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HYDROGEOLOGICAL STUDY OF RUM JUNGLE MINE SITE - INITIAL REVIEW & DATA GAP ANALYSIS - REV0

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1 INTRODUCTION

1.1 TERMS OF REFERENCE

The former Rum Jungle mine site is located 105 km by road south of Darwin in the headwaters of the East Finniss River (Figure 1-1). Rum Jungle was one of Australia's first major uranium mines and produced approximately 3,500 tonnes of uranium between 1954 and 1971. Acid rock drainage (ARD) and heavy metal mobilization at the site led to significant environmental impacts on groundwater and the East Finniss River and localized concentrations of radioactive tailings that presented a potential radiological hazard (Kraatz, 2004).

From 1983 to 1986, Rum Jungle was rehabilitated under an $18.6 million cooperative agreement between the Commonwealth and Northern Territory Governments. Initial monitoring activities indicated that the rehabilitation program met its original objectives yet longer-term monitoring has documented a gradual deterioration of the site's historic reclamation works. Today, the contamination of local groundwater and the East Finniss River continues and the site is recognized as an ongoing environmental concern (Ryan et al., 2009).

In 2009, the Mining Performance Division of the Department of Resources (DoR) was tasked with developing a comprehensive rehabilitation plan for the Rum Jungle mine site. Scoping studies completed in recent years have suggested that the current understanding of the local hydrogeology at Rum Jungle mine site is very limited and will have to be better characterized prior to further rehabilitation planning (Kraatz, 2004; Moliere et al., 2007).

In May 2010, Robertson GeoConsultants Inc. (RGC) was commissioned by the DoR to complete an Initial Data Review & Data Gap Analysis for the historic Rum Jungle mine site. This review is intended to assist in future rehabilitation planning and is a deliverable under Contract No. RFQME0061 (Tasks 2 and 3 of RGC proposal P154).
1.2 **STUDY OBJECTIVES & SCOPE OF WORK**

The objectives of this study are as follows:

- Complete an initial review of hydrogeological data for the Rum Jungle mine site (Task 1);
- Identify critical data gaps that require further study and/or analysis (Task 2); and
- Propose additional studies and/or fieldwork that would fill the identified data gaps (Task 3).

The development of detailed work plans for any additional drilling and/or sampling that may be required at the Rum Jungle mine site would likely require a detailed data review and hence is beyond the scope of this report.
2 INITIAL DATA REVIEW

2.1 DATA SOURCES

A wide range of information was provided to RGC by the Department of Resources (DoR) for this initial data review. Data sources include a large number of reports that summarize various studies and/or monitoring programs for the Rum Jungle mine site and numerous drawings, spreadsheets and databases relevant to this study.

2.1.1 Reports

A total of 15 reports were reviewed for this study covering the following main subject areas:

- Historic Mining & Rehabilitation Works
- Geology (Rum Jungle, Browns Project & Regional)
- Hydrogeology (Rum Jungle & Browns Oxide project)
- Review & Assessment of Rehabilitation (incl. cover performance)
- Groundwater & Surface Water Quality Monitoring
- Pit water quality studies

The amount of information provided in these reports is substantial and a detailed review of all these studies was beyond the scope of this initial data review. Instead, RGC’s review focused on those studies that relate specifically to the hydrogeology of the Rum Jungle mine site. Particular attention was paid to identifying major data gaps in the studies provided (which are summarized in Section 3 of this report). As outlined below, a more detailed review of some earlier hydrogeological studies and/or re-interpretation of previously-analyzed raw data will likely be required during a subsequent phase of this study.

2.1.2 Geological Database (Compass)

In addition to the reports mentioned above, the DoR also provided a copy of an ACCESS database that was recently obtained from Compass Resources. This database includes a comprehensive set of exploration drilling data plus a series of digital maps covering geology, topography, drill hole and monitoring bore locations. This database also included a series of satellite photos of the study area and scanned images of earlier geological maps.

This database was reviewed and relevant data and drawings were extracted and/or plotted to assist in our initial review.
2.1.3 Groundwater GIS Database (ERISS)

RGC was also provided with a GIS database developed by the Supervising Scientist Division of the Department of Environment, Water, Heritage, and the Arts (DEWHA) in 2007 (see Lowry and Staben, 2007). This database includes an updated summary of monitoring bore information, including re-surveyed x-y coordinates, bore completion details (historic drill logs in pdf format and completion details in ACCESS), and groundwater quality and level data collected since the 1980s.

RGC uploaded this database in ArcView v.9.2 to test its functionality and to assist in our initial review and data gap analysis. Some discrepancies were noted between the database purchased from Compass and the ERISS GIS database. Specifically, some of the locations of several older monitoring bores at the Rum Jungle mine site did not match. These discrepancies were acknowledged in Lowry and Staben (2007) and did not affect the data review. Note that data from the ERISS database was used whenever a discrepancy between the two databases was evident.

2.2 SITE DESCRIPTION

2.2.1 Location & Climate

The Rum Jungle mine site is located in Australia’s Northern Territory about 105 km by road south of Darwin (Figure 2-1). The site is located along the East Finniss River (a tributary of the Finniss River) in the Van Diemen region of the Timor Sea drainage system (CSIRO, 2009).

The landscape in this region comprises a patchwork of harsh, dry escarpments, tablelands, and low-lying river flats that are generally dry from May to October and often flooded throughout the remainder of the year (CSIRO, 2009). The climate is considered tropical with high temperatures year-round (averaging 28°C). Mean annual rainfall for the Van Diemen region is 1390 mm although large inter-annual variation is observed. Mean annual potential evapotranspiration for the region is 1936 mm, which indicates water limitation on an annual basis (but not necessarily during the wet season) (CSIRO, 2009).

Rivers and streams in the Timor Sea drainage system are relatively large by Australian standards and this system is second only to the Tasmanian drainage system in terms of streamflow per unit area (CSIRO, 2009). Continuous flow in most rivers does not occur year-round due to very low rainfall in the dry season.

2.2.2 Regional Geology

The Pine Creek Orogen (PCO) covers 66,000 km² of northern Australia and forms the northern margin of the North Australian Craton (Plumb, 1979). The PCO is comprised of sequences of carbonaceous, clastic, and volcanogenic sediments deposited upon rifted Archean crystalline
basement (Figure 2-2) (Worden, 2006). The Rum Jungle area is situated in the central to western part of the PCO and features two dome-like Archean basement highs: the Rum Jungle Complex and the Waterhouse Complex (McCready et al., 2001). Both complexes consist primarily of granitic intrusions that are now overlain by a Paleoproterozoic sequence of metasedimentary and subordinate metavolcanic rocks called the Mount Partridge Group (and repetitive clastic-carbonate sequences of the Namoona Group). From youngest to oldest, the three major formations of the Mount Partridge Group are the Crater Formation, the Coomalie Dolostone, and the Whites Formation (Table 2-1).

