicate that for the Tau Pit, the groundwaters in the vicinity of the pit have alkalinities high enough to buffer the pH to values slightly less than 8.

The numerical groundwater flow modelling and stable isotope analysis show that the Tholo pit is predominantly surface water runoff and formed after above average rainfall in the 2009/2010 seasons during which the pits were flooded. It is therefore concluded that sulfosalts, efflorescent salts and sulfates which formed during the dry season on the BIF/GIF highwalls were rinsed off into the pit lake and there is insufficient buffering provided by the groundwater inflows, resulting in the high sulfate and iron waters with low pH.

Possible Mitigation Measures

Increasing the pH through the addition of lime (CaO) or limestone ($CaCO_3$) is probably the simplest means to improve the water quality in the Tholo Pit. Such a process will have several effects including a possible reduction in the long term rate of sulfide mineral oxidation.

A more complicated alternative might be to add organic matter (organic carbon) and reform sulfide minerals, but this would require a detailed testing program to assess its potential success. The addition of organic matter should permit sulfate reduction to take place, which would allow for the formation of sulfide minerals. Some neutralizing agents would in all likelihood also be added to the lake in this approach.

Future mining activities and planning should take into consideration the final pit depth to ensure that there will be sufficient groundwater inflow into the pit lake to buffer acidic surface water runoff following storm events. This could also be mitigated by backfilling the pits to the static water table depth to restrict access by the fauna to the pit lakes.

Conclusions

Combined groundwater flow and geochemical modeling have provided insight into the predicted water levels and associated chemistry that may be expected within open pits left behind after mining operations.

The dry climate and high evaporation rate will prevent the pits from filling to the static water level so they will always be a sink to groundwater flow. Numerical groundwater flow modeling indicates that a shallow pit lake only about 10 m deep will form in Tholo, while significantly deeper lakes are expected in Kwena and Tau pits, 35 and 95 m deep, respectively.

The chemistry of the pit lakes depends on the interaction between the water and the mineralogy of the surrounding rocks. The ore which is mined in this area is associated with the BIF/GIF which are sulfide bearing rocks and are potentially acid generating.

Geochemical modeling of the pits indicates that the water within Tau pit will be within acceptable limits in terms of pH and iron concentrations due to the buffering capacity of the groundwater inflows, although arsenic is elevated and could be a risk to wildlife. Tholo pit lake is characterised by low pH and high iron and sulfate concentrations. Most of the water currently in the Tholo pit is surface water runoff following high intensity rainfall events which washed off the salts from the predominantly GIF/BIF formations in the pit walls. The low inflows of groundwater do not provide sufficient buffering capacity to neutralise the low pH / high sulfate water composition. Further research is needed to understand the behaviour of arsenic in the pit lakes.

Mitigation measures could include addition of lime to raise the pH, and/or addition of organic carbon to enhance sulfate reduction. The depth of the pits should be taken into consideration to allow sufficient groundwater inflows to buffer the acidic runoff, and backfilling of the pits to the static water table depth could be considered.

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