Post-closure mining pit lake water quality modelling

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Abstract

A developing iron ore mining project in Western Australia's Pilbara arid zone region was required to provide predictions of final pit lake water quality for a mine closure plan to be included in the mine EIA and approvals documentation. A site wide numerical groundwater model was developed using FEFLOW to model the open pit strip mining dewatering requirements over the 15 year life of the project and rebound during closure. Key water quality toxicant and pollutant influences were modelled using a GOLDSIM based water quality model in the three final pit lakes from the cessation of mine dewatering to 100 years post closure. The models predicted increasing mining pit lake salinity due to arid zone conditions annual evaporation rate (3300 mm),low rainfall (300mm) and increasing concentration of key toxicants. The pit lake water quality is predicted to not be suitable for discharge to surface waters due to elevated salinity and Zinc levels.

Keywords: mine water quality, mining void pit lakes, mine closure, surface and groundwater modelling.

Introduction

This study focuses on the predicting the pit lake water quality after closure at a development iron ore mining project in Western Australia's extremely arid Pilbara eastern region, in the iron rich Hamersley Ranges on the edge of the Little Sandy Desert, one of the driest locations on Earth. The project was required to provide predictions of final pit lake water quality for a mine closure plan to be included in the EIA and mine development approvals documentation. Three final open pit voids were predicted to remain after backfilling and closure revegetation. Pits A, and B are located close to each other in similar geological units while Pit C is located 18km to the southeast.

Groundwater Model

A project wide numerical groundwater model was developed using FEFLOW to model the open pit strip mining dewatering requirements over the life of the project. The groundwater model was then used to develop groundwater rebound predictions and inflow rates in the remaining open pits, for post closure pit lake scenarios. The 3 final pit voids were predicted to fill with groundwater after mine dewatering was ceased at mine close and form pit lakes over time. The modelling predicted pit lake inflow would reach equilibrium with local groundwater levels after 8 to 15 years depending on the pit geometry, underlying strata hydraulic conductivity, and depth of mine dewatering during the project mining phase.

Model hydraulic parameters were based on those reported in local groundwater water exploration drilling studies and combined with airlift test results in the study area. Pit A and B were assigned hydraulic parameters in Table 1.

Table 1 *Hydraulic parameters assigned to Pit A and B*

Unit	K_h (m/d)	K_v (m/d)	S_y
Marra Mamba (All Members)	2.7	2.7	0.04
Jeerinah	0.0375	0.00375	0.005
Wittenoom	0.4	0.04	0.005
Other Units	0.4	0.4	0.005

Pit C to the southeast was assigned hydraulic parameters in Table 2. Parameters for faults, alluvium and granite, which are observed throughout the entire region around the three proposed pit lakes are reported in Table 3, where K_h is the horizontal conductivity, K_y is the vertical conductivity and S_y is the specific yield. A specific storage (ability of the rock to store water under pressure) of $5x10^{-6}$ m^{-1} (equivalent to the compressibility of water) was assumed for the modelling exercise.

Table 2 *Hydraulic parameters assigned to Pit C*

Unit	K_h (m/d)	K_v (m/d)	S_y
Marra Mamba (Ore)	3	3	0.08
Marra Mamba (Other)	2	2	0.08
Jeerinah	0.04	0.004	0.005
Wittenoom	0.1	0.01	0.005
Greenstone	0.001	0.0001	0.001
Bangemall	0.001	0.0001	0.001

Table 3 *Hydraulic parameters assigned to the entire region*

Unit	K_h (m/d)	K_v (m/d)	S_y
Faults	0.01	0.001	0.001
Alluvium	1	0.1	0.0625
Granite	0.001	0.0001	0.001

Parameters for faults, alluvium and granite, which are observed throughout the entire region are reported in where K_h is the horizontal conductivity, K_y is the vertical conductivity and S_y is the specific yield (the capacity of the rock to store water). A specific storage (ability of the rock to store water under pressure) of $5x10^{-6}$ m^{-1} (equivalent to the compressibility of water) has been assumed for this exercise. The model was set up in the FEFLOW modelling code using a free and movable surface, meaning the top slice of the model corresponds to the water table. As the model is dewatered, the top slice drops through the existing layers. As it drops, the model maintains the geological distribution as defined in the input data sets.