The Crater Formation comprises coarse and medium grained siliciclastics whereas the Coomalie Formations comprise magnesite and dolomite with minor chert lenses (McCready et al., 2001). In contrast, the Whites Formation (which hosts uranium and polymetallic mineralization) comprises graphitic, sericitic, chloritic, and calcareous slate-phyllite-schist. Hence the Whites Formation marks a distinct change in the sedimentary and environmental conditions that occurred in the Early Proterozoic.

The local geology as mapped by Lally (2003) is shown in Figure 2-3. A NW-SE geological section through the Browns oxide project at the Rum Jungle site is shown in Figure 2-4. Rocks of the entire Mount Partridge Group have been folded, faulted and metamorphosed to greenschist facies during the 1880 Ma Barramundi orogeny but the original stratigraphic succession has been preserved (McCready et al., 2004). Brittle failure associated with deformation has produced a number of faults, some of which follow the northeast-southwest structural trend.

The Mount Partridge Group is locally (and unconformably) overlain by hematite quartzite breccia of the Proterozoic Geolsec Formation. The Rum Jungle Complex (and all Proterozoic sediments and metasediments) have undergone in situ lateritization since the early Mesozoic era and Tertiary period and hence deeply-weathered soil profiles characterize the Rum Jungle mine site. The site also features Quaternary soils and alluvium but no sedimentological record of the (South Australian) Permo-Carboniferous glaciation is apparent in the study area.

2.2.3 Ore Deposit

The Rum Jungle mineral field of north-central Australia contains numerous polymetallic ore bodies. The largest of the ore bodies are the now mined-out Woodcutters Pb-Zn-Ag and Whites Pb-Cu-U ore bodies and the Browns Oxide Pb-Cu-Ni-Co ore body (partially mined). Each of these deposits occurs within the Whites Formation near its contact with the Coomalie Dolostone (Figure 2-4).

The uranium and base metals deposits at the Rum Jungle mine site (i.e. Whites ore deposit) are strongly associated with faults zones and hence appear to be structurally-controlled. Specifically, ore
has been deposited along shear zones that intersect local faults by selective replacement along bedding planes in carbonaceous slates.

In addition to a structural control, there is also an apparent paleogeographic control on the composition of base metal occurrences (i.e. Pb-Zn-Ag deposits occur in an open shelf setting whereas Pb-Cu-Zn-Co-Ni and uranium deposits occur in restricted embayments). One such embayment occurs along the Giant’s Reef Fault and hosts the Whites and Browns ore bodies. The embayment is a triangular area defined by the Giant’s Reef Fault to the south and by east-trending ridges of the Crater Formation to the north (Figure 2-2). The area lies on the shallow-dipping limb of a northeast-trending, south-west plunging asymmetric syncline cut by northerly faults (shown in an idealized cross-section with a northwest and southeast trend in Figure 2-4).

### 2.2.4 History of Mining at Rum Jungle

Uranium from the White’s ore body was initially mined underground from 1950 to 1953. Production from Whites Open Cut began in 1953 and the deposit was mined out to a depth of 100 m by 1958 (Figure 2-5). Dysons Open Cut was mined in 1957/1958. Some ore was also mined in 1958 from the Mount Burton Open Cut (located 4 km west of the Rum Jungle treatment plant). Ore from these operations was stockpiled and progressively treated in order to fulfill a contract to provide uranium oxide concentrate to the UK-US Combined Development Agency (CDA) (WNO, 2010).

In 1960, the Rum Jungle South ore body was discovered 7 km south of the treatment plant. A sales contract for uranium from this ore body was not signed until 1961 when the Commonwealth Government decided to proceed with developing it (WNO, 2010). The Rum Jungle South ore body was subsequently mined to a depth of 67 m to access relatively high-grade uranium (0.37%) and some associated metals (copper in particular). The Rum Jungle South mine site is not included within the scope of this study.

The Intermediate ore body was mined exclusively for copper, which was extracted from ore on a heap leaching pad located between the Intermediate Open Cut and Whites Open Cut (Ryan et al., 2009).

Until 1962, the uranium treatment plant at the Rum Jungle mine site used an acid leach and ion exchange process to treat ore from the Whites and Dysons Open Cuts. After 1962 a solvent extraction/magnesia precipitation process was used instead of ion exchange to treat ore from the Rum Jungle South ore body.

A total of about 863,000 tonnes of high-grade uranium oxide (U₃O₈) ore was ultimately treated at the Rum Jungle treatment plant to produce 3,530 tonnes of U₃O₈ (along with 20,000 tonnes of copper concentrate) (WNO, 2010). Estimates of total U₃O₈ production do vary though and some sources estimate that nearly 2 million tonnes of U₃O₈ ore was treated to produce 4,500 tonnes of U₃O₈. Most
of the ore at the Rum Jungle mine site was mined from the Whites and Rum Jungle South ore bodies.

When operations began the mill tailings were discharged to an almost flat area to the north of Whites Open Cut (Figure 2-5). Drainage from this area formed a small creek called ‘Old Tailings Creek’ before it reached 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 “Old Tailings Dam”.

Starting in 1961, tailings were discharged into the mined-out Open Cuts. From 1961 to 1965, tailings were discharged into Dysons Open Cut until it was full. From 1965 until closure in 1971, tailings were discharged into Whites Open Cut (Watson, 1979).

2.2.5 Rehabilitation Works

Towards the end of mining at the Rum Jungle site, the Australian Atomic Energy Agency (AAEC) attempted to identify major sources of contamination at the site and the extent and degree of environmental damage. Despite recognition of widespread contamination of groundwater and surface water by ARD products at that time, the Commonwealth Government decided not to rehabilitate the Rum Jungle mine site and the site was left ‘as is’ (WNO, 2010).

Later attempts to rehabilitate the site in 1977 ultimately led to the establishment of a working group that was commissioned to provide a comprehensive rehabilitation plan for the mine site. An $18.6 million program funded by the Commonwealth Government was subsequently undertaken from 1982 to 1986 (Kraatz, 2004). The rehabilitation works are briefly summarized in the sub-sections below.

2.2.5.1 Overburden Heaps

Figure 2-6 shows the layout of the different mine waste units at the Rum Jungle mine site. The Whites Overburden Heap was rehabilitated in 1983/1984 while the Intermediate and Dysons Overburden Heaps were rehabilitated two years later. Rehabilitation consisted primarily of covering the Overburden Heaps with a three layer cover system that included a low permeability clay layer.

The cover system was designed to reduce infiltration to less than five percent of incident rainfall and therefore restrict the movement of pollutants from the heaps. A reduction in oxygen flow into the heaps as a result of the cover system was also expected to reduce oxidation rates and the ongoing generation of pollutants. In addition to being covered, the Overburden Heaps were also re-shaped and outfitted with engineered drainage structures that could quickly and safely dispose of stormwater.

The cover system included:

- A compacted clay layer (minimum thickness 255 mm) as a moisture barrier;
To control the flow of polluted groundwater from springs on the northeastern and southwestern sides of Whites Overburden Heap, a subsoil drainage system was constructed to intercept groundwater at the interface between the original ground surface and underside of the Overburden Heap in the areas where the springs had been observed.

