Probabilistic Analysis of Mine Void Salinity and Lake Level Associated with Climate Change

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Abstract A probabilistic method based on Monte Carlo simulation with input from a numerical groundwater model was developed by Rio Tinto Iron Ore (RTIO) in assessing closure of one of many open pit mines operated by RTIO. The mine is located in an area subjected to annual cyclonic downpour in the Pilbara region of Western Australia. The benefit of this methodology is that it is simple, transparent and provides regulatory agencies with an appreciation of the uncertainties associated in predicting recharge events. The result is a probability density graph which shows the probability of salinities and lake levels in the proposed pit-lake.

Key Words modelling, Monte Carlo, closure, salinity, pit-lake, climate change

Introduction

RTIO operates under an ISO14001 framework using its Iron Environmental Management System (IEMS). One of the key components of IEMS is to ensure that environmental planning processes are fully integrated with the overall business planning process to ensure that RTIO objectives and targets are both realistic and resourced and also conform to the regulators' requirements. To achieve this obligation, it is necessary to develop a methodology for predicting salinity levels in pit-lake that is transparent, robust, meet regulatory requirements and that can be easily applied to the other mine sites.

Predicting salinity levels in lake-forming mined out voids after mine closure has been a challenge since consideration of mine closure has become part of open pit mine planning. What is certain is that the pre-mining environment will be changed. Changes can be minimised by understanding the risks imposed by the closure plans. Environmental impact on the areas down gradient of the pit-lake can be minimised by applying an understanding of the hydrologic and hydrogeologic interactions with the final landform. The final landform design can potentially be re-engineered to reduce or eliminate liability and ongoing maintenance costs after closure.

Understanding hydrologic and hydrogeologic cycles alone is complex and the impact of climate change on these cycles is difficult to predict using complex ocean-coupled climate models. A risk based approach using Monte Carlo simulation simplifies the mechanisms for assessing the uncertainties associated with the numerous potential hydrologic interactions used to estimate pit-lake salinity. Monte Carlo simulation randomly samples each input variable within its sensitivity range to produce a probability distribution based on hundreds or thousands of iterations of different inputs. This approach overcomes the limitation posed by traditional sensitivity analysis, varying one variable at a time, which becomes cumbersome if more than two values are allowed to change concurrently. The methodology also enables simple future or past climate scenarios to be used, such as increasing rainfall or evaporation rates, for comparison with existing climate outcomes to qualify climate change risk.

The site selected is a typical site in the Pilbara region which is characterised by fluctuating annual rainfall ranging from 100 mm to 800 mm, averaging around 380 mm, associated with tropical lows and thunderstorm activity that develops along the monsoon trough and establishes over the top half of the continent during summer. Annual pan evaporation is around 3,000 mm. Recharge to the groundwater system is thought to be dominated by flow in ephemeral creeks such that the uncertainties associated with rainfall recharge makes traditional pit-lake numerical groundwater model predictions, which employed a single "typical" rainfall sequence inadequate for assessing the closure plans. The numerical model shows that the lake is a throughflow lake. As a result further analysis of the lake salinity is required to assess its impact on the area down-gradient of the lake.

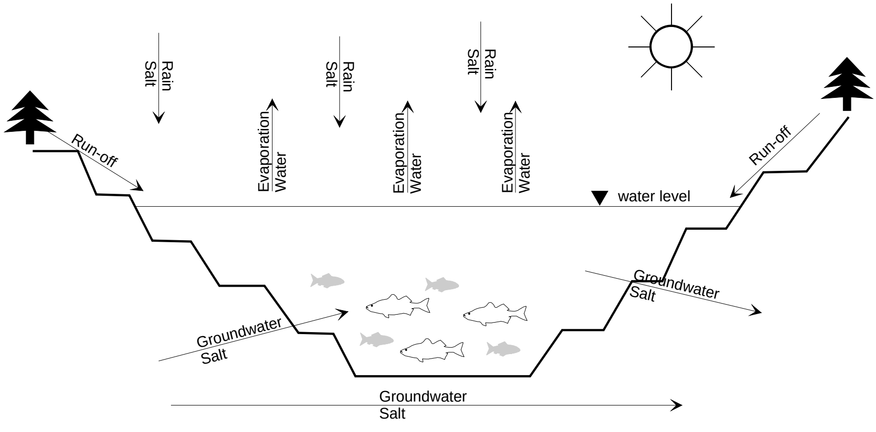

Figure 1 *Pit-lake contributing flows*

This paper presents an example of a risk-based Monte Carlo method applied by the Technical and Closure teams for predicting the salinity of a proposed pit-lake in the Pilbara region of Western Australia.

