Combined numerical and analytical modelling as a means to assess closure options for open-pit mines, Pilbara region

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Abstract

The Yandicoogina iron ore mine is operated in a complex hydrological environment. A combination of numerical and analytical modelling has been used to determine the optimal use of limited waste material to backfill pits, and minimise impacts on the local groundwater and surface water environments. The modelling suggests that selective distribution of the waste material can result in a wide spectrum of water salinities, ranging from fresh to saline. This is particularly true for the two pits located down gradient which receive through-flow from up gradient pits. In addition, this study shows that the salinity of the pits is primarily controlled by surface water inflow from surrounding catchments.

Keywords: Closure, modelling, salinity

Introduction

As a number of large-scale mine sites in Western Australia approach the end of their operating lives, closure planning for existing mines, and for future mining developments has become an ever greater priority for mining companies and for regulators. Numerous factors, including social, economic and environmental concerns are of interest when developing robust closure plans; not least of which is ensuring that the hydrologic environment surrounding mining operations is returned to a state which best replicates pre-disturbance conditions.

Rio Tinto Iron Ore (RTIO) operates the large-scale (52 Mt/a) Yandicoogina iron ore mine, in the Pilbara region of northwest Australia (Fig. 1). Mining of the two current pits will be exhausted in the near future, and expansion of the mine to include additional pits is currently being investigated. A total of six discrete pits, along a 40 km section of the deposit, are currently envisaged by the end of mine life in 2038, each separated by surface creek-lines (Fig. 1).

Previous closure plans for similar deposits in the region have put forward broad-scale, conceptual plans (URS 2010); that have focussed on the localised impacts of mine expansions, rather than whole system impacts (Hamersley Iron 1998); or where comprehensive modelling has been undertaken, and regional impacts considered, have proposed minor changes to the groundwater environment (BHP Billiton 2004, Hall et al 2006).

The Channel Iron Deposit (CID) orebody at RTIO Yandicoogina lies below water table (BWT), and active dewatering is undertaken to facilitate mining. The low ratio of overburden material to ore (1:1), means that insufficient material will be available to backfill all of the pits to above the pre-mining water table. Consequently, without resorting to quarrying additional material and further altering the surrounding landscape, upon the conclusion of mining activities at least one and possibly multiple open BWT voids will remain. In conjunction with mine planning engineers, a series of backfilling scenarios, utilising calculated available waste rock, have been designed in order to determine the effects on open pit water quality of various final landform configurations (RPS Aquaterra 2012).

While the mine voids directly intersect the groundwater environment, they also exist in close proximity to two large, ephemeral, surface water flow systems – Marillana Creek and Weeli Wolli Creek (Fig. 1). Typical of surface water systems in the region, the creeks only flow after large and sustained rainfall events. The creeks are also recognised as the primary source of recharge to the groundwater environment. Increases in groundwater levels of up to 10m have been recorded in response to surface flooding (Kirkpatrick and Dogramaci 2010a). Shallow, alluvial gravel aquifers along the creek-beds support riparian vegetation, including prominent Smooth-barked Coolibah (*Eucalyptus victrix)*.

Given the high degree of interaction between the surface water and groundwater environments at Yandicoogina (Dogramaci et al 2012), modelling of the system poses many challenges. Numerous flood models have been developed for the Yandicoogina site, to determine risks to open pit mining and suitable mitigation strategies; while at least six iterations of groundwater modelling have been undertaken to determine dewatering requirements and closure options. To date, no integrated surface water-groundwater models have been developed for the system, and no existing models had been capable of predicting water quality in either the groundwater or surface water environments. In order to better understand the potential impacts on the hydrological environment of BWT mine voids, and to determine the most acceptable closure strategy – maintaining groundwater through-flow and quality in the regional aquifers – a 3-dimensional numerical groundwater flow model and an analytical water and solute mass balance model have been developed in parallel, to produce statistical predictions of the likely outcomes.

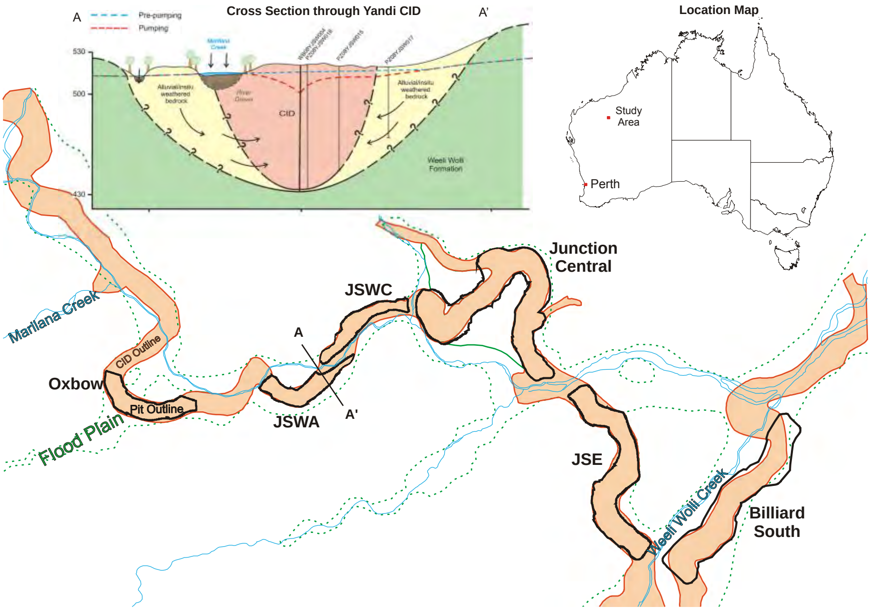

Figure 1 *Location map showing CID, floodplain, pit outlines and creeks, including a cross-section of the conceptual model*