2.2.5.2 Open Cuts

Polluted water from Whites Open Cut was pumped out and treated with lime to remove heavy metals and neutralize pH. The treated, less dense water was returned (with minimal turbulent mixing) to the surface of the pit where a lower density layer was established on top of the denser untreated water. The treated pit water layer in Whites Open Cut was low in heavy metals and initially extended to a depth of about 20 m.

Given the lower level of contaminants in Intermediate Open Cut and the smaller volume involved, this pit water was first treated in situ with lime and the aid of an aeration mixing device. The settled precipitate was subsequently removed by a sludge pump.

Dysons Open Cut had been used for the disposal of tailings during mining (Figure 2-5). During rehabilitation, tailings from the dam area and Old Tailings Creek were placed directly onto existing tailings within the lower portion of the Open Cut. Geotextile and a one meter thick rock blanket connected to a subsoil drainage system were then installed to provide a suction break layer for any pore water released during the subsequent consolidation of tailings. Copper heap leach material and contaminated soils were placed in alternating layers over the rock blanket and then compacted. Given the nature of materials placed in the Open Cut, a slightly thicker cover system than that used on the Overburden Heaps was designed to restrict infiltration.

2.2.5.3 Tailings Dam & Copper Heap Leach Pad

Following the removal of tailings and contaminated subsoil from the tailings dam, the area was limed and re-shaped to control drainage. A one-layer cover system was installed to enable the establishment of vegetation, which included native tree and shrub species. A subsoil drainage system and four-layer cover system were installed over the copper heap leach area to deal with the highly mobile and toxic metals in the near surface zones under the pile and in the area surrounding the heap.

The current condition of the Rum Jungle mine site is shown in Figure 2-7.
2.3 SITE HYDROGEOLOGY

The Rum Jungle mine site features an extensive network of groundwater bores that have been installed over the last 50 years or so. The network of groundwater bores is shown in Figure 2-8 with bores coded by the depth of the screening interval. Groundwater level and some flow testing data are available for a selection of these groundwater bores. The following sections provide an overview of these data and a broad description of groundwater flow conditions at the Rum Jungle mine site.

2.3.1 Aquifer Characterization

The Rum Jungle mine site features a shallow/porous aquifer unit and deeper/fractured (and possibly karstic) aquifer unit. These units are hydraulically connected and hence it appears that the aquifer may reasonably be regarded as a single aquifer with two units rather than separate shallow and deep aquifers. The aquifer is predominantly unconfined although some pump test data suggest semi-confined conditions. Confining conditions at the site are likely localized in certain areas and are unlikely to be influential at regional scales.

The shallow unit consists of mixed deposits of in-situ weathered bedrock (“saprolite”) and soil material of a colluvium-alluvium mix. There are zones of permeable clayey-sand that are interspersed with mottled zones of ferruginous sandy clays. In proximity of the East Finnis River and its tributaries the shallow soils are predominantly comprised of riverine sands. The deeper unit consists of several lithologies, including granite, dolostone, shale and schist. Investigation by Water Studies (2000) showed that karstic zones with high groundwater inflows may be found in the dolostone and some aquifer testing results at bores RN22107 and RN22108 could be indicative of presence of permeable karstic features within the fresh to slightly weathered Coomalie Dolostone.

In general, groundwater flow in the shallow aquifer unit is controlled by primary permeability of unconsolidated overburden soils (or highly weathered bedrock) whereas groundwater flow in the deeper aquifer unit is controlled by secondary permeability (faults, fractures and/or karstic features). Available hydraulic conductivity (K) values for shallow laterite and deeper bedrock units at the Rum Jungle mine site are shown in Table 2-2. The reported K values typically range from $10^{-4}$ to $10^{-5}$ m/s but are likely biased high due to the lack of hydraulic testing in low-yielding bores.

Note that several lithologies within the study area (e.g. Crater formation, fresh granite) have not yet been hydraulically tested. Note also that very little information is available on the hydraulic properties of structural features in the study area. The major fault intersecting the Browns Oxide project is believed to be very transmissive as inferred from high bore yields (20 L/s) at TPB3 (Water Studies, 2002). In contrast, the Giant’s Reef Fault has been inferred to be a hydraulic barrier due to the presence of granitic material on its southeastern flank (Water Studies, 2002; Coffey, 2006). Structural
controls are likely a very important feature of groundwater flow (and contaminant transport) at Rum Jungle and will require further characterization works.

2.3.2 Groundwater Levels & Recharge Conditions

Groundwater at the Rum Jungle mine site is generally found less than 12 m below ground surface with an average depth-to-water of 4 m (Coffey, 2006). Groundwater levels are strongly influenced by seasonal variations in rainfall though with levels in the wet season typically 5 m higher than in the dry season. This suggests active recharge to unconfined aquifers and dynamic discharge processes such as exfiltration to surface water features during the wet season.

Long-term climate statistics and groundwater level data suggest that that nearly half of the rainfall that occurs from November to March enters the sub-surface as recharge. Recharge in fractured and karstic dolostone could be even higher. Recharge to the groundwater system could be also provided by the ephemeral Finniss River and by water stored within the Intermediate Open Cut and Whites Open Cut.

2.3.3 Groundwater Flow Regime

Shallow groundwater at the site is inferred to flow to the north and west away from Whites Overburden Heap (Figure 2-9). Groundwater in Whites and Dysons Overburden Heaps tend to mound and hence particularly strong (horizontal) hydraulic gradients are observed between the two Overburden piles (which ultimately drives flow in the area). The highest groundwater levels were observed in Whites Overburden Heap with water actively discharging into the Sweetwater Dam area to the east, west and northwest. No shallow bores were sampled to the south of Whites Overburden Heap so the direction of groundwater flow in this area is not constrained.

Groundwater flow fields and inferred directions of groundwater flow for the shallow aquifer unit are based on a limited number of water level measurements that are normally taken near the end of the wet season (when the bores contain water). The small number of bores sampled (and their bias towards the wet season) only allow for a qualitative interpretation of flow in the vicinity of the Whites Overburden Heap. It is likely that water management operations (i.e. the diversion channel and fresh/acid water dams) have influenced shallow groundwater flow patterns in this area to some extent but this aspect of groundwater flow is not well understood.

Deeper groundwater flow at the Rum Jungle mine site generally flows to the north away from the Whites Overburden Heap and towards the diversion channel and the East Finiss River (Figure 2-10). Based on our experience at the Woodcutter’s mine, deep groundwater flow is likely influenced by permeable structures such as the Giant’s Reef Fault and/or other northeast-southwest trending faults and fractures that run through the Rum Jungle mine site. However, limited data is available on the role these faults play in groundwater flow at the Rum Jungle mine site.
Groundwater flow between Dysons and Whites Open Cut appears to be more complex than elsewhere at the site (or at least less consistent). Groundwater in this area flows to the east and west but generally trends towards the north. Transient recharge during large (and small) scale cycles could explain the apparently conflicting flow directions in this area. Note that little is known about vertical fluxes in permeable faults and/or induced by highly saline waters (sulphate 22,000 mg/L) inside the mine area but these fluxes could be significant.