Risk Based Monte Carlo Method

The risk based Monte Carlo method required input values and associated input sensitivities to be defined for each water balance value. Figure 1 illustrates the water balance potential flow paths for the pit-lake salinity model. The sensitivities may be expressed as a percentage, range or distribution depending on the level of confidence associated with each input.

A numerical groundwater model was run to quantify the relationship between the rates of inflows and outflows and lake levels as shown on Figure 2 as random inputs into the Monte Carlo simulations. Additional random inputs to the Monte Carlo simulations include rainfall rates, evaporation rates and runoff coefficients to create a stochastic model.

The rate of salinisation of the pit-lake is dependent upon the surface area exposed to evaporation. The larger the lake area, the more evaporation will occur. The designed geometry of the final landform was used to calculate the lake level and lake area from the volume of water in the pit-lake. Figure 3 shows the changes in lake volume and lake area as the lake level rises.

Rainwater entering the lake was divided into incidental rain and catchment runoff. Incidental rain assumes that 100% rainfall enters the evolving lake area whereas catchment runoffs were calculated by multiplying the runoff coefficient with the catchment area beyond the lake. Other parameters included in the model were; initial lake level, initial lake area, initial lake volume, initial

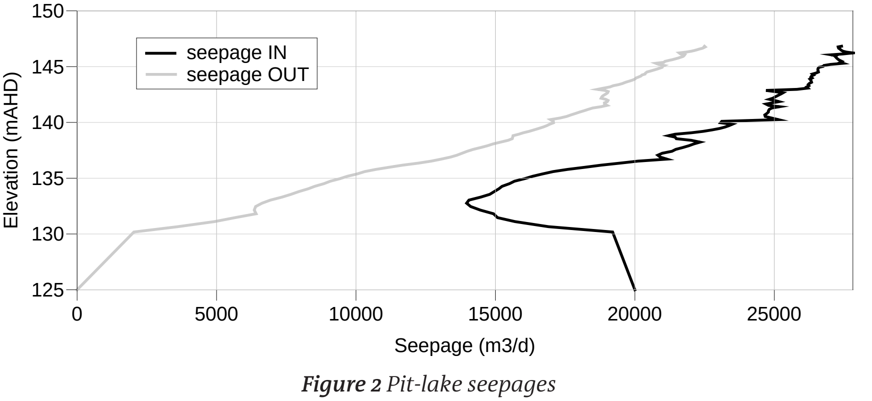

Figure 2 *Pit-lake seepages*

***Table 1** Catchment Data*

Surface water catchment	9,410,000	m^2
Initial water level	125.0	mAHD
Initial lake area	424	m^2
Initial lake volume	1,148	m^3
Lake overflow level	150	mAHD
Full volume	33,440,200	m^3
Initial salinity in lake	0.7	kg/m^3
Salinity of groundwater	0.7	kg/m^3
Salinity of rainwater	0.005	kg/m^3

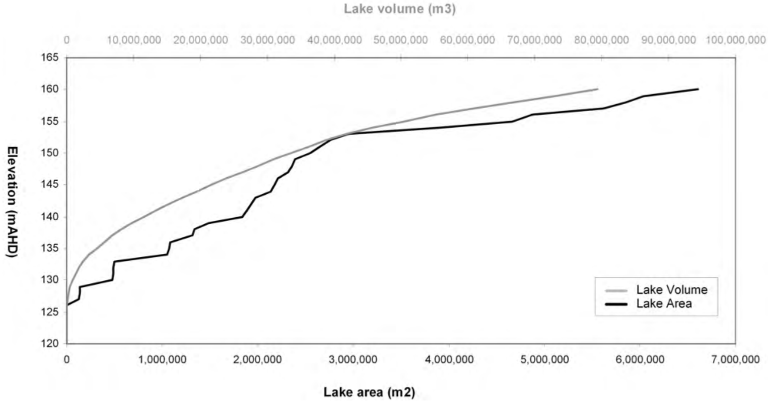

***Figure 3** Pit-lake volume and area versus elevation*

lake salinity, rainwater salinity, groundwater salinity and lake overflow level. Table 1 lists the fixed and initial values.

