ENVIRONMENTAL PERFORMANCE ASSESSMENT FOR THE PREFERRED REHABILITATION STRATEGY, RUM JUNGLE

Submitted to:

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EXECUTIVE SUMMARY

General

This RGC Report 183006/7 entitled ‘Environmental Performance Assessment for the Preferred Rehabilitation Strategy, Rum Jungle’ was prepared for the Northern Territory (NT) Department of Mines and Energy (DME) by Dr. Paul Ferguson and Dr. Christoph Wels of Robertson GeoConsultants Inc. (RGC). Senior review was provided by Dr. David Jones of DR Jones Environmental Excellence. This report is a Stage 5 deliverable under RGC contract D14-0114 with the DME.

Current Rehabilitation Planning

DME has developed a preferred rehabilitation strategy for the former Rum Jungle mine site (‘Rum Jungle’). Rehabilitation objectives include achieving Locally Derived Water Quality Objectives (LDWQOs) for the East Branch of the Finniss River (EBFR). This will be achieved by substantially reducing inputs of Acid and Metalliferous Drainage (AMD) to groundwater and surface water.

The preferred rehabilitation strategy involves:

- Backfilling the Main Pit with the highest sulphide content Potentially Acid Forming (PAF) waste rock from Rum Jungle and Mt. Burton.
- Constructing a purpose-built Waste Storage Facility (WSF) to contain the remaining PAF waste rock, Non Acid Forming (NAF) waste rock, and tailings dredged from the Main Pit.
- Re-instating the EBFR near its former, pre-mining course with flows through the flooded Intermediate Pit.

Leachate from the WSF will be collected using a basal liner and diverted to the Intermediate Pit after rehabilitation is complete. The pH of leachate will be near-neutral due to the amendment of re-located waste rock with fine-grained limestone. WSF leachate will therefore contain low concentrations of most metals, such as copper (Cu), and high concentrations of dissolved sulphate (SO₄) and other major ions (e.g. magnesium, calcium). Residual, AMD-impacted groundwater will persist for some time after rehabilitation until existing contamination has been flushed from the groundwater system by rainfall infiltration and groundwater flows from upgradient.

Study Objectives and Scope

DME requested that RGC evaluate the degree and timing of future improvements in groundwater and surface water quality after the preferred rehabilitation strategy has been implemented. Study objectives are to:

- Simulate post-rehabilitation groundwater flow and contaminant transport at Rum Jungle.
- Predict concentrations of dissolved sulphate (SO₄) and copper (Cu) in the Intermediate Pit and the EBFR post rehabilitation.
- Recommend technical studies that may help refine prediction of post-rehabilitation conditions at the site and define effective monitoring strategies to assess the future performance of the rehabilitation.

To achieve these objectives, the following modeling tasks were completed:
• The previously-developed, transient numerical groundwater flow and transport model (“2016 model”) was adapted to simulate post-rehabilitation groundwater conditions for 30 years after rehabilitation. The “2016 model” is described in RGC Report 183006/6 entitled ‘Groundwater Flow and Transport Model for Current Conditions, Rum Jungle’ (RGC, 2016f).

• An Excel-based mixing model was developed to estimate post-rehabilitation SO₄ and Cu loading and concentrations in the Intermediate Pit and the EBFR.

Simulated Groundwater Flow Post Rehabilitation

The “2016 model” for current conditions was modified to reflect post-rehabilitation conditions, including re-location of the waste rock dumps (WRDs), backfilling the Main Pit, and construction of the WSF. The future groundwater flow field is predicted to differ from the current groundwater flow field in those areas where significant earthworks are planned:

• Backfilling of the Main Pit will significantly alter the local groundwater flow field in this area. During the dry season, groundwater is predicted to flow through the backfilled pit in a northwesterly direction with water levels ranging from 59 m AHD near the northwestern margin of the backfilled pit to 61 m AHD near the southeastern margin. During the wet season, groundwater is predicted to mound (to about 63.5 m AHD) into the domed fill of the backfilled Main Pit.

• Construction of the WSF is predicted to result in an overall decline of 1 to 3 m in seasonal groundwater levels beneath the facility due to significantly reduced recharge over the footprint of this lined facility.

Transport Model Setup

After rehabilitation, residual, AMD-impacted groundwater present in the shallow groundwater system (overburden and bedrock units) will become a diminishing source of SO₄, but will remain the main source of Cu to the EBFR. Additional sources of SO₄ and Cu loading will come from:

• Cu desorbing from contaminated soils and bedrock.

• Leachate from limed waste rock used to backfill the Main Pit below the water table.

• Leakage through the basal liner of the WSF (“basal seepage”).

SO₄ and Cu concentrations in leachate from the backfilled Main Pit and WSF are predicted to be 10,000 mg/L SO₄ and 200 µg/L Cu. These concentrations represent Saline Drainage (SD) being produced from neutralised waste rock. The simulated SO₄ and Cu concentrations for current groundwater conditions (RGC, 2016f) were used as initial concentrations in order to predict future, post-closure groundwater quality and contaminant loading to surface water.

Simulated SO₄ Transport in Groundwater After Rehabilitation

The predicted conditions for SO₄ transport in groundwater and loading to surface water after rehabilitation are summarized below:

• Residual SO₄ in shallow overburden soils (model layers 1 and 2) and shallow bedrock (model layer 3) beneath and downgradient of the former WRDs and other impacted areas (i.e. the Copper Extraction Pad area, Old Tailings Dam area) is predicted to clean up within 10 to 15 years due to flushing by local recharge. Residual SO₄ at greater depths in bedrock is predicted to flush more gradually.
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- A new \( \text{SO}_4 \) plume will develop downgradient of the backfilled Main Pit in less than 5 years:
  - In shallow overburden (layers 1 and 2) the new \( \text{SO}_4 \) plume is predicted to migrate in a predominantly northwesterly direction and discharge into the realigned EBFR channel.
  - In bedrock (layers 3 to 6) the new \( \text{SO}_4 \) plume is predicted to migrate preferentially into the Coomalie Dolostone to the north and from there in a southwesterly direction to the Intermediate Pit.
  - A secondary plume (with lower \( \text{SO}_4 \) concentrations) is also predicted to travel in Coomalie Dolostone from the backfilled Main Pit in a southwesterly direction towards the East Finniss Diversion Channel (EFDC).

- A small amount of leachate from the WSF is predicted to generate a new \( \text{SO}_4 \) plume in the Old Tailings Dam area within about 5 years. The \( \text{SO}_4 \) plume in shallow laterite beneath the WSF is predicted to discharge near the downgradient (western) toe of the new facility. The \( \text{SO}_4 \) plume in saprolite and shallow bedrock (layers 2 to 3) is predicted to extend from the toe of the facility to the Old Tailings Dam area and discharge to Old Tailings Creek. The \( \text{SO}_4 \) plume in deeper bedrock (layers 4 and 5) is predicted to extend to the lower East Branch of Finniss River.

- The total \( \text{SO}_4 \) load to surface water is predicted to decrease rapidly from about 1400 t/year (current conditions) to about 610 t/year (a 56% reduction) within 5 years after rehabilitation. The long-term \( \text{SO}_4 \) load to surface water from groundwater after 30 years is predicted to be 420 t/year representing a 70% reduction from current conditions.

- The \( \text{SO}_4 \) load from the backfilled Main Pit (309 t/year) is predicted to be the largest future long-term point source after rehabilitation at Rum Jungle, representing about 74% of the predicted total long-term \( \text{SO}_4 \) load. In contrast, the future \( \text{SO}_4 \) load from the WSF represents only about 15% of the predicted total long-term \( \text{SO}_4 \) load to surface water.

### Simulated Cu Transport in Groundwater Post Rehabilitation

For Cu transport, three different attenuation scenarios were considered for simulation of future conditions (see RGC, 2016f):

- ‘No Attenuation’ scenario (conservative transport).
- ‘Moderate Attenuation’ scenario (sorption in overburden and bedrock and chemical precipitation in dolostone plus copper removal in limed footprint areas).
- ‘High Attenuation’ scenario (sorption in overburden and shallow bedrock beneath WRDs and chemical precipitation in all bedrock lithologies plus Cu removal in limed footprint areas).

RGC considers the ‘moderate attenuation’ scenario to be the scenario that most closely represents current Cu transport at Rum Jungle (RGC, 2016f). The predicted, post-rehabilitation Cu transport for this scenario can be summarized as follows.

- The new waste storage facilities (backfilled Main Pit and WSF) will not represent a significant source of future Cu loads. As a result, residual Cu currently present in groundwater and sorbed to aquifer materials will continue to represent the primary source of future Cu loads to surface water.
- Removal of waste rock and contaminated WRD footprint area soils and liming of the residual footprints in Dysons Area (Dysons WRD and backfilled Dysons Pit) and the Main and Intermediate WRDs is predicted to result in very rapid cleanup of the footprint area (layer 1)
and gradual decline in Cu concentrations in the deeper saprolite (layer 2). However, flushing of residual Cu from the underlying bedrock (layers 3 to 6) is predicted to be very slow (much longer than 30 years).

- Cu concentrations in the deeper bedrock (layers 3 to 6) of the Copper Extraction Pad area (CEPA) are predicted to clean up very slowly (i.e. 30+ years due to desorption of Cu from bedrock. Note that Cu in seepage from backfilled waste rock (200 µg/L Cu) in the Main Pit is much lower than the residual Cu present in groundwater in bedrock in the CEPA. Hence, seepage from the backfilled Main Pit will tend to dilute the residual copper plume in the CEPA.

- Flows of leachate, and associated Cu load, from the WSF are too small to produce any significant Cu plume or Cu load to Old Tailings Creek and the lower EBFR.

- The total Cu load to surface water is predicted to initially decrease from 2.7 t/year (current conditions) to 1.3 t/year (a 50% reduction) within 5 years after rehabilitation. This initial reduction is primarily due to removal of above-grade and near-surface Cu sources (waste rock, contaminated soils and foundation material) and liming of the footprint areas.

- Longer-term reduction in Cu loads from groundwater to surface water will be a slow process because elevated Cu concentrations will be sustained by ongoing desorption from the rock substrate. The total Cu load to surface water after 30 years is predicted to be 1.0 t/year (a 63% reduction from current conditions).

Future Cu transport was simulated for the ‘no attenuation’ and ‘high attenuation’ scenarios to evaluate the sensitivity of predicted post-rehabilitation performance to uncertainty in geochemical controls. The influence of attenuation on future Cu transport can be summarized as follows:

- The conservative transport scenario ("No Attenuation") is predicted to result in rapid flushing of all residual Cu plumes, in particular in the shallow soils and shallow bedrock (similar to the case of sulphate described above). This scenario produces the highest Cu loads to surface water early on (Years 1 and 2) but Cu loads subsequently fall well below those predicted for the ‘moderate attenuation’ scenario. After 30 years, the Cu loads for the conservative scenario are predicted to have declined to 0.3 t/year. i.e. 70% lower than the Cu load predicted for the ‘moderate attenuation’ scenario.

- In the ‘no attenuation’ scenario, essentially all of the Cu load represents Cu initially stored in groundwater (‘residual plume’) that is gradually flushed from the aquifer. In contrast, in the ‘moderate attenuation’ scenario, a significant portion of the current total Cu load is gradually released via desorption from the solid phase. This desorption process accounts for the delayed flushing of the Cu plume and overall higher loads over the medium-term time frame to the surface water.

- The ‘high attenuation’ scenario is predicted to generate the lowest Cu loads to surface water throughout the modeling period by removing essentially all of the dissolved Cu load from bedrock except acidic shallow bedrock beneath the re-located WRDs. In this scenario, predicted Cu loads to surface water gradually fall from about 0.5 t/year in Year 1 to 0.15 t/year in Year 30. That is, 85% below the Cu load predicted at year 30 for the ‘moderate attenuation’ scenario.
Transport Model Sensitivity

A limited sensitivity analysis was completed to assess the influence of transport parameters on the predicted contaminant loads from groundwater to surface water. It was found that:

- **SO₄** transport is significantly influenced by the effective porosity. A higher effective porosity that is assigned to the rock units in the model. A twofold increase in effective porosity increases the total SO₄ mass to surface water by up to 65%.
- **Cu** transport and loads to surface water are not significantly influenced by the change in transport parameters. This lack of sensitivity is a result of the dominating control of chemical reactions assumed for the ‘moderate attenuation’ scenario. In other words, Cu transport is much more sensitive to the uncertainty in chemical attenuation than uncertainty in transport parameters.

Post-Rehabilitation Water Quality Conditions

The Intermediate Pit is predicted to receive 535 t/year SO₄ and 0.44 t/year Cu post-rehabilitation. Simulated, post-rehabilitation loads from groundwater are the largest sources of SO₄ and Cu to the pit (i.e. 60% of the SO₄ load and 93% of the Cu load). Leachate collected from the WSF accounts for 34% of the SO₄ load to the pit, but only 1% of the Cu load.

To simulate the precipitation of dissolved Cu from pit water, a 100 µg/L Cu solubility limit was applied. This concentration is based on (i) the solubility of Cu at near-neutral to alkaline pH conditions and (ii) observed pit water quality since 2010. About 36% (0.16 t/year Cu) of the Cu load that reports to the Intermediate Pit is predicted to precipitate from pit water if the 100 µg/L Cu solubility limit is applied. Most of this precipitated mass would remain in the pit as sludge, and the residual dissolved Cu load would report to the EBFR via outflows from the Intermediate Pit during the wet season.

Similarly, for the EBFR, solubility limits of 20 µg/L Cu and 50 µg/L Cu were applied during dry season and the wet season, respectively. These solubility limits are based on observation of dissolved Cu concentrations in the EBFR at GS8150097 (as too few dissolved Cu concentrations are available at GS8150327). Dissolved Cu concentrations at GS8150097 clearly suggest lower dissolved Cu concentration under lower flow conditions, possibly due to the predominance of particulate Cu under these conditions. Moreover, the data suggest an upper limit for dissolved Cu at the circum-neutral pH conditions in the EBFR (as per the solubility curve for Cu).

Predicted loads to the EBFR for 30 years post rehabilitation are summarized below:

- **For SO₄**, a load of 749 t/year SO₄ is predicted to report to the EBFR at gauge GS9150327. 72% (535 t/year) of the SO₄ load is delivered to the EBFR via the Intermediate Pit. This load is related to groundwater discharge to the Intermediate Pit and flows of leachate from the WSF (see above). 27% (202 t/year) of the load is related to the discharge of residual, AMD-impacted groundwater directly to the EBFR (mainly from the footprints of the Main WRD and Intermediate WRD). The remaining 1% is from upstream EBFR flows through the EFDC. 749 t/year SO₄ in the EBFR is about 60% lower than the ~1800 t/year SO₄ load that was observed in the EBFR from 2010 to 2015.
- **For Cu**, 1.06 t/year Cu is predicted to report to the EBFR at gauge GS8150327. 73% of this Cu load is related to residual, AMD-impacted groundwater that reports directly to the EBFR from the former footprints of the Main and Intermediate WRDs. 26% is delivered to the EBFR.
via the Intermediate Pit and 1% is from upstream EBFR flows through the EFDC. 50% of the Cu load to the EBFR (0.5 t/year Cu) reports to gauge GS8150327 in the form of dissolved Cu. This dissolved Cu load is about 60% lower than the dissolved Cu load in the EBFR at gauge GS8150327 from 2010 to 2015.

Assuming loads from the ‘high attenuation’ Cu transport scenario, 0.29 t/year Cu reports to the EBFR at gauge GS8150327. This load is only 27% of the Cu load from the ‘moderate attenuation’ scenario because Cu loads to the river from groundwater are much lower. These estimates indicate that post-rehabilitation Cu concentrations in the EBFR will be determined mainly by Cu loads from residual, AMD-impacted groundwater. The predicted load of dissolved Cu at gauge GS8150327 over the 30-year simulation period was 0.2 t/year (or 60% lower than the dissolved Cu load from the ‘moderate attenuation’ scenario).

Using the predicted SO$_4^-$ and dissolved Cu loads in the EBFR at gauge GS8150327, monthly (flow weighted) concentrations were computed to allow a comparison with LDWQOs. The key findings are summarized below:

- For the first 10 years after rehabilitation, the flow-weighted SO$_4^-$ concentration in the EBFR is 32 mg/L SO$_4^-$ This is less than 50% of the flow-weighted SO$_4^-$ concentration from 2010 to 2015 (and less than 3% of the 997 mg/L SO$_4^-$ LDWQO. After ten years, the flow-weighted SO$_4^-$ concentration in the river is 19 mg/L SO$_4^-$ or less.

- With respect to Cu, the annual, flow-weighted mean Cu concentration is predicted to be 18 µg/L for the first 10 years after rehabilitation (assuming the ‘moderate attenuation’ Cu transport scenario). This concentration is 56% lower than the flow-weighted mean Cu concentration at gauge GS8150327 since the gauge was installed in 2010, and 35% lower than the 27.5 µg/L LDWQO for Cu. From 10 to 30 years after rehabilitation, the flow-weighted Cu concentration in the EBFR decreases to 13 µg/L Cu, less than 50% of the LDWQO.

- Assuming the ‘high attenuation’ Cu transport scenario, the flow-weighted annual Cu concentration is predicted to be 8 µg/L for the first 10 years after rehabilitation. This concentration is 70% lower than the 27.5 µg/L LDWQO for Cu. From 10 to 30 years after rehabilitation, the mean flow-weighted Cu concentration decreases to less than 3 µg/L Cu.

**Recommendations**

The following technical studies are recommended for the next phase of the Rum Jungle Rehabilitation Project (see Section 5 for additional details):

- Determine the physical and geochemical properties of tailings from the Main Pit in order to estimate a geochemical source term for these tailings after they have been neutralized by addition of lime and placed in the new WSF.

- Complete additional laboratory testing and groundwater modeling to improve and expand water quality predictions:
  - Develop site-specific R$_f$ values for Cu and other metals for which there are LDWQOs (i.e. Mg, Al, Co, Fe, Mn, Ni, and Zn).
  - Update the contaminant transport model to reflect site-specific R$_f$ values for laterite and bedrock, and extend to scope of the transport modeling to include other contaminants for which there are LDWQOs (i.e. Mg, Al, Co, Fe, Mn, Ni, and Zn).
o Optimize, using the updated flow and transport mode, the design of Main Pit backfill with the aim to minimize contaminant loading to the re-aligned EBFR channel.

o Evaluate the effect of liming the former WRD footprints on future Cu transport (using laboratory testing and/or field trials).

- Use the groundwater model to evaluate water management of the Main Pit during rehabilitation and its effect on post rehabilitation water quality:
  o Evaluate the effect of Main Pit dewatering (required for backfilling of the pit) on groundwater flow and contaminant transport during rehabilitation.
  o Evaluate passive and ‘active’ re-flooding of the backfilled Main Pit and its effect on contaminant transport and loading to surface water post rehabilitation.

- Optimize the design of Main Pit backfill (placement of PAF vs. NAF or clean fill, barrier layers, etc.) with the aim to minimize shallow contaminant loading to the re-aligned EBFR channel using the updated flow and transport model.

- Develop a limnological model for the Intermediate Pit in order to refine the approach to seepage management post-rehabilitation (i.e. depth of seepage discharge, etc.).

A post-rehabilitation Adaptive Management Plan (AMP) should be developed for surface water quality. The different components of this plan would be implemented in the event that there are issues meeting LDWQOs. The AMP will contain “early warning” trigger values and changes to routine monitoring and management of pit water and surface water at gauge GS8150327 that will be associated with meeting key, post-rehabilitation Operation, Maintenance, and Surveillance (OMS) objectives. The post-rehabilitation groundwater monitoring program needs to be finalized. Figure 5-1 shows proposed groundwater monitoring locations near the WSF, former WRD footprints, and near the backfilled Main Pit.
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ENVIRONMENTAL PERFORMANCE ASSESSMENT FOR THE PREFERRED REHABILITATION STRATEGY, RUM JUNGLE

1 INTRODUCTION

1.1 GENERAL

This is RGC Report 183006/7 entitled ‘Environmental Performance Assessment for the Preferred Rehabilitation Strategy, Rum Jungle’. It was prepared for the Northern Territory (NT) Department of Mines and Energy (DME) by Dr. Paul Ferguson and Dr. Christoph Wels of Robertson GeoConsultants Inc. (RGC). Senior review was provided by Dr. David Jones of DR Jones Environmental Excellence. This report is a Stage 5 deliverable under RGC contract D14-0114 with the DME.

1.2 TERMS OF REFERENCE

The former Rum Jungle (Rum Jungle) is located 105 km by road south of Darwin in the headwaters of the East Branch of the Finniss River (EBFR). Rum Jungle was one of Australia’s first major uranium mines and produced approximately 3,500 tonnes of uranium and 20,000 tonnes of copper concentrate between 1953 and 1971 (Davy, 1975). Acid and Metalliferous Drainage (AMD) at the site has led to significant environmental impacts on local groundwater and the EBFR (Kraatz, 2004).