North of the Whites Open Cuts near the former ‘tailings dam’, groundwater flows in a westerly direction and also trends towards the north.

### 2.4 WATER QUALITY

#### 2.4.1 Groundwater Quality Database

A groundwater GIS database for the Rum Jungle mine site was developed in 2007 by the Supervising Scientist Division of DEWHA (see Lowry and Staben, 2007). The aim of database development was to compile groundwater monitoring data from various sources and subsequently provide these data to stakeholders in a consistent and documented format, datum, and projection (Ryan et al., 2009).

During data compilation, the limitations of historic monitoring data became apparent. Specifically, groundwater monitoring data had not been collected since 1988 and hence no time series data was available to document any changes in groundwater quality that could have occurred in the 25 years since initial rehabilitation. Hence additional data were collected in 2008/2009 to provide a snapshot of current conditions at the Rum Jungle mine site and thereby enable any changes in groundwater quality since rehabilitation to be identified.

Groundwater sampling was conducted at the beginning and end of the 2008/2009 wet season by the Environmental Research Institute of the Supervising Scientist (ERISS) and the Northern Territory Department of Regional Development, Primary Industry, Fisheries, and Resources. The bores sampled were selected based on their proximity to potential contaminant sources or specific hydrogeologic features (i.e. faults, rock types, etc) and the length of the historic monitoring record (see Ryan et al., 2009). Samples of seepage from waste rock and water from the East Finniss River were also collected at the time of groundwater sampling. The locations of the monitoring bores and surface water stations sampled in 2008/09 are shown in Figure 2-11.

Measurements of pH, electrical conductivity (EC) and the concentrations of sulphate (SO$_4$) and dissolved zinc (Zn) in selected monitoring bores at the Rum Jungle mine site are shown in Figures 2-12 to 2-15. Dissolved Zn was selected as a surrogate of metal contamination in groundwater for purposes of this report because it tends to co-vary with other metals, like copper (Cu), cobalt (Co),
manganese (Mn), and nickel (Ni). A brief QA/QC check of the groundwater quality data revealed that most of the data are reliable although some inconsistencies in the data were identified (possibly due to transcription errors). These minor inconsistencies did not appreciably affect the broad perception of groundwater quality conditions at the site and hence none of the data were excluded from consideration at this time.

2.4.2 Contaminant Sources

The following mine waste areas and historic features of the Rum Jungle mine site were identified as potential contaminant sources to groundwater and surface water at the site:

- Overburden Heaps (Whites, Dysons, and Intermediate);
- Open Cuts (Dysons, Whites, and Intermediate);
- Old Tailings Dam (now relocated); and
- Historic copper leach pad (now relocated).

Note that the old tailings and the copper leach material were later backfilled into the Whites Open Cut and Dysons Open Cut, respectively (see Section 2.2.5).

Samples of seepage are routinely collected as part of surface water monitoring at the Rum Jungle mine site. Seepage samples from the backfilled Dysons Open Cut and Dysons Overburden Heap are collected at Site 11 and Site 8, respectively, and seepage from White’s Overburden Heap is collected at Sites 4 and 5 (Table 2-4).

The exact nature of these seepage water sampling sites should be confirmed before detailed interpretation of water quality data is completed. However, it is clear from the initial data review that seepage from waste rock in Whites, Dysons, and the Intermediate Overburden Heaps and seepage/pit water from Dysons Open Cut is highly-impacted by ARD. Specifically, seepage is highly-acidic (pH < 3) and characterized by elevated levels of SO$_4$ and various metals (i.e. Al, Cu, Co, Mn, Ni, and Zn).

2.4.3 ARD Impact on Receiving Groundwater

The acidity and SO$_4$/metals concentrations in groundwater adjacent to Whites and Dysons Overburden Heaps are similar to waste rock seepage from these Heaps. This is a clear indication that waste rock seepage is a major source of ARD products to groundwater and that seepage continues to affect groundwater at the Rum Jungle mine site.

Groundwater downgradient of Whites Open Cut and the Intermediate Open Cut is also highly-impacted by ARD but the exact source of ARD products is not as well understood. High levels of
ARD products could be due to the interaction of groundwater with the partially backfilled open cuts or the flow of impacted groundwater from upgradient sources (i.e. Overburden Heaps).

High levels of ARD products were not identified in groundwater near Dysons Open Cut but seepage from waste rock in this area is known to be very acidic and contain high levels of ARD products. Hence the absence of ARD products in this area may be a result of poor spatial and vertical coverage of available monitoring bores and not the absence of contaminants in groundwater.

Groundwater north of the Open Cuts near the ‘Old Tailings Dam’ and south of Whites Overburden shows no appreciable impact by ARD. Groundwater in these areas is considered representative of background water quality conditions near the Rum Jungle mine site.

No samples of groundwater were collected from bores located east of Dysons Overburden or the area downgradient of the mine site in the East Finniss River valley in October 2008 or April 2009. Hence water quality conditions in these areas are currently not known. Several bores near the Browns Oxide Mine (west of the Intermediate Open Cut) were sampled in March 2010 though and there appears to be little impact by ARD in this area.

Changes in water quality over the last 25 years were difficult to ascertain due to the limited amount of data that has been collected over that time period and missing data in the historic records that are available. Some groundwater quality data collected after initial rehabilitation of the site in the mid-1980s is available though and was reviewed for purposes of this report (see Table 2-5).

In 1983, groundwater quality at bores RN022082 and RN022083 was identified as being particularly poor due to seepage from Whites Overburden Heap (Appleyard, 1983). Specifically, SO$_4^-$ concentrations in these bores exceeded 10,000 mg/L and metals (including Cu, Co, Mn, Ni, and Zn) were on the order of tens to hundreds of mg/L (see Table 2-5a,b). Data from 1983 represents groundwater quality conditions during the time that the Rum Jungle mine site was being rehabilitated (i.e. Whites Overburden Heap was not completed sealed with a cover until 1984).

Since rehabilitation, groundwater quality at bore RN022082 (screened in waste rock) has improved considerably but conditions east of Whites Overburden Heap at bore RN022083 have remained relatively unchanged (or even deteriorated slightly). Most notable at bore RN022082 is the order-of-magnitude decrease in Cu, Co, Mn, Ni, and Zn concentrations in deep and shallow groundwater this location. No historic SO$_4^-$ data for the shallower bore (RN022082S) is available but SO$_4^-$ concentrations in bore RN022082D decreased from 49,000 mg/L in 1983 to ~7,000 mg/L in 2008/2009. Groundwater at bore RN022082 remains highly-impacted by ARD though despite order-of-magnitude decreases in some ARD indicator species.

Metals concentrations in groundwater near Whites Open Cut (at bore RN022107) and the Intermediate Open Cut (at bore RN022108) decreased considerably since rehabilitation in the 1980s.
SO$_4$ concentrations at bore RN022107 also decreased whereas SO$_4$ concentrations at bore RN022108 were slightly higher in 2008/2009 than in 1983. Appleyard (1983) noted some ambiguity regarding the source of SO$_4$ at these locations (i.e. natural vs. ARD-related SO$_4$ in groundwater). The interaction of groundwater with standing water in nearby Open Cuts may be a source of some uncertainty regarding the origin of SO$_4$ in groundwater.

