Current Groundwater Quality Conditions at the Historic Rum Jungle Mine Site, Northern Australia

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Abstract
Rum Jungle was one of Australia’s first major uranium mines and produced approximately 3,500 tonnes of uranium in the 1950s but acid rock drainage (ARD) and heavy metal mobilization at the site have led to significant environmental impacts on groundwater and the East Finniss River. Recent studies have documented a deterioration of the site’s historic reclamation works and hence a worsening scenario in terms of environmental impact.

Recent data reviews identified numerous gaps in the existing network of monitoring wells at the site and hence a series of additional wells was installed in late 2010. Data from these wells have significantly improved our understanding of the extent of ARD impact at the site and hence the focus of this paper is to provide an overview of current groundwater quality conditions at the mine site.

Study Area

Location & Climate

The historic Rum Jungle mine site is located in Australia’s Northern Territory (NT) about 105 km by road south of Darwin near the township of Batchelor.

Local climate is considered tropical/monsoonal with more than 1500 mm of annual rainfall and a distinct wet period (‘the Wet Season’) that lasts from November to April. 90% or more of annual rainfall occurs during the Wet Season and no sustained rainfall is observed from May to October (i.e. ‘the Dry Season’). Mean maximum temperatures at the mine site range from 31°C in July to 37°C in October and savannah woodlands (predominantly Eucalyptus trees and various grass species) surround the mine site (Taylor et al., 2003).

Local Geology

The Rum Jungle mineral field forms part of the Pine Creek orogen of northern Australia and contains numerous polymetallic ore deposits. The geology of the mineral field comprises two Archean granitic basement domes overlain by a Paleoproterozoic sequence of metasedimentary and subordinate metavolcanic rocks (McCready et al., 2004). Near the Rum Jungle mine site, this sequence of rocks overlies the Rum Jungle Complex and is comprised of the Crater Formation, the Coomalie Dolostone, and the Whites Formation (Figure 1).

Rocks of the entire Mount Partridge Group were folded, faulted and metamorphosed to sub-greenschist facies about 1.9 billion years ago during the Barramundi orogeny but the original stratigraphic succession has been preserved. Brittle failure associated with deformation has produced a number of faults that follow the northeast-southwest structural trends of the Rum Jungle mine site.
Figure 1: Stratigraphic sequence at the Rum Jungle mine site

The Rum Jungle mine site is situated in a triangular area of the Rum Jungle mineral field that is bounded by the Giant’s Reef Fault to the south and by east-trending ridges of the Crater Formation to the north. This triangular area is known as The Embayment and it lies on the shallow-dipping limb of a northeast-trending, southwest plunging asymmetric syncline that has been cut by northerly-dipping faults.

Each of the polymetallic ore deposits in The Embayment occurs within the Whites Formation near its contact with the Coomalie Dolostone and mineralization is strongly associated with fault zones (and hence structurally-controlled). Specifically, ore has been deposited in carbonaceous slates of the Whites Formation by selective replacement along shear zones that intersect local faults (Ahmad et al., 2006).

Note that the Rum Jungle Complex and rocks of the Mount Partridge Group have undergone in situ lateritization since the early Mesozoic era and Tertiary period and hence the site features deeply-weathered soil profiles and some Quaternary soils/alluvium. However, no sedimentological record of the (South Australian) Permo-Carboniferous glaciation is apparent in the study area and most deposits of alluvium tend to be relatively thin (< 5 m).

Site Layout

The Rum Jungle mine site features three waste rock piles or ‘Overburden Heaps’, two flooded Open Cuts, and a backfilled Open Cut (see Figure 2). Other notable features of the mine site shown in Figure 2 are the East Finniss Diversion Channel (EFDC), the former tailings dam area along Old Tailings Creek, and the former copper heap leach pad between the flooded Open Cuts.
Figure 2: Layout of the Rum Jungle mine site

The main features of the mine site are described briefly in the sub-sections below.