The model accounts for salt concentration from the surrounding groundwater and the pit-lake. Seepage into the pit-lake from the pit wall and floor carries with it a particular salt concentration from the groundwater and seepage out of the lake carries with it salt concentration from the evolving lake. The model assumes instantaneous and complete mixing and no salinity stratification.

Stochastic models of daily conditions were created from random values for rainfall, evaporation, event based runoff coefficients, groundwater inflow and outflow rates according to the input sensitivity distribution. Each model run was set up to calculate daily salinity and lake level for 7,300 days (20 years) with 1,500 simulations. The large volume of data generated was reduced to an assessment of salinity and lake level for the end of the dry (31 October) and the wet (30 April) season after 1, 3, 5, 10, 15 and 20 years. The distribution of these values was subsequently used to create the probability density and cumulative probability graphs used to predict salinity levels in the pit-lake after mine closure.

Results and Discussions

Figure 4 shows the outcome of one 20 year simulation. The graphs show lake level will rise to about 138 mAHD after 10 years and thereafter the depth and lake area remains relatively stable. Salinity will rise very quickly in the first few years post-mining but will level off at just below 1,100mg/L. The graphs also captures localised salinity decreases with instantaneous lake level rises due to recharge events.

An analysis of the probability density graphs (Figure 5) show that salinity range from 927mg/L to 1,090mg/L with 95% probability that it will be less than 1,050mg/L in the dry season at the end of year 20. Lake level will be between 136.9mAHD to 139.2mAHD with 86% probability that it will be less than 138.5mAHD in the wet season at the end of year 20.

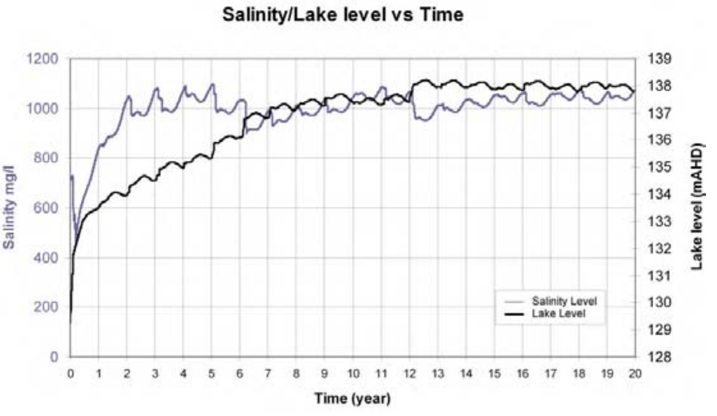

Figure 4 *Pit-lake salinity and level versus time*

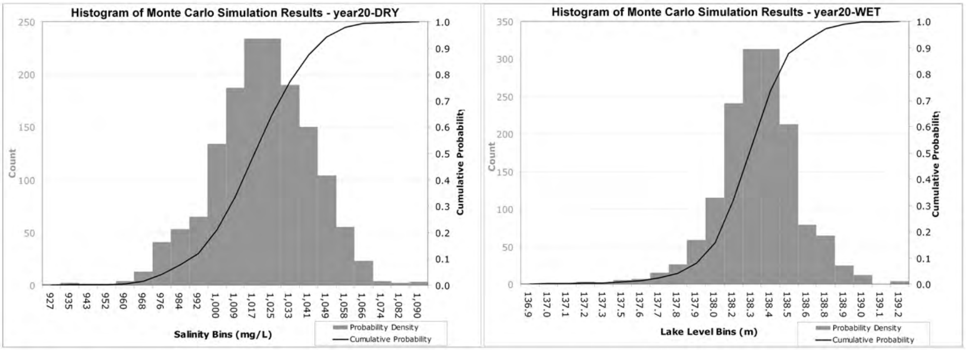

Figure 5 *Probability density and cumulative probability graphs for salinity and lake level after 20 years*

Conclusions

Prediction of salinity and lake levels in pit-lake relies on assumptions and estimates on the input variables in the model. When there is significant uncertainty or natural climate variability associated with the inputs, traditional pit-lake numerical groundwater model approaches for assessing closure plans can be inadequate. The risk based Monte Carlo method enable a range of potential hydrologic and hydrogeologic conditions to be quickly modelled consistent with the level of confidence associated with each input. The resulting probability density and cumulative probability graphs represent all likely hydrologic and hydrogeologic condition, are simple to interpret and provide a transparent, risk based approach to closure as encouraged by Australian government regulators.

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