Numerical groundwater flow modelling at the historic Rum Jungle mine site, Northern Territory, Australia

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ABSTRACT: Rum Jungle was one of Australia’s first major uranium mines and produced 3,500 tonnes of uranium oxide and 20,000 tonnes of copper in the 1950s and 1960s. After mine closure, acid rock drainage and the mobilization of metals in mine waste led to significant impacts on groundwater and the nearby East Branch of the Finniss River. Rehabilitation attempts were made in the 1970s and 1980s but water quality conditions have deteriorated over the last 30 years. A revised rehabilitation plan for the site is being developed by the NT Department of Resources. A transient groundwater flow model was developed for the site to assist in this rehabilitation planning.

The objective of numerical modeling is to simulate seasonal variations in groundwater flow under current conditions and subsequently evaluate alternative rehabilitation options. This paper describes the initial modeling phase, including the conceptual flow model for the site, the calibration of the numerical flow model to monitoring data for the 2010/2011 wet season, and the verification of the model using results from recent pit de-watering.

1 INTRODUCTION

Acid rock drainage (ARD) and heavy metal mobilization at the former Rum Jungle Mine Site have led to significant environmental impacts on local groundwater and the East Branch of the Finniss River (Kraatz, 2004).

Rehabilitation in the 1980s involved treatment of highly-impacted pit water, covering the waste rock dumps (WRDs) to reduce infiltration and oxygen transport, and backfilling one of the open pits with tailings and highly-contaminated soils (Allen & Verhoeven, 1986). Contaminant loads from the mine site were substantially reduced by rehabilitation measures but groundwater and the East Branch of the Finniss River remain impacted by ARD (Ferguson et al., 2012).

In 2009, the Mining Performance Division of the Department of Resources (DoR) was tasked with developing a revised rehabilitation strategy for the former Rum Jungle Mine Site. Robertson GeoConsultants Inc. (“RGC”) developed a transient groundwater flow model for the Rum Jungle mine site to assist with this rehabilitation planning. The overall objective of this modeling work was to understand current groundwater conditions and to evaluate alternative rehabilitation options. The objectives of the initial phase of modeling work were to:

- Develop a conceptual flow model that describes the principal hydrogeologic features of the mine site and all available groundwater monitoring data/hydraulic testing data;
• Calibrate a transient numerical flow model to groundwater level data collected from August 2010 to November 2011 and verify the numerical flow model; and
• Estimate contaminant loads from the above-ground mine waste units to groundwater and the East Branch of the Finniss River using the calibrated flow model.
This paper summarizes the results of this initial phase of modeling and preliminary contaminant load estimates.

2 BACKGROUND

2.1 Climate & Hydrology
The former Rum Jungle Mine Site is located 105 km by road south of Darwin in Australia’s Northern Territory (NT). The region is characterized by a tropical savannah-like climate and typically receives about 1500 mm of annual rainfall. 90% or more of this rainfall occurs during a distinct wet season that lasts from November to April.

The East Branch of the Finniss River flows through the mine site and was diverted during mining operations to allow access to the Main and Intermediate ore bodies. Flows from the upper East Branch of the Finniss River and Fitch Creek currently flow directly into the East Finniss Diversion Channel (EFDC) and through the Open Pits before flow resumes northward via the natural course of the East Branch of the Finniss River (Figure 1).

Figure 1. Open pits, waste rock dumps (WRDs), and other pertinent features of the Rum Jungle Mine Site

2.2 Geology
The Rum Jungle Mine Site is situated in a triangular area of the Rum Jungle mineral field known as The Embayment. The main lithologic units in The Embayment are the Rum Jungle Complex and meta-sedimentary and subordinate meta-volcanic rocks of the Mount Partridge Group. The Rum Jungle Complex consists mainly of granites and occurs primarily along the southeastern side of the Giant’s Reef Fault, whereas the Mount Partridge Group occurs north of the fault and consists of the Crater Formation, the Geolsec Formation, the Coomalie Dolostone, and the Whites Formation.