Physiography

The climate of the Pilbara region is semi-arid, featuring a cool, dry season from April to October and a hot, wet season from November to March. During the wet season, rainfall is predominantly associated with tropical depressions and cyclonic activity originating from the tropics. Sparse rainfall in the dry season typically originates in the Indian Ocean (Dogramaci et al. 2012). Average annual rainfall at Yandicoogina is 400 mm, and approximately 85% of this total falls in the period December to March (Kirkpatrick and Dogramaci 2010a).

Creek systems in the region are typically ephemeral. Creek-flow typically occurs following major and sustained rainfall events. The highest reported flow at the Western Australian Department of Water's Tarina gauging station, 10km upstream of Yandicoogina on Weeli Wolli creek, is 2100 m^3/s in December 1999, following Tropical Cyclone John (this reading is outside of the station's rating and an estimate only). This event is believed to correspond to a 1 in 100 year Annual Recurrence Interval flood event (Cheng 2010). The Marillana and Weeli Wolli creek systems traverse flood plains of alluvial material, which infills palaeo-valleys cut into the Palaeo-Proterozoic bedrock of the Hamersley Range (Fig. 1). Alluvial aquifers immediately underlying the creeks remain unsaturated throughout the dry season, until recharged during wet season flooding (Kirkpatrick and Dogramaci 2010b).

The Yandicoogina CID occupies a significant proportion of the Marillana and Weeli Wolli palaeo-valleys. In its upstream sections, the CID forms a series of low outcropping mesas; while downstream, the deposit is overlain by up to 40 m of alluvial material. The CID is up to 90 m thick and forms the major aquifer in the area. RTIO and BHP Billiton Iron Ore have been mining the deposit, in a series of open pits, since 1998 and 1991 respectively.

In order to set robust closure objectives for the mining operations – which will allow replication of the initial hydrological system; it is critical that that system and its constituent components be thoroughly understood.

Methods

Working in conjunction with mine planning engineers, four closure scenarios were selected from an initial eight identified options, to be evaluated from a hydrological perspective:

- Mining of six individual pits as open pit voids (No Backfill Option).
- Mining of individual pits, achieving in-pit backfill to 2 metres above pre-mining ground water levels (Complete Backfill Option).
- The combination of leaving the three upstream pits as open voids and the backfilling of the three downstream pits to specified levels (Selective Backfill Option).
- Mining of a complete channel as an open void, with no backfill (Continuous Channel Option).

During the initial analysis of these options, it was determined that the additional material required to achieve the Complete Backfill Option was not locally available, and this option was not progressed further. The Continuous Channel Option envisages combining the six individual pits into one continuous channel, by mining underneath present-day creek-lines, and diverting creek flow into the resultant void. This option would, however, result in the loss of extensive stretches of current riparian habitat.

To better understand how the hydrological systems of the Yandicoogina area will behave post mine-closure, a series of modelling exercises were undertaken. During the initial stages of the exercise it was found that no off-the-shelf software was available to investigate the hydraulic and hydrochemical interactions between surface water and groundwater systems, in conjunction with BWT mining voids. After researching various modelling options, it was determined that two parallel models would be necessary to achieve the aims of the investigation.

Accordingly, an existing numerical groundwater model for the Yandicoogina CID aquifer (Inverarity 2011) was adapted, to study the interactions between pit lakes, the aquifer and the surface creek systems. Independently, an analytical model was constructed, informed by the output of the numerical model, while also including the functionality to model concentrations of dissolved solids (chiefly dissolved salt) in the voids. During the construction of the analytical model, calibration scenarios were concurrently modelled with the numerical model, using real-world data to calibrate the water balance components of the pit voids of one model to the other. This process continued in an iterative fashion, until consistent results were obtained from each, via independent methods.

The calibrated analytical model was used to predict salinity concentrations in pit voids, via a simple mass balance, for the closure scenarios identified at the start of the exercise. Monte Carlo simulations were run for each scenario, to determine variability in the predicted results.