In 2009, DME was tasked with developing a comprehensive rehabilitation strategy for Rum Jungle. Scoping studies completed prior to 2009 suggested that local hydrogeology was poorly understood and that further study was needed prior to rehabilitation planning (Kraatz, 2004; Moliere et al., 2007). RGC was therefore retained in May 2010 to assist the DME with aspects of site rehabilitation planning that pertain to the contamination of groundwater and surface water by AMD and radionuclides.

Since 2009, DME has developed a preferred rehabilitation strategy for Rum Jungle. Rehabilitation objectives include achieving Locally Derived Water Quality Objectives (LDWQOs) for the EBFR. This will be achieved by reducing impacts to groundwater and surface water by AMD.

The preferred rehabilitation strategy involves:
- Backfilling the Main Pit with Potentially Acid Forming (PAF) waste rock, spent heap leach material, and contaminated soils from Rum Jungle and Mt Burton.
- Constructing a purposed built Waste Storage Facility (WSF) to contain the remaining PAF waste rock, Non Acid Forming (NAF) waste rock, and tailings dredged from the Main Pit.
- Re-instating the EBFR near its former, pre-mining course (and through the flooded Intermediate Pit).

Leachate from the WSF will be collected (using a basal liner) and diverted to the Intermediate Pit after rehabilitation is complete.

DME requested that RGC evaluate groundwater and surface water conditions after the preferred rehabilitation strategy has been implemented. Of particular interest is the timing of future improvements in groundwater quality at the site and future concentrations of key contaminants of concern in the EBFR. RGC completed this evaluation by adapting a transient numerical flow and transport model for groundwater that was calibrated to current conditions (2010 to 2015), and by developing an Excel-based mixing model to estimate SO\textsubscript{4} and Cu concentrations in the EBFR over 30 years after rehabilitation.

1.3 STUDY OBJECTIVES AND SCOPE

1.3.1 Study Objectives

Study objectives are to:
- Simulate groundwater flow and contaminant transport at Rum Jungle after the preferred rehabilitation strategy has been implemented.
- Estimate concentrations of dissolved sulphate (SO\textsubscript{4}) and copper (Cu) concentrations in the Intermediate Pit and the EBFR after rehabilitation.
- Discuss the implications of the simulated, post-rehabilitation conditions for future rehabilitation planning.
- Recommend technical studies that may help refine prediction of post-rehabilitation conditions at the site and determine how the future performance of the rehabilitation could be effectively monitored.

1.3.2 Scope of Work

To achieve these objectives, RGC completed the following:
- Adapted the transient numerical flow and transport model for current conditions to simulate post-rehabilitation groundwater conditions for 30 years.
• Developed a mixing model for the Intermediate Pit and the EBFR to estimate SO₄ and Cu concentrations in surface water after rehabilitation.

An assessment of potential water quality impacts to the Intermediate Pit and the EBFR during the construction phase of rehabilitation was beyond the scope of this report. These impacts are addressed in RGC, 2016d. Also, RGC has restricted their performance assessment to issues that pertain directly to residual Acid and Metalliferous Drainage (AMD) impacts and potential future impacts by Saline Drainage (SD) to groundwater and surface water.

1.4 REPORT ORGANIZATION

The remainder of this report is subdivided into the following sections:

• **Section 2. Background** describes the location and key features of Rum Jungle, and pertinent findings from previous studies.

• **Section 3. Simulated Groundwater Conditions after Rehabilitation** describes the methods and results of numerical modeling of groundwater flow and transport of SO₄ and Cu in groundwater after rehabilitation.

• **Section 4. Post-Rehabilitation Load Balances and Water Quality** describes water and contaminant load balances for the Intermediate Pit and the EBFR after rehabilitation.

• **Section 5. Findings and Recommendations** summarizes key modeling results, and their implications for future rehabilitation planning, and provides recommendations for additional studies and post-rehabilitation groundwater and surface water monitoring.

1.5 SUPPORTING RGC REPORTS

This report is one of several completed by RGC during the latest phase of rehabilitation planning for Rum Jungle. The results of these related studies are summarized in a series of reports which are listed below for ease of reference:


• RGC (2016c), Options Assessment for Pit Backfilling, RGC Report No. 183006/3.


• RGC (2016e), Groundwater Remediation Strategy for the former Copper Extraction Pad area, RGC Report No. 183006/5.

• RGC (2016g), Environmental Performance Assessment for the Final Rehabilitation Strategy, RGC Report No. 183006/7.

These reports provide important background information for this study (and vice versa) and this report should therefore be read in conjunction with these other reports.
2 BACKGROUND

2.1 RUM JUNGLE AND RELATED SITES

2.1.1 Overview – Rum Jungle

Rum Jungle is located 105 km by road south of Darwin near the town of Batchelor. The site covers 650 ha and is situated in an area of relatively flat relief that is bisected by ephemeral tributaries of the EBFR (namely, Fitch Creek and the upper EBFR) (Figure 2-1).

Fitch Creek flows next to the Main WRD, the largest of the historic WRDs, and the upper EBFR flows westward through Dysons Area (near the eastern boundary of the site). The EBFR joins the Finniss River about 8 km downstream of Rum Jungle. The Finniss River then flows west for about 60 km before discharging into Fog Bay about 65 km southwest of Darwin.

The confluence between Fitch Creek and the upper EBFR is located north of the Main WRD (near the Main North WRD). Under lower flow conditions, the combined flow from Fitch Creek and the upper EBFR flows through the East Finniss Diversion Channel (EFDC). Lower flow conditions occur at the beginning and the end of the wet season. Under higher flow conditions, most of the water in the EBFR flows through the Main and Intermediate Pits via engineered inlets and outlets (see Section 2.2.4 for additional details).

Currently, Rum Jungle features three mined-out pits, and four WRDs (Figure 2-1). The Main and Intermediate Pits are currently flooded with relatively clean water (see Section 2.4.1). Dysons Pit was partially backfilled with tailings during operations, and then additionally backfilled with tailings from the Old Tailings Dam area, contaminated soils, and spent heap leach material in the 1980’s (see Allen and Verhoeven). Dysons (backfilled) Pit and Dysons WRD are located in ‘Dysons Area’ near the eastern site boundary.

Dysons Area is located about 1 km east of the central mining area to the north of the upper EBFR. The central mining area contains the Main and Intermediate Pits, the Main and Intermediate WRDs, and the Copper Extraction Pad area. The Copper Extraction Pad area is the location of a former heap leach pad that was operated between the Main and Intermediate Pits from 1965 to 1971 (see Section 2.4.4 for additional details). North of the central mining area is the Old Tailings Dam area, a flat area where tailings produced while mining the Main and Intermediate ore bodies were discharged into a series of small impoundments near Old Tailings Creek (see Section 2.4.5).

2.1.2 Satellite Sites

In 2011, the current NPA was extended to include Rum Jungle Creek South, Mount Burton, and Mount Fitch (see DME, 2013). Historically, ore from Rum Jungle Creek South and Mount Burton were
trucked to Rum Jungle for milling and processing. Some key aspects of these sites are summarized here:

- Rum Jungle Creek South is located about 5 km south of Rum Jungle. Rum Jungle Creek South was mined for uranium from 1961 to 1963. 2000 t of uranium oxide was produced, or 60% of the total concentrate produced by the processing plant at Rum Jungle. Tailings produced from milling ore from Rum Jungle Creek South were hydraulically-placed in the Main Pit. Since being mined, the Rum Jungle Creek South pit has flooded, and it was declared a Recreational Reserve in 1973 (see DME, 2013, for additional details).
- Mount Burton was a small mine located downstream of Rum Jungle about 3 km from the confluence between the EBFR and the Finniss River. The deposit there was mined out in 1958.
- Also mined in 1958 was the Main (extended) deposit that lies between the Main ore body and Dysons ore body. Waste rock from this pit was placed in the Main North WRD – this small WRD is located near the EFDC (and beneath the main access road to the site) (Figure 2-1).
- In 1968, some exploration was done at Mount Fitch, but this deposit was never mined (see DME, 2013).

2.2 PHYSICAL SETTING

2.2.1 Climate

Rum Jungle is characterized by a tropical wet-dry monsoonal climate. Mean annual precipitation (MAP) is 1459 mm (all of which occurs as rainfall). More than 90% of MAP occurs during a distinct wet season that lasts from November to April (Figure 2-2). Mean monthly maximum temperatures at the Batchelor Airport range from 31°C in June to 37°C in October (during the ‘build up’ to the wet season).

2.2.2 Regional Geology

Rum Jungle is situated in the central to western part of the Pine Creek Orogen in northern Australia. According to Plumb (1979), the Pine Creek Orogen covers an area of 66,000 km² and forms the northern margin of the North Australian Craton. It is comprised of sequences of carbonaceous, clastic, and volcanogenic sediments deposited upon rifted Archean crystalline basement (see Worden, 2006, and references therein).

According to McCready et al. (2004), the area around Rum Jungle features two dome-like Archean basement highs – the Rum Jungle Complex and the Waterhouse Complex. Both complexes consist primarily of granitic intrusions that are now overlain by a Paleoproterozoic sequence of meta-sedimentary and subordinate meta-volcanic rocks called the Mount Partridge Group.
The Mount Partridge Group consists of repetitive clastic-carbonate sequences of the Namoona Group (see McCready et al., 2004 for additional details). From oldest to youngest, the three major formations of the Mount Partridge Group are:

- **Crater Formation**: coarse and medium-grained siliciclastics (e.g. sandstone).
- **Coomalie Dolostone**: magnesite and dolomite with minor chert lenses.
- **Whites Formation**: graphitic, sericitic, chloritic, and calcareous slate-phyllite-schist.

The Mount Partridge Group has been folded, faulted and metamorphosed to greenschist facies, but the original stratigraphic succession has been preserved (McCready et al., 2004). Brittle fracture associated with deformation produced a number of faults, some of which follow the northeast-southwest structural trend in the area. Protorezoic-age Geolsec Formation lies unconformably over the Mount Partridge Group and consists of hematite quartzite breccia (Ahmad et al., 2006).

### 2.2.3 Local Geology

Rum Jungle is situated in a triangular area of the Pine Creek Orogen that is defined by the Giant’s Reef Fault to the south and by east-trending ridges of the Crater Formation to the north (Figure 2-3). This triangular area is known as ‘The Embayment’, and it lies on the shallow-dipping limb of a northeast-trending, southwest-plunging asymmetric syncline cut by north striking faults.

Each of the polymetallic ore deposits within The Embayment occurs within the Whites Formation near its contact with Coomalie Dolostone. Deposits are strongly associated with fault zones (and hence structurally controlled). Specifically, ore was deposited in carbonaceous slates by selective replacement along shear zones that intersect local faults (Ahmad et al., 2006). Whites Formation occurs within the central mining area (near the pits) and in Dysons Area. Most of the bedrock to the north of the central mining area is Coomalie Dolostone, and bedrock to the south of the Giant’s Reef Fault is granite of the Rum Jungle Complex.

Near surface, *in situ* lateritization has occurred since the early Mesozoic era and Tertiary period and as such deeply-weathered soil profiles are present over much of Rum Jungle. Laterite tends to occur above the Coomalie Dolostone, whereas saprolite is more common in areas where the predominant bedrock type is Geolsec Formation or Rum Jungle Complex. Alluvium occurs near Fitch Creek and the upper EBFR. Unconsolidated sediments also occur in the EFDC, but they are relatively thin and discontinuous.

### 2.2.4 Hydrology

The EBFR flows through the central mining area of Rum Jungle. River flows vary predictably in response to intra-annual variability in rainfall (and typically vary by several orders-of-magnitude over the course of a year) (Figure 2-4). Early wet season flows in the river (or ‘first flush’) are usually
observed in early December or January in response to high-intensity rainfall events that can occur during the early wet season. Sustained flows in the EBFR typically occur by mid-January and continue until the end of May with peak flows usually occurring in February or March. No appreciable flow is observed from June to November due to minimal rainfall.

The EBFR was diverted to allow open pit mining of the Main and Intermediate ore bodies. Peak river flows are currently routed through the Main Pit and the Intermediate Pit (which are connected by a shallow channel through the Copper Extraction Pad area) (see Section 2.3.1). Non-peak flows are diverted through the EFDC, which was incised into bedrock and laterite to allow mining from the Main Pit (and later the Intermediate Pit). Surface water enters the site from the east via the upper EBFR (which flows through Dysons Area) and from the southeast via Fitch Creek (see Section 2.1.1).

The Old Tailings Dam area is drained by a small ephemeral creek known as Old Tailings Creek. Old Tailings Creek reports to the EBFR about 1.5 km downstream (northwest) of the central mining area. During the wet season, low-lying parts of the site, including the Old Tailings Dam area, are often flooded. Water ponds in some areas due to groundwater discharge and surface water flows.

Flows (and water quality) in the EBFR are currently monitored at gauges GS8150200, GS8150327, and GS8150097. Some key features of these gauges:

- Gauge GS8150200 drains an area of 53 km² that includes the central mine area and Dysons Area, but does not capture flows from Old Tailings Creek. This gauge was established in 1991 and has since been used to monitor flows and water quality conditions in the EBFR (Lawton and Overall, 2002a).
- Gauge GS8150327 is located downstream of Old Tailings Creek about 2.5 km downstream of gauge GS8150200. This gauge was installed by the DME in 2010, and it captures flows from the entire Rum Jungle site (i.e. Dysons Area, the central mining area, and the Old Tailings Dam area).
- Gauge GS8150097 is located about 8 km downstream of Rum Jungle. Gauge GS8150097 has long been considered the principal compliance point for surface water monitoring, and has therefore been monitored almost continuously since 1964 (Davy, 1975).

Water quality (and flows) have also been sporadically monitored at Dysons gauge along the upper EBFR. Historic flow data (from the 1990s) are available for gauge GS8150213 (at the inlet to the Main Pit). Flows from the Intermediate Pit (at gauge GS8150212) were also monitored at that time. Flows at gauge GS8150212 was also monitored during the 2010/2011 wet season before the flow monitoring equipment was destroyed by a fire (M. Greally, personal communication).
2.2.5 Hydrogeology

Shallow groundwater flows in unconsolidated hydrostratigraphic units, including weathered soils (i.e. laterite and saprolite) and alluvium near the creeks and the EBFR. These materials are underlain by various bedrock lithologies, including the Rum Jungle Complex, Coomalie Dolostone, Whites Formation, and the Geolsec Formation. The primary permeability of bedrock tends to decrease with depth (as bedrock becomes more competent). The Rum Jungle Complex (and Geolsec Formation) are characterized by lower hydraulic conductivity (K) than the Coomalie Dolostone. Local aquifer heterogeneity (due to fracturing, weathering, etc.) is considerable, so K values vary substantially within a particular hydrostratigraphic unit (see RGC, 2016f, for further details).

Groundwater levels are typically located within 10 m of ground surface in the dry season, and can approach ground surface in low-lying areas of the site during the wet season. Groundwater at Rum Jungle generally flows towards the EBFR and its tributaries (as they are natural groundwater discharge zones).

In the central mining area, the local groundwater flow regime is affected by the WRDs and the flooded Main and Intermediate Pits. The WRDs are zone of preferential recharge to groundwater (as rainfall infiltration rates are higher than natural ground, and the WRDs tend to store water infiltrating into the WRD). The flooded pits often represent sources of recharge to groundwater during the dry season and receive groundwater inflows during the wet season (depending on the pit water elevation compared to surrounding groundwater elevations).

2.3 SITE HISTORY

2.3.1 Initial Discovery and Ownership

In 1949, uranium mineralization near Rum Jungle was first reported by a local farmer, J.M. White. Subsequent drilling investigations confirmed the Dysons uranium deposit, and the polymetallic Main and Intermediate ore bodies. In 1952, the Commonwealth provided the funds to set up the mine and the treatment plant needed to provide uranium oxide concentration to the UK-US Combined Development Agency (CDA) (Mulligan, 1999).

In 1953, Consolidated Zinc Pty Ltd. (now a part of Rio Tinto) set up a company called Territory Enterprises Pty Ltd to manage the development and operation of Rum Jungle as an agent of the Commonwealth Government (Allen and Verhoeven, 1986). Territory Enterprises Pty Ltd managed the mine under contract to the Australian Atomic Energy Commission (AAEC) (now ANSTO) (see DME, 2013 for additional details).
2.3.2 Historic Mining Operations

Large scale mining operations at Rum Jungle began in 1953 and were completed by 1971. The mine had a processing plant near the Main Pit that processes ore from the Main, Intermediate, and Dysons ore bodies, as well as ore from Rum Jungle Creek South and Mount Burton.

According to the World Nuclear Organization (2014), the mine(s) produced 3,530 t of U$_3$O$_8$ and 27,000 t of copper concentrate. The Main ore body was mined initially by underground methods from 1950 to 1953, and then by open pit methods until 1958. The Main ore body produced about 30% of the U$_3$O$_8$ (1,088 t) and 85% (17,000 t) of the copper concentrate. Dysons ore body was mined for 534 t U$_3$O$_8$ in 1957/1958 and the Intermediate ore body was mined for 10,000 t of copper concentrate in 1964/1965.

From 1965 to 1971, heap leaching trials were conducted in the Copper Extraction Pad area between the Main and Intermediate Pits. The heap leach pad was used to process low-grade oxide ore and sulphide ore from the Intermediate ore body (see Section 2.2 for additional details). According to Davy (1975), seepage losses during the trials (or 'Heap Leach Experiment') were substantial, and groundwater near the former pad remains characterized by up to 900,000 µg/L Cu (RGC, 2016f).

2.3.3 Historic AMD Sources

AMD caused severe impacts to local groundwater and the EBFR during mining operations. Key sources of AMD were the WRDs, tailings in the Old Tailings Dam area, stockpiled ore and heap leach material, and the flooded open pits (see Allen and Verhoeven, 1986). Historic seepage water quality (and pertinent groundwater quality data) compiled from historic reports are summarized in Table 2-1. Also provided are Fe and Cu concentrations in the pregnant liquor from that oxide pile (the last step of the heap leaching process that was used to process ore from the Intermediate ore body from 1965 to 1971).
Of particular interest from Table 2-1 are the much higher metal concentrations in seepage form the Main and Intermediate WRDs than are observed today (e.g. in August 2010). In 1974, when these samples were collected by ANSTO (for Davy, 1975), the WRDs had not been shaped to facilitate surface water runoff, nor had they been covered to reduce infiltration by rainfall. At this time, Davy (1975) predicted that 50 to 60% of annual rainfall could have infiltrated. These large volumes of water (and Cu concentrations of 90,000 to 120,000 µg/L) led to the WRDs being identified as one of the three key point sources of AMD (the other two being the flooded pits and tailings in the Old Tailings Dam area).

Both pits flooded with highly-impacted groundwater after mining operations ceased. Prior to the treatment of the Main Pit water in 1985, it was highly-acidic (pH 2.5) and characterized by 8,200 mg/L SO₄ and 55,000 µg/L Cu (Table 2-2a). Pit water from the Intermediate Pit was slightly less acidic by comparison and characterized by lower SO₄ concentrations, but Cu concentrations were comparable to concentrations in the Main Pit (Table 2-2a).

After pit water from the Main Pit was treated (and the Intermediate Pit initially flushed), concentrations in pit water were substantially reduced. Concentrations have been further reduced since 1985 by annual flushing from the EBFR. In 1985, a layer of contaminated water overlying the submerged tailings in the bottom of the Main Pit was left untreated to avoid disturbing the tailings. In 1990, the top of this layer of untreated water was detected at 22 m below the surface of the pit lake. The top of this layer has subsequently decreased to a depth of 26 m in 1991, 33 m in 1998, and 41 m in 2008.  

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(see RGC, 2016f). This trend indicates that contaminated water is gradually being “eroded” by mixing with overlying uncontaminated pit water as the pit is flushed by inflows from the EBFR.

In 2008, the volume of the layer of impacted bottom water in the Main Pit was likely about 100 ML (assuming it was 5 m thick). This volume was predicted using the volume-elevation curve for the Main Pit (assuming the bottom of the pit is at 15 m AHD). Today (in 2016), there could be less of this water (i.e. 25 ML) if the thickness of the layer has been further reduced by annual flushing (and assuming that the volume-elevation curve for the Main Pit is accurate).

There is also a layer of more impacted water at the bottom of the Intermediate Pit. Water within this layer is more impacted than shallow pit water, but it is not characterized by high metals or reduced pH (only elevated EC and SO₄). The less impacted condition of deep water in the Intermediate Pit is related mainly to the approach to treating pit water in 1985, which involved induced mixing by aeration from the bottom of the pit (not pumping and treating pit water, as was done for the Main Pit) (see Allen and Verhoeven, 1986). Also a factor was the absence of stratification in the Intermediate Pit before pit water was flushed.

Shallow pit water in the Intermediate Pit does contain more Cu than pit water from the Main Pit, possibly due to discharge of some severely-impacted groundwater from the Copper Extraction Pad area to the Intermediate Pit. This is consistent with the groundwater flow field for this area of the site (and previous modeling results that indicated some groundwater discharge to the pit from upgradient) (see RGC, 2016f, and references therein).