2.3 Site Layout
The mine site features three waste rock dumps (WRDs), the flooded Main and Intermediate Open Pits, Dyson’s (backfilled) Open Pit (or ‘Landform’) and the partially-mined Browns Oxide Open Pit (see Figure 1). Other notable features include the East Finniss Diversion Channel
(EFDC), the former Tailings Dam area along Old Tailings Creek, and the former Copper Extraction Pad between the flooded Open Pits (see Ferguson et al., 2012 for additional details).

3 CONCEPTUAL FLOW MODEL

3.1 Model Domain

Figure 2 shows the boundaries of the model domain for the Rum Jungle Mine Site. The boundaries of the model domain (shown in red) were defined by local topographic highs and low-lying drainage lines (creeks) such that cross-boundary flows into the modeled domain can be assumed to be negligible.

Vertically, the model domain extends from ground surface to a maximum depth of about 150 m (or about 50 m deeper than the maximum depth reached during mining). All lithological contacts and/or faults within the model domain were assumed to be vertical in orientation and extend through the entire bedrock aquifer.

3.2 Aquifer Units & Properties

The aquifer system at the Rum Jungle Mine Site is thought to be comprised primarily of relatively shallow (typically < 100 m deep), unconfined bedrock aquifers. No information is currently available on the potential presence of deeper, confined aquifers of regional extent yet such aquifers (if present) are not considered likely to influence the shallow groundwater flow that controls contaminant transport.

Bedrock of the Rum Jungle Complex and the Mount Partridge Group comprise the main aquifer of the mine site (see Figure 3). The hydraulic properties of the bedrock aquifer differ according to lithology and the degree of weathering and/or fracturing (RGC, 2012). The degree of fracturing in the bedrock aquifer is likely depth-dependent to some extent so deeper bedrock of the Rum Jungle Complex and the Mount Partridge Group is expected to be less fractured (and hence characterized by lower secondary permeability).
3.3 Groundwater Flow Regime

Cross-boundary flows to the model domain are considered negligible so local topographic highs (i.e. ridge lines) represent no-flow boundaries and the only source of water to the model domain is recharge by rainfall infiltration. Groundwater recharge occurs mainly during the wet season and higher elevation areas tend to be preferentially recharged due to the greater available storage above the water table (RGC, 2012).

Unimpacted groundwater from upland areas tends to flow towards the lower elevation areas that correspond to the current course of the East Branch of the Finniss River and its pre-mining course in the central mine reach. Upward vertical gradients in these low-lying areas indicate that groundwater discharges in these areas and hence contributes to surface water flows.

Groundwater flow fields within the model domain have been altered by the presence of the above-ground mine waste units. Of particular interest is the ‘mounding’ of groundwater levels that occurs beneath and near the Main WRD (and Dyson’s WRD). This mounding suggests that the heaps represent areas of preferential recharge. Groundwater flow fields are also affected by the flooded Open Pits, which can act as sources or sinks for groundwater depending on the season (RGC, 2012).

3.4 Contaminants in Groundwater

Conceptual representations of the major contaminant plumes at the Rum Jungle Mine Site are delineated in Figure 4. High concentrations of SO\textsubscript{4} and metals characterize groundwater near the WRDs/backfilled Open Pit and in the vicinity of the former Copper Extraction Pad (Ferguson et al., 2012).

Metals concentrations are particularly high near the Main WRD due to the low buffering capacity of the underlying Rum Jungle Complex. Groundwater affected by seepage from the Main WRD generally moves eastward towards Fitch Creek or westward towards the Intermediate WRD. The extents of contaminant plumes originating from the Intermediate WRD are more difficult to ascertain but the majority of contaminants are thought to report to the EFDC via toe seepage/shallow groundwater discharge from the northern edge of the heap.
In Dyson’s Area, highly-impacted groundwater resides in the shallow bedrock aquifer south of Dyson’s WRD and Dyson’s (backfilled) Open Pit. This groundwater discharges primarily to the upper East Branch of the Finniss River as impacted groundwater does not appear to be transported westward beyond Dyson’s Area due to local topography and/or the low permeability of bedrock (Ferguson et al., 2012).