Groundwater Model Domain and Mesh Geometry

The mesh and domain of the created model are shown in Figure 1.

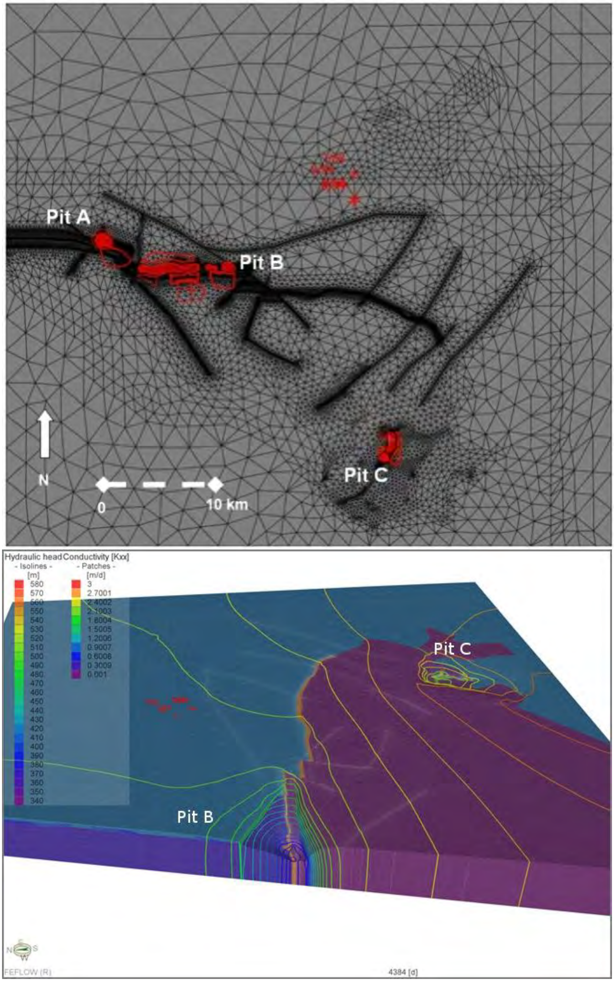

***Figure 1** Model domain and mesh setup and example FEFLOW output for dewatering phase*

The southern boundary was placed to the south of the Pit C area to capture the previously conceptualised geology of this region and to allow sufficient space for dewatering without boundary effects becoming significant. To allow sufficient space for dewatering to occur in the high conductivity Marra Mamba unit, the western boundary was placed about 8 km to the West of Pit A.

Groundwater Quality

Salinity and Zinc were chosen for modelling as they were highlighted as potentially being of high consequence based on guideline values for potable water (NHMRC 2011). Arsenic, Selenium and nitrates are also known to have elevated concentrations within the Pilbara region (DOW 2011) and hence were modelled for comparative purposes. The groundwater concentrations from the limited monitoring program are shown in Table 4.

Table 4 *Groundwater quality values used for Pit Lake Modelling (SGS 2011)*

Pollutant	Pit A		Pit B		Pit C	
	Total	Filtered	Total	Filtered	Total	Filtered
Salinity (EC µS/cm)	2100	N/A	700	N/A	1300	N/A
Arsenic (µg/L)	1*	1*	1*	1*	1*	1*
Selenium (µg/L)	2	2	1*	1*	1*	1*
Zinc (µg/L)	6	3	240	2	190	4
Nitrates (mg/L)	0.021	N/A	0.028	N/A	0.044	N/A
pH	9.2	N/A	8.6	N/A	8.3	N/A

*Below detection limit of 1 µg/L; modelled with concentrations at detection limit.