From 1965 to 1971, a heap leach pad was operated between the Main and Intermediate Pits. This area of the site is referred to as the Copper Extraction Pad area. The heap leaching process initially involved piling low-grade (0.7 to 2.0% Cu) sulphide ore from the Intermediate ore body onto a low-permeable pad and then spraying the top of the pile with pH 2 acid. The acidic mixture used to leach copper from the sulphide ore consisted of mill process water, barren liquor, and pit water from the Main Pit. Liquor drained from the sulphide pile (nominally pH 1.5) was then pumped onto a pile of oxide ore (2% Cu) to leach additional copper before the pregnant liquor was pumped to launders for copper recovery (by cementation) (see Davy, 1975).

The heap leaching operation was not particularly efficient, and substantial losses of pregnant liquor occurred by seepage to groundwater and evaporation. Davey (1975), for instance, estimates that ~2 L/s was lost to evaporation and infiltration to groundwater during the wet season, while ~4 L/s was lost during the dry season. Pregnant liquor typically contained 1,000,000 µg/L Cu (Table 2-1) and concentrations of up to 9,000,000 µg/L Cu were observed. Losses appear to have occurred from the heap leach pad itself, and from the various ditches and storage ponds that were used for the heap leaching process. Moreover, overflow from the system and excess barren liquors (with pH < 2) were discharged to Copper Creek (which flowed northwest to the EBFR).
Table 2-2a

Historic Pit Water Quality Data (Main Open Pit)

<table>
<thead>
<tr>
<th>Depth m</th>
<th>Date</th>
<th>pH</th>
<th>EC, uS/cm</th>
<th>SO₄, mg/L</th>
<th>Al, ug/L</th>
<th>Cu, ug/L</th>
<th>Fe, ug/L</th>
<th>Mn, ug/L</th>
<th>Ni, ug/L</th>
<th>Zn, ug/L</th>
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<tr>
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Typical water quality immediately prior to rehabilitation (from Mining and Processing Engineering Services report), dissolved metal concentrations

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<th>Date</th>
<th>pH</th>
<th>EC, uS/cm</th>
<th>SO₄, mg/L</th>
<th>Al, ug/L</th>
<th>Cu, ug/L</th>
<th>Fe, ug/L</th>
<th>Mn, ug/L</th>
<th>Ni, ug/L</th>
<th>Zn, ug/L</th>
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<td>55,000</td>
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<tr>
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<td>210,000</td>
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Pit water quality in 1991 (from Henkel, 1991b), dissolved metal concentrations

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<th>Date</th>
<th>pH</th>
<th>EC, uS/cm</th>
<th>SO₄, mg/L</th>
<th>Al, ug/L</th>
<th>Cu, ug/L</th>
<th>Fe, ug/L</th>
<th>Mn, ug/L</th>
<th>Ni, ug/L</th>
<th>Zn, ug/L</th>
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<td>- 50</td>
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<tr>
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<td>310</td>
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<td>- 6,900</td>
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<tr>
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<td>- 6,900</td>
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Pit water quality in April 1998 (from Lawton and Overall, 2002), dissolved metal concentrations

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<th>EC, uS/cm</th>
<th>SO₄, mg/L</th>
<th>Al, ug/L</th>
<th>Cu, ug/L</th>
<th>Fe, ug/L</th>
<th>Mn, ug/L</th>
<th>Ni, ug/L</th>
<th>Zn, ug/L</th>
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<tbody>
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<td>460</td>
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</tr>
<tr>
<td>Apr-98</td>
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<td>172</td>
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<td>100</td>
<td>440</td>
<td>340</td>
<td>60</td>
<td>50</td>
<td></td>
</tr>
<tr>
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<td>100</td>
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<td>30</td>
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<tr>
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</tr>
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<td>740</td>
<td>90</td>
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</tr>
<tr>
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Depth profiling in May 2008 (by Tropical Water Solutions Pty Ltd.), dissolved metal concentrations

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<th>SO₄, mg/L</th>
<th>Al, ug/L</th>
<th>Cu, ug/L</th>
<th>Fe, ug/L</th>
<th>Mn, ug/L</th>
<th>Ni, ug/L</th>
<th>Zn, ug/L</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-</td>
<td>- 60</td>
<td>112</td>
<td>95</td>
<td>440</td>
<td>50</td>
<td>73</td>
<td>24</td>
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</tr>
<tr>
<td>May-08</td>
<td>-</td>
<td>- 60</td>
<td>163</td>
<td>108</td>
<td>700</td>
<td>50</td>
<td>74</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>May-08</td>
<td>-</td>
<td>- 60</td>
<td>172</td>
<td>110</td>
<td>740</td>
<td>50</td>
<td>74</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>May-08</td>
<td>-</td>
<td>- 63</td>
<td>214</td>
<td>120</td>
<td>1,000</td>
<td>50</td>
<td>77</td>
<td>26</td>
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</tr>
<tr>
<td>May-08</td>
<td>-</td>
<td>- 7,710</td>
<td>170,000</td>
<td>38,000</td>
<td>851,000</td>
<td>219,000</td>
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<td>6,200</td>
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Main Open Pit (eastern side), total metal concentrations

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<th>SO₄, mg/L</th>
<th>Al, ug/L</th>
<th>Cu, ug/L</th>
<th>Fe, ug/L</th>
<th>Mn, ug/L</th>
<th>Ni, ug/L</th>
<th>Zn, ug/L</th>
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</thead>
<tbody>
<tr>
<td>Aug-10</td>
<td>-</td>
<td>- 64</td>
<td>56</td>
<td>45</td>
<td>420</td>
<td>780</td>
<td>64</td>
<td>22</td>
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Main Open Pit (western side), total metal concentrations

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<th>SO₄, mg/L</th>
<th>Al, ug/L</th>
<th>Cu, ug/L</th>
<th>Fe, ug/L</th>
<th>Mn, ug/L</th>
<th>Ni, ug/L</th>
<th>Zn, ug/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug-10</td>
<td>-</td>
<td>- 63</td>
<td>67</td>
<td>47</td>
<td>410</td>
<td>780</td>
<td>62</td>
<td>22</td>
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Note: Red numbers indicate that the concentration was below the indicated detection limit and hyphens indicate that data is unavailable.
### Table 2-2b

**Historic Pit Water Quality Data (Intermediate Pit)**

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<th>Date</th>
<th>Depth (m)</th>
<th>pH</th>
<th>EC (µS/cm)</th>
<th>SO₄ (mg/L)</th>
<th>Al (ug/L)</th>
<th>Cu (ug/L)</th>
<th>Fe (ug/L)</th>
<th>Mn (ug/L)</th>
<th>Ni (ug/L)</th>
<th>Zn (ug/L)</th>
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</thead>
<tbody>
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<td>2,000</td>
<td>60,000</td>
<td>14,000</td>
<td>7,000</td>
</tr>
<tr>
<td>Pit water quality in 1990 (from Henkel, 1991b), dissolved concentrations</td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
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<td>-</td>
<td>1,200</td>
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<td>2,100</td>
<td>-</td>
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</tr>
<tr>
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<td>900</td>
<td>460</td>
<td>-</td>
<td>1,100</td>
<td>-</td>
<td>2,100</td>
<td>-</td>
<td>320</td>
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</tr>
<tr>
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<td>4.7</td>
<td>890</td>
<td>450</td>
<td>-</td>
<td>1,100</td>
<td>-</td>
<td>2,000</td>
<td>-</td>
<td>310</td>
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</tr>
<tr>
<td>17 Oct-90</td>
<td>4.7</td>
<td>890</td>
<td>460</td>
<td>-</td>
<td>1,100</td>
<td>-</td>
<td>2,000</td>
<td>-</td>
<td>320</td>
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<td>-</td>
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<td>-</td>
<td>320</td>
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<td>-</td>
<td>2,100</td>
<td>-</td>
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</tr>
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<td>-</td>
<td>420</td>
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<tr>
<td>Pit water quality in 1991 (from Henkel, 1991b), dissolved metal concentrations</td>
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<td></td>
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<td></td>
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<td>840</td>
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<tr>
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<td>880</td>
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<tr>
<td>22 May-91</td>
<td>5.5</td>
<td>250</td>
<td>110</td>
<td>-</td>
<td>470</td>
<td>-</td>
<td>1,200</td>
<td>-</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>24 May-91</td>
<td>5.2</td>
<td>380</td>
<td>220</td>
<td>-</td>
<td>540</td>
<td>-</td>
<td>1,500</td>
<td>-</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>26 May-91</td>
<td>5.4</td>
<td>3600</td>
<td>2800</td>
<td>-</td>
<td>550</td>
<td>-</td>
<td>3,600</td>
<td>-</td>
<td>550</td>
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</tr>
<tr>
<td>28 May-91</td>
<td>6.1</td>
<td>3700</td>
<td>3100</td>
<td>-</td>
<td>170</td>
<td>-</td>
<td>4,400</td>
<td>-</td>
<td>320</td>
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</tr>
<tr>
<td>30 May-91</td>
<td>6.4</td>
<td>3700</td>
<td>3100</td>
<td>-</td>
<td>150</td>
<td>-</td>
<td>4,300</td>
<td>-</td>
<td>390</td>
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<tr>
<td>Pit water quality in April 1998 (from Lawton and Overall, 2002), dissolved metal concentrations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 Apr-98</td>
<td>6.9</td>
<td>143</td>
<td>53</td>
<td>220</td>
<td>200</td>
<td>370</td>
<td>380</td>
<td>110</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>5 Apr-98</td>
<td>6.7</td>
<td>141</td>
<td>-</td>
<td>210</td>
<td>100</td>
<td>380</td>
<td>370</td>
<td>100</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>10 Apr-98</td>
<td>6.5</td>
<td>130</td>
<td>48</td>
<td>210</td>
<td>100</td>
<td>330</td>
<td>370</td>
<td>80</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>15 Apr-98</td>
<td>5.6</td>
<td>124</td>
<td>-</td>
<td>150</td>
<td>200</td>
<td>30</td>
<td>660</td>
<td>90</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>20 Apr-98</td>
<td>5.5</td>
<td>125</td>
<td>51</td>
<td>160</td>
<td>200</td>
<td>20</td>
<td>660</td>
<td>90</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>25 Apr-98</td>
<td>5.4</td>
<td>137</td>
<td>-</td>
<td>160</td>
<td>200</td>
<td>30</td>
<td>720</td>
<td>130</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>30 Apr-98</td>
<td>5.3</td>
<td>161</td>
<td>71</td>
<td>180</td>
<td>300</td>
<td>60</td>
<td>910</td>
<td>150</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>31 Apr-98</td>
<td>5.0</td>
<td>240</td>
<td>-</td>
<td>330</td>
<td>400</td>
<td>60</td>
<td>1,190</td>
<td>190</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>32 Apr-98</td>
<td>4.7</td>
<td>418</td>
<td>-</td>
<td>480</td>
<td>600</td>
<td>60</td>
<td>1,650</td>
<td>300</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>33 Apr-98</td>
<td>4.5</td>
<td>1104</td>
<td>-</td>
<td>1,140</td>
<td>1,100</td>
<td>110</td>
<td>3,540</td>
<td>980</td>
<td>950</td>
<td></td>
</tr>
<tr>
<td>34 Apr-98</td>
<td>4.8</td>
<td>2278</td>
<td>-</td>
<td>1,550</td>
<td>1,100</td>
<td>16,050</td>
<td>9,600</td>
<td>1,830</td>
<td>2,010</td>
<td></td>
</tr>
<tr>
<td>35 Apr-98</td>
<td>4.7</td>
<td>3478</td>
<td>2410</td>
<td>350</td>
<td>100</td>
<td>25,000</td>
<td>9,750</td>
<td>1,140</td>
<td>740</td>
<td></td>
</tr>
<tr>
<td>Depth profiling in May 2008 (by Tropical Water Solutions Pty Ltd.), dissolved metal concentrations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 May-08</td>
<td>-</td>
<td>-</td>
<td>45</td>
<td>103</td>
<td>103</td>
<td>160</td>
<td>316</td>
<td>61</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>15 May-08</td>
<td>-</td>
<td>-</td>
<td>45</td>
<td>138</td>
<td>115</td>
<td>220</td>
<td>312</td>
<td>60</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>31 May-08</td>
<td>-</td>
<td>-</td>
<td>101</td>
<td>33</td>
<td>76</td>
<td>60</td>
<td>638</td>
<td>86</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Intermediate Open Pit (eastern side), total metal concentrations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 Aug-10</td>
<td>-</td>
<td>-</td>
<td>65</td>
<td>61</td>
<td>82</td>
<td>210</td>
<td>340</td>
<td>63</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Intermediate Open Pit (western side), total metal concentrations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 Aug-10</td>
<td>-</td>
<td>-</td>
<td>63</td>
<td>72</td>
<td>100</td>
<td>290</td>
<td>340</td>
<td>65</td>
<td>24</td>
<td></td>
</tr>
</tbody>
</table>

Note: Red numbers indicate that the concentration was below the indicated detection limit and hyphens indicate that data is unavailable.

### 2.3.4 Historic Contaminant Loads to the EBFR

In the 1970s, high concentrations of dissolved metals in the EBFR were of particular concern because they caused deleterious effects downstream of the site. Acute effects of elevated metal concentrations in the EBFR included fish kills downstream of the site. These fish kills occurred periodically during the ‘first flush’ of contaminants from the site during the early wet season. Chronic effects of elevated metals included dieback of vegetation near the East Branch and a reduced...
abundance and diversity of fish and macroinvertebrates downstream of the site (see Twining et al., 2002).

Dissolved Cu, manganese (Mn), and zinc (Zn) were identified as the key contaminants of concern and targeted for reduction during rehabilitation (see Allen and Verhoeven, 1986). From 1969 to 1984 (when initial rehabilitation works commenced), the average Cu load in the EBFR at gauge GS8150097 was 56 t Cu/year and the average SO\textsubscript{4} load was 7,220 t SO\textsubscript{4}/year (see Figure 2-5). Loads in Figure 2-5 were compiled from previous studies and monitoring reports, e.g. Davy (1975). The highest SO\textsubscript{4} load (12,000 t) was observed in 1970/1971, and the lowest SO\textsubscript{4} load (3,300 t) was observed in 1969/1970 (one of the driest years on record, i.e. 896 mm rainfall). Cu loads from 1969 to 1984 ranged from 23 t to 95 t.

### Table 2-3

<table>
<thead>
<tr>
<th>Source Area, \text{m}^2</th>
<th>SO\textsubscript{4}, mg/L</th>
<th>Cu, \text{ug/L}</th>
<th>Recharge, mm</th>
<th>Recharge (or Flow), ML</th>
<th>SO\textsubscript{4} Load, t/yr</th>
<th>Cu Load, t/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seepage from the Main WRD 330,000</td>
<td>10,000</td>
<td>100,000</td>
<td>650</td>
<td>215</td>
<td>2,145</td>
<td>21</td>
</tr>
<tr>
<td>Seepage from the Intermediate WRD 80,000</td>
<td>25,000</td>
<td>225,000</td>
<td>650</td>
<td>52</td>
<td>1,300</td>
<td>12</td>
</tr>
<tr>
<td>Seepage from Dyson's WRD 90,000</td>
<td>5,000</td>
<td>7,500</td>
<td>650</td>
<td>59</td>
<td>293</td>
<td>0.4</td>
</tr>
<tr>
<td>Seepage from Old Tailings Dam 275,000</td>
<td>5,000</td>
<td>30,000</td>
<td>400</td>
<td>110</td>
<td>550</td>
<td>3</td>
</tr>
<tr>
<td>Seepage from former mill area 54,000</td>
<td>5,000</td>
<td>60,000</td>
<td>144</td>
<td>8</td>
<td>39</td>
<td>0.5</td>
</tr>
<tr>
<td>Seepage from Copper Extraction Pad area (shallow) 34,000</td>
<td>2,500</td>
<td>7,500</td>
<td>284</td>
<td>9</td>
<td>22</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Sub-total:</strong> 863,000</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>452</td>
<td>4,349</td>
<td>37</td>
</tr>
</tbody>
</table>

| Estimated Losses from Groundwater Geochemical reactions (e.g. precipitation), 30% for Cu | n/a | n/a | n/a | n/a | 0 | -11 |

| Estimated Contaminant Loads to EBFR from Surface Water Surface loads (e.g. from tailings, pit water) | n/a | n/a | n/a | n/a | 145 | 2,871 | 30 |

| **TOTAL:** | n/a | n/a | n/a | n/a | 597 | 7,220 | 56 |

| Observed Contaminant Loads in the East Branch of the Finniss River Mean Annual Loads, 1969 to 1984 | n/a | n/a | n/a | n/a | 7,220 | 56 |

Davy (1975) suggests that the majority of the load in the EBFR before rehabilitation was related to seepage from the Main and Intermediate WRDs, and surface water flows from the Main Pit and the Old Tailings Dam area. This is consistent with the conceptual load balance for pre-rehabilitation conditions from RGC (2016f), which is provided in Table 2-3. The load balance reflects higher recharge estimates for the WRDs (i.e. 50% of MAP), and higher contaminant concentrations in seepage from the WRDs before initial rehabilitation (from Table 2-1). Note that surface water loads (i.e. from tailings and pit water) were predicted by difference (as there were insufficient flow and water quality data to predicted loads directly). Also, RGC assumed 30% loss of Cu by adsorption to
aquifer materials (and the precipitation of secondary minerals) (see RGC, 2016f, for additional
details).

2.3.5 Rehabilitation in 1984/1985

In 1984/1985, the Main, Intermediate, and Dysons WRDs were re-shaped and covered as part of
rehabilitation of the site (Allen and Verhoeven, 1986). Some of the Main North WRD was re-located
to the toe of the Main WRD at this time and the residual waste rock was covered and re-vegetated. A
625 mm thick, three-layer cover system was placed on the Main and Intermediate WRDs. On the top
surface of these WRDs, the cover consists of:

- 150 mm erosion protection zone (top layer).
- 250 mm moisture retention zone (middle layer).
- 225 mm low permeability sealing zone (bottom layer).

The cover was designed to be thicker (750 mm) over the batters of the WRDs. During rehabilitation,
the Main WRD was covered entirely. Cover placement on the northern batter of the Intermediate
WRD (adjacent to the EFDC) was not completed. Also, only the top of Dysons WRD was re-shaped
and covered. This was done to save costs, as Dysons WRD was considered a relatively small source
of AMD due to its relatively low sulphide content (Allen and Verhoeven, 1988).

Aside from re-shaping and covering the WRDs, rehabilitation in 1984/1985 also included:

- Backfilling Dysons Pit with additional tailings and contaminated soils collected from the
  former heap leach area and the Old Tailings Dam.
- Treating highly-contaminated water that had filled the Main and Intermediate Pits.
- Establishing the system of inlets and outlets that allow the EBFR to flush through the pits
during the wet season.

Following tailings removal, the Old Tailings Dam area was also limed and re-shaped to control
drainage in 1985 (see Allen and Verhoeven, 1986). A one-layer cover was also installed to enable
the establishment of vegetation. According to Fawcett (2007), some residual tailings remain in this
area and may require removal during implementation of the preferred rehabilitation strategy. The
presence of tailings was confirmed during RGC’s geotechnical investigation of the Old Tailings Dam
area (see RGC, 2016b).

2.3.6 Contaminant Loads after Initial Rehabilitation

Two years of routine monitoring after rehabilitation demonstrated that the rehabilitation implemented
in 1984/1985 had achieved the objectives that were established under the Rehabilitation Agreement
(see Verhoeven, 1988). Subsequent studies of water quality indicate that this level of performance
was maintained (see Kraatz, 2004). This is consistent with reduced contaminant loads in the EBFR
since 1985 (see Figure 2-5). There has also been a significant recovery of fish fauna in the river and an increased number of macroinvertebrate taxa after rehabilitation due to the reduced contaminant load from the site (see Jeffree and Twining, 1998).

2.4 CURRENT SITE COMPONENTS

A brief description of key site components is provided in the sub-sections below.

2.4.1 Main and Intermediate Pits

The Main Pit was mined to about 111 m below ground surface (bgs). The Intermediate Pit was mined to about 57 m bgs. Both pits have been partially backfilled with tailings. The Main Pit contains up to 900,000 m$^3$ of tailings that have formed a relatively flat surface near the middle of the pit (RGC, 2016c). The Intermediate Pit contains 200,000 m$^3$ of tailings that are primarily hung up along the northern side wall.

2.4.2 Dysons Pit

Dysons Pit was mined to a depth of about 47 m bgs in 1957/1958. It was partially backfilled with tailings during mining operations. These tailings were placed hydraulically (as a slurry). Tailings recovered from the Old Tailings Dam area were placed into the pit in 1984/1985. 460,000 m$^3$ of leached, low-grade ore and contaminated soils removed from the Copper Extraction Pad area were then placed to create an above-grade landform. Tailings and shallow backfill materials are separated by a rock drain and geosynthetic layer.

Dysons Pit was covered in 1984/1985 to reduce the infiltration of rainfall and limit the ingress of oxygen (see Allen and Verhoeven, 1986, for additional details). A conceptualized cross-section of Dysons (backfilled) Open Pit from Fawcett (2007) is provided in Figure 2-6. This cross-section illustrates the different types of backfill and their depths from ground surface. Tailings are likely submerged year-round and hence they do not likely impact shallow groundwater quality near the pit (see RGC, 2016f).