Moderately-elevated SO₄ concentrations characterize groundwater north of the central mine reach but metal concentrations in this area are low. This suggests that metals are naturally attenuated in groundwater due to the high buffering capacity of the Coomalie Dolostone and the low solubility of most metals under near-neutral pH conditions. Major ions, such as SO₄ and Mg, are unaffected by this buffering reaction (or retardation) and therefore transported conservatively in groundwater (hence the larger extents of TDS plumes compared to metal plumes).

### 3.5 Recharge

Recharge to undisturbed areas of the model domain occurs primarily during the wet season when the majority of rainfall occurs. Previous studies have estimated that only 10% of incident rainfall to natural ground surfaces in humid areas of northern Australia infiltrates to groundwater (as the remainder of incident rainfall is lost via evapotranspiration and surface runoff).

Seasonal variations in groundwater levels suggest that rainfall infiltration to the Coomalie Dolostone is higher than to the other units of the Mount Partridge Group and the Rum Jungle Complex. Recharge to the Coomalie Dolostone is therefore likely higher than the generalized values for undisturbed ground (say 10 to 15% of incident rainfall), whereas annual infiltration rates for the Whites Formation and the Rum Jungle Complex are likely lower by comparison (say 5 to 10% and 2%, respectively).

Net infiltration rates for the mine waste units are thought to be higher than recharge to groundwater via natural ground surfaces. This was particularly likely when the WRDs were uncovered in the 1970s and early 1980s. Daniel et al. (1982) estimated that 50 to 60% of annual rainfall percolated through the Main WRD before rehabilitation. Based on previous investigations and preliminary contaminant load estimates, current rates of net infiltration were estimated to be about 25% of incident precipitation for the Main and Intermediate Heaps and 50% for the Dyson’s WRD.
3.6 Groundwater-surface water interactions

The Main and Intermediate Open Pits cut deeply into the bedrock aquifer in the central mining reach and can therefore interact significantly with groundwater in adjacent zones of the bedrock aquifer. Pit water and groundwater level data suggest that the flooded Open Pits tend to receive flows of groundwater during the wet season but act primarily as sources of water to the groundwater system during the dry season (RGC, 2012).

Higher flows from the Intermediate Open Pit than the Main Open Pit are expected due its strong hydraulic connection to the Coomalie Dolostone and the partial backfilling of the Main Open Pit with low-permeability tailings (which has likely sealed the deeper pit walls from the surrounding bedrock aquifer).

The Browns Oxide Open Pit is expected to interact significantly with the groundwater system at the Rum Jungle Mine Site because it was actively de-watered in 2010/2011. Specifically, the Browns Oxide Open Pit is expected to be a major sink for groundwater and therefore likely influences the groundwater flow field west of the Intermediate Open Pit near the East Branch of the Finniss River. Other major discharge zones for groundwater include Fitch Creek and the upper East Branch of the Finniss River, sections of the EFDC, and the East Branch of the Finniss River downstream of the mine site.

3.7 Conceptual Groundwater Budget

Using percentage infiltration rates and the areas of undisturbed ground and mine waste units, annual recharge to the groundwater system in the model domain was estimated to be 56 to 129 L/s. The lower estimate reflects 2% recharge for the Rum Jungle Complex, 10% for the Coomalie Dolostone, and 25% for the mine waste units, whereas the upper bound estimate corresponds to twice the recharge assumed for the lower bound.

Flows to and from the flooded Open Pits and groundwater discharge to the East Branch of the Finniss River and its tributaries were estimated via Darcy flow calculations and weighted K values (results not provided in this paper). This conceptual groundwater budget provides reasonable upper and lower bounds for numerical modeling and emphasizes the significance of groundwater discharge to the East Branch of the Finniss River and to the Browns Oxide Open Pit (RGC, 2012).

4 NUMERICAL MODELING

4.1 Numerical Methods

4.1.1 Model Setup & Discretization

Groundwater flow was simulated with MODFLOW-2000 using the Layer Property Flow (LPF) package and the Preconditioned Conjugate Gradient 2 (PCG2) solver to solve the flow matrix (Harbaugh et al., 2000; Hill, 1990). MODFLOW was run transiently (monthly time steps) to simulate seasonal variations in groundwater levels from August 2010 to November 2011.