Pit Lake Water Quality Model

A GoldSim model with add-in Contaminant Transport Module was created to model the water quality of the three pit lakes. The model was set up on a monthly timestep and spanned a period 96 years, which was considered adequate for assessment of the pit water quality at steady state depth after rebound to the water table had occurred and stabilised, and for mine closure impact assessment. This is shown diagrammatically in Figure 2.

Time series rainfall data was created from Pilbara based weather stations in the vicinity of the study including Newman Aerodrome (007176), Sylvania (007079), Meekatharra Airport (007045) and Murramunda (007102) (BoM 2011). Se Figure 3 for details on weather station and site location and climate data for the area. Runoff was generated for each pit via an Australian Water Balance Model (AWBM). It was assumed that the catchment extent was the outer rim of the pit. AWBM parameters were applied which represent typical mining pit runoff characteristics. Groundwater flux inputs were derived via the FEFLOW model using the same climate time series as described above (SKM 2011c). In addition to the groundwater quality data shown in Table 5, a conservative value for salinity was attributed to rainfall and runoff and set to 15 µS/cm and 75 µS/cm respectively. Pit lake dimensions for each of the three lakes were taken from the relevant mine design CAD mining pit plans. The initial conditions for modelling were that the pit voids were empty of water prior to cessation of dewatering and ground water quality entering the pit voids/lakes was allowed to remain constant over time.

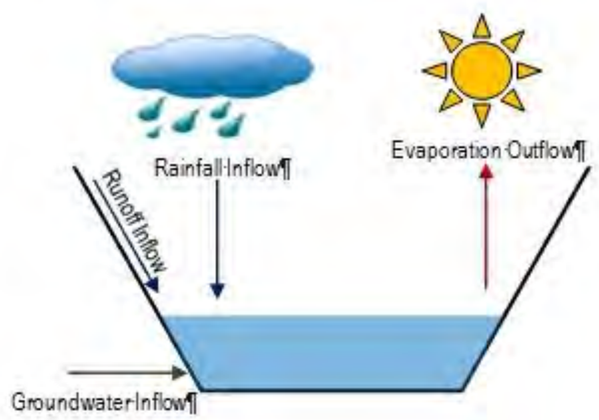

Figure 2 *Pit Lake Water Quality Model*

Results

Charts of predicted pit lake depth and salinity and water quality concentrations over time are shown for each pit lake in Figure 4. All pit lakes experience an increase in water depth to a level approximating that of local groundwater six to twenty years after dewatering ceases. The pits are then at steady state whereby groundwater inflows are approximately equivalent to the evaporation outflows. The salinity concentration increases consistently during the period when the pit water is rebounding to natural water table levels as the saline groundwater flows in and water is evaporated out, resulting in salt accumulating within the pit. The predicted pit salinity concentration after 96 years is approximately of the range 3700 - 9500 mg/L.

Discussion

For the majority of months in the Pilbara region, evaporation is greater than rainfall. Hence the addition of water to the pits via rainfall and runoff was fairly insubstantial, with the exception of two rainfall events around the 85^{th} year of simulation. These are observed in the Pit Lake B and C charts particularly as sudden dilution events. The pit lake B had relatively low predicted groundwater inflows, hence the effects of the high rainfall events are more apparent. The results indicate that the pits accumulate water mainly via groundwater inflows due to the arid nature of the study. After a period of approximately 5 to 20 years, the water depth in the pit lakes reaches steady state and has returned to near normal water table depths. All three pit lakes become brackish with salt concentrations reaching approximately one quarter to one third that of sea water in the case of the Pit 3 lake.