RGC (2016a) classified 70% of the shallow backfill materials as PAF-I material (the most AMD-generating PAF-type). PAF-I material has an average Neutralization Potential Ratio (NPR) of 0.1 that reflects high AP values (i.e. close to 100 kg H$_2$SO$_4$/t, on average) and low ANC (Table 2-4). The other 30% of shallow backfill materials are classified as PAF-II material (which is thought to generate less AMD than PAF-I material). PAF-III type materials were not identified in Dysons Pit.

Shallow backfill materials are characterized by high incipient acidity (up to 146 kg H$_2$SO$_4$/t), and an average rinse pH of 4.3. These values are similar to PAF-I material in the Intermediate WRD (and suggest that backfill could contain more than 50 kg H$_2$SO$_4$/t of existing acidity) (Table 2-5). No
information on the proportion of existing acidity that is titratable acidity, but based on samples from the Intermediate WRD, titratable acidity could be less than 20% of the existing acidity content (as jarosite acidity appears to be predominate in this material) (see RGC, 2016a, for additional details).

Shallow backfill materials in Dysons Pit are above the groundwater level in the pit and are actively oxidizing (and leaching contaminants). Seepage from these materials reports to ground surface via a toe drain along the southwest batter (and ultimately to the upper EBFR). Dieback in this area is significant due to the high salt and metal concentrations in seepage (see Table 2-6 in Section 2.4.3).

### Table 2-4

**Average ABA Parameters for PAF and NAF Waste Rock**

<table>
<thead>
<tr>
<th>Type</th>
<th>AMD Potential</th>
<th>$S_{total}$, %</th>
<th>$S_{sulphide}$, %</th>
<th>AP, kg H$_2$SO$_4$/t</th>
<th>ANC, kg H$_2$SO$_4$/t</th>
<th>NAPP, kg H$_2$SO$_4$/t</th>
<th>NPR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Potentially Acid Forming (PAF) Waste Rock</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAF-I High</td>
<td>3.6 (1.4)</td>
<td>3.6 (1.3)</td>
<td>99.5 (38.6)</td>
<td>6.6 (15.4)</td>
<td>92.9 (44.8)</td>
<td>0.1 (0.3)</td>
<td></td>
</tr>
<tr>
<td>PAF-II Medium</td>
<td>1.1 (0.4)</td>
<td>0.9 (0.4)</td>
<td>26.4 (10.9)</td>
<td>7.2 (7.2)</td>
<td>19.2 (12.5)</td>
<td>0.3 (0.3)</td>
<td></td>
</tr>
<tr>
<td>PAF-III Low</td>
<td>0.4 (0.5)</td>
<td>0.3 (0.5)</td>
<td>8.0 (12.2)</td>
<td>11.9 (20.7)</td>
<td>-3.9 (10.3)</td>
<td>1.3 (1.0)</td>
<td></td>
</tr>
<tr>
<td><strong>Non Acid Forming (NAF) Waste Rock</strong></td>
<td>SD only</td>
<td>0.08 (0.08)</td>
<td>0.03 (0.03)</td>
<td>1.1 (0.9)</td>
<td>16.5 (8.0)</td>
<td>-15.4 (7.8)</td>
<td>24.3 (25.8)</td>
</tr>
</tbody>
</table>

Notes: All values are averages with one standard deviation in parentheses. SD denotes ‘saline drainage’.

Samples from 2011 and 2014 are used to calculate averages.

### Table 2-5

**Average Acidity Content of PAF and NAF Waste Rock (Rinse pH < 5)**

<table>
<thead>
<tr>
<th>Type</th>
<th>AMD Potential</th>
<th>Rinse pH</th>
<th>Jarosite Acidity, kg H$_2$SO$_4$/t</th>
<th>Titratable Acidity, kg H$_2$SO$_4$/t</th>
<th>Incipient Acidity, kg H$_2$SO$_4$/t</th>
<th>Total Acidity, kg H$_2$SO$_4$/t</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Potentially Acid Forming (PAF) Waste Rock</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAF-I High</td>
<td>High</td>
<td>4.2 (0.8)</td>
<td>8.5 (10.2)</td>
<td>2.1 (2.4)</td>
<td>100.6 (38.5)</td>
<td>124.8 (40.8)</td>
</tr>
<tr>
<td>PAF-II Medium</td>
<td>Medium</td>
<td>4.2 (1.0)</td>
<td>5.7 (6.0)</td>
<td>1.0 (0.9)</td>
<td>25.9 (11.5)</td>
<td>30.4 (13.8)</td>
</tr>
<tr>
<td>PAF-III Low</td>
<td>Low</td>
<td>4.9 (1.3)</td>
<td>2.3 (3.5)</td>
<td>0.7 (0.9)</td>
<td>9.3 (13.6)</td>
<td>12.3 (15.2)</td>
</tr>
<tr>
<td><strong>Non Acid Forming (NAF) Waste Rock</strong></td>
<td>Minimal*</td>
<td>6.1 (1.2)</td>
<td>0.1 (0.2)</td>
<td>0.1 (0.1)</td>
<td>1.7 (2.1)</td>
<td>1.2 (1.1)</td>
</tr>
</tbody>
</table>

#### 2.4.3 Waste Rock Dumps

During mining operations, waste rock removed from the Main, Intermediate, and Dysons ore bodies was stored in three major WRDs, and the smaller Main North WRD (Figure 2-1).
In 1984/1985, the WRDs were re-shaped and covered as part of rehabilitation. Covers were designed to reduce infiltration to less than 5% of incident rainfall by water storage-and-release mechanisms and be shedding rainfall as runoff. Routine monitoring by ANSTO suggests that the covers achieved the infiltration design criterion for about 10 years, but infiltration rates have since increased as the covers have degraded over time (see Taylor et al., 2003).

80% of the waste rock in the Intermediate WRD is classified as PAF-I material and the other 20% is PAF-II, i.e. moderate AP and ANC values. PAF-II waste rock will generate substantial AMD in the future, but less than PAF-I waste rock. The Main WRD contains a mixture of PAF-I, PAF-II, and PAF-III waste rock and NAF waste rock (see Figure 2-7). According to RGC (2016a), PAF-III waste rock has a low sulphide content (and relatively high ANC), so it’s the least acid-generating PAF type.

NAF waste rock is defined by a Neutralization Potential Ratio (NPR) value of two or higher and an existing acidity content of less than 0.5 kg H₂SO₄/t (see Table 2-4). NAF waste rock has a very low sulphide content and has not generated appreciable AMD since it was placed in the 1950s and 1960s. Non-mineralized NAF waste rock does not require containment, so it could be used to construct the WSF or to backfill the unsaturated zone of the Main Pit (see RGC, 2016a).

Today, the WRDs are the largest source of AMD to groundwater and the EBFR. Some key observations regarding seepage water quality are summarized here (see Table 2-6):

- Toe seepage from the Intermediate WRD is characterized by the highest concentrations of SO₄ and dissolved metals (i.e. Cu, Co, Mn, Ni, and Zn). These high concentrations are consistent with the high sulphide content of waste rock in this dump (see SRK, 2012). These high concentrations may also reflect the poor performance of the cover in some areas and/or the absence of a cover near the northern batter.

- Many of the metals that are elevated in seepage from the Intermediate WRD are also elevated in seepage from Dysons Pit. This similarity is related to the use of waste rock and leached material from the Intermediate ore body to backfill the shallow portions of Dysons pit and cover the tailings that fill the majority of the original pit volume. The tailings are submerged beneath the groundwater table throughout the year and covered by a layer of oxygen-consuming backfill so the ongoing oxidation rate of the tailings is essentially zero.

- Toe seepage from the Main WRD is characterized by lower concentrations of SO₄ and dissolved metals than seepage from the Intermediate WRD. Possible explanations include (i) the dilution of toe seepage by shallow groundwater flows, (ii) the lower sulphide content of waste rock, and/or (iii) heterogeneity in seepage water quality from this large WRD (see RGC, 2012).

- Concentrations of SO₄ and metals in seepage from Dysons WRD are typically lower than in seepages from the Main and Intermediate WRDs and Dysons Pit. These lower
concentrations reflect in part the much lower initial sulphide content of waste rock from this WRD and the mining of Dysons ore body exclusively for uranium (not a suite of metals).

Table 2-6
Seepage Water Quality Data for the Existing WRDs and Dysons Pit, 2008 to 2015

<table>
<thead>
<tr>
<th>Location/Sample Type</th>
<th>n</th>
<th>Season</th>
<th>Field pH</th>
<th>Field EC, uS/cm</th>
<th>SO₄, mg/L</th>
<th>Al, ug/L</th>
<th>Fe, ug/L</th>
<th>Cu, ug/L</th>
<th>Co, ug/L</th>
<th>Mn, ug/L</th>
<th>Ni, ug/L</th>
<th>U, ug/L</th>
<th>Zn, ug/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main WRD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toe seepage (August 2010), NE</td>
<td>1</td>
<td>Dry</td>
<td>3.7</td>
<td>6,000</td>
<td>5,190</td>
<td>12,900</td>
<td>4,800</td>
<td>4,400</td>
<td>5,180</td>
<td>11,100</td>
<td>3,840</td>
<td>568</td>
<td>7,140</td>
</tr>
<tr>
<td>Toe seepage (2009 to 2012), NE</td>
<td>3</td>
<td>Wet</td>
<td>3.7</td>
<td>4,780</td>
<td>4,445</td>
<td>10,445</td>
<td>3,100</td>
<td>3,160</td>
<td>2,000</td>
<td>7,200</td>
<td>3,428</td>
<td>86</td>
<td>7,018</td>
</tr>
<tr>
<td>Standard Deviation (σ):</td>
<td></td>
<td></td>
<td>0.3</td>
<td>1,690</td>
<td>622</td>
<td>1,871</td>
<td>945</td>
<td>317</td>
<td>748</td>
<td>2,567</td>
<td>435</td>
<td>73</td>
<td>764</td>
</tr>
<tr>
<td>Toe seepage (April 2015), SW</td>
<td>1</td>
<td>Wet</td>
<td>4.3</td>
<td>4,300</td>
<td>-</td>
<td>2,310</td>
<td>60</td>
<td>2,610</td>
<td>1,330</td>
<td>1,980</td>
<td>1,150</td>
<td>190</td>
<td>2,430</td>
</tr>
<tr>
<td>Toe seepage (April 2015), SW</td>
<td>1</td>
<td>Wet</td>
<td>4.3</td>
<td>5,690</td>
<td>-</td>
<td>3,370</td>
<td>40</td>
<td>1,340</td>
<td>2,450</td>
<td>3,200</td>
<td>2,010</td>
<td>207</td>
<td>4,030</td>
</tr>
<tr>
<td>Toe seepage (April 2015), NE</td>
<td>1</td>
<td>Wet</td>
<td>3.7</td>
<td>8,180</td>
<td>-</td>
<td>72,700</td>
<td>310,000</td>
<td>11,300</td>
<td>31,700</td>
<td>41,000</td>
<td>29,600</td>
<td>657</td>
<td>64,200</td>
</tr>
<tr>
<td>Intermediate WRD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toe seepage (August 2010)</td>
<td>1</td>
<td>Dry</td>
<td>3.3</td>
<td>12,600</td>
<td>13,800</td>
<td>196,000</td>
<td>349,000</td>
<td>34,900</td>
<td>74,700</td>
<td>64,300</td>
<td>18,100</td>
<td>156,000</td>
<td></td>
</tr>
<tr>
<td>Toe seepage (March 2012), Seep 1</td>
<td>1</td>
<td>Wet</td>
<td>3.8</td>
<td>4,192</td>
<td>5,870</td>
<td>20,500</td>
<td>58,100</td>
<td>5,600</td>
<td>21,700</td>
<td>28,600</td>
<td>15,100</td>
<td>228</td>
<td>22,000</td>
</tr>
<tr>
<td>Toe seepage (March 2012), Seep 2</td>
<td>1</td>
<td>Wet</td>
<td>3.5</td>
<td>660</td>
<td>5,630</td>
<td>42,800</td>
<td>133,000</td>
<td>7,150</td>
<td>21,200</td>
<td>28,600</td>
<td>16,800</td>
<td>363</td>
<td>32,000</td>
</tr>
<tr>
<td>Toe seepage (March 2012), Seep 3</td>
<td>1</td>
<td>Wet</td>
<td>3.7</td>
<td>639</td>
<td>6,520</td>
<td>44,900</td>
<td>169,000</td>
<td>9,660</td>
<td>27,800</td>
<td>35,300</td>
<td>23,800</td>
<td>441</td>
<td>48,700</td>
</tr>
<tr>
<td>Bore MB12-30S (February 2014)</td>
<td>1</td>
<td>Wet</td>
<td>4.2</td>
<td>4,751</td>
<td>2,770</td>
<td>22,600</td>
<td>74,900</td>
<td>10,100</td>
<td>30,700</td>
<td>18,100</td>
<td>15,000</td>
<td>167</td>
<td>15,200</td>
</tr>
<tr>
<td>Bore MB12-30S (April 2015)</td>
<td>1</td>
<td>Wet</td>
<td>4.4</td>
<td>5,547</td>
<td>3,840</td>
<td>38,000</td>
<td>145,000</td>
<td>17,800</td>
<td>20,000</td>
<td>34,900</td>
<td>16,000</td>
<td>480</td>
<td>29,100</td>
</tr>
<tr>
<td>DYSONS'S WRD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toe seepage (April 2009)</td>
<td>1</td>
<td>Dry</td>
<td>2.9</td>
<td>4,851</td>
<td>3,430</td>
<td>154,000</td>
<td>49,000</td>
<td>188</td>
<td>648</td>
<td>10,700</td>
<td>2,100</td>
<td>1,980</td>
<td>265</td>
</tr>
<tr>
<td>Toe seepage (August 2010)</td>
<td>1</td>
<td>Wet</td>
<td>3.7</td>
<td>4,220</td>
<td>2,710</td>
<td>87,800</td>
<td>5,800</td>
<td>157</td>
<td>395</td>
<td>5,060</td>
<td>1,240</td>
<td>1,170</td>
<td>175</td>
</tr>
<tr>
<td>Toe seepage (2011 to 2012)</td>
<td>9</td>
<td>Wet</td>
<td>4.3</td>
<td>1,481</td>
<td>934</td>
<td>8,654</td>
<td>1,028</td>
<td>2,433</td>
<td>5,699</td>
<td>14,134</td>
<td>4,430</td>
<td>154</td>
<td>195</td>
</tr>
<tr>
<td>Standard Deviation (σ):</td>
<td></td>
<td></td>
<td>0.1</td>
<td>475</td>
<td>430</td>
<td>3,752</td>
<td>810</td>
<td>1,672</td>
<td>3,413</td>
<td>8,378</td>
<td>2,523</td>
<td>52</td>
<td>81</td>
</tr>
<tr>
<td>DYSONS'S (back-filled) Open Pit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toe seepage (December 2011)</td>
<td>1</td>
<td>Dry</td>
<td>3.8</td>
<td>4,549</td>
<td>2,990</td>
<td>-</td>
<td>-</td>
<td>20,000</td>
<td>22,700</td>
<td>51,500</td>
<td>19,700</td>
<td>1,590</td>
<td>860</td>
</tr>
<tr>
<td>Toe seepage (2011 to 2012)</td>
<td>7</td>
<td>Wet</td>
<td>3.6</td>
<td>3,457</td>
<td>2,250</td>
<td>22,350</td>
<td>4,865</td>
<td>26,714</td>
<td>24,014</td>
<td>65,514</td>
<td>19,157</td>
<td>1,321</td>
<td>870</td>
</tr>
<tr>
<td>Standard Deviation (σ):</td>
<td></td>
<td></td>
<td>0.3</td>
<td>719</td>
<td>782</td>
<td>9,137</td>
<td>5,152</td>
<td>10,145</td>
<td>8,162</td>
<td>17,265</td>
<td>6,906</td>
<td>468</td>
<td>284</td>
</tr>
<tr>
<td>MB10-16 (November 2010)</td>
<td>1</td>
<td>Dry</td>
<td>3.5</td>
<td>4,066</td>
<td>2,720</td>
<td>18,300</td>
<td>400</td>
<td>31,700</td>
<td>24,790</td>
<td>48,000</td>
<td>19,800</td>
<td>1,800</td>
<td></td>
</tr>
</tbody>
</table>

Note: Data for 2010 (highlighted) are considered the most representative seepage water quality data, other data provided for purposes of comparison.

Metal concentrations are dissolved

### 2.4.4 Additional Waste Rock and Contaminated Soils

During future rehabilitation, waste rock, tailings, and contaminated soils will be collected from around the site and re-located to the WSF (O’Kane Consultants Inc., 2016). In 2011, the DME commissioned a contaminated site survey to collect samples of waste rock or contaminated soils in these areas, including the Main North WRD, the ore stockpile, and the pit levees (see CSA Global, 2011). In 2014, RGC collected additional samples from some of these areas to provide infill data and additional geochemical characterization information that was beyond the scope of CSA Global’s assessment (see RGC, 2016b). For more details on how these materials will be handled during rehabilitation, see Section 2.7.3 on the WSF.

### 2.5 Current Impacts by AMD

#### 2.5.1 Groundwater Quality Impacts

Rum Jungle features an extensive monitoring bore network that consists of historic, ‘RN’ bores, and additional ‘MB’ bores installed in 2010, 2012, and 2014 (see Figure 2-8). Most of the historic, ‘RN’
bores were installed in 1983 as part of groundwater investigations undertaken in support of the initial rehabilitation plan for the site (e.g. Appleyard, 1983). Additional bores were installed in 2010, 2012, and 2014 in order to augment the network of historic bores\(^1\).

The MB10 bores were installed in November and December 2010 as part of RGC’s initial investigation of groundwater conditions across Rum Jungle (see RGC, 2012). The MB12 bores were installed to further characterize groundwater conditions in (i) the Copper Extraction Pad area and (ii) the area near the Main and Intermediate WRDs. The MB14 bores were installed in October and November 2014 in the Old Tailings Dam area when the DME planned to construct the new WSF there (see RGC, 2015).

Conceptual representations of \(\text{SO}_4\) and \(\text{Cu}\) plumes in shallow groundwater are provided in Figure 2-9a,b. Not shown are the high concentrations of \(\text{SO}_4\) and \(\text{Cu}\) in deeper groundwater in the Copper Extraction Pad area. These plumes do, however, illustrate the extent of current groundwater impacts. Some key observations are summarized here:

- Cu concentrations are highest near the Main WRD due to the low buffering capacity of the underlying Rum Jungle Complex. Groundwater affected by seepage from the Main WRD generally moves eastward towards Fitch Creek or westward towards the Intermediate WRD but some transport towards the EFDC and Main Pit also likely occurs.
- The extents of contaminant plumes originating from the Intermediate WRD are more difficult to ascertain, but the majority of contaminants are thought to report to the EFDC via toe seepage/shallow groundwater discharge from the northern edge of the WRD.
- In Dysons Area, highly-impacted groundwater resides in the shallow bedrock aquifer near Dysons WRD and south of Dysons Pit and ultimately discharges to the upper EBFR. Impacted groundwater does not appear to be transported westward beyond Dysons Area due to local topography and/or the low permeability of bedrock.
- Moderately-elevated \(\text{SO}_4\) concentrations characterize groundwater north of the central mine reach but dissolved metal concentrations in this area are low. This suggests that metals are naturally attenuated in groundwater due to the high buffering capacity of the Coomalie Dolostone and the low solubility of most metals under near-neutral pH conditions. Major ions, such as \(\text{SO}_4\) and Mg, are unaffected by this buffering reaction (or retardation) and therefore transported conservatively in groundwater (hence the larger extents of TDS plumes compared to metal plumes).

\(^1\) The bore network at the Rum Jungle also includes two bores screened in tailings and shallow backfill in Dysons Pit (bores DO20 and DO21), and six open exploration holes in the Copper Extraction Pad area. SRK installed the DO bores in 2011 during their waste characterization program (see SRK, 2012).
In the Copper Extraction Pad area, the highest copper concentrations are observed in monitoring bores MB10-23 (561,000 µg/L Cu) and MB12-35 (551,000 µg/L Cu). Groundwater from both of these monitoring bores is acidic (pH < 4.5) and characterized by 3,500 to 8,500 mg/L SO₄. These bores are located near a major fault that runs across the Copper Extraction Pad area in a south-westerly direction from the Main Pit to the Intermediate Pit (see RGC, 2016f). According to RGC (2016e), there is likely 24 ML of contaminated groundwater in the Copper Extraction Pad area – this volume corresponds to one pore volume, and several pore volumes may have to be treated in order to remediate this area.

2.5.2 Surface Water Quality Conditions Downstream

Selected water quality data (i.e. pH, major ions, and some dissolved metals) from the following locations are summarized in Figure 2-10.

- Upper EBFR (upstream of Dysons Area).
- Fitch Creek (upstream of the site).
- Upper EBFR at Dysons gauge (downstream of Dysons Area).
- EBFR at gauge GS8150200.
- EBFR at gauge GS8150327.
- EBFR at gauge GS8150097.