All drainage features were modeled using the drain (DRN) package. Groundwater extraction due to pumping of private production wells was assumed to be negligible at the scale of the model domain and the process of evapotranspiration was accounted for by the use of net infiltration rates.

4.1.2 Spatial Discretization

The model domain was spatially discretized into a 3-dimensional grid with a uniform grid spacing of 25 m. Initially, 3-layer and 4-layer models were developed and partially-calibrated but the model domain was ultimately discretized as a 6-layer model (see Figure 5).

Current topography at the Rum Jungle Mine Site was used to define the top of Layer 1 and the top of Layer 2 outside of the footprints of the WRDs and Dyson’s (backfilled) Open Pit. Within the footprints of these mine waste units, the top of Layer 2 was defined by the pre-mining ground elevation in that area (implying that the thickness of Layer 1 is variable).
The tops and bottoms of Layers 3 to 6 are offset by the thicknesses listed above and hence are fixed throughout the model domain.

Layer 1 is only active within the footprints of the WRDs and Dyson’s (backfilled) Open Pit. Layers 2 to 6 were active throughout the model domain except for within the boundaries of the three open pits. Inactive cells in these layers represent mined-out portions of the model domain that are now flooded with surface water and hence not part of the groundwater system.

4.1.3 Recharge
Groundwater recharge to the bedrock aquifer in undisturbed areas of the Rum Jungle Mine Site and the above-ground mine waste units was estimated as follows:

- Total rainfall accumulation for the 2010/2011 wet season was estimated from measurements collected from the rain gauge near the Main WRD;
- An amount of rain needed to ‘wet up’ the unsaturated zone during the early wet season was subtracted from the total rainfall accumulation to yield an estimate of net rainfall; and then
- Net rainfall was multiplied by a percentage infiltration rate to yield a “net recharge rate”.

Total rainfall was 2,576 mm for the 16-month simulation period. Net rainfall was estimated to be 2,372 mm by subtracting the average amount of rainfall that accumulates during the early wet season before an increase in groundwater levels was observed.

Figure 3 shows the final distribution of hydrostratigraphic units used to assign recharge rates (and hydraulic properties) to the model domain. Recharge rates were initially assigned solely by lithology as per the conceptual model but rates were later modified as part of the calibration process. Also modified during calibration was the number of recharge polygons per lithologic unit (see RGC, 2012 for more details).

4.1.4 Sources & Sinks
Heads in cells from Layers 2, 3, and 4 that are intersected by the perimeters of the Main and Intermediate Open Pits were specified using a transient head boundary (see Figure 5). These cells represent the bedrock aquifer that is in contact with standing water within the pits and were assigned a head that is equal to the observed pit water level.
Relatively shallow creeks, engineered drainage features, and areas where seepage is known to express itself at ground surface are represented by drain nodes in Layers 1 and 2 of the model. Drain conductances across the model domain were typically set to one or two orders of magnitude higher than K values for the surrounding aquifer.

4.2 Model Calibration

The model domain was initially discretized solely on the basis of lithology and estimates of recharge, horizontal and vertical hydraulic conductivity ($K_H$ and $K_V$, respectively), specific storage ($S_s$), and specific yield ($S_y$) from the conceptual model were assigned. The model was then calibrated by manually adjusting recharge and the aquifer properties within an acceptable range in order to fit simulated water levels to observed water levels.

The quality of the fit between simulated and observed water levels was visually evaluated based on the geodetic elevation of the simulated water level and the early wet season response of the simulated water level to recharge (RGC, 2012).

Groundwater levels in close to sixty wells across the model domain were simulated during the calibration process. An example of the match between simulated and observed groundwater levels in the Coomalie Dolostone is shown in Figure 6. These plots highlight the rapid increase in groundwater levels during the early wet season and the more gradual recession of groundwater levels towards the end of the wet season and into the dry season (i.e. from April to August 2011).