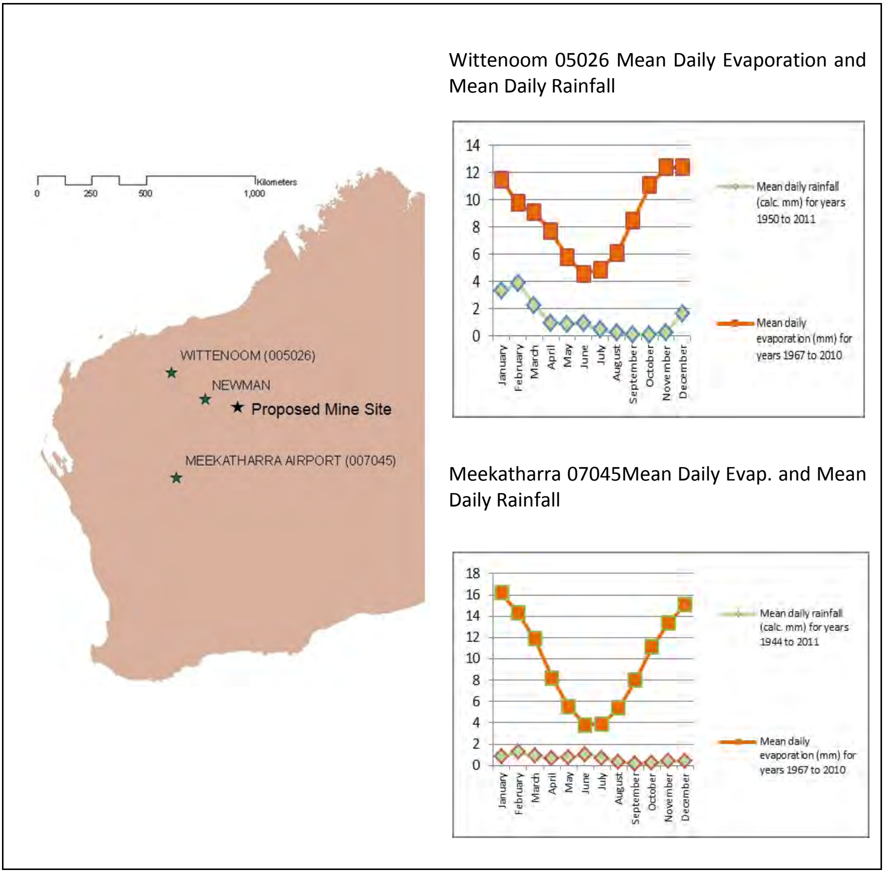

***Figure 3** Weather Station and Site Location and Climate Data for Western Australia*

All three heavy metals modelled are elevated compared to the ANZECC water quality objectives (ANZECC, 2000) for surface waters. A summary of the contaminant concentrations after 96 years is presented in Table 5 and 6.

Table 6 shows that elevated salinity and zinc levels make the pit water unsuitable for discharge to surface waters without further investigation, treatment and management. All other contaminants modelled are either not elevated or at guideline levels. These pit lakes will likely continue to increase in their pollutant concentrations until evaporation rates decrease due to elevating levels of salt, pH prevents further concentration of dissolved metals or similar stability point will be reached.

Pit lake C has higher salinity levels compared to the other pit lakes due to the localised increased salinity of groundwater inflows. Other differences between the pit lake concentrations are due to differing pit geometries at steady state.