Upstream of Rum Jungle, surface water is characterized by low SO₄ and dissolved metal concentrations. At Dysons gauge, the upper EBFR is characterized by elevated SO₄ and Cu concentrations during the wet season. Cu concentrations are particularly high due to the effect of seepage from Dysons Pit (which is a strong source of Cu, but a relatively minor SO₄ source compared to the Main and Intermediate WRDs). This is consistent with RGC’s conceptual load balance which suggests that about 10% of the Cu load originates from Dysons Area.

Downstream of the site, much higher concentrations of SO₄ and dissolved metals are observed in the EBFR than upstream of the site (or at Dysons gauge). Note that data from gauge GS8150200 are the most variable as the EBFR is thought to be poorly mixed at this location. Further downstream, where the river is thoroughly mixed, concentrations are more consistent. Of interest are similar concentrations at gauge GS8150327 and gauge GS8150097, which suggests no additional loads between these gauges. Also, the similarity in water quality conditions indicates that gauge GS8150327 could supplant gauge GS8150097 for future compliance monitoring.

According to RGC (2016f), the flow-weighted mean SO₄ concentration at gauge GS8150327 from 2010 to 2015 is 75 mg/L SO₄. This is much lower than the LDWQO for SO₄ from Hydrobiology (2016). The flow-weighted mean Cu concentration for gauge GS8150327 is 80 µg/L Cu (or about three times higher than the LDWQO from Hydrobiology (2015) (see Section 2.6.1). Further
downstream at gauge GS8150097, the flow-weighted Cu concentration is 61 µg/L Cu. This is about two times higher than the LDWQO (which is the same at both gauges). Flow-weighted concentrations of other metals are below the corresponding LDWQOs.

2.5.3 **Current Contaminant Loads (2010 to 2015)**

RGC (2016f) predicted loads of SO₄, Cu, and Zn in the EBFR at gauges GS8150200, GS8150327, and GS8150097 from 2010 to 2015. Loads were predicted from flow measurements and a database of surface water quality data provided by DME. Contaminant loads in the EBFR are lower today than they were in the 1990s (and much lower than in the 1970s, when up to 95 t Cu was observed in the river (see Figure 2-5). On average, 1,840 t/year SO₄ and 2.7 t Cu is predicted to report to the EBFR under current conditions.

Table 2-7 summarizes a conceptual load balance that accounts for the average SO₄ and Cu load in groundwater and the EBFR. The load balance (from RGC, 2016f) suggests that ~60% of the annual SO₄ load (and 80% of the annual Cu load) enters the groundwater system from the WRDs and other point sources of AMD, such as Dysons Pit and shallow contaminated soils in the former mill area and Copper Extraction Pad area. The remainder of the annual loads reports to the EBFR from diffuse sources around the site, and from the Intermediate Pit (which receives flows of impacted groundwater from deeper zones of the Copper Extraction Pad area).

### Table 2-7

**Conceptual Load Balance for Groundwater and the EBFR, Current Conditions (‘Average Year’)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Area, m²</th>
<th>SO₄, mg/L</th>
<th>Cu, µg/L</th>
<th>Recharge, mm</th>
<th>Recharge (or Flow), ML</th>
<th>SO₄ Load, t/yr</th>
<th>Cu Load, t/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Contaminant Loads to Groundwater (2010 to 2015), 1438 mm rainfall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seepage from the Main WRD</td>
<td>330,000</td>
<td>5,000</td>
<td>5,000</td>
<td>325</td>
<td>107</td>
<td>536</td>
<td>0.5</td>
</tr>
<tr>
<td>Seepage from the Intermediate WRD</td>
<td>80,000</td>
<td>15,000</td>
<td>35,000</td>
<td>325</td>
<td>26</td>
<td>390</td>
<td>0.9</td>
</tr>
<tr>
<td>Seepage from the Dyson's (backfilled) Pit</td>
<td>61,000</td>
<td>2,500</td>
<td>30,000</td>
<td>196</td>
<td>12</td>
<td>30</td>
<td>0.4</td>
</tr>
<tr>
<td>Seepage from Dyson's WRD</td>
<td>90,000</td>
<td>2,500</td>
<td>2,500</td>
<td>650</td>
<td>58</td>
<td>146</td>
<td>0.1</td>
</tr>
<tr>
<td>Seepage from former mill area</td>
<td>54,000</td>
<td>1,500</td>
<td>30,000</td>
<td>144</td>
<td>8</td>
<td>12</td>
<td>0.2</td>
</tr>
<tr>
<td>Seepage from Copper Extraction Pad area (shallow)</td>
<td>34,000</td>
<td>5,000</td>
<td>7,500</td>
<td>144</td>
<td>5</td>
<td>24</td>
<td>0.0</td>
</tr>
<tr>
<td>Sub-total</td>
<td>649,000</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>216</td>
<td>1,138</td>
<td>2.2</td>
</tr>
<tr>
<td>Estimated Losses from Groundwater</td>
<td></td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>0</td>
<td>-0.7</td>
</tr>
<tr>
<td>Geochemical reactions (e.g. precipitation), 30% for Cu</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>702</td>
<td>1.1</td>
</tr>
<tr>
<td>Estimated Contaminant Loads to EBFR from Surface Water</td>
<td></td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>1,840</td>
<td>2.7</td>
</tr>
</tbody>
</table>

**TOTAL:**

| n/a | n/a | n/a | n/a | n/a | 1,840 | 2.7 |

**Observed Contaminant Loads in the East Branch of the Finniss River**

Mean Annual Loads, Adjusted for ‘Average Year’

1,840 2.7
RGC (2016f) simulated SO₄ and Cu transport in groundwater for current conditions using a solute transport model. That model simulated 1439 t/year SO₄ discharging from groundwater to surface water for an average year, or about 26% more than conceptualized in Table 2-7. These higher loads were due in part to additional, so-called ‘constant sources’ that were incorporated into the numerical model to approximate the release of SO₄ and Cu soils (and liquor) in the Copper Extraction Pad area. RGC (2016f) assumed that SO₄ (i) behaves conservatively in groundwater (i.e. no losses due to geochemical reactions) and (ii) that its rate of movement in groundwater is not retarded by adsorption.

RGC (2016f) also simulated Cu transport in groundwater for current conditions. Assuming conservative transport the model predicted 3.1 t/year Cu to the EBFR (Table 2-8). Also simulated was a ‘moderate attenuation’ scenario, and a ‘high attenuation’ scenario in order to evaluate the implications of geochemical controls on Cu transport in groundwater. For the high attenuation scenario, the annual Cu load to the EBFR is 1.1 t/year Cu. This load represents 50% of the current load in the EBFR (from 2010 to 2015).

For the moderate attenuation scenario, 2.7 t/year Cu reports to the river from groundwater. This is higher than the conceptual load from groundwater, but identical to the total predicted load (i.e. point sources and diffuse sources combined). Importantly, none of the scenarios suggest that residual Cu loads from the former plant area, or the Old Tailings Dam area, are a major source to groundwater under current conditions. Instead, seepages from the Main WRD, Intermediate WRD, Dysons Pit, and loads from the Copper Extraction Pad area to the Intermediate Pit are the key sources of Cu to surface water (and the EBFR).

### Table 2-8

**Simulated Copper Loads from Groundwater to Surface Water (from RGC, 2016f)**

<table>
<thead>
<tr>
<th>Reach</th>
<th>No Attenuation</th>
<th>Moderate Attenuation</th>
<th>High Attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t/yr</td>
<td>%</td>
<td>t/yr</td>
</tr>
<tr>
<td>Dyson’s Reach</td>
<td>0.5</td>
<td>17%</td>
<td>0.3</td>
</tr>
<tr>
<td>Main WRD</td>
<td>0.6</td>
<td>20%</td>
<td>0.7</td>
</tr>
<tr>
<td>Intermediate WRD</td>
<td>1.0</td>
<td>32%</td>
<td>1.2</td>
</tr>
<tr>
<td>Main Pit to Intermediate Pit</td>
<td>0.1</td>
<td>3%</td>
<td>0.1</td>
</tr>
<tr>
<td>Brown’s Oxide Pit</td>
<td>0.8</td>
<td>27%</td>
<td>0.4</td>
</tr>
<tr>
<td>OTD Reach</td>
<td>0.0</td>
<td>0%</td>
<td>0.0</td>
</tr>
<tr>
<td>Lower EBFR (d/s of Intermediate Pit)</td>
<td>0.0</td>
<td>0%</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>TOTAL</strong>:</td>
<td><strong>3.1</strong></td>
<td><strong>100%</strong></td>
<td><strong>2.7</strong></td>
</tr>
</tbody>
</table>
2.6 **FINAL REHABILITATION OBJECTIVES**

The following sections summarize objectives of the preferred rehabilitation strategy for Rum Jungle.

### 2.6.1 LDWQOs for the EBFR

A key objective of the preferred rehabilitation strategy is to achieve LDWQOs downstream of the site. Hydrobiology (2015) proposes LDWQOs for different zones along the EBFR (Table 2-9):

- Zone 2 WQOs apply to the upper EBFR (downstream of Dysons Area) and in the EBFR downstream of the central mining reach (at gauge GS8150200).
- Zone 3 WQOs apply to the EBFR at gauges GS8150327 and GS8150097.
- Zone 4 and 5 WQOs apply to the EBFR further downstream of gauge GS8150097.
- Zone 6 WQOs apply to the Finniss River at gauge GS8150204.

#### Table 2-9

<table>
<thead>
<tr>
<th>River Zone</th>
<th>Site/Location</th>
<th>EC (µS/cm)</th>
<th>SO₄ (mg/L)</th>
<th>Mg (mg/L)</th>
<th>Al (µg/L)</th>
<th>Cu (µg/L)</th>
<th>Co (µg/L)</th>
<th>Fe (µg/L)</th>
<th>Mn (µg/L)</th>
<th>Ni (µg/L)</th>
<th>Zn (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Branch of the Finniss River</td>
<td>2 Upper EBFR at Dyson’s Gauge</td>
<td>2985</td>
<td>1192</td>
<td>86.6</td>
<td>236</td>
<td>60.2</td>
<td>89</td>
<td>300</td>
<td>759</td>
<td>130.4</td>
<td>210.5</td>
</tr>
<tr>
<td></td>
<td>2 EBFR at gauge GS8150200</td>
<td>2985</td>
<td>1192</td>
<td>86.6</td>
<td>236</td>
<td>60.2</td>
<td>89</td>
<td>300</td>
<td>795</td>
<td>130.4</td>
<td>210.5</td>
</tr>
<tr>
<td></td>
<td>3 EBFR at gauge GS8150327</td>
<td>2985</td>
<td>997</td>
<td>86.6</td>
<td>150</td>
<td>27.5</td>
<td>25.9</td>
<td>300</td>
<td>443</td>
<td>43.1</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>4 EBFR upstream of confluence with Finniss River</td>
<td>427</td>
<td>761</td>
<td>33.2</td>
<td>117</td>
<td>7.9</td>
<td>3.6</td>
<td>300</td>
<td>228</td>
<td>32.5</td>
<td>180</td>
</tr>
<tr>
<td>East Branch of the Finniss River</td>
<td>6 Finniss River at Gauge GS8150204</td>
<td>191</td>
<td>594</td>
<td>33.2</td>
<td>117</td>
<td>3.4</td>
<td>2.8</td>
<td>300</td>
<td>140</td>
<td>20</td>
<td>26.1</td>
</tr>
</tbody>
</table>

See Hydrobiology (2016) for additional details.

Hydrobiology (2015) considered a range of environmental values, with the LDWQOs generally based on the most conservative of these (aquatic ecosystem protection levels). LDWQOs from Table 2-9 are the concentrations of SO₄, Mg, and metals that will be adequately protective of environmental values downstream of Rum Jungle.

### 2.6.2 Physical and Geochemical Stability of Mine Waste

A key rehabilitation objective is to ensure the long-term physical and geochemical stability of waste rock and tailings at the site.

### 2.6.3 Post-Closure Land-Use

A key rehabilitation objective Rum Jungle is to encourage beneficial post-rehabilitation land uses at the site consistent with the views and interests of the Traditional Aboriginal Owners of the site (see DME, 2013, for additional details).
2.7 PREFERRED REHABILITATION STRATEGY

To achieve the objectives outlined above, DME has developed a preferred rehabilitation strategy. The preferred rehabilitation strategy has continued to be refined by the DME and their consultants. Below is a summary of key aspects of the preferred rehabilitation strategy.

2.7.1 Re-Locate ‘High Priority’ PAF Waste to the Main Pit

The Main Pit will be backfilled to above ground surface (see Figure 2-11). PAF waste rock will be placed in the saturated zone of the Main Pit (below the dry season water table) so this waste remains inundated by groundwater year-round. Because this waste rock will have limited contact with atmospheric oxygen, it will generate minimal new AMD after rehabilitation.

Existing acidity in waste rock will also be neutralised during rehabilitation (by lime addition) to immobilize otherwise soluble metals (and limit impacts to groundwater downgradient). Waste rock in the Main Pit may still release sulphate (SO$_4$), calcium (Ca), magnesium (Mg), and relatively small amounts of dissolved metals that are mobile under circum-neutral pH conditions (e.g. Cd, Pb, and Zn).

2.7.2 Construct a WSF for Residual PAF Waste Rock and Contaminated Materials

A new above-ground WSF will be constructed near the northern lease boundary of the site (see Figure 2-11). The new WSF will contain waste rock and contaminated materials that cannot be placed in the Main Pit due to volume restrictions. Waste rock will be placed and compacted in thin lifts to reduce rainfall infiltration and limit the ingress of oxygen. This will reduce the generation of AMD and limit the amount of seepage that has to be managed after rehabilitation (see Section 2.7.5). Waste rock will also be amended with enough neutralant (“liming”) to neutralize existing acidity and ameliorate the existing load of soluble metals.

2.7.3 Remediate Impacted Groundwater in the former Copper Extraction Pad area

Groundwater near the former Copper Extraction Pad between the Main and Intermediate Pits contains up to 1,000 mg/L of dissolved copper (Cu) (see RGC, 2016e). A pump-and-treat system will be constructed to remediate impacted groundwater in this area. The system will likely be operated during the first two years of the construction phase of rehabilitation in order to reduce contaminant concentrations in groundwater before the Main Pit is de-watered. This timing will prevent inflows of highly-impacted groundwater to the pit while it is being dewatered and backfilled. Accordingly, six to eight pumping bores will be installed to pump a total of 3 to 4 L/s of impacted groundwater to the water treatment system RGC (2016e).
2.7.4  Manage Long-Term Seepage from the WSF via the Intermediate Pit

Small amounts of leachate from the WSF will be collected and managed after rehabilitation. This seepage will report to the flooded Intermediate Pit, where it will be diluted and dissolved metal concentrations further reduced by geochemical processes.
3 SIMULATED GROUNDWATER CONDITIONS POST REHABILITATION

3.1 MODELING OBJECTIVES

The overall objective of the groundwater modeling described in this section was to predict the effects of the preferred rehabilitation strategy on future (post-rehabilitation) groundwater flow and transport of selected contaminants of concern (SO$_4$ and Cu).

Specific modeling objectives included:

- Predict the fate of “residual” contaminant plumes of SO$_4$ and Cu in groundwater from rehabilitated mine waste units (re-located WRDs, remediated Copper Extraction Pad area).
- Predict the fate of new SO$_4$ and Cu plumes in groundwater downgradient of the backfilled Main Pit and WSF.
- Predict future (post-rehabilitation) SO$_4$ and Cu loads to surface water (Intermediate Pit, EFDC, and the EBFR).

3.2 MODELING APPROACH

3.2.1 Model Adjustment to Post-Rehabilitation Conditions

The calibrated flow and transport model for current conditions (“2016 model”) described in RGC (2016f) was modified to assess post-closure conditions and inform the environmental performance of the preferred rehabilitation strategy. Modifications to the model required for assessment of post-rehabilitation conditions included:

- Adjustment of surface topography to reflect post-closure conditions (namely, the removal of WRDs, re-alignment of EBFR in the central mining area, backfilling of the Main Pit, and new WSF).
- Adjustment of flow boundary conditions to reflect post-rehabilitation conditions (i.e. removal of constant heads formerly representing flooded Main Pit, adjustments of drains representing realigned EBFR, and WSF).
- Removal of current sources of SO$_4$ and Cu (e.g. WRDs, Copper Extraction Pad area, contaminated soils, etc.) and introduction of new contaminant source terms for waste rock in the backfilled Main Pit and WSF).

3.2.2 Future Transport Modeling

The simulated SO$_4$ and Cu concentrations for current conditions (from RGC, 2016f) were used as initial concentrations for prediction of post-closure groundwater quality and contaminant loading to surface water. For Cu transport, the attenuation scenarios developed in RGC (2016f) were used to simulate future conditions:
• ‘No Attenuation’ (conservative transport, i.e. retardation factor, $R_f = 1$).
• ‘Moderate Attenuation’ (sorption in overburden and bedrock and chemical precipitation in the Coomalie Dolostone).
• ‘High Attenuation’ (sorption in overburden and shallow bedrock beneath WRDs and chemical precipitation in all bedrock lithologies).

Based on comparisons between simulated and observed spatial distributions of Cu concentrations in groundwater and between simulated and predicted loads of Cu in the EBFR today, RGC (2016f) considers the ‘moderate attenuation’ scenario to be the one that best simulates the drivers of current Cu transport at Rum Jungle. However, there is significant uncertainty in reactive transport modeling and there are few data (e.g. leaching testing of contaminated soils) available to constrain estimates of retardation. Moreover, the “high attenuation” scenario (with irreversible reaction in bedrock) is plausible, and the “no attenuation” scenario provides a useful (albeit likely unrealistic) reference scenario representing conservative transport. Consequently, both the no and moderate attenuation scenarios for copper were used to test the sensitivity of predicted post-rehabilitation performance to uncertainty in geochemical controls.

Implementation of the preferred rehabilitation strategy will take several years and involve dewatering of the Main Pit, followed by gradual re-location of the various mine waste units (WRDs, contaminated soils etc.) into the Main Pit and the WSF. An explicit simulation of actual rehabilitation works was beyond the scope of this study. Instead, groundwater flow and contaminant transport for post-rehabilitation conditions was simulated assuming all rehabilitation works have been completed and hydrogeological conditions have reached a new, post-rehabilitation equilibrium.

Based on some preliminary pit dewatering and reflooding modeling completed (using the current condition model) reflooding of the backfilled Main Pit by groundwater inflow could be in the order of 5-10 years. Some recovery of the groundwater levels in the surrounding bedrock aquifer and the backfilled waste rock will already have occurred after completion of the rehabilitation works. In addition, reflooding of the Main Pit could be accelerated by actively flooding the backfilled waste rock (either during backfill or immediately after). This aspect of rehabilitation works and its effect on post-rehabilitation contaminant transport in groundwater and loading to surface water could be evaluated further in the next phase of rehabilitation planning.

The following sections describe the numerical implementation of this modeling approach to simulate historic and current contaminant transport.

### 3.3 NUMERICAL METHODS

The numerical methods used for the post-rehabilitation (“future”) model are very similar to those used for the 2016 model (see RGC, 2016f). The following section only describes adjustments to the numerical model for the future model.
3.3.1 Time Discretization

The future flow and transport model was run using transient flow and transient transport for 30 years (nominally from 2016 to 2046). The model was run in two phases. Each model phase runs 15 years into the future, and has 183 monthly stress periods, starting in January and ending 15 years later in April, during the wet season. Each 12-month period has 44 time steps. The months of May and June were both simulated with 10 flow time steps each, due to the larger number of unsaturated model cells that developed during these months. July was simulated with 6 flow time steps, and April with 5 flow time steps. March and August has 3 flow time steps each, and February has 2 flow time steps. All other months were simulated with a single flow time step.

For each transport stress period, MT3D automatically selected the appropriate transport step sized. The maximum allowable transport steps per stress period was 60,000.

3.3.2 Adjustments to Flow Model

The following adjustments were made to the 2016 flow model for simulation of post-rehabilitation conditions:

- The monthly net precipitation values (used to compute recharge) were adjusted to represent long-term average conditions. To this end, the monthly net precipitation (after adjustment of soil moisture deficit (SMD) and excess rainfall) calibrated for the period January 2012 to December 2014 was averaged. The average total precipitation for this 3-year period was 1484 mm/year, which is close to the MAP for the site (1459 mm/year).

- The time-variant heads representing the flooded pits and the lower EBFR in the transient flow model were also computed by averaging the (known) time-variant heads for the 3-year calibration period.

- Evapotranspiration introduced numerical instability into transport runs and was therefore not simulated for the future transient flow and transport model.

- The constant head boundaries (formerly representing the flooded Main Pit) were removed to simulate the groundwater levels in the backfilled Main Pit.