**Open Cuts**

The White’s and Intermediate Open Cuts were mined out in the 1950s and 1960s and later flooded when mine de-watering ceased (Davy, 1975). White’s Open Cut was mined to about 105 m below ground surface (bgs) and hence is the deeper of the two Open Cuts (although it was partially backfilled with tailings and mine wastes in the 1960s).

Dyson’s Open Cut was mined to a depth of about 50 m bgs in the late 1950s. Tailings were discharged to this Open Cut from 1961 to 1965 (when the Intermediate ore body was being mined) and Dyson’s Open Cut was later backfilled entirely with additional tailings, heap leach material, and contaminated soils during rehabilitation attempts in the 1980s (Allen and Verhoeven, 1986).

**Overburden Heaps**

The White’s, Intermediate, and Dyson’s Overburden Heaps are comprised of waste rock removed during mining operations. Each of these heaps was covered in the 1980s to reduce rainfall infiltration although the covers have deteriorated to different extents since that time (Ritchie and Bennett, 2003; Taylor et al., 2003).

**East Finniss Diversion Channel**

The mine site is located along the East Branch of the Finniss River (hereafter the ‘East Finniss River’) about 8.5 km upstream of its confluence with the West Branch of the Finniss River.

Surface water enters the mine site via the upper East Finniss River and Fitch Creek. Before mining these creeks met near the NE corner of White’s Overburden Heap and subsequently flowed eastward via the natural course of the East Finniss River. However, the original course of the East Finniss River
ran through the White’s and Intermediate ore bodies so flow was diverted to the EFDC during mining operations.

Today, flows from the upper East Finniss River and Fitch Creek flow directly into the EFDC and into White’s Open Cut near the former Acid Dam. Water then flows from White’s Open Cut to the Intermediate Open Cut via a channel that roughly follows the original course of the East Finniss River. Outflow from the Intermediate Open Cut to the EFDC occurs near the western boundary of the mine site and combined flows from the Open Cuts and EFDC continues eastward via the natural course of the East Finniss River.

**Former heap leach area**

In the 1960s, copper from sub-grade ore (and the oxidized capping) of the Intermediate Open Cut was extracted in the 1960s via heap leaching on a ‘non-permeable’ pad located between the White’s and Intermediate Open Cuts (Davy, 1975). Contamination of the local soils was extensive and the area was ultimately rehabilitated in the 1980s.

**Old Tailings Dam area**

The former tailings dam area represents a relatively flat area north of White’s Open Cut where slurried tailings were discharged during mining operations. Drainage from this area formed a small creek that eventually discharged to the East Finniss River (Watson, 1979). Perimeter walls were later built towards the eastern end of the creek to form a series of small dams commonly referred to as the “Old Tailings Dam”.

Most of the tailings in this area were later removed during site rehabilitation in the 1980s and the area was limed, re-shaped, and covered to promote the re-establishment of vegetation (Allen and Verhoeven, 1986).

**Monitoring Well Network**

The mine site features a network of historic monitoring wells that have been installed for various purposes since the 1940s (i.e. groundwater monitoring, production, etc.). 103 of these wells remain accessible and have been used for water level monitoring since mid-2010. Most of the historic monitoring wells are shallow (<5 m in depth) and are clustered together near one of the major mine waste units or along the principal drainages of the site.

27 monitoring wells were installed in 2010 at the mine site to augment the existing well network and fill gaps that existed in certain areas of the site (i.e. north of the Open Cuts and in the former heap leach area). Most of the new monitoring wells were installed near the Open Cuts and former heap leach area as these areas were particularly under-represented in the historic well network.