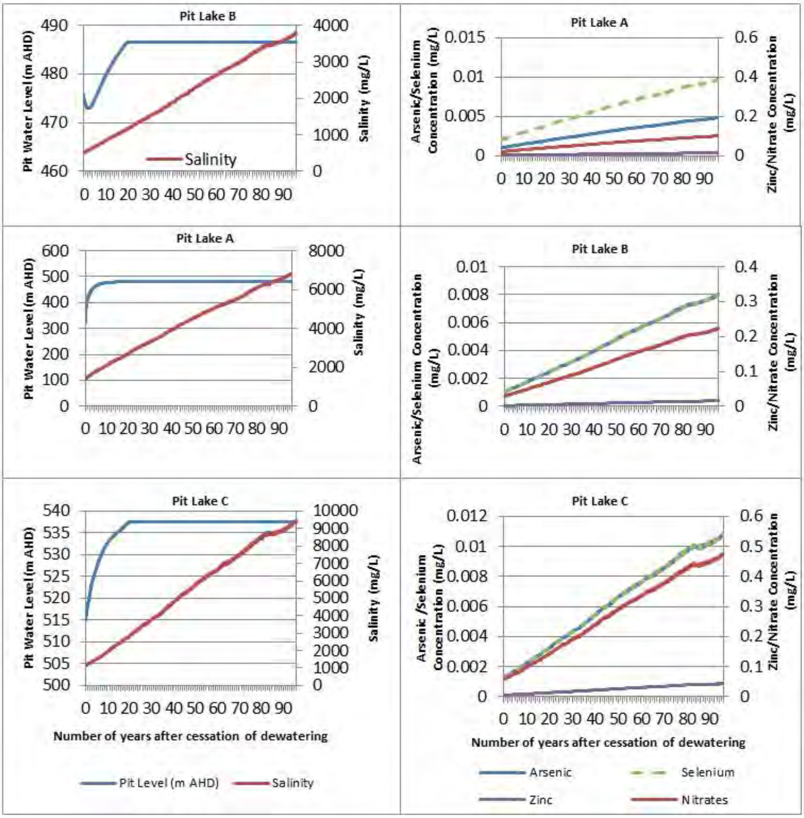

***Figure 4** Pit lake salinity, depth and water quality (As, Se, Zn, NO_3)*

***Table 5** Comparison with Livestock water quality standards (ANZECC 2000)*

Pit	Salinity [1]	Arsenic[2]	Selenium[3]	Zinc[4]	Nitrates[5]
Pit Lake A	*x* 1.4	Not elevated	Not elevated	Not elevated	Not elevated
Pit Lake B	*x* 1.0	Not elevated	Not elevated	Not elevated	Not elevated
Pit Lake C	*x* 2	Not elevated	Not elevated	Not elevated	Not elevated

[1] ANZECC Guideline Livestock Objective 2000 – 5,000 mg/L (ANZECC 2000)
[2]ANZECC Guideline Livestock Objective: Arsenic 0.5 - 5 mg/L, (ANZECC 2000)
[3]ANZECC Guideline Livestock Objective: Selenium 0.02 mg/L, (ANZECC 2000)
[4]ANZECC Guideline Livestock Objective: Zinc 20 mg/L, (ANZECC 2000)
[5] ANZECC Guideline Livestock Objective: Nitrate 400 mg/L (ANZECC 2000)

Table 6 *Comparison with surface water quality standards (ANZECC 2000)*

Pit	Salinity [1]	Arsenic[2]	Selenium[3]	Zinc[4]	Nitrates[5]
Pit Lake A	*x* 16	Not elevated	At guideline	*x* 1.25	Not elevated
Pit Lake B	*x* 9	Not elevated	Not elevated	*x* 2.5	Not elevated
Pit Lake C	*x* 21	At guideline	At guideline	*x* 5	Not elevated

[1]Surface waters salinity default trigger value is 20-250 uS/cm (Approx 35 – 415 mg/L) (ANZECC 2000)

[2]ANZECC 95% Trigger value for: Arsenic < 0.013 mg/L, (ANZECC, 2000)

[3]ANZECC 95% Trigger value for: Selenium < 0.011 mg/L, (ANZECC, 2000)

[4]ANZECC 95% Trigger value for: Zinc < 0.008 mg/L, (ANZECC, 2000)

[5] ANZECC 95% Trigger value for: NOx < 0.7 mg/L (ANZECC, 2000)

Conclusion

The results of the pit lake water quality modelling demonstrate that after mining has been completed at the proposed mine project site and ground water rebound occurs, the pits will tend to become brackish over a period of around 100 years. Due to the high evaporation rates experienced in the arid Pilbara, net flow will be into the pits which will limit the effect of increased salinity on groundwater quality. Stock and wildlife, such as birds, that manage to gain access to the pit lakes, may be deterred from drinking the water due to its elevated salinity. Levels of pollutants of concern for stock are not elevated for any of the parameters included in the pit water quality model (ANZECC 2000). The final pit lake water quality will not be suitable for discharge to surface waters without additional treatment and management, due to elevated salinity and zinc levels.

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