- The waste rock and clean fill backfilled in the Main Pit were explicitly included in the model domain. The post-rehabilitation topography for the central mining area (OKC drawing file 871-6-RJ-Rehabilitated Site) was imported into the numerical model and assigned as top of Layer 1. Backfill hydrogeological properties were derived from values provided by OKC\(^2\):

  - Un-compacted waste rock in deep portion of Main Pit (Layer 6):
    - \( K_h = 5 \times 10^{-6} \text{ m/s}; S_y = 0.16; n_s = 0.25 \)

  - Compacted waste rock in remainder of Main Pit (Layers 2 to 5):

---

\(^2\) OKC Technical Memorandum dated December 17 2015 and an email from OKC dated September 10, 2015.
• $K_h = 1 \times 10^{-6}$ m/s; $S_y = 0.11$; $n_s = 0.22$
  - Clean fill (laterite soil) above water table (Layer 1)
    • $K_h = 1 \times 10^{-5}$ m/s; $S_y = 0.05$ and $n_s = 0.15$

• The WSF above the basal liner was not modeled explicitly in the groundwater model. Instead, leakage through the basal liner of the WSF was applied as recharge to the model. The footprint of the WSF used to apply seepage recharge was mapped to the model using the outline provided in OKC drawing 871-6-RJ-WSF.

• New drain nodes (with corresponding drain elevations) were assigned to the following areas to reflect the post-rehabilitation conditions (see Figure 3-1)
  - Footprints of the relocated WRDs where contaminated soils were removed and replaced with clean fill (using surface elevations provided in OKC drawing file 871-6-RJ-Rehabilitated Site).
  - Realigned EBFR channel through the central mining area (around Main Pit and new outlet from Intermediate Pit) using invert elevations provided in OKC drawing file 871-6-RJ-Rehabilitated Site).
  - New toe drains along the perimeter of the WSF (using invert elevations provided in OKC drawing 871-6-RJ-WSF).

### 3.3.3 Future Source Terms

Most of the known point sources of SO₄ and Cu to groundwater (WRDs, contaminated soils) would be re-located during the construction phase of rehabilitation. Sources in the model representing those relocated contaminant sources were removed from the future model, and the following new point sources were introduced:

• Waste rock in backfilled Main Pit.
• Basal seepage from the WSF.

Table 3-1 and 3-2 summarize the source concentrations and numerical implementation of these new contaminant sources in the transport model for future conditions.

Figures 3-2a/b show the source terms implemented in the numerical model for future conditions. The contaminant source in the backfilled Main Pit was represented in the transport model using constant concentrations applied to the layers representing backfilled waste rock. Seepage from the WSF was simulated by applying a constant concentration to recharge over the footprint of the WSF.
Seepage from the WSF represents leakage through defects in the basal liner. A constant rate of “basal” seepage of 19 mm/year was assumed based on seepage modeling completed by OKC (OKC, 2015).

The primary source of contaminant loading from the backfilled Main Pit is recharge through the overlying clean fill into the underlying contaminated waste rock. Net recharge over the (domed) clean fill on the Main Pit was assumed to be about 25% of monthly net precipitation. Lateral groundwater flow through the backfilled Main Pit represents a secondary (minor) source of contaminant loading from the Main Pit.

### 3.3.4 Geochemical Reactions

SO$_4$ is assumed to be non-reactive (“conservative”), i.e. no geochemical reactions are assumed to influence SO$_4$ transport along the groundwater flow path (RGC, 2016f). In contrast, Cu transport in groundwater can be expected to be substantially influenced by geochemical reactions, including:

- Sorption of Cu on soils and/or bedrock (e.g. on Fe-oxihydroxides, clays etc.).
- Chemical precipitation of Cu as copper hydroxides or Cu hydroxyl carbonates-malachite (pH-controlled) in bedrock units that have adequate buffering capacity to neutralize AMD (e.g. the Coomalie Dolostone).

---

Table 3-1

**Sulphate Source Terms for Future Transport Model (Post-Rehabilitation)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Area (m$^2$)</th>
<th>Type</th>
<th>Concentration (mg/L)</th>
<th>Layer(s)</th>
<th>Recharge (mm/yr)</th>
<th>Load (t/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Pit</td>
<td>95,000</td>
<td>Constant</td>
<td>10,000</td>
<td>2-6</td>
<td>325</td>
<td>309</td>
</tr>
<tr>
<td>WSF</td>
<td>412,000</td>
<td>Recharge Concentration</td>
<td>10,000</td>
<td>1</td>
<td>19</td>
<td>78</td>
</tr>
</tbody>
</table>

**Total Load = 387**

Table 3-2

**Copper Source Terms for Future Transport Model (Post-Rehabilitation)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Area (m$^2$)</th>
<th>Type</th>
<th>Concentration (mg/L)</th>
<th>Layer(s)</th>
<th>Recharge (mm/yr)</th>
<th>Load (t/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Pit</td>
<td>95,000</td>
<td>Constant</td>
<td>0.2</td>
<td>2-6</td>
<td>325</td>
<td>0.006</td>
</tr>
<tr>
<td>WSF</td>
<td>412,000</td>
<td>Recharge Concentration</td>
<td>0.2</td>
<td>1</td>
<td>19</td>
<td>0.002</td>
</tr>
</tbody>
</table>

**Total Load = 0.008**
The numerical implementation of these geochemical reactions in the future model are identical to those used in the current model (see RGC, 2016f) (see Section 3.2.2 for scenario descriptions). The following assumptions were made for the scenarios:

- For the ‘no attenuation’ scenario (i.e. conservative transport), the chemical reaction package in MT3DMS was turned off so that no sorption or chemical reactions was simulated by the model (i.e. $R_f=1$; $\beta=0$).
- For the ‘moderate attenuation’ scenario, overburden was assigned a $R_f$ of 3.5 and bedrock units other than the Coomalie Dolostone were assigned a $R_f$ of 100. In addition, all model zones representing the Coomalie Dolostone were assigned a first-order reaction rate of $\beta = 1 \, \text{s}^{-1}$.
- For the ‘high attenuation’ scenario, all overburden (model layers 1 and 2) and shallow bedrock (model layer 3) underlying mine waste units (except Coomalie Dolostone in the Old Tailings Dam area) was assigned a $R_f$ of 3.5 and all other bedrock (all lithologies) was assigned a first-order reaction of $\beta = 1 \, \text{s}^{-1}$.

The preferred rehabilitation strategy involves liming the footprints of the former WRDs following the removal of the waste to neutralize residual acidity and precipitate initially soluble Cu. The effect of the liming of the clean back-fill in those footprint areas was simulated by assigning a first-order reaction rate of $\beta = 1 \, \text{s}^{-1}$ to Layer 1 for the ‘moderate attenuation’ and ‘high attenuation’ scenarios.

### 3.3.5 Initial Concentrations

Figures 3-3a/b to 3-6a/b show the initial concentrations assumed for the post-rehabilitation model for sulphate and copper, respectively.

These initial concentrations were developed in two steps:

- First, the simulated $SO_4$ (or Cu) concentrations for current groundwater conditions (in 2015) were assigned to the future model.
- Second, these ‘current condition’ concentrations were adjusted to reflect planned groundwater cleanup during rehabilitation works, including:
  - Initial concentrations for $SO_4$ and Cu were set to 0 mg/L within the footprints of the former WRDs and Dysons Pit (clean fill in Layer 1).
  - Initial concentrations for $SO_4$ and Cu were set to 0 mg/L within the footprint of the CEPA and the former mill site (clean fill in Layer 1)$^3$.

---

$^3$ RGC has proposed to clean-up highly impacted groundwater in the Copper Extraction Pad area using pump-and-treat (RGC, 2016e). However, there is some uncertainty as to the resulting groundwater concentrations after pump-and-treat. RGC has conservatively assumed initial concentrations in model layers 2-6 representing simulated $SO_4$ and Cu copper concentrations for current conditions.
Note that the initial concentrations for Cu vary depending on the assumed attenuation scenario. Also note that the ‘no attenuation’ scenario assumes a much larger residual Cu plume in deeper bedrock than the ‘moderate attenuation’ or ‘high attenuation’ scenarios.

### 3.4 Simulation of Post-Rehabilitation Groundwater Flow

#### 3.4.1 Groundwater Flow Field

Figures 3-7a/b show the simulated hydraulic heads in model layer 3 (shallow bedrock) for the dry season and wet season, respectively.

The future groundwater flow field is predicted to differ from the current groundwater flow field in those areas where major earthworks are planned as part of rehabilitation. The main changes in the groundwater flow field from current conditions can be summarized as follows:

- Backfilling of the Main Pit will significantly alter the local groundwater flow field in this area, as the controlling effect of the annual flooding of the pit on groundwater levels has been removed. During the dry season, groundwater is predicted to flow through the backfilled pit in a northwesterly direction with water levels ranging from 59 m AHD near the northwestern margin of the backfilled pit to 61 m AHD near the southeastern margin. During the wet season, groundwater is predicted to mound (to about 63.5 m AHD) into the domed fill of the backfilled Main Pit.

- Construction of the WSF is predicted to result in an overall decline in groundwater levels beneath the facility of approximately 1 to 3 m due to significantly reduced recharge over the footprint of this facility.

Additional transient flow modeling (not shown here) was completed assuming a range of infiltrations rates (from monthly rainfalls from 2010 to 2015) to assess the potential range in seasonal and interannual groundwater levels in proximity of the WSF (not shown here). These transient model runs indicate that groundwater levels beneath the WSF will fluctuate seasonally by about 5 to 8 m bgs. Peak wet season groundwater levels are predicted to reach into the foundation layer during high precipitation periods (e.g. April 2011) but are not predicted to reach the basal liner of the WSF.

#### 3.4.2 Groundwater Inflows and Outflows

Figure 3-8 shows the simulated monthly inflows (recharge) and outflows (discharge to drains and constant heads) for the different “reaches” of the EBFR drainage system. Figure 3-9 shows the delineation of these model reaches and the monthly water balance for the entire model domain. Table 3-3 summarizes the simulated total annual groundwater discharge to the different model reaches (drains and constant heads combined).
It should be emphasized that the simulated fluxes are representative of long-term average monthly precipitation conditions. In reality, recharge as well as groundwater discharge to surface water will vary from year to year (and within a given wet season) depending on the actual precipitation regime.

Table 3-3

Simulated average annual groundwater discharge by model reach.

<table>
<thead>
<tr>
<th>Site Component</th>
<th>Flow, L/s</th>
<th>Flow, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dyson's WRD</td>
<td>10.6</td>
<td>9%</td>
</tr>
<tr>
<td>Dyson's (backfilled) Pit</td>
<td>3.9</td>
<td>3%</td>
</tr>
<tr>
<td>Main WRD</td>
<td>21.1</td>
<td>17%</td>
</tr>
<tr>
<td>Intermediate</td>
<td>2.3</td>
<td>2%</td>
</tr>
<tr>
<td>Main Pit</td>
<td>4.6</td>
<td>4%</td>
</tr>
<tr>
<td>Intermediate Pit</td>
<td>1.9</td>
<td>2%</td>
</tr>
<tr>
<td>Browns Oxide Pit</td>
<td>17.5</td>
<td>14%</td>
</tr>
<tr>
<td>New WSF</td>
<td>7.4</td>
<td>6%</td>
</tr>
<tr>
<td>Lower East Branch of the Finniss River</td>
<td>52.3</td>
<td>43%</td>
</tr>
<tr>
<td></td>
<td>121.6</td>
<td>100%</td>
</tr>
</tbody>
</table>

Key observations of the simulated water balance for post-rehabilitation conditions are as follows:

- The primary source of inflow to the groundwater system is recharge from rainfall (mean annual average of 126 L/s). Recharge occurs from November through May with peak recharge in the months from December to March.
- The primary outflow from the groundwater system occurs via drains (mean annual average of 83 L/s) represented by drainage lines, creeks and the EBFR. Discharge to these surface water features is also highly seasonal with highest discharge rates occurring during the wet season.
- A secondary outflow from the groundwater system occurs to surface water bodies represented by constant heads (mean annual average of 38 L/s) which include (i) the flooded Intermediate Pit, (ii) flooded Brown’s Oxide Pit and EBFR (downgradient of Old Tailings Creek). Groundwater discharge to constant heads show less seasonal fluctuations primarily because these water bodies connect to the deeper bedrock aquifer.
- The lower EBFR receives the highest groundwater discharge (52 L/s), followed by the Main WRD reach (21.1 L/s), Brown’s Oxide Pit (17.5 L/s) and Dysons reach (14.5 L/s). The realigned EBFR channel around the backfilled Main Pit receives 4.6 L/s and the Old Tailings Creek and unnamed drainages draining the WSF area receive 7.4 L/s.
3.5 SIMULATION OF POST-REHABILITATION SULPHATE TRANSPORT

Figures 3-10a to 3-10f show the distribution of simulated SO$_4$ concentrations for 5, 10, 15 and 30 years post-rehabilitation. The future groundwater flow field in the respective model layer (for wet season conditions) is also shown for reference (black contour lines). Figure 3-11 shows the associated transient mass fluxes of sulphate reporting to different reaches of the EBFR (and tributaries) and across the model domain (“total flux”) for the 30-year modeling period. Table 3-4 summarizes annual average sulphate loads to surface water by model reach.

Table 3-4

<table>
<thead>
<tr>
<th>Reach</th>
<th>Current SO$_4$ Load t/yr</th>
<th>5 Years</th>
<th>10 Years</th>
<th>15 Years</th>
<th>30 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% Change</td>
<td>% Change</td>
<td>% Change</td>
<td>% Change</td>
</tr>
<tr>
<td>Dyson’s Reach</td>
<td>202</td>
<td>-81%</td>
<td>-88%</td>
<td>-91%</td>
<td>-95%</td>
</tr>
<tr>
<td>Main WRD</td>
<td>461</td>
<td>-67%</td>
<td>-83%</td>
<td>-89%</td>
<td>-94%</td>
</tr>
<tr>
<td>Intermediate WRD</td>
<td>408</td>
<td>-89%</td>
<td>-92%</td>
<td>-92%</td>
<td>-93%</td>
</tr>
<tr>
<td>Main Pit</td>
<td>74</td>
<td>162%</td>
<td>162%</td>
<td>160%</td>
<td>159%</td>
</tr>
<tr>
<td>to Intermediate Pit</td>
<td>211</td>
<td>-48%</td>
<td>-57%</td>
<td>-56%</td>
<td>-60%</td>
</tr>
<tr>
<td>Brown’s Oxide Pit</td>
<td>18</td>
<td>-18%</td>
<td>-30%</td>
<td>-31%</td>
<td>-32%</td>
</tr>
<tr>
<td>WSF</td>
<td>22</td>
<td>-38%</td>
<td>-31%</td>
<td>-31%</td>
<td>-31%</td>
</tr>
<tr>
<td>Lower EBFR (d/s of Intermediate Pit)</td>
<td>42</td>
<td>2%</td>
<td>9%</td>
<td>10%</td>
<td>14%</td>
</tr>
<tr>
<td>TOTAL:</td>
<td>1439</td>
<td>611</td>
<td>498</td>
<td>457</td>
<td>419</td>
</tr>
</tbody>
</table>

The following sections describe the predicted future sulphate transport for different model reaches.

3.5.1 Dysons Area

In Dysons Area, the only remaining source of SO$_4$ after rehabilitation is the residual plume from the (re-located) Dysons WRD and Dysons Pit. Although waste rock and contaminated soils will be removed from Dysons Pit, the pore water in the backfilled tailings stored in Dysons Pit will remain a minor future source of SO$_4$. The predicted future SO$_4$ trends in Dysons Area can be summarized as follows:

- Residual SO$_4$ in shallow overburden soils (layers 1 and 2) and shallow bedrock (layer 3) is predicted to clean up in less than 5 years due to flushing by local recharge. Residual sulphate at greater depths in bedrock is predicted to flush more gradually.
- Seepage from the backfilled tailings in the Dysons Pit are predicted to contribute only a minor sulphate load to the receiving groundwater.
- Sulphate load to the upper EBFR in the Dysons Area is predicted to decline gradually (5 to 10 years) after rehabilitation. The long-term SO$_4$ load from Dysons Area is about 11 t/year (95% reduction compared to the current loading).
3.5.2 **Main and Intermediate WRD Reach**

Seepage from the Main and Intermediate WRDs reports to Fitch Creek (east), Wandering Creek (west) and the EFDC (north). Both WRDs will be relocated and foundation soils removed and replaced with clean fill, and the footprint area limed to neutralize acidity and precipitate residual soluble metals. Hence, the only remaining SO$_4$ source in this area will be the residual sulphate plumes present in groundwater in deeper overburden and bedrock (layers 2 to 7).

The predicted future SO$_4$ trends in the reach of the (re-located) Main and Intermediate WRDs can be summarized as follows:

- Residual SO$_4$ in shallow overburden soils (layers 1 and 2) and shallow bedrock (layer 3) is predicted to clean up in 10 to 15 years due to flushing by local recharge. Residual SO$_4$ at greater depths in bedrock is predicted to flush more gradually.
- Elevated SO$_4$ concentrations (>1,000 mg/L SO$_4$) are predicted to remain present for extended periods (> 30 years after rehabilitation) in localized groundwater discharge zones (e.g. Fitch Creek, EFDC) where more impacted groundwater from deeper bedrock is predicted to discharge into layer 3 and 2.
- SO$_4$ load to the Main WRD reach is predicted to decline gradually (5 to 10 years) after rehabilitation. The long-term SO$_4$ load in this reach is about 26 t/year (a 94% reduction from current loads).
- SO$_4$ load to the Intermediate WRD reach is predicted to decline rapidly (~5 years) after rehabilitation. The long-term sulphate load in this reach is about 29 t/year (a 93% reduction from current loads).

3.5.3 **Main Pit Reach**

The Main Pit reach post rehabilitation includes the re-aligned EBFR from the confluence with Fitch Creek (just upgradient of the Main Pit) to the Intermediate Pit. Currently this reach receives only minor loading from contaminated soils on the Copper Extraction Pad area and the former mill area, plus inputs to deep groundwater from the tailings present in the deep portion of the Main Pit. After rehabilitation, the waste rock to be placed into the Main Pit (layers 2 to 6) will represent a new source of SO$_4$ (assumed be 10,000 mg/L SO$_4$ based on batch leach testwork, see RGC, 2016a).

The predicted future SO$_4$ trends in the reach of the backfilled Main Pit can be summarized as follows:

- A new SO$_4$ plume is predicted to develop rapidly (in less than 5 years) from the new source of backfilled waste rock in the Main Pit. Note that some impact is also predicted for the clean fill (layer 1) overlying the backfilled waste rock. The higher concentrations predicted in parts of layer 1 can in part be attributed to numerical dispersion. However, some increase in SO$_4$ in the clean fill can be driven by seasonal fluctuations in the water table.
• In backfill and shallow overburden (layers 1 and 2) the new SO\textsubscript{4} plume is predicted to migrate in a predominantly northwesterly direction and discharge into the realigned EBFR.

• In bedrock (layers 3 to 6) the new sulphate plume from the backfilled Main Pit is predicted to migrate preferentially into the Coomalie dolostone to the north and from there in a southwesterly direction to the Intermediate Pit.

• A secondary plume (with lower SO\textsubscript{4} concentrations) is also predicted to travel in Coomalie Dolostone from the backfilled Main Pit in a southwesterly direction towards the EFDC.

• SO\textsubscript{4} load to the realigned channel of the EBFR near the Main Pit is predicted to increase rapidly after rehabilitation.
  o SO\textsubscript{4} loads to the channel are predicted to fluctuate seasonally from almost no load during the late dry season to peak loads of about 500 t/year during the wet season.
  o The long-term average annual SO\textsubscript{4} load in this reach is predicted to be about 193 t/year, about three times the current load to this reach.

• An additional 84 t/year is predicted to discharge directly into the Intermediate Pit via groundwater flow from the former plant area and the area near the Intermediate WRD (as per the local groundwater flow field in that area).

• The SO\textsubscript{4} load from the backfilled Main Pit (309 t/year) is predicted to be the largest future long-term point source after rehabilitation, representing about 74% of the predicted total long-term sulphate load from Rum Jungle after rehabilitation.

3.5.4 WSF Reach and Lower EBFR

The WSF reach includes the Old Tailings Creek area (near the Old Tailings Dam area) and the unnamed drainage to the northwest of the Old Tailings Dam area where the WSF would be constructed. Currently this reach receives only minor loading from residual tailings in the Old Tailings Dam area. After rehabilitation, fugitive seepage through the basal liner of the WSF will represent a new source of SO\textsubscript{4} (with 10,000 mg/L SO\textsubscript{4}).

The lower EBFR represents the reach from the Intermediate Pit to gauge GS8150327, i.e. the downstream boundary of the model domain. This reach currently receives SO\textsubscript{4} loads from the Old Tailings Dam area (via deeper groundwater flow in bedrock) and can be expected to also receive additional SO\textsubscript{4} loads from the WSF (via deeper groundwater flow in bedrock).

The predicted future SO\textsubscript{4} trends in the reach of the new WSF and lower East Branch of the Finniss River can be summarized as follows:

• The residual SO\textsubscript{4} plume in the Old Tailings Dam area (< 500 mg/L SO\textsubscript{4}) is predicted to flush out rapidly (in less than 5 years) from both the overburden soils (layers 1 and 2) and underlying Coomalie Dolostone (layers 3 to 5).
• A new SO₄ plume will develop due to seepage through the basal liner of the new WSF. This plume is predicted to approach steady-state concentrations in about 5 years. The SO₄ plume in shallow laterite soil is predicted to discharge near the downgradient (western) toe of the new facility. The SO₄ plume in saprolite and shallow bedrock (layers 2 to 3) is predicted to extend from the toe of the facility to the Old Tailings Dam area and discharge to Old Tailings Creek. The SO₄ plume in deeper bedrock (layers 4 and 5) is predicted to extend to the lower East Branch of Finniss River.