**Data**

Seepage water quality data are provided in Table 1 and groundwater quality data for a selection of wells installed in 2010 are provided in Table 2.
### Table 1: Selected ARD indicator species in seepage from mine waste units

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<th>Date</th>
<th>pH</th>
<th>EC</th>
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<th>Fe</th>
<th>Cu</th>
<th>Co</th>
<th>Ni</th>
<th>U</th>
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<td>6000</td>
<td>5190</td>
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SO₄ and metals concentrations in mg/L

### Table 2: Selected ARD indicator species in groundwater

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<th>Al</th>
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SO₄ and metals concentrations in mg/L (concentrations less than indicated detection limit shown in red)
Discussion

After a brief description of background water quality conditions and sources of ARD products to the groundwater system, groundwater quality and local flow fields in the following ‘priority’ areas are discussed in separate sub-sections:

- Dyson’s Area
- Near the White’s and Intermediate Overburden Heap
- Near the former heap leach area and flooded Open Cuts
- North of the Open Cuts

Groundwater levels in January 2011 (not provided) were used to infer directions of groundwater flow across the mine site (see Figure 3). Geodetic groundwater levels are shown next to the monitoring wells in Figure 3 & the inferred direction of groundwater flow is illustrated by arrows. Blue arrows indicate the movement of clean (unimpacted) groundwater whereas orange and red arrows indicate the movement of moderately- and highly-impacted groundwater, respectively.

Figure 3: Inferred directions of groundwater flow at the Rum Jungle mine site

Groundwater quality and water level data are discussed together throughout the following sub-sections as sources of recharge and the subsequent movement of groundwater in the sub-surface can often be deduced from the degree (and extent) of ARD impact in receiving groundwater.
Background Conditions

Unimpacted groundwater in the bedrock aquifer at the Rum Jungle mine site is typically neutral to slightly alkaline (pH 7 to 8) and characterized by EC less than 500 µS/cm and low concentrations of SO₄ and dissolved metals. Groundwater of this type has been identified upgradient of the mine site (at well RN022085), in the relatively high elevation area northeast of Old Tailings Creek, and on the far side of Old Tailings Creek.

Unimpacted groundwater is thought to flow from these areas towards the lower elevation areas of the site near the flooded Open Cuts and former heap leach area. Note that unimpacted groundwater has also been identified in relatively deep Coomalie Dolostone (at well PMB13), which suggests that contamination by ARD in this area is limited to shallower zones of the bedrock aquifer.

Seepage water quality

Seepages from the four major mine waste units at the site provide the bulk of contaminant loads to the East Finniss River (via the EFDC or the flooded Open Cuts) and are geochemically distinct from one another (see Table 1).

Aside from being highly-acidic (pH<4) and characterized by high concentrations of SO₄, other characteristic features of seepage are summarized as follows:

- Seepage from Dyson’s Overburden Heap tends to be characterized by higher concentrations of dissolved U and lower concentrations of Cu, Co, Ni, and Zn than seepage from Dyson’s (backfilled) Open Cut; this is consistent with Dyson’s ore body being mined solely for uranium whereas high metals concentrations in the backfilled pit are related to tailings and contaminated soils stored therein;

- Seepage from White’s Overburden Heap is characterized by high concentrations of nearly every dissolved metal as the ore body was mined for uranium and a suite of other metals; seepage from this heap contributes the most volumetrically to the EFDC and hence East Finniss River downstream; and

- Seepage from the Intermediate Overburden Heap is the most concentrated source of contaminants at the mine site as metals concentrations can be orders of magnitude higher than in seepage from the White’s Overburden Heap or seepages in Dyson’s Area; of particular interest is the very high Cu concentrations (which reflect the geochemistry of the Intermediate ore body).

Dyson’s Area

The bedrock aquifer in Dyson’s Area is cross-cut by the Giant’s Reef Fault and a series of NE-trending faults. Dyson’s Overburden Heap lies to the south of the Giant’s Reef Fault and hence is underlain exclusively by the Rum Jungle Complex, whereas Dyson’s (backfilled) Open Cut lies between two of the NE-trending faults in pyritic black shale of the Whites Formation.