![Figure 6. Simulated and observed groundwater levels for a selection of wells screened in the Coomalie Dolostone.](image)

4.3 Numerical Modeling Results

4.3.1 Calibrated Recharges & Hydraulic Properties

The key aspects of the calibrated recharge rates and hydraulic properties of the hydrostratigraphic units are summarized as follows:

- The Coomalie Dolostone is the most permeable aquifer unit (i.e. up to $1.5 \times 10^{-4}$ m/s) in permeable zones north of the central mine reach and recharge was typically 20% of net rainfall;
- The Whites Formation is inferred to be an order-of-magnitude or more less permeable than the Coomalie Dolostone (i.e. $K = 10^{-5}$ m/s); this unit is typically more permeable in the central mine reach than in the area west of the Main Open Pit and in Dyson’s Area;
- The Rum Jungle Complex is typically characterized by relatively low K values (i.e. $K < 1 \times 10^{-6}$ m/s) at greater depths and near the northeast corner of the Main WRD; shallow zones of the bedrock aquifer east of the Main WRD towards Fitch Creek are relatively permeable due to weathering.
Waste rock in the WRDs is inferred to be relatively permeable \((K \approx 5 \times 10^{-5} \text{ m/s})\) and characterized by higher specific yields than bedrock aquifer units. The mixture of waste rock, tailings, and contaminated soils used to backfill Dyson’s (backfilled) Open Pit is inferred to be much less permeable by comparison (i.e. \(K = 2 \times 10^{-7} \text{ m/s}\)) due to the presence of fine tailings in the mixture (RGC, 2012).

4.3.2 Simulated Flow Fields

The simulated groundwater flow field for April 2011 (the height of the wet season) is shown in Figure 7. Groundwater generally flows from topographic highs towards the central mine reach and the East Branch of the Finniss River. Groundwater levels near the Main WRD were simulated to ‘mound’ due to the low \(K\) of the Rum Jungle Complex and flow occurs radially outward as a result. Mounding was not simulated near the Intermediate WRD due to the presence of the more permeable Coomalie Dolostone and Whites Formation in this area.

![Figure 7. Simulated groundwater flow field for April 2011 (wet season).](image)

4.3.3 Simulated Groundwater Budget

Key aspects of the simulated groundwater budget are summarized as follows:

- The Main and Intermediate Open Pits represent a net source of water to the groundwater system; specifically, net annual flows to groundwater from the Main and Intermediate Open Pits are 4 L/s and 7 L/s, respectively; higher flows from the Intermediate Open Pit are related to its strong hydraulic connection to highly-permeable zones of the Coomalie Dolostone;
- The Browns Oxide Open Pit receives a net annual inflow of 22 L/s and hence is a major discharge zone for groundwater due to active de-watering; groundwater discharge to the pit is highest in the wet season when groundwater levels in the vicinity of the pit rise (and pumping rates are highest);
- Annual groundwater discharge to the East Branch of the Finniss River downstream of gauge GS8150200 (at mine site) was simulated to be 44 L/s; groundwater discharge to the various creeks and tributaries of the East Branch of the Finniss River represents an additional 73 L/s;
- Shallow drains near the major mine waste units capture 12 L/s of toe seepage and shallow groundwater discharge; flows from the Main WRD and Dyson’s WRD account for
half of this annualized flow (4 L/s and 2 L/s, respectively); flows from the Intermediate WRD and Dyson’s (backfilled) Open Pit both represent less than 1 L/s. Note that simulated seepage flows are generally consistent with preliminary contaminant load estimates from RGC (2012) but re-calibration of the model with observed toe seepage during the 2011/2012 wet season is planned to confirm this.

4.4 Model Verification

In late 2008, water from the Intermediate Open Pit was pumped to the nearby Browns Oxide mine (for processing) resulting in a drawdown of the pit water level by about 11 m over three months. During this pit dewatering, the groundwater levels at three wells in the central mine reach (wells RN022107, RN022108, and RN022081) were monitored. The response of the groundwater system to drawdown of the Intermediate pit (in essence a large-scale pumping test) was simulated to verify the numerical model calibration.

The model generally reproduced the observed drawdown in groundwater levels in the surrounding bedrock aquifer in response to pumping of the Intermediate Pit very well (see Figure 8). The calibrated model confirmed that the cone of depression due to pumping of the Intermediate Pit affects groundwater levels in the Coomalie Dolostone and Whites Formation near the pit but not groundwater levels in the Rum Jungle Complex (see Figure 8).