Most of the other bores at the Rum Jungle mine site showed no definitive change in groundwater quality over the last 25 years or so. This is due in part to the lack of complete water quality data from the 1980s (i.e. missing metals and/or SO$_4$ concentrations) but may also reflect the relatively stable condition of local groundwater system in terms of ARD loading. The marked improvement in groundwater quality near Whites Overburden Heap also reflects the focus of the rehabilitation program on that area. Overall, it is evident that initial rehabilitation attempts in the late 1970s have resulted in some improvements in groundwater quality near Whites Overburden Heap but that the condition of groundwater remains relatively poor in this area and near other mine waste units.

### 2.4.4 Impacts of Mining on Surface Water

The Whites and Intermediate ore bodies lay underneath the former creek bed of the East Finniss River. Hence the East Finniss River was diverted south of the Open Cuts into the East Finniss Diversion Channel (EFDC). Note that Fitch Creek discharges into the EFDC upstream of the Whites Overburden Heap.

Water samples from the creeks and the EFDC are routinely collected as part of the surface water monitoring program (see Figure 2-11 for station locations). The stations are summarized as follows:

- Site 07: East Finniss River before it enters the mine site
- Site 06: Fitch Creek before it enters the mine site
- Sites 09 and 10: East Finniss River downstream of Dysons Open Cut and Overburden Heap
- Site 03: EFDC near its confluence with Fitch Creek
- Site 02: EFDC upstream of Intermediate Open Cut
- Site 01: EFDC downstream of Intermediate Open Cut

The creeks entering the Rum Jungle mine site are characterized by circum-neutral pH and low levels of major ions and dissolved metals. Hence these creeks are not impacted by ARD and reflect background surface water quality. In the East Finniss River, concentrations of SO$_4$ and dissolved metals increase and pH decreases after it flows past Dysons Overburden and (backfilled) Dysons Open Cut. Water quality at this location is only moderately-impacted by seepage from mine waste.
units though, as the concentrations of key ARD indicator species remain much lower than in seepage (Table 2-4).

In the EFDC downstream of Whites Overburden Heap (at Station 3), surface water is highly-impacted by seepage from the nearby waste rock heap (i.e. at Stations 4 and 5). Concentrations of $\text{SO}_4$ and dissolved metals are particularly high at the end of the dry season. This likely indicates a larger relative contribution by impacted groundwater to the creek during baseflow conditions due to less dilution by seasonal stream flow but additional data would be needed to confirm this hypothesis.

Further downstream at Station 2, surface water in the EFDC appears to be more impacted by ARD than surface water at Station 3 (i.e. 7,190 mg/L $\text{SO}_4$ and dissolved metals concentrations in the tens of mg/L during the dry season). This is consistent with findings from Moliere et al. (2007), wherein the potential for groundwater discharge from the waste rock heap area adjacent to the EFDC was highlighted. Specifically, Moliere et al. (2007) considered an input of highly-impacted seepage from the toe of the Intermediate Overburden Heap to be most likely although this hypothesis could not be tested with rigor due to a lack of groundwater quality data at that time.

A sample collected from bore RN023057 in April 2009 indicates that shallow groundwater near the Intermediate Overburden Heap is highly-impacted by ARD and hence the discharge of groundwater from this area to the EFDC could represent a potential source of ARD products. Nonetheless, surface runoff directly from the Intermediate and Whites Overburden Heaps also represent sources that have not yet been constrained. Given the near two-fold discrepancy between estimated and observed metals loads to the EFDC at Station 2 (Moliere et al., 2007), the issue of relative load contributions by groundwater and surface water in the area upstream of this station is critical to future rehabilitation planning and hence will likely require more study (i.e. additional sampling and possibly drilling).

Surface water exiting the Rum Jungle mine site at Station 1 shows a relatively modest impact by ARD (Table 2-4). $\text{SO}_4$ concentrations are less than 1,000 mg/L at Station 1 and pH is circum-neutral. The near-neutral pH causes very low Al concentrations at this location (i.e. near background levels) whereas less pH-dependent metals like Cu, Co, Mn, Ni, and Zn remain elevated. The rapid improvement in water quality between Stations 1 and 2 is very likely caused by the inflow of well-buffered water from the Intermediate Open Cut (which occurs via a channel immediately downstream of Station 2). Note also that the highest-yielding bore at the Rum Jungle mine site (bore RN022108) is located between the Intermediate Open Cut and the East Finniss River at Station 1 suggesting significant aquifer permeability in this area. Hence, discharge of well-buffered groundwater (possibly recharged by the Intermediate Open Cut) may also contribute to the improvement in stream water quality between Stations 1 and 2.
3 DATA GAP ANALYSIS

Based on our initial data review (see Section 2) we have identified numerous data gaps in the areas of groundwater flow characterization and contaminant transport at the Rum Jungle mine site. Specifically, deficiencies in following areas were identified:

- Site geology & 3D geometry
- Aquifer characterization
- Groundwater flow conditions
- Contaminant source characterization
- Spatial extent of groundwater contamination
- Contaminant load balance & geochemical controls on transport

Each of these areas is critical to developing a rehabilitation plan for the Rum Jungle mine site and hence is discussed separately in the sub-sections below.

3.1 SITE GEOLOGY & 3D GEOMETRY

The Rum Jungle mine site is characterized by a complex, three-dimensional geology including folded and faulted lithological units and numerous structures (faults, fractures) that are believed to influence groundwater flow and contaminant transport. Yet, to the best of our knowledge a 3D geological model that allows visualization of this complex geology has not yet been developed for the Rum Jungle mine site.

The lack of a 3D geological model of the Rum Jungle mine site is considered a significant data gap because it limits the ability to conceptualize groundwater flow at the site and to fully interpret the monitoring data from the existing network of monitoring bores. It is therefore recommended that such a geological model be developed for the Rum Jungle mine site (see Section 4).

Ideally, the 3D geological model should not only include major lithologies and structural elements but also all surface topography, existing mine features (overburden heaps, open cuts, underground workings) and the network of existing monitoring bores (all in 3D). Such a comprehensive 3D model of the Rum Jungle mine site would aid considerably in the interpretation of groundwater quality data and the limited hydraulic testing data that is currently available. Moreover, it would also assist in deciding where additional bores should be installed and which hydrogeological features/lithologies at the site require additional hydraulic testing.

A better spatial representation of the bore network vis-à-vis the lithological units and structural features would also aid in determining which bores should be flow-tested or if additional, purpose-
drilled bores are necessary. Finally, a 3D geological model would assist in the development of a conceptual and numerical model of the site (see below).

### 3.2 AQUIFER CHARACTERIZATION

A review of drilling information and hydraulic testing (initial bore yields, constant-discharge tests) indicates large variations in hydraulic properties (transmissivity, storage properties) of the local aquifer system. Although some of this variation can undoubtedly be attributed to differences in the lithology, other factors such as degree of weathering, structural controls and/or karst formation likely contribute significantly to the observed aquifer heterogeneity.