Results and Discussion

As a result of high evaporative losses, modelling of the No Backfill Option indicates that groundwater through-flow between pits will be reduced compared to pre-mining conditions and the water quality in the two downstream-most pits is likely to become saline (>20000 mg/L). By a process of calibration, the Selective Backfill Option aimed to use the limited available backfill material to minimise the impact of evaporative losses from the pits. The final landform chosen for this option resulted in the maintenance of groundwater through-flow. The highest predicted salinity in any one pit void in this scenario is 4800 mg/L; while three pits achieve salinity levels below 1000 mg/L (Fig. 2). Creek-flow diverted into the void in the Continuous Channel Option is sufficiently large compared to the evaporative losses from the pit lake, that salinity levels in this scenario are very low – the results of the Monte Carlo simulations indicate a 95% confidence interval of 140 mg/L ± 60 mg/L (Fig.3). The open void will regularly overtop, following creek-flow events. Groundwater outflow is also predicted to be very fresh.

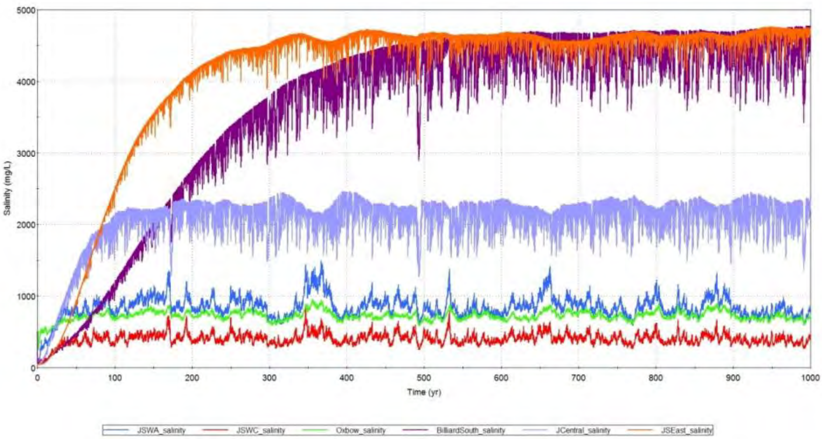

Figure 2 *Salinity levels over time in 6 pits – Selective Backfill Option*

Comparison of the outputs from the numerical and analytical models suggests that the physical processes of greatest importance – recharge, evaporation and groundwater through-flow – are adequately simulated in both models. Additional scenarios involving diversion of creek-flow into individual pits – whether with no backfill or selective backfill – resulted in elevated water levels in pit voids compared to the surrounding aquifer groundwater levels, and the subsequent reversal of the groundwater flow direction along the channel, and deterioration of upstream water quality.

While it is believed that the fundamental parameters and conditions of the models accurately reflect real-world conditions; additional factors, such as backfill material permeability are currently unknown, and could affect the outcomes of the modelled scenarios. The modelled scenarios also ignore the presence of Waste Fines Cells in the excavated palaeochannel. Existing cells have been constructed to allow groundwater through-flow to pass around and below them, but the effects of the resulting head difference between cells and surrounding aquifer on flow has not been examined in detail, in relation to these scenarios. It has been assumed that the RTIO closure scenarios occur after the cessation of discharge to Marillana Creek by BHPBIO, and the dissipation of groundwater mounding in the vicinity of the discharge location.

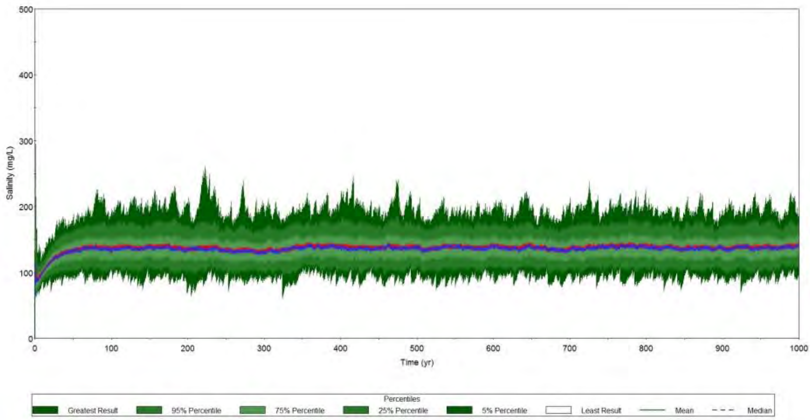

***Figure 3** Salinity levels over time in Continuous Channel*

Our scenarios have also used recorded creek-flow data from local stream-gauging stations as input for future predictions. While the accuracy of this data is believed to be acceptable for low-intensity events, it is uncertain whether the stations have sufficiently captured high-intensity events. This uncertainty however, is likely to result in better outcomes for the Continuous Channel Option, while its effect on the No Backfill and Selective Backfill Options remains undetermined. To better understand the implications of this uncertainty, a necessary precursor is an increased understanding of recharge processes across the floodplains. Field studies are currently being undertaken into this topic, and it will be an integral requirement of future modelling work to integrate the resultant findings.

Conclusions

A combined use of numerical and analytical modelling has determined that selectively backfilling the pit voids resulting from mining of the Yandicoogina CID will result in acceptable outcomes – the maintenance of groundwater through-flow and of groundwater quality – without adversely affecting local riparian vegetation. The development of the Complete Channel Option is predicted to result in fresher water within the resultant pit lake, but will result in the loss of riparian habitat.

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