Model verification results indicate that the strong hydraulic connection that is known to exist between the Intermediate Open Pit and the Coomalie Dolostone is well-simulated by the model (see water levels for well RN022108). The model also simulates the more modest drawdown of groundwater levels in zones of the bedrock aquifer that are located at greater distance from the Intermediate Pit (e.g. at well RN022107) and/or only weakly-connected to the flooded Intermediate Open Pit (e.g. at well RN022081). These results indicate that the major hydraulic connections between the Coomalie Dolostone and the flooded Open Pits are well-represented in the numerical flow model.

Figure 8. Simulated and observed water levels during the pit de-watering trial used for model validation.

4.5 Model Limitations

The numerical model is generally limited by simplifying assumptions related to our conceptual flow model, including the use of a fixed proportion of net monthly rainfall as a proxy for groundwater recharge, the discretization of the model domain into only six hydrostratigraphic layers, and the use of an equivalent porous medium approach for groundwater flow in the fractured bedrock aquifer. These assumptions are not considered problematic at regional scales but
may hinder our ability to predict groundwater flow locally near the Overburden Heaps and Dyson’s (backfilled) Open Pit.

Another limitation of the model is the non-uniqueness of the flow solution that arises from the correlation between calibrated recharge and K values and the lack of calibration to flows. The non-uniqueness of the flow solution was evaluated via a series of sensitivity runs that showed that observed groundwater levels could be simulated via a number of different combinations of recharge and K (see RGC, 2012 for more details). Re-calibration of the groundwater flow model to seepage flow estimates or results from additional large-scale pumping tests would reduce this uncertainty (see planned future work in section 6).

5 IMPLICATIONS FOR REHABILITATION

5.1 Contaminant Loads to Groundwater

Simulated toe seepage from the numerical model and seepage water quality data from Ferguson et al., (2012) were used to estimate annual contaminant loads from the WRDs and Dyson’s (backfilled) Open Pit for current conditions (see Table 1).

Key aspects of these preliminary load estimates are summarized as follows:

- The Main Overburden Heap accounts for 50% of the estimated annual SO$_4$ load to the East Branch of the Finniss River and is estimated to be a major source of metals (i.e. 15 to 30%);
- The Intermediate Overburden Heap accounts for an estimated 25% of the annual SO$_4$ load to the East Branch of the Finniss River and is estimated to be a significant source of metals (~30% of Cu and Mn, 50% of Ni, and nearly 80% of Zn);
- Dyson’s Overburden Heap accounts for an estimated 15 to 20% of the annual SO$_4$ load from the mine waste units and close to 75% of the annual Fe load; this heap is estimated to be a relatively minor source of other metals due in part to the nature of waste rock from Dyson’s Open Pit (which was mined solely for U and not a suite of metals);
- Dyson’s (backfilled) Open Pit is estimated to be a minor source of SO$_4$ but a major source of Cu, Mn, and Ni; these high loads are related to seepage from the mixture of highly-contaminated soils and heap leach material used to backfill the shallow portions of the open pit.

<table>
<thead>
<tr>
<th>Mine Waste Unit</th>
<th>Flow, ML</th>
<th>Annual contaminant loads (in t/yr)</th>
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<tr>
<td></td>
<td></td>
<td>SO$_4$</td>
</tr>
<tr>
<td>Main WRD</td>
<td>200</td>
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<tr>
<td>Intermediate WRD</td>
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<td>593</td>
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<td>Dyson's WRD</td>
<td>64</td>
<td>385</td>
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<tr>
<td>Dyson's (backfilled) Open Pit</td>
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<td>152</td>
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<tr>
<td>Total:</td>
<td>311</td>
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</table>

5.2 Flowpath Analyses

Flowpath analyses were used to evaluate how contaminants are transported in groundwater away from the above-ground mine waste units and near the former Copper Extraction Pad area (see RGC, 2012). These analyses provide some perspective on how contaminants move in groundwater under current conditions. An example flowpath analysis for the central mine reach
is shown in Figure 9 and some pertinent findings are summarized below for the high-priority areas of the mine site.