Considering the complexity of the aquifer system(s) at Rum Jungle, the extent of available aquifer characterization is considered inadequate for rehabilitation planning. Specifically, data gaps in the following key areas of aquifer characterization were identified:

- Hydraulic characterization of various rock types and/or unconsolidated sediments
- Potential changes in rock porosity due to chemical leaching (i.e. secondary porosity)
- Hydraulic characterization of local and regional structures (fractures, faults)

Each of these data gaps is discussed briefly in the subsections below:

#### 3.2.1 Hydraulic Characterization of Rock Types & Overburden Heaps

Groundwater flow at the Rum Jungle mine site occurs in shallow laterite and deeper carbonates of the Coomalie and Whites Formations but reliable information on (primary) hydraulic characteristics of these units is not available. Also lacking is confirmation that karstic formations (i.e. sinkholes, etc) are present in local bedrock and if so, whether these features affect local storativity/transmissivity. Limited data is also available on what lithologies at the site act as aquitards and/or aquicludes (i.e. granites) and whether the assumption of unconfined conditions across the site is valid.

#### 3.2.2 Potential Changes in Porosity due to Chemical Leaching

No information is available on how the prolonged exposure of local lithologies to acidic, high-\( \text{SO}_4 \) waters has altered the effective permeability of the carbonate bedrock although some changes in secondary porosity are expected. At a highly-impacted historic mine site like Rum Jungle, the lack of information on secondary porosity represents a significant data gap because rocks situated along preferred flowpaths would be the most affected by chemical leaching and contaminant transport is expected to continue along these flowpaths in the future.
3.2.3 Hydraulic Characterization of Structural Features

Limited to no information is currently available on the hydraulic properties of structural features known to be present at Rum Jungle, including regional faults such as the Giant’s Reef Fault as well as other NE-SW trending faults associated with the local syncline and smaller N-S trending faults and fractures zones.

This lack of hydraulic characterization of structural features represents a significant data gap at the Rum Jungle mine site. These faults are critical to understanding groundwater flow and contaminant transport at the site because of their potential to act as either hydraulic barriers to flow or preferential pathways for groundwater flow/contaminant transport.

The Giant’s Reef Fault, for instance, could act as a hydraulic barrier to flow between the Rum Jungle Complex and the adjacent Mount Partridge Group, whereas other NE/SW trending structures (associated with the mineralized syncline) could act as a conduit for contaminant transport towards the East Finniss River.

3.3 GROUNDWATER FLOW CONDITIONS

3.3.1 Conceptual Flow Model

Our initial review of earlier hydrogeological studies at the site (Section 2) suggests that the conceptual model of groundwater flow at the Rum Jungle mine site is poorly developed. Data gaps in the conceptual model include significant uncertainty about:

- The type and spatial extent of major aquifer unit(s) and the influence of geological structures (faults, fractures, discontinuities etc) on groundwater flow;
- The magnitude of recharge to the bedrock aquifer (from the various mine waste units and undisturbed areas),
- The direction of groundwater flow in three dimensions (i.e. horizontal and vertical hydraulic gradients); and
- The interaction of groundwater and surface water, including flooded and/or backfilled open cuts and the East Finniss River;

To illustrate the lack of a conceptual model, consider the following three fundamental questions on groundwater flow which cannot be answered with the existing data:

- What is the overall direction of regional groundwater flow near the site and does it generally follow topography? If not, what hydrogeologic features and/or processes affect the flow of groundwater into and out of the site?
What is the effect of the major mine waste units (i.e. Overburden Heaps) and Open Cuts on local gradients (vertical and horizontal) and are there seasonal changes in hydraulic gradients due to preferential/transient recharge in the wet season?

How does local groundwater interact with the East Finniss River within and downgradient of the site? In other words, does groundwater discharge to the Finniss River or is local groundwater recharged by the river? Are there seasonal differences in groundwater-surface water interaction?

The monitoring bore network at the Rum Jungle mine site is extensive but most bores are screened in shallow parts of local aquifers (< 3 m) near mine waste units. Hence there is considerable lack of information on groundwater in deep bedrock and in the vicinity of the East Finniss River (upgradient and downgradient of the site). Moreover, groundwater level monitoring is usually undertaken near the end of the wet season when water levels at the site are high enough to be measured in existing bores. A sizeable data gap therefore exists due to poor spatial and vertical coverage of the existing network of monitoring bores.

Additional site characterization work (drilling, hydraulic testing and groundwater monitoring) will be required to fill this critical data gap (see Section 4).

3.3.2 Numerical Flow Model

According to DoR, a preliminary numerical groundwater flow model has been developed by ERISS (M. Fawcett, pers. comm.). However, this flow model was not available for our initial data review. Nevertheless, it is our understanding that this model is preliminary in nature and may not be adequate for rehabilitation planning.

In our opinion, the lack of a detailed numerical model of groundwater flow for the Rum Jungle mine site is an important data gap. The development of a numerical model of groundwater flow provides an opportunity to synthesize all existing site characterization and monitoring data and provides a good check on the validity of the conceptual model and water balance for the site. Furthermore, once calibrated, such a model will also allow an assessment of alternative rehabilitation options for the Rum Jungle mine site (i.e. relocation of mine waste units, cover placement, and/or seepage interception). In our opinion, the development of a numerical groundwater flow model for the Rum Jungle mine site is an important component of future rehabilitation planning (see Section 4).

3.4 Contaminant Source Characterization

Historic and ongoing seepage from the various mine waste units at the Rum Jungle mine site has resulted in wide-spread contamination of local groundwater and surface water. Earlier studies have focused primarily on seepage from the three Overburden Heaps (and in particular Whites and
Dysons) yet seepage from the backfilled and/or flooded Open Cuts and residual contamination from rehabilitated areas (e.g. Old Tailings Dam, copper heap leach pad) may also represent significant contaminant sources to groundwater.

Seepage from Whites and Dysons Overburden Heaps is currently sampled as part of routine surface water monitoring but it is unclear to RGC whether these samples represent pure seepage or seepage that has been diluted somewhat by mixing with receiving groundwater. Moreover, the representativeness of seepage samples has not been verified by a comprehensive survey of seepage rates and seepage water quality across the site (i.e. opportunistic/spot sampling and not just sampling at a single location).

Similarly, it is unclear whether seepage from the backfilled Dysons Open Cut (collected at surface) is representative of pore water in the backfilled Open Cut which may represent a major source of contamination to the local groundwater.

It is also unclear whether the observed poor water quality observed in the deeper portion of the Whites Open Cut represent residual contamination (from historic operations) or whether these contaminants are leached from the (now flooded) tailings or are caused by “throughflow” of contaminated groundwater. Finally, little information is currently available on the residual contamination (dissolved in groundwater and/or sorbed on soils) in the rehabilitated footprint areas of the now relocated old tailings and the copper heap leach pad.

In our opinion, additional source characterization (sampling and geochemical assessment) will be required to assess the “source terms” for a load balance model (see Section 4).