Most of the wells in Dyson’s Area are clustered together near the southern toe of Dyson’s Overburden Heap along the upper East Finniss River channel. Groundwater flow in this area appears limited to shallow deposits of alluvium associated with the Upper East Finniss River (meaning that most water infiltrating in this area likely moves laterally towards the river channel and not downward into the Rum Jungle Complex). This is supported by the presence of highly-impacted groundwater in shallow alluvium screened by wells RN023413 and RN023419 and only modestly-impacted groundwater at PMB2 (i.e. ~1000 mg/L SO₄ and low metals concentrations).
Most of the other wells in the Dyson’s Area are located north of the Giant’s Reef Fault closer to Dyson’s (backfilled) Open Cut and are screened deeper in the bedrock aquifer. Note that the occurrence of different bedrock units in this area is structurally-controlled by the NE-trending faults that ultimately intersect the Giant’s Reef Fault to the south. Groundwater quality near the western toe of Dyson’s (backfilled) Open Cut (at wells RN023792 and RN022036) is characterized by near-background concentrations of SO$_4$/dissolved metals and hence appears to be unimpacted by ARD. This suggests that Dyson’s (backfilled) Open Cut is not a source of ARD products to deep groundwater in this area or that contaminants that enter the bedrock aquifer are preferentially transported towards the Giant’s Reef Fault via the NE-trending fault that lies east of these wells.

No information is available on the transmissivity of faults in this area but it seems more than likely that the majority of contaminant loads from Dyson’s (backfilled) Open Cut are confined to the braided drainage channel that connects to drains within the landform. The poor condition of groundwater in the Dry Season (data not provided) and the likelihood of appreciable flows year-round in permeable sediments of the channel suggests a chronic load of contaminants to the upper East Finniss River from this channel. However, the stability of groundwater quality conditions at well RN023790 suggests only a weak connection between this channel and deeper groundwater and that the majority of contaminant loads in groundwater from the channel report to the upper East Finniss River.

**Near the Overburden Heaps**

The White’s and Intermediate Overburden Heaps are well-established as the main sources of ARD products to groundwater at the mine site. White’s Overburden Heap is underlain by the relatively impermeable Rum Jungle Complex whereas the Intermediate Overburden Heap is underlain by the more permeable Whites Formation and Coomalie Dolostone.

Groundwater beneath the heap (at wells RN022082S/D) and along the perimeter of the heap is highly-impacted by ARD. Due to ‘tight’ bedrock beneath the White’s Overburden Heap, seepage from the heap has resulted in some localized mounding of the groundwater table in this area (i.e. groundwater flows out in each direction from White’s Overburden Heap). Consequently, seepage from the White’s Overburden Heap is observed at shallow depths year-round and seepage discharges from the toe of the White’s Heap throughout the Wet Season. Note that no such mounding of groundwater levels occurs near the Intermediate Overburden Heap due to the higher permeability of bedrock underlying this heap (i.e. the Coomalie Dolostone and Whites Formation).

High SO$_4$ and metals concentrations characterize deeper groundwater in this area yet the downward movement of contaminated groundwater downward is likely limited. Moreover, groundwater quality in the Rum Jungle Complex beneath White’s Overburden Heap has generally improved since the heap was covered in the mid-1980s due to reduced infiltration, which is consistent with reduced contaminant loads from waste rock.

Groundwater from wells screened near the perimeter of White’s Overburden Heap is highly-acidic (pH 3.6 to 5.2) and characterized by very high concentrations of Mg (2,000 to 2,500 mg/L), SO$_4$ (9,000 to 11,000 mg/L), and nearly every dissolved metal in the suite (data not provided). The particularly high metals concentrations in several wells close to the toe of the heap are related to their proximity to a seepage face that characterizes the southwestern batten of White’s Overburden Heap during the Wet Season. Contamination from this area extends to the eastern toe of the Intermediate Overburden Heap.

Contaminant loads from the Intermediate Overburden Heap are likely directed northwest towards Wandering Creek and/or the EFDC near wells PMB5 and PMB6 and not towards White’s Overburden Heap. This conception of contaminant transport is consistent with the identification of highly-impacted groundwater at well RN023057 in 2009 and historic data from wells RN023058 and RN023059 (which
suggest some contaminant transport westward towards Wandering Creek). However, groundwater from wells PMB5 and PMB6 is only modestly-impacted by ARD and hence it appears that the majority of contaminant loads from the Intermediate Overburden Heap are delivered to the EFDC via the nearby seepage face (and do not report to groundwater via sub-surface flow from the heap).