![Figure 9. Flowpath analysis for groundwater in the central mine reach.](image)

**5.2.1 Main & Intermediate WRDs**

Near the Main WRD, groundwater flows radially outward from the center of the dump due to the ‘mounding’ of water levels. This mounding is caused by high recharge and the low permeability of the underlying Rum Jungle Complex. Groundwater in this area tends to be highly-impacted by ARD due to the low buffering capacity of the Rum Jungle Complex (see Figure 4).

Mounding does not occur near the Intermediate WRD and hence contaminants from this dump are transported northward to the EFDC due to the prevailing direction of groundwater flow. Some buffering of groundwater near the Intermediate WRD may occur but highly-impacted (shallow) seepage suggests that the buffering capacity of bedrock may have been overwhelmed (at least in shallow soils/bedrock).

The flowpath analysis for the Main and Intermediate WRDs indicates that the majority of contaminant loads from waste rock in these dumps report to the East Branch of the Finniss River via toe seepage and shallow groundwater flow. The transport of contaminants in deeper zones of the bedrock aquifer is therefore limited and surface water quality conditions in the East Branch could be improved over a relatively short time period by reducing contaminant loads from the Main WRD and in particular the Intermediate WRD.

**5.2.2 Dyson’s Area**

Contaminants from Dyson’s WRD and Dyson’s (backfilled) Open Pit are delivered primarily to the East Branch of the Finniss River via toe seepage or shallow groundwater flows. Groundwater quality data are consistent with the results of the flowpath analysis, as shallow groundwater is highly-impacted but groundwater further west contains only modest levels of contaminants (Ferguson et al., 2012). This pattern of contaminant transport is explained mainly by local topography but also the low permeability of the deeper bedrock aquifer in Dyson’s Area.

**5.2.3 Central mine area**

In the central mine reach, contaminants in groundwater appear to have been transported from the central mine reach towards the East Branch of the Finniss River prior to development of the Browns Oxide Open Pit (see Figure 9, right panel). This flowpath is consistent with groundwater quality data from Ferguson et al. (2012), which indicate the presence of a TDS plume (but metals concentrations in groundwater are low).

De-watering of the Browns Oxide Open Pit appears to have caused a cone of depression to develop in the central mine reach that causes groundwater to move westward towards the Intermediate Open Pit and the Browns Oxide Open Pit itself (see Figure 9, left panel). This cone of depression may ultimately lead to the transport of highly-impacted groundwater from the Copper Extraction Pad area towards the Browns Oxide Open Pit. However, there is no evidence that this has yet occurred and pit de-watering is not expected to continue indefinitely.
6 FUTURE WORK

The next phase of work at the Rum Jungle Mine Site will involve the evaluation of alternative rehabilitation options with the numerical flow model. Planned work to be completed prior to predictive groundwater flow modeling includes the following:

- Update the numerical flow model with groundwater and pit water level data for the 2011/2012 wet season (which showed a distinctly different rainfall pattern);
- Re-calibrate the numerical flow model with seepage flow measurements collected by the DoR during the 2011/2012 wet season;
- Refine the preliminary contaminant load estimates with additional seepage flow data and observed loads in the East Branch of the Finniss River for the 2010/2011 and 2011/2012 wet seasons;

These updates to the model will reduce the uncertainty that characterizes the current model calibration and will ensure that two very different water years are included in the final calibration (the 2011/2012 wet season was much drier than the 2010/2011 wet season). Finally, additional drilling is planned in the former Copper Extraction Pad area to better delineate the extent of highly-impacted groundwater in this area (see Ferguson et al, 2012) and to assess its potential to move towards the EFDC and the Browns Oxide Open Pit after rehabilitation.

Completion of the recommended work will allow a comprehensive assessment of how the water quality conditions in the East Branch of the Finniss River could be improved by the alternative rehabilitation options and thereby enable the DoR to select the preferred rehabilitation option in light of stakeholder interests and priorities.

7 REFERENCES


Ferguson, P.R., C. Wels and M. Fawcett (2012), Current water quality conditions at the historic Rum Jungle Mine Site, northern Australia. Proceedings of 9th International Conference on Acid Rock Drainage (ICARD), May 20-26, 2012, Ottawa, Canada.