• SO₄ concentrations in the plume from the new WSF are predicted to be typically less than 1,000 mg/L SO₄, except for within the footprint itself and in immediate proximity of the WSF where concentrations may reach 2,500 mg/L SO₄. In summary, basal seepage from the new WSF will likely be diluted at least four times beneath the facility and up to at least 10 times in groundwater downgradient.

• SO₄ load to the WSF reach (unnamed drainage near WSF and Old Tailings Creek) is predicted to decrease initially (flushing of residual plume form OTD area), and then increase (all within the first 5 years after rehabilitation). SO₄ loads to this reach are predicted to fluctuate seasonally from almost no load during the late dry season to peak loads of about 55 t/year during the wet season. The long-term average annual SO₄ load in this reach is predicted to be about 15 t/year over 30 years, representing a 13% reduction compared to current conditions.

• SO₄ load to the lower East Branch of the Finniss River is predicted to slightly increase within 5 to 7 years after rehabilitation. SO₄ loads to this reach are predicted to fluctuate seasonally from about 27 t/year during the late dry season to peak loads of about 70 t/year during the wet season. The long-term average annual SO₄ load in this reach is predicted to be about 49 t/year, representing a 14% increase compared to current conditions.

• The combined SO₄ load from the WSF and lower East Branch of the Finniss River (originating from the new WSF) is about 64 t/year. This future SO₄ load from the new WSF represents only about 15% of the predicted total long-term sulphate load from the Rum Jungle site post rehabilitation.

3.6 SIMULATED COPPER TRANSPORT

3.6.1 Overview

As described earlier, the 'moderate attenuation' scenario is considered to be the scenario that most closely represents current copper transport at Rum Jungle (RGC, 2016f). There is significant uncertainty in reactive transport modeling though, so the other two scenarios (i.e. 'no attenuation' and 'high attenuation') scenarios were also simulated to evaluate the sensitivity of predicted post-rehabilitation performance to uncertainty in geochemical controls. The following sections provide a
detailed description of the predicted future copper transport for the moderate attenuation scenario (by model reach). This is followed by a comparison of the different attenuation scenarios.

### 3.6.2 Moderate Attenuation Scenario

Figures 3-12a to 3-12c show the simulated Cu concentrations for future conditions (i.e. 15 and 30 years after rehabilitation is complete). The future groundwater flow field in the respective model layers (for wet season conditions) is also shown for reference (black contour lines). Table 3-5 summarizes annual average copper loads to surface water by model reach.

#### Table 3-5

**Predicted Future Copper Loads to Surface Water by Model Reach**

<table>
<thead>
<tr>
<th>Reach</th>
<th>Current Cu Load</th>
<th>Predicted Cu Load after Rehabilitation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 Years</td>
<td>10 Years</td>
</tr>
<tr>
<td></td>
<td>15 Years</td>
<td>30 Years</td>
</tr>
<tr>
<td>Dyson's Reach</td>
<td>0.22 -58%</td>
<td>0.18 -66%</td>
</tr>
<tr>
<td>Main WRD</td>
<td>0.29 -53%</td>
<td>0.21 -66%</td>
</tr>
<tr>
<td>Intermediate WRD</td>
<td>0.10 -89%</td>
<td>0.05 -95%</td>
</tr>
<tr>
<td>Main Pit</td>
<td>0.00 -100%</td>
<td>0.00 -100%</td>
</tr>
<tr>
<td>to Intermediate Pit</td>
<td>0.19 -77%</td>
<td>0.12 -85%</td>
</tr>
<tr>
<td>Brown's Oxide Pit</td>
<td>0.02 -49%</td>
<td>0.01 -62%</td>
</tr>
<tr>
<td>WSF Reach</td>
<td>0.00 125%</td>
<td>0.00 107%</td>
</tr>
<tr>
<td>Lower EBFR (d/s of Intermediate Pit)</td>
<td>0.01 -59%</td>
<td>0.00 -62%</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td><strong>3.08 -73%</strong></td>
<td><strong>0.83 -61%</strong></td>
</tr>
<tr>
<td>Moderate Attenuation</td>
<td>0.22 -70%</td>
<td>0.08 -73%</td>
</tr>
<tr>
<td>Main WRD</td>
<td>0.33 -52%</td>
<td>0.30 -57%</td>
</tr>
<tr>
<td>Intermediate WRD</td>
<td>0.57 -53%</td>
<td>0.52 -56%</td>
</tr>
<tr>
<td>Main Pit</td>
<td>0.05 -25%</td>
<td>0.05 -29%</td>
</tr>
<tr>
<td>to Intermediate Pit</td>
<td>0.28 -28%</td>
<td>0.27 -30%</td>
</tr>
<tr>
<td>Brown's Oxide Pit</td>
<td>0.00 -24%</td>
<td>0.00 -24%</td>
</tr>
<tr>
<td>WSF Reach</td>
<td>0.01 -32%</td>
<td>0.00 -69%</td>
</tr>
<tr>
<td>Lower EBFR (d/s of Intermediate Pit)</td>
<td>0.01 -77%</td>
<td>0.00 -78%</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td><strong>2.66 -50%</strong></td>
<td><strong>1.33 -54%</strong></td>
</tr>
<tr>
<td>High Attenuation</td>
<td>0.20 -79%</td>
<td>0.03 -84%</td>
</tr>
<tr>
<td>Main WRD</td>
<td>0.33 -85%</td>
<td>0.04 -89%</td>
</tr>
<tr>
<td>Intermediate WRD</td>
<td>0.09 -67%</td>
<td>0.08 -73%</td>
</tr>
<tr>
<td>Main Pit</td>
<td>0.01 9%</td>
<td>0.00 -10%</td>
</tr>
<tr>
<td>to Intermediate Pit</td>
<td>0.15 -44%</td>
<td>0.12 -56%</td>
</tr>
<tr>
<td>Brown's Oxide Pit</td>
<td>0.00 -97%</td>
<td>0.00 -98%</td>
</tr>
<tr>
<td>WSF Reach</td>
<td>0.01 -34%</td>
<td>0.00 -67%</td>
</tr>
<tr>
<td>Lower EBFR (d/s of Intermediate Pit)</td>
<td>0.00 -90%</td>
<td>0.00 -93%</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td><strong>1.12 -68%</strong></td>
<td><strong>0.35 -75%</strong></td>
</tr>
</tbody>
</table>

The key findings of these Cu predictions are summarized below by model reach:

- **Dysons Area.** The only remaining Cu source in this area after rehabilitation is the residual Cu plume from the (re-located) Dysons WRD and Dysons Pit. Although contaminated soils
and waste rock will be removed from Dysons Pit, the pore water in the backfilled tailings in Dysons Pit will remain a future source of copper. The predicted future Cu trends in Dysons Area can be summarized as follows:

- A notable reduction in residual Cu concentrations is only predicted in shallow overburden soils (layer 1) consisting primarily of limed, clean fill and shallow saprolite (layer 2). However, the flushing of Cu from these shallow soils is predicted to be much slower than for sulphate due to ongoing desorption of copper. The residual copper plume in the bedrock (layers 3 to 5) is not predicted to reduce significantly in spatial extent or concentrations over 30 years.
- Cu load to the upper EBFR in Dysons Area is predicted to decline initially by about 30% due to removal of the Cu sources (waste rock, contaminated soils and foundation material) and liming of the foot print areas. Thereafter, copper loading is predicted to decrease very gradually. The total Cu load in Dysons reach after 30 years is about 0.05 t/year, representing a 90% reduction compared to current loads.

- **Main and Intermediate WRD Reach.** The Main and Intermediate WRDs will be relocated and foundation soils removed and replaced with clean fill and limed. Hence, the only remaining Cu source in this area will be the residual Cu plumes present in groundwater in deeper overburden and bedrock (layers 2 to 7). The predicted future copper trends in the reach of the (relocated) Main and Intermediate WRDs can be summarized as follows:
  - Removal of waste rock and contaminated foundation soils (followed by backfilling with clean material and liming) is predicted to result in very rapid cleanup of the foot print area (layer 1) and gradual decline in copper concentrations in the deeper saprolite (layer 2). In contrast, flushing of residual copper in the underlying bedrock (layers 3 to 6) is predicted to be very slow (i.e. much longer than 30 years).
  - Cu load to the Main and Intermediate WRD reaches is predicted to decline initially by about 30-35% due to removal of the Cu sources (waste rock, contaminated soils and foundation material) and liming of the foot print areas. Thereafter, Cu loads are predicted to decrease very gradually.
  - The total Cu load to the Main and Intermediate WRD reaches after 30 years is about 0.22 t/year and 0.37 t/year, respectively. This represents a 63% reduction compared to current loads.

- **Main Pit Reach.** Currently, this reach receives only minor loading of Cu from contaminated soils in the Copper Extraction Pad area and the former mill area, plus deep seepage from the tailings present in the deep portion of the Main Pit. After rehabilitation, the waste rock to be placed into the Main Pit (layers 2 to 6) would represent a new Cu source, although Cu concentrations in pore water will likely be low (0.2 mg/L Cu) due to amendment of waste rock
with lime (see RGC, 2016a). The predicted future copper trends in the reach of the backfilled Main Pit can be summarized as follows:

- Cu concentrations in clean fill (layer 1) are predicted to be very low due to removal of contaminated soils and liming. Cu concentrations in saprolite (layer 2) are also predicted to decline, although more gradually, due to flushing of the residual Cu by local recharge.
- Cu concentrations in the deeper bedrock (layers 3 to 6) are predicted to clean up very slowly (much longer than 30 years) due to desorption of Cu from the bedrock. Note that the assumed Cu concentration in seepage from backfilled waste rock (0.2 mg/L Cu) is significantly lower than the residual Cu in bedrock in the Copper Extraction Pad area. Hence, seepage from the backfilled Main Pit will tend to dilute the residual Cu plume in the Copper Extraction Pad area.
- The residual Cu plume in the former mill area (to the east of the Main Pit) is predicted to be essentially stagnant (with very little loading to the backfilled Main Pit because of a combination of low bedrock permeability in the Geolsec and high retardation.
- Cu load to the realigned EBFR channel in the Main Pit reach is predicted to decline initially by about 50% due to removal of the Cu sources (contaminated soils from the leach pad operation). Thereafter, Cu loading is predicted to decrease very gradually. The total Cu load in the Main Pit reach after 30 years is about 0.03 t/year, representing a 63% reduction compared to current loading.
- The new Cu load from the backfilled Main Pit (0.006 t/year) is predicted to contribute less than 20% to the Cu load predicted to the realigned channel. The main sources of future Cu loading to surface water are residual copper plumes in groundwater from the Intermediate WRD and the CEPA which are predicted to still discharge to the Intermediate WRD reach (0.37 t/yr) and the Intermediate Pit (0.3 t/yr) after 30 years.

**WSF Reach and lower EBFR.** Currently, this reach receives only very minor loading from residual Cu concentrations related to seepage from tailings in the former Old Tailings Dam area. After rehabilitation, seepage through the basal liner of the WSF will represent a new source of Cu. However, Cu concentrations in leachate from the WSF would be low (0.2 mg/L) and flow rates will be very low as well (i.e. 19 mm/yr). Together these will result in a very small Cu load (0.002 t/year) from the new WSF. The predicted future copper trends in the reach of the WSF and lower EBFR can be summarized as follows:

- Small remaining pockets of residual Cu in the Old Tailings Dam area (in layer 2) are predicted to flush out over the next 15 years.
- Seepage rates and associated Cu load from the WSF are too small to produce any significant Cu plume in groundwater.
### 3.6.3 Comparison of Attenuation Scenarios

Figures 3-13a to 3-13f compare the predicted Cu concentrations for the different attenuation scenarios for longer-term conditions (30 years after rehabilitation). Figures 3-14a to 3-14h show the associated transient mass fluxes of Cu (for all four attenuation scenarios) reporting to different reaches of the EBFR (and tributaries) and across the model domain (“total flux”).

The key findings of this sensitivity analysis on the influence of attenuation on future copper transport can be summarized as follows:

- The conservative transport scenario (“no attenuation”) is predicted to result in rapid flushing of all residual copper plumes, in particular in the shallow soils and shallow bedrock (similar to the case of SO$_4$ described above). This scenario produces the highest Cu loads to surface water early on (in Years 1 and 2), but Cu loads subsequently fall below those predicted for the ‘moderate attenuation’ scenario. After 30 years, the copper loads for the conservative scenario are predicted to have declined to 0.3 t/year. i.e. 70% lower than Cu load predicted for the ‘moderate attenuation’ scenario.

- In the conservative scenario, essentially all of the Cu load represents Cu initially stored in groundwater (“residual plume”) that is gradually flushed from the aquifer. In contrast, in the ‘moderate attenuation’ scenario, a significant portion of the copper load is gradually released from the solid phase (via desorption). This desorption process accounts for the delayed flushing of the copper plume and overall higher loads discharging to the surface water.

- The ‘high attenuation’ scenario is predicted to generate the lowest Cu loads to surface water throughout the modeling period by removing all Cu loading from bedrock (except shallow bedrock beneath the former mine waste units). In this scenario, predicted Cu loads to surface water gradually fall from about 0.5 t/year in Year 1 to 0.15 t/year in Year 30. i.e. 85% below the Cu load predicted for the ‘moderate attenuation’ scenario.

### 3.7 Sensitivity Analysis of Transport Parameters

A sensitivity analysis was completed to assess the influence of transport parameters on the predicted contaminant loads from groundwater to surface water. Transport parameters varied for the sensitivity analysis included the effective porosity (+/- a factor of 2) and dispersivity (up by a factor of 2). Sensitivity analyses were completed for the conservative SO$_4$ run and for the ‘moderate attenuation’ scenario for Cu.

Table 3-6 summarizes the sensitivity runs completed and the predicted total (model-wide) load to surface water predicted for each scenario. Figures 3-15 and 3-16 shows the simulated total mass flux from groundwater to surface water (model wide) over the 30-year modeling period for sulphate and copper, respectively.
The key findings of this sensitivity analysis on transport parameters are as follows:

- Changes in transport parameters significantly influences the transport of the conservative sulphate:
  - A higher effective porosity results in longer travel times but also a higher volume of impacted groundwater ("residual plume") stored in the aquifer system. As a result, flushing of the residual sulphate plume is slower and the total mass discharging to surface water is higher. A twofold increase in effective porosity increases the total sulphate mass to surface water by up to 65%.
  - A higher dispersivity results in more spreading of the solute plume along the flow path. This will tend to increase the arrival of the leading edge of a new plume but slow down flushing of the residual plume. A two-fold increase in dispersivity increased SO₄ loads to surface water marginally (by about 6%).

- Cu transport and loading to surface water was not significantly influenced by the change in transport parameters. This lack of sensitivity is a result of the dominating control of chemical reactions assumed for the moderate attenuation scenario. In other words, Cu transport is much more sensitive to the uncertainty in chemical attenuation than uncertainty in transport parameters.

### Table 3-6

Influence of Transport Parameters on Predicted Future Sulphate and Copper Loads

<table>
<thead>
<tr>
<th>Reach</th>
<th>Future Year 5 Load t/yr</th>
<th>Future Year 10 Load t/yr</th>
<th>Future Year 15 Load t/yr</th>
<th>Future Year 30 Load t/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sulphate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base Case</td>
<td>611</td>
<td>498</td>
<td>457</td>
<td>419</td>
</tr>
<tr>
<td>2x Porosity</td>
<td>828</td>
<td>835</td>
<td>752</td>
<td>667</td>
</tr>
<tr>
<td>2x Dispersivity</td>
<td>651</td>
<td>536</td>
<td>495</td>
<td>419</td>
</tr>
<tr>
<td><strong>Copper</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base Case</td>
<td>1.3</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>2x Porosity</td>
<td>1.3</td>
<td>1.2</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>1/2 Porosity</td>
<td>1.3</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>2x Dispersivity</td>
<td>1.3</td>
<td>1.2</td>
<td>1.1</td>
<td>0.9</td>
</tr>
</tbody>
</table>
4 POST-REHABILITATION LOADS AND WATER QUALITY CONDITIONS

An Excel-based mixing model was developed in order to predict SO₄ and Cu loads and concentrations in the Intermediate Pit and the East Branch of Finniss River (at gauge GS8150327) for the first 30 years after rehabilitation. The model includes two separate mixing 'reactors': (i) the Intermediate Pit and (ii) the EBFR reach between the Intermediate Pit and gauge GS8150327. The following sections describe the methods and water quality predictions for those two model reaches.

4.1 PREDICTED WATER QUALITY IN THE INTERMEDIATE PIT

4.1.1 Model Structure and Inputs

Inflows to the Intermediate Pit are assumed to be (i) “internal” seepage collected above the liner from the WSF (i.e. leachate), (ii) groundwater inflows from upgradient, and (iii) surface water flows from the reinstated EBFR. Some pertinent information on how loads from these three sources were predicted is provided here:

- **Leachate from the WSF.**
  - OKC (2015) estimates 50 m³/day (or 0.6 L/s) of leachate from the WSF after rehabilitation. This leachate will be collected by a drain system above the basal liner and delivered to the Intermediate Pit by pipe.
  - RGC (2016a) estimates that leachate from lime-amended waste rock may contain 10,000 mg/L SO₄ and 200 µg/L Cu. These concentrations were predicted from leach extraction tests done with waste rock amended with fine-grained CaCO₃.
  - Flows of leachate and concentrations of SO₄ and Cu were assumed to be constant post rehabilitation.

- **Groundwater inflows from upgradient.**
  - Simulated monthly SO₄ and Cu loads from groundwater to the Intermediate Pit for 30 years post-rehabilitation were incorporated (see Section 3.5 and 3.6). Simulated SO₄ and Cu loads from Dysons Area, the Main Pit area (i.e. the backfilled pit and former plant area), the area near the Intermediate Pit, and a portion of the load from the Intermediate WRD were assumed to report to the Intermediate Pit.
  - For Cu, simulated loads from the ‘moderate attenuation’ scenario were used as a ‘base case’ scenario. This is the scenario that RGC considers to be the most likely to represent post-rehabilitation Cu transport. Simulated loads from the ‘high attenuation’ scenario are also discussed for purposes of comparison. Simulated loads from both scenarios are transient loads that change over time as residual, AMD-impacted groundwater is flushed, and plumes from new sources of SD begin to reach the Intermediate Pit.

- **Surface water flows in the reinstated EBFR.**
Daily flows of the EBFR were predicted using the SIMHYD hydrological runoff model developed by Water Technology for Rum Jungle for the historical 30-year period from 1955 to 1985. This runoff model was incorporated into a Goldsim model that RGC developed to simulate water management during the construction phase of rehabilitation (see RGC, 2016d).

The percentage split of flows between the EFDC and the reinstated EBFR was taken from the Option 14 channel arrangement.

To estimate background loads in the EBFR, RGC assumed 1 mg/L SO$_4$ and 1 µg/L Cu in river water. These concentrations are based on routine monitoring of surface water quality upstream of the site.

SO$_4$ and Cu loads from these three sources were mixed in the Intermediate Pit (800,000 m$^3$) assuming continuous mixing and uniform concentration with depth. A daily time step was used for the 30-year simulation period. To approximate pH-controlled geochemical reactions in the pit, an upper limit (or ‘threshold concentration’) of 100 µg/L Cu was applied to total Cu concentrations in the Intermediate Pit. This concentration corresponds to the solubility limit of Cu at pH 7.8. It is also the 80$^{th}$ percentile for total Cu in the Intermediate Pit since 2010.

If the predicted total Cu concentration in pit water is less than 100 µg/L Cu, the Cu load from the Intermediate Pit is conservatively assumed to report to the EBFR downstream as dissolved Cu. If the total Cu concentration in pit water is predicted to be higher than 100 µg/L Cu, the excess Cu load above that concentration was assumed to remain in the Intermediate Pit as sludge.

SO$_4$ and Cu loads from these three sources were mixed in the Intermediate Pit (800,000 m$^3$) assuming continuous mixing and uniform concentration with depth. A daily time step was used for the 30-year simulation period. SO$_4$ is assumed to behave conservatively, so there are no changes to the SO$_4$ concentration within the Intermediate Pit or in the EBFR downstream. However, dissolved Cu concentrations are strongly controlled by pH, so a solubility limit of 100 µg/L Cu was applied to dissolved Cu concentrations in the Intermediate Pit. This limit was applied to approximate the pH-controlled geochemical reactions that control dissolved Cu concentrations in pit water after mixing.

100 µg/L Cu corresponds to the solubility limit of Cu at pH 7.8 and is also the 80$^{th}$ percentile Cu concentration for the Intermediate Pit from 2010 to 2015 (see RGC, 2016f). If the predicted Cu concentration in pit water is less than 100 µg/L Cu, the Cu load from the Intermediate Pit is conservatively assumed to report to the EBFR downstream as dissolved Cu. If the dissolved Cu concentration in pit water is predicted to be higher than 100 µg/L Cu, the excess Cu load above that concentration was assumed to precipitate and remain in the Intermediate Pit as sludge.