### 3.5 Spatial Extent of Groundwater Contamination

Historic and ongoing seepage from the various mine waste units, including mine waste rock piles ("Overburden Heaps"), backfilled or flooded open cuts, as well as the historic tailings impoundments and copper leach pads, has resulted in significant groundwater contamination at the Rum Jungle mine site. Despite the installation of over 60 monitoring bores at the site (see Figure 2-8) the spatial extent of the groundwater contamination is currently not well understood.

A review of installation details indicates that the majority of groundwater monitoring bores (about 40) represent very shallow bores (typically less than 3 m deep) which only monitor very shallow subsurface flow (often seasonal only). Considering the large footprint area impacted by mine waste seepage and the (inferred) aquifer heterogeneity of the fractured bedrock the number of monitoring bores screened in fractured bedrock (about 20) is not adequate to properly define the spatial extent of groundwater contamination.
Of particular concern is the general lack of groundwater monitoring bores (i) downgradient (north) of the Rum Jungle mine site, (ii) in immediate vicinity of the East Finniss River and (iii) in deeper bedrock on the site. A better delineation of the spatial extent (including depth) of groundwater contamination and associated contaminant load stored in the aquifer system (dissolved in groundwater and sorbed on the solids) is considered an important requirement for assessing long-term performance of completed rehabilitation works and the need for additional, future rehabilitation (see Section 4).

### 3.6 Contaminant Loading to Receiving Groundwater & The Finniss River

Several studies have attempted to quantify the contaminant loads from known contaminant sources (e.g. Whites and Dysons Overburden Heaps) to the groundwater and ultimately the East Finniss River (Lawton and Overall, 2002a) but load estimates from these studies have typically been considerably lower than contaminant loads measured in the East Finniss River itself (Kraatz, 2004).

The discrepancy between load estimates to the Finniss River could be the result of an underestimation of contaminant loading from the major contaminant sources (i.e. waste rock heaps) or higher than expected contaminant loads from other sources (like the Open Cuts or old tailings). Geochemical characterization of the different contaminant sources and quantification of their contaminant loads to groundwater and/or the Finniss River is considered critical to the assessment of alternative rehabilitation strategies for the Rum Jungle mine site.

An important data gap in the context of contaminant loading is the lack of a detailed (synoptic) survey of stream water quality along the East Finniss River during different flow conditions. Such a detailed survey, if combined with flow measurements, would provide a means to estimate contaminant loads to the river and identifying specific areas of contaminant loading (see Section 4).

Based on our review of the existing studies the issue of geochemical controls on contaminant transport has also not received adequate attention. The following geochemical controls are likely influencing contaminant transport at Rum Jungle:

- Metal attenuation (sorption, precipitation) along the flow path, in particular in those areas where carbonate rocks provide neutralization of acidic seepage from the mine waste units;
- Potential increase in secondary permeability due to dissolution of carbonate/dolomite bedrock by acidic mine waste seepage;
- Potential increase in secondary permeability due to dissolution of carbonate/dolomite bedrock by sulphate-rich groundwater (“de-dolomitization” effect);
- Acidification of local groundwater due to depletion and/or coating of acid-neutralizing bedrock along the flow path.
Metal attenuation often has a beneficial influence during the early stages of mining by delaying transport of metals in groundwater along the leading edge of the contaminant transport. However, metal sorption/precipitation processes may also delay the decrease in dissolved metal concentrations in groundwater following load reduction (after rehabilitation works) provided those geochemical processes are fully or partially reversible.

The long-term passage of acidic seepage waters through carbonate/dolomite bedrock may also result in a change of secondary permeability due to dissolution, in particular along preferential flow paths such fractures where small increases in surface area can result in significant increases in transmissivity. A related aspect of long-term exposure to acidic seepage is the potential for gradual depletion of the neutralizing capacity of the local bedrock (by depletion and/or coating).

In our opinion, the geochemical controls discussed above may significantly influence long-term contaminant transport at the Rum Jungle mine site (and loading to the Finniss River) and should therefore be studied in more detail prior to finalizing additional rehabilitation measures for the site (see Section 4).
4 RECOMMENDATIONS FOR FUTURE WORK

This report summarizes an initial data review conducted by RGC and highlights numerous data gaps related to groundwater flow and contaminant transport that are critical to developing an effective rehabilitation plan for the Rum Jungle mine site.

Based on our initial review we recommend that any further study of the hydrogeology of the Rum Jungle mine site proceed via the following stages:

- Detailed Data Review & Workplan Development
- Field Program
- Groundwater Flow Modeling & Contaminant Load Balance Assessment

The likely scopes of each stage are briefly outlined in the sub-sections below.

4.1 DESKTOP REVIEW & WORKPLAN DEVELOPMENT

This stage would involve an in-depth review of relevant hydrogeological data and thereby provide the basis for developing a detailed scope of work for additional drilling and fieldwork. This stage includes the development of a 3D geologic model, a comprehensive review of site hydrogeology, a detailed review of geochemical data, and the development of a preliminary flow and load balance model.

4.1.1 Hydrogeological Review & Conceptual Model

Initially, a detailed review of exploration drill logs, geological maps and cross-sections, monitoring bore logs, and structural geology should be completed with an emphasis on describing the local hydrogeology of the Rum Jungle mine site. This review will enable the development of a three-dimensional geologic ‘model’ (in GMS software) to visualize local lithologies, structural features & the existing monitoring bore network in 3D.

A preliminary conceptual model of groundwater flow at the Rum Jungle mine site should then be developed to aid in subsequent data interpretation and workplan development. This preliminary model would include:

- site reconnaissance & inspection of all existing groundwater bores; comprehensive water level survey during dry season; determine number and locations of additional monitoring bores to be drilled;
- detailed review of historical mine dewatering (if available), analysis of existing pumping test data, and recent dewatering of Browns oxide project; determine requirements for additional hydraulic testing of main aquifer units;
assess structural controls on local groundwater flow and discharge to the East Finniss River, including review of information on regional faults (i.e. Giant’s Reef Fault) and local structural features (faults, fractures, discontinuities) as well as occurrence of karst in local bedrock; determine requirements for additional characterization of structural features (drilling and/or hydraulic testing);

assess groundwater-surface water interaction at the Rum Jungle mine site, i.e. groundwater discharge/recharge into flooded Open Cuts and into the East Finniss River/Diversion Channel and potential seasonal variations; determine the required frequency of surface and groundwater monitoring (water levels and water quality);

develop a preliminary water balance for the local groundwater system, including recharge from local precipitation, mine waste seepage and regional groundwater inflow and discharge from the site via groundwater flow and/or discharge to the flooded Open Cuts and/or the East Finniss River;

4.1.2 Detailed Geochemical Review

This stage consists of a comprehensive review & interpretation of all available groundwater/surface water quality for the Rum Jungle mine site. The objective is to better constrain sources of contaminants to groundwater and the East Finniss River/Diversion Channel and would likely include the following tasks:

site reconnaissance & inspection of all existing surface water stations (creeks and seeps); detailed survey of stream water quality along East Finniss River/Diversion Channel & comprehensive sampling of groundwater quality during the dry season; determine requirements for additional surface and/or groundwater monitoring stations to be sampled for water quality;

review of historical mining practices, source characterization studies and rehabilitation works; determine historical and current contaminant sources (water quality) to groundwater and the East Finniss River;

assess historical migration of contaminants in groundwater; evaluate past, current and potential future geochemical controls (neutralization, sorption, precipitation) on contaminant migration at Rum Jungle;

review earlier contaminant load balance studies, including estimates of contaminant loading to the East Finniss River; determine validity of earlier load balance estimates and requirements for future monitoring of surface water and groundwater quality (locations, frequency) for load balance modeling;
4.1.3 Preliminary Flow and Load Balance Models

Upon completion of the hydrogeological and geochemical reviews mentioned above, it would be beneficial to develop preliminary flow and load balance models for the Rum Jungle mine site. Development of these models would help identify inconsistencies in the conceptual model and thereby focus subsequent field studies and drilling.