Upstream near the head of the EFDC, groundwater from well PMB4 is also only modestly-impacted by ARD and hence data support the assertion that only minor loads are delivered to groundwater beneath the EFDC. Moreover, as the EFDC does not penetrate deep into bedrock as the Open Cuts do, there is no reason to believe that local groundwater flow fields in this area have been appreciably affected by its presence (i.e. groundwater does not upwell to the EFDC nor flow westward along the EFDC). Instead, groundwater likely flows northwest beneath the EFDC northwest towards the former heap leach area.

The only indication of any hydraulic connection between the EFDC and the bedrock aquifer are historic accounts of water from White’s Open Cut reporting to the middle reach of the EFDC via a cavern in the Coomalie Dolostone (Davy, 1975). Note that this hydraulic connection was more apparent in the 1970s when the condition of water in the Open Cut was very poor but the connection likely still exists. That being said, any groundwater discharge to the EFDC that is supported by water from the flooded White’s Open Cut is likely a source of dilution today (and very minor in comparison to dilution by surface water inflows to the EFDC from the upper East Finniss River) and hence the EFDC is not considered a major discharge zone for groundwater.

Near the former heap leach area & flooded Open Cuts

The direction of groundwater flow near the flooded Open Cuts and former heap leach area appears to be influenced by the presence of the Open Cuts themselves and fault structures in this area. Specifically, groundwater from the higher-elevation area near well PMB14 flows along the N-S trending fault that cuts across the former heap leach area whereas groundwater within the former heap leach area itself appears to flow westward towards the Intermediate Open Cut via the fault that hosts mineralization at the site. Hence these faults appear to be preferential flowpaths for groundwater flow (and contaminant transport) although the rate of flow ultimately depends on both their transmissivity and the magnitude of local hydraulic gradients (which appear to be relatively weak).

Preferential flowpaths may also characterize the Coomalie Dolostone, which is intersected by both the White’s and Intermediate Open Cuts. Specifically, the northern third of the Intermediate Open Cut intersects the Coomalie Dolostone whereas this unit is intersected by the northern and southern portions of White’s Open Cut. A strong hydraulic connection between the Intermediate Open Cut and the Coomalie Dolostone was demonstrated by a ‘large-scale’ pumping test conducted in late 2008.

Groundwater quality at PMB9S is relatively unimpacted by ARD but samples from the deeper of the two nested wells (well PMB9D) is highly-impacted by ARD (~3000 mg/L SO$_4$ and elevated levels of dissolved metals). These data suggest that well PMB9D screens the zone of the Coomalie Dolostone that is well-connected to the Intermediate Open Cut (as an increase in EC levels during that test are thought to reflect highly-impacted groundwater being pulled from the Coomalie Dolostone nearer the Intermediate Open Cut). The implication is that the area near well PMB9D is hydraulically-connected to the bedrock aquifer beneath the former heap leach area.

Wells PMB11, PMB23, and PMB24 are each located near the former heap leach area. Well PMB11 is thought to screen a sand-filled cavity in the bedrock aquifer beneath the former heap leach area whereas wells PMB23 and PMB24 are screened in the Coomalie Dolostone to the southwest. Groundwater from these wells (and well RN023054) are characterized by extremely high metals
concentrations that are thought to essentially represent a mixture of groundwater and seepage lost during the heap leaching process.

Note that groundwater from each of these wells is characterized by concentrations of $\text{SO}_4$ and dissolved metals that are comparable to water currently at the bottoms of the Open Cuts. Prior to treatment in the 1980s, the same type of water characterized the entire water columns of the White’s and Intermediate Open Cuts and hence it seems likely the water that currently resides in the former heap leach area is the same type that initially filled the Open Cuts when de-watering ceasing the 1950s. This is consistent with observations from Davy (1975) and explains the relatively clean groundwater at well PMB22 (which is screened in the Coomalie Dolostone slightly north of the former heap leach area and hence not affected by historic seepage losses).