4.1.4 Detailed Workplans

The detailed hydrogeological and geochemical reviews and preliminary flow and load balance models should be summarized in a report that also contains the exact number and locations of new monitoring bores to be drilled, bores to be hydraulically tested, and sampling locations. The initial data review provided in this report enables some preliminary estimates of the scope of the field work that would be required to fill the data gaps identified in Section 3.

4.1.4.1 Drilling Program

The initial data review indicates that additional monitoring bores will likely be needed in the following areas:

- Upgradient of White’s Overburden and east of Dyson’s Overburden
  These areas are likely unimpacted by ARD but additional, highly-productive bores are needed to establish background water quality conditions and groundwater levels upgradient of the Rum Jungle mine site
- Between White’s Open Cut and the Intermediate Open Cut (former copper heap leach pad)
  Groundwater close to White’s Open Cut appears to be highly-impacted by ARD but groundwater further downgradient appears unimpacted; several new wells (shallow and deep) would provide information on hydraulic gradients/groundwater flow direction in this area and hence aid in determining contaminant sources to groundwater
- Between Whites and Intermediate Overburden Heaps
  ARD-impacted groundwater in this area represents a potential source of contaminants to the adjacent East Finniss Diversion Channel but additional information on the extent of ARD impact, direction of groundwater flow in this area, and potential interaction between surface waters and groundwater is necessary to test this hypothesis
- In the East Finniss River valley downgradient of the site
  Particular emphasis should be placed on constraining groundwater quality conditions in the East Finniss River channel (in alluvial sediments and underlying fractured bedrock); this will help evaluate the interaction of surface water and groundwater and aid in the preparation of a contaminant load balance
In total, it is anticipated that about 4 to 6 shallow monitoring bores (less than 5 m depth) (near the East Finniss River), 8 to 10 intermediate monitoring bores (15 – 30 m depth), and 4 to 6 deep monitoring bores (~50 to 60 m depth) will be required. It is anticipated that bore holes will likely be drilled with direct circulation (DC) air-rotary with down-hole percussion hammer (150 to 165 mm bit). Note, however, that drilling in fluvial sediments and/or karstic bedrock may require the use of casing advance. All monitoring bores will likely be completed as single monitoring bores (i.e. one piezometer per hole) using 80 mm-diameter PVC casing (to be confirmed).

4.1.4.2 Hydraulic Testing & Sampling Program

The hydraulic testing program will consist of slug tests and/or pumping tests on selected bores installed as per Section 4.2.1 plus any targeted hydraulic testing recommended in the Phase 2 report. At this point it is anticipated that up to twelve existing bores and/or newly drilled bores be selected for additional single-well hydraulic testing (slug testing and/or mini-pump tests). In addition, up to 3 “targeted” pumping tests may be conducted in monitoring bores intersecting known structures (e.g. the Giant’s Reef Fault, NW/SE trending fault(s), and/or N-S trending fault(s)). Finally, consideration will be given to performing longer-term pumping tests in one or two high-yielding bores at Rum Jungle to assess structural controls and hydraulic properties of the fractured bedrock aquifer system.

Each of the wells installed during the field program should also be sampled for water quality at this time, thereby filling any remaining data gaps and completing the dry season water quality survey begun during site reconnaissance.

4.2 GROUNDWATER FLOW MODELING & CONTAMINANT LOAD ASSESSMENT

At this point the conceptual hydrogeological model developed in previous stages should be refined and numerical flow modeling should be completed. Flow estimates will then be used to prepare a detailed contaminant load balance for the Rum Jungle mine site. Some of the specifics of numerical flow modeling and load balances are outlined below:

4.2.1 Numerical Flow Modeling

Numerical flow modeling will involve development of a three-dimensional groundwater flow model for the Rum Jungle mine site. The objectives of the numerical modeling of groundwater flow are as follows:

- Verify the conceptual model of groundwater flow at the Rum Jungle mine site;
- Estimate the amount of recharge from the various mine waste units (i.e. waste rock heaps, Open Cuts, former ‘tailings dam’, etc) to the local groundwater system;
Estimate the amount of groundwater entering the site & discharging to the East Finniss River (and underlying fluvial aquifer);

Assess alternative rehabilitation strategies (e.g. waste relocation, cover placement, seepage interception etc).

Model development will likely require the following steps:

Step 1: Construct a (simplified) numerical model that retains the salient features of the conceptual model;

Step 2: Calibrate the numerical model for ‘dry season’ (i.e. baseflow conditions) and the ‘wet season’ (i.e. active recharge) using observed groundwater water levels, seepage rates from mine waste units and streamflow in the East Finniss River;

Step 3: Use calibrated model to evaluate current seepage rates and predict future seepage conditions under different rehabilitation scenarios, and

Step 4: Carry out sensitivity analyses to evaluate the sensitivity of the model results to various model input parameters.

4.2.2 Load Balance Model

The results of the groundwater flow model (i.e. predicted rates of mine waste seepage and groundwater flow) will be integrated with water quality data to prepare a conservative contaminant load balance for the Rum Jungle mine site. At this point, the development of a 3D solute transport model for prediction of future contaminant transport is not anticipated although the potential benefit(s) of such a model for rehabilitation planning should be re-evaluated after completion of Phases 2 and 3.

4.2.3 Final Report on Hydrogeological Aspects of Rehabilitation Planning

The results of numerical modeling and load balance assessment should be provided to the DoR in the form of a final report on hydrogeological aspects of rehabilitation planning. The focus of this report should be on how different rehabilitation scenarios are expected to influence groundwater and surface water quality in the future and which of the scenarios is preferable in terms of final rehabilitation planning.
5 CLOSURE

Robertson GeoConsultants Inc. (RGC) is pleased to submit this report entitled Hydrogeological Study of Rum Jungle Mine Site - Initial Review & Data Gap Analysis - REV0.

This report was prepared by Robertson GeoConsultants Inc. for the use of NT Department of Resources.

We trust that the information provided in this report meets your requirements at this time. Should you have any questions or if we can be of further assistance, please do not hesitate to contact the undersigned.

Respectfully Submitted,

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