At this time we conceptualize the Intermediate Open Cut as a discharge zone for groundwater from the former heap leach area but weak hydraulic gradients in this area suggest that the amount of groundwater that discharges each year may be rather small. Instead, contaminated groundwater in the former heap leach area could be representative a rather immobile TDS/metals plume that was mobilized temporarily in 2008 by the strong gradients created by the pumping test conducted in 2008.

**North of the Open Cuts**

Detailed water quality surveys conducted in the mid-1990s suggest that the area immediately downstream of gauge GS8150200 is a discharge zone for groundwater (Lawton and Overall, 2002). This scenario is consistent with comments from Davy (1975) and the local groundwater flow field shown in Figure 3.

Groundwater quality conditions at wells PMB7 and PMB16 are representative of the type of impacted groundwater that likely discharges to the East Finniss River within 500 m of gauge GS8150200 (i.e. surface outflow from the mine site). Specifically, groundwater in this area contains the high concentrations of $\text{SO}_4$ but low concentrations of metals that are indicative of a neutralized TDS plume.

This plume likely originates in the former heap leach area near wells PMB23 and PMB24 and characterizes the bedrock aquifer at well RN022543 (near the perimeter of the Intermediate Open Cut), well PMB12 (northeast of well PMB16), and wells PMB7 and PMB16 near the East Finniss River. It is difficult however to ascertain the timing of conservative contaminant transport as groundwater likely moves slowly in this area due to weak hydraulic gradients (and hence the TDS plume could be relatively immobile).

**Summary & Conclusions**

Recent groundwater quality data has enabled a preliminary conception of groundwater quality conditions at the former Rum Jungle mine site. Key findings are summarized as follows:

- Groundwater contamination tends to be limited to shallow aquifer zones as deep groundwater often appears unimpacted or only modestly impacted by conservatively-transported ARD species; this trend is particularly evident in Dyson’s Area, which is characterized by highly-impacted seepage and very shallow groundwater but impacts to deeper groundwater in Dyson’s area appear to be minimal;

- The White’s and Intermediate Overburden Heaps are the main sources of ARD products to shallow groundwater, whereas deeper groundwater near the Open Cuts is impacted primarily by residual seepages related to historic heap leaching; very high concentrations of metals in particular reflect the poor condition of groundwater beneath the former heap leach area;
The impact of ARD on groundwater appears to diminish considerably with distance from seepage sources as groundwater across much of the site tends to be well-buffered and hence characterized by low concentrations of dissolved metals; much of the impact on groundwater is therefore limited to increased TDS (primarily Ca, Mg and SO$_4$) and groundwater tends to be neutral to slightly alkaline; the presence of the Coomalie Dolostone (and its high buffering capacity) is of particular importance as this unit has received a substantial contaminant load from upgradient but continues to buffer receiving groundwater;

A TDS plume extends to the north and northwest of the flooded Open Cuts and former heap leach area into the vicinity of the East Finniss River; the presence of impacted groundwater in this area is consistent with reports of groundwater discharge to the East Finniss River immediately downgradient of the mine site.

In summary, groundwater quality across much of the former Rum Jungle mine site remains impacted to some extent by ARD despite attempts to rehabilitate the site in the 1970s and 1980s. However, highly-impacted groundwater is restricted to areas immediately downgradient of the major mine waste units or in the former heap leach area as groundwater north of the the Open Cuts is only modestly-impacted by ARD. This is consistent with the relatively slow movement of groundwater across the site due to weak hydraulic gradients and, to an extent, the reduction of contaminant loads due to historic rehabilitation attempts (i.e. covering the heaps and removing tailings/contaminated soils from the Old Tailings Dam area and former heap leach area). Routine monitoring data and the development of a numerical groundwater flow model over the next 2 to 3 years will however enable better characterization of contaminant transport via groundwater and thereby assist the DoR in developing a comprehensive rehabilitation plan for the mine site.

References