The use of an ‘upper limit’ reflects the fact that dissolved Cu concentrations in the Intermediate Pit are controlled by pH. Under current conditions, dissolved Cu does not typically exceed 100 µg/L due to buffering of current concentrations in seepage within the Intermediate Pit. The use of the same
upper threshold of 100 µg/L for the post-rehabilitation mixing model implicitly assumes that the buffering capacity of the Intermediate Pit, which is fed by the EBFR from upstream, will continue to be adequate to maintain similar pH conditions after rehabilitation. Should this assumption be invalid due to higher acidity and/or Cu loads to the Intermediate Pit or only partial mixing, hydrated lime may have to be added to pit water during the dry season to raise the pH sufficiently to precipitate the dissolved Cu.

4.1.2 Predicted SO₄ and Cu Loads to Intermediate Pit

The Intermediate Pit is predicted to receive mean annual loads of 535 t/year SO₄ and 0.44 t/year Cu to the pit over 30 years post rehabilitation (Table 4-1a). Simulated loads from groundwater are the largest sources of SO₄ and Cu to the pit after rehabilitation (i.e. 61% of the SO₄ load, and 93% of the Cu load). Leachate collected from the WSF accounts for 34% of the SO₄ load to the pit, but only 1% of the Cu load. This is consistent with the geochemical composition of leachate collected from the WSF (i.e. 10,000 mg/L SO₄ but only 200 µg/L Cu). Background loading from the catchment of the upper EBFR (upstream of Rum Jungle) account for less than 5 to 6% of the annual SO₄ and Cu loads (see Table 4-1a).

SO₄ concentrations in the Intermediate Pit are unaffected by geochemical reactions (i.e. it is conservative). The SO₄ load to the Intermediate Pit is therefore the same as the load from the Intermediate Pit to the EBFR. For Cu, 4.7 t Cu (or 0.16 t/year) precipitate in the Intermediate Pit and remain in the pit as accumulated sludge. These loads correspond to 36% of the total Cu load to the pit (see Table 4-1a).

<table>
<thead>
<tr>
<th>Source</th>
<th>SO₄ (30 years)</th>
<th>Cu (30 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t</td>
<td>t/year</td>
</tr>
<tr>
<td>Inflows from East Branch of the Finniss River</td>
<td>785</td>
<td>26</td>
</tr>
<tr>
<td>Groundwater discharge from upgradient areas</td>
<td>9,746</td>
<td>325</td>
</tr>
<tr>
<td>Leachate collected from the new WSF</td>
<td>5,524</td>
<td>184</td>
</tr>
<tr>
<td><strong>Sub-Total:</strong></td>
<td><strong>16,055</strong></td>
<td><strong>535</strong></td>
</tr>
<tr>
<td><strong>Losses by Precipitation Reactions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remaining in pit water as sludge</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>TOTAL (loads leaving the pit):</strong></td>
<td><strong>16,055</strong></td>
<td><strong>535</strong></td>
</tr>
</tbody>
</table>

The contaminant load balance for the Intermediate Pit assuming simulated Cu loads from the ‘high attenuation’ scenario is summarized in Table 4-1b. Predicted Cu loads to the Intermediate Pit are relatively low for this scenario because Cu is assumed to be precipitated out (or irreversibly sorbed)
in bedrock, thus significantly reducing the future copper load from upgradient groundwater. Consequently, Cu concentrations in pit water are lower compared to the ‘moderate attenuation’ scenario, so less Cu is precipitated from the pit water as sludge. These estimates emphasize the influence of Cu transport in groundwater on post-rehabilitation Cu concentrations in the Intermediate Pit and, in turn, the post-rehabilitation conditions in the EBFR (see Section 4.2).

Table 4-1b

Predicted Contaminant Load Balance for the Intermediate Pit, 'High Attenuation' scenario (for 30 years after rehabilitation)

<table>
<thead>
<tr>
<th>Source</th>
<th>SO(_4) (30 years)</th>
<th>Cu (30 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t/year</td>
<td>% t/year</td>
</tr>
<tr>
<td>Inflows from East Branch of the Finniss River</td>
<td>785</td>
<td>26</td>
</tr>
<tr>
<td>Groundwater discharge from upgradient areas</td>
<td>9,746</td>
<td>325</td>
</tr>
<tr>
<td>Leachate collected from the new WSF</td>
<td>5,524</td>
<td>184</td>
</tr>
<tr>
<td>Sub-Total</td>
<td>16,055</td>
<td>535</td>
</tr>
<tr>
<td>Losses by Precipitation Reactions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remaining in pit water as sludge</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL (loads leaving the pit)</td>
<td>16,055</td>
<td>535</td>
</tr>
</tbody>
</table>

4.1.3 Predicted SO\(_4\) and Cu Concentrations in Pit Water

Flow-weighted, mean annual SO\(_4\) and dissolved Cu concentrations in water flowing from the Intermediate Pit after rehabilitation are summarized in Table 4-2. Daily predictions of SO\(_4\) and dissolved Cu concentrations are shown in Figure 4-1. These concentrations reflect the assumptions on mixing in the Intermediate Pit described in Section 4.1.1. Loads for these same ‘base case’ mixing conditions, but assuming simulated loads from the ‘high attenuation’ Cu transport scenario, are also provided in Table 4-2. After rehabilitation, predicted SO\(_4\) and Cu concentrations in the Intermediate Pit are much lower than mean concentrations from 2010 to 2015 due to smaller loads from groundwater and from Dysons Area via the upper EBFR.
4.1.4 Model Sensitivity to Inputs and Mixing Volumes

Shown in Tables 4-3a and 4-3b are SO$_4$ and Cu concentrations for a ‘lower bound’ scenario and an ‘upper bound’ scenario. These scenarios were run in order to evaluate the sensitivity of the mixing model to key inputs. Changes to the ‘base case’ scenario for these scenarios are summarized here:

- ‘Upper Bound’ scenario
  - 20,000 mg/L SO$_4$ and 1,000 µg/L Cu in seepage from WSF.
  - Mixing in only 50% of the full volume of the Intermediate Pit.
- ‘Lower Bound’ scenario.
  - 7,500 mg/L SO$_4$ and 100 µg/L Cu in seepage from the WSF.

For the ‘base case’ scenario, the flow-weighted mean SO$_4$ concentration in pit water for the first 10 years after rehabilitation is predicted to be 31 mg/L SO$_4$. The upper and lower bounds for this period are 39 mg/L SO$_4$ and 29 mg/L SO$_4$, respectively. These estimates indicate that SO$_4$ concentrations are sensitive to the mixing volume and the SO$_4$ concentration in seepage collected form the WSF, yet ‘upper bound’ SO$_4$ concentrations are still quite low (i.e. less than half of the mean SO$_4$ concentration in pit water from 2010 to 2015) (See Table 4-3).

Predicted Cu concentrations from the sensitivity runs suggest that Cu concentrations are not very sensitive to the mixing volume or the Cu concentration in seepage collected from the WSF. This is mainly because Cu loads from the WSF represent a much smaller proportion of the total load to the Intermediate Pit than for SO$_4$. For the ‘upper bound’ scenario, the reduced mixing volume resulted in predicted Cu concentrations that were higher than 100 µg/L Cu. When this occurred, the corresponding load above that concentration was assumed to be removed from the system, thereby
maintaining a relatively stable dissolved Cu concentration in the Intermediate Pit. These variations are within the uncertainty of the analysis, so both scenarios have essentially the same load.

If dissolved copper concentrations are not limited by the 100 µg/L Cu solubility limit (i.e. assuming conservative mixing), predicted Cu concentrations in the Intermediate Pit would increase to 200 to 300 µg/L Cu. These concentrations could occur in pit water at a pH of 7.0 to 7.5 as a result of higher acidity loads from leachate collected from the WSF or from groundwater inputs. The solubility limit for the Intermediate Pit to 300 µg/L Cu to evaluate how a lack of Cu precipitation in the pit as sludge could affect loads to the EBFR.

Assuming no sludge precipitation in the Intermediate Pit, Cu loads to the EBFR would increase by about 50% (to 0.44 t/year Cu over 30 years). Specifically, the dissolved Cu load under these conditions would increase to 0.3 t/year Cu (from 0.2 t/year Cu for the ‘base case’ scenario). This is a substantial load increase, but flow-weighted dissolved Cu concentrations in the EBFR only increase by 2 µg/L as a result of the higher dissolved loads from the Intermediate Pit. This is because Cu concentrations in the EBFR are driven mainly by Cu loads from the former Intermediate and Main WRD foot print areas which discharge to the EFDC and by-pass the Intermediate Pit (see Section 4.2.3).

Table 4-3a

| Predicted Annual, Flow-Weighted Mean SO₄ and Cu Concentrations in Pit Water after Rehabilitation, 'Moderate Attenuation' Cu transport scenario |
|---|---|---|
| Source | SO₄ in Pit Water, mg/L | Dissolved Cu in Pit Water, µg/L |
| Mean Concentrations for Intermediate Pit, 2011 to 2015 | 85 | 40 |
| Base Case’ Scenario | | |
| 0 to 10 years after rehabilitation | 31 | 10.4 |
| 10 to 20 years | 17 | 6.4 |
| 20 to 30 years | 14 | 5.5 |
| Entire, 30 year simulation period | 19 | 6.9 |
| Upper Bound’ Scenario | | |
| 0 to 10 years after rehabilitation | 39 | 9.5 |
| 10 to 20 years | 23 | 5.9 |
| 20 to 30 years | 19 | 5.0 |
| Entire, 30 year simulation period | 25 | 6.3 |
| Lower Bound’ Scenario | | |
| 0 to 10 years after rehabilitation | 29 | 10.4 |
| 10 to 20 years | 15 | 6.4 |
| 20 to 30 years | 13 | 5.5 |
| Entire, 30 year simulation period | 17 | 6.9 |
Table 4-3b

Predicted Annual, Flow-Weighted Mean SO$_4$ and Cu Concentrations in Pit Water after Rehabilitation, ‘High Attenuation’ Cu transport scenario

<table>
<thead>
<tr>
<th>Source</th>
<th>$SO_4$ in Pit Water, mg/L</th>
<th>Dissolved Cu in Pit Water, ug/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Concentrations for Intermediate Pit, 2011 to 2015</td>
<td>85</td>
<td>40</td>
</tr>
<tr>
<td><strong>Base Case’ Scenario</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to 10 years after rehabilitation</td>
<td>31</td>
<td>7.1</td>
</tr>
<tr>
<td>10 to 20 years</td>
<td>17</td>
<td>3.6</td>
</tr>
<tr>
<td>20 to 30 years</td>
<td>14</td>
<td>2.8</td>
</tr>
<tr>
<td>Entire, 30 year simulation period</td>
<td>19</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>Upper Bound’ Scenario</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to 10 years after rehabilitation</td>
<td>39</td>
<td>6.1</td>
</tr>
<tr>
<td>10 to 20 years</td>
<td>23</td>
<td>3.2</td>
</tr>
<tr>
<td>20 to 30 years</td>
<td>19</td>
<td>2.5</td>
</tr>
<tr>
<td>Entire, 30 year simulation period</td>
<td>25</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>Lower Bound’ Scenario</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to 10 years after rehabilitation</td>
<td>29</td>
<td>7.1</td>
</tr>
<tr>
<td>10 to 20 years</td>
<td>15</td>
<td>3.6</td>
</tr>
<tr>
<td>20 to 30 years</td>
<td>13</td>
<td>2.7</td>
</tr>
<tr>
<td>Entire, 30 year simulation period</td>
<td>17</td>
<td>4.0</td>
</tr>
</tbody>
</table>

4.2 Predicted Water Quality Conditions for EBFR

4.2.1 Model Structure and Inputs

SO$_4$ and Cu concentrations in the EBFR at gauge GS8150327 were predicted by assuming the following sources to the river:

- Outflows from the Intermediate Pit.
- Flows from Fitch Creek, EFDC and Wandering Creek (i.e. local runoff not diverted through the Intermediate Pit).
- Incremental surface flows to the EBFR between the outlet from the Intermediate Pit and gauge station GS8150327.
- Groundwater flows to the EBFR from residual SO$_4$ and Cu plumes and the new plume from the WSF.

As for the Intermediate Pit, simulated SO$_4$ and Cu loads from the ‘moderate attenuation’ transport scenario were incorporated into the ‘base case’ scenario for the EBFR. Simulated loads to the EBFR for 30 years after rehabilitation were overlapped with (daily) flow data from 1955 to 1985. This allowed simulated loads to the river to be diluted with actual, observed flows from the historic record. During the dry season, simulated loads to the river were allowed to accumulate and were then mixed with flows from the subsequent early wet season (typically November flows). Because historic flows...
from gauge GS8150327 were unavailable, flows at gauge GS8150097 were pro-rated to the smaller catchment area at gauge GS8150327.

To develop a solubility limit for dissolved Cu in the EBFR, dissolved Cu concentrations in the EBFR at downstream gauge GS8150097 were compared to instantaneous discharge. Data for GS8150097 were used as a proxy for gauge GS8150327 because too few data were available at GS8150327 (installed in 2010). Dissolved Cu concentrations as a function of instantaneous discharge at GS8150097 are shown in Figure 4-2. This plot shows that the lowest dissolved Cu concentrations are observed when there is reduced flow in the EBFR are lowest, and that higher flows occur as flow increases.

To simulate this trend at GS8150327, any predicted Cu concentration above 50 µg/L Cu during the wet season was assumed to precipitate from the EBFR and be delivered downstream as a particulate load. In the dry season, a 20 µg/L Cu limit was used to reduce dissolved Cu concentrations in the river (as the majority of the Cu load in the river is thought to be particulate load). These limits are intended to approximate how dissolved Cu concentrations are moderated by the pH of river water. Post rehabilitation, these values are likely conservative, as the buffering capacity of the EBFR will likely be higher due to more alkalinity (and the solubility of Cu will therefore by lower). Note that the use of this Cu limit does not imply that higher dissolved Cu concentrations could not occur locally, or over a period of several days when flows are small and discontinuous in the river channel. These small-scale variations are beyond the scope of the current mixing model, but could be simulated during a subsequent project phase after additional input on how to apply LDWQOs is available.

4.2.2 Predicted SO₄ and Cu Contaminant Loads

Predicted SO₄ and Cu loads to the EBFR are summarized in Table 4-4a ('moderate attenuation') and Table 4-4b ('high attenuation'). Some key findings for the ‘base case’ scenario are summarized here:

- For SO₄, a predicted 745 t/year SO₄ reports to the EBFR at gauge GS9150327 over the 30-year modeling period. 72% of the SO₄ load is from groundwater and WSF leachate that reports to the Intermediate Pit. 27% is from residual, AMD-impacted groundwater that reports directly to the EBFR (via EFDC) (i.e. bypassing the Intermediate Pit). The remaining 1% is from runoff from unimpacted upgradient areas through the EFDC.

- For Cu (‘moderate attenuation’ scenario), a predicted 1.06 t/year Cu reports to the EBFR at gauge GS8150327. 20% of this Cu load is delivered to the EBFR via outflows from the Intermediate Pit. These loads originate primarily from groundwater that discharges to the Intermediate from upgradient (e.g. from the CEPA). 71% of the Cu load in the EBFR is from residual, AMD-impacted groundwater from the footprints of the Main and Intermediate WRDs that discharges directly to the EBFR/EFDC (bypassing the Intermediate Pit).
Assuming loads from the ‘high attenuation’ Cu transport scenario, 0.28 t/year Cu reports to the EBFR at gauge GS8150327. This load represents only 26% of the Cu load from the ‘moderate attenuation’ scenario because Cu loads directly to the river from groundwater are much lower (i.e. 0.11 t/year Cu vs. 0.77 t/year Cu; see Tables 4-4a,b). These estimates indicate that post-rehabilitation Cu concentrations in the EBFR will be determined mainly by Cu loads from residual, AMD-impacted groundwater.

### Table 4-4a. Predicted Post-Rehabilitation Contaminant Load Balance for the EBFR, ‘Moderate Attenuation’ Cu transport scenario (30 years)

<table>
<thead>
<tr>
<th>Source</th>
<th>SO$_4$ (30 years)</th>
<th>Cu (30 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t/year</td>
<td>%</td>
</tr>
<tr>
<td>Dissolved loads from Intermediate Pit (from GW and WSF leachate)</td>
<td>16,055</td>
<td>535</td>
</tr>
<tr>
<td>EBFR flows through the EFDC</td>
<td>218</td>
<td>7</td>
</tr>
<tr>
<td>Load from residual groundwater to EBFR (Main and Int. WRD)</td>
<td>6,066</td>
<td>202</td>
</tr>
<tr>
<td>TOTAL (loads to the EBFR at GS8150327)</td>
<td>22,339</td>
<td>745</td>
</tr>
</tbody>
</table>

Annual dissolved Cu load in EBFR is 0.5 t/year (annual SO$_4$ load is 745 t/year, i.e. conservative transport)

### Table 4-4b. Predicted Post-Rehabilitation Contaminant Load Balance for the EBFR, ‘High Attenuation’ Cu transport scenario (30 years)

<table>
<thead>
<tr>
<th>Source</th>
<th>SO$_4$ (30 years)</th>
<th>Cu (30 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t/year</td>
<td>%</td>
</tr>
<tr>
<td>Dissolved loads from Intermediate Pit (from GW and WSF leachate)</td>
<td>16,055</td>
<td>535</td>
</tr>
<tr>
<td>EBFR flows through the EFDC</td>
<td>218</td>
<td>7</td>
</tr>
<tr>
<td>Load from residual groundwater to EBFR (Main and Int. WRD)</td>
<td>6,066</td>
<td>202</td>
</tr>
<tr>
<td>TOTAL (loads in the EBFR at GS8150327)</td>
<td>22,339</td>
<td>745</td>
</tr>
</tbody>
</table>

Annual dissolved Cu load in EBFR is 0.2 t/year (annual SO$_4$ load is 745 t/year, i.e. conservative transport)

#### 4.2.3 Predicted SO$_4$ and Cu Concentrations

Predicted mean annual, flow-weighted SO$_4$ and Cu concentrations in the EBFR are summarized in Table 4-5. Monthly, flow-weighted mean SO$_4$ concentrations in the EBFR at GS8150327 are shown in Figures 4-2a. Monthly, flow-weighted mean Cu concentrations for the ‘moderate attenuation’ scenario and ‘high attenuation’ scenario are shown in Figures 4-2b. Also shown on these figures are monthly, flow-weighted SO$_4$ and Cu concentrations at gauge GS8150327 for the period 2010 to 2015. The latter concentrations were computed from the discharge record and patched SO$_4$ and Cu concentrations that RGC used to estimate loads from 2010 to 2015 (see RGC, 2016f).
Some key findings are summarized here:

- **Post-Rehabilitation SO₄ Concentrations:**
  - For the first 10 years after rehabilitation, the flow-weighted SO₄ concentration in the EBFR is 32 mg/L SO₄. After 10 years, flow-weighted mean concentrations decrease to 19 mg/L SO₄ as SO₄ from residual AMD-impacted groundwater is flushed by rainfall infiltration and clean groundwater inflows from upgradient.
  - The highest monthly flow-weighted SO₄ concentrations occur in November and December (i.e. up to 180 mg/L SO₄), and then concentrations decrease during the wet season (see Figure 4-2a). The higher SO₄ concentrations during the early wet season are still at least five times lower than the LDWQO (997 mg/L SO₄) and about 50% lower than the flow-weighted SO₄ concentration for 2010 to 2015.
  - High SO₄ concentrations at this time are related to the inverse relationship between SO₄ concentrations and instantaneous flow in the EBFR, which indicates higher SO₄ concentrations generally occur under lower flows conditions. After rehabilitation, SO₄ concentrations in November are substantially reduced, although the current mixing model is not well-suited to characterizing SO₄ concentrations during the early wet season. Higher SO₄ concentrations could therefore occur locally during periods of intermittent flow or during the earliest stages of the wet season (i.e. over days, as opposed to the entire month). However, SO₄ concentrations higher than the LDWQO are unlikely if the river is flowing.
  - After ten years, the flow-weighted SO₄ concentration in the river is 22 mg/L SO₄ or less (or about 2% of the LDWQO).

- **Post-Rehabilitation Cu concentrations** (‘moderate attenuation’ Cu transport scenario):

<table>
<thead>
<tr>
<th>Source</th>
<th>Total Cu in EBFR</th>
<th>Dissolved Cu in EBFR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg/L/yr</td>
<td>ug/L/yr</td>
</tr>
<tr>
<td><strong>Observed Contaminant Loads in the East Branch of the Finniss River</strong> (adjusted to average year), 2010 to 2015</td>
<td>1,807</td>
<td>64</td>
</tr>
<tr>
<td><strong>Locally-Derived Water Quality Objective (LDWQO)</strong></td>
<td>-</td>
<td>997</td>
</tr>
<tr>
<td><strong>Base Case’ Scenario (‘moderate attenuation’)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to 10 years after rehabilitation</td>
<td>958</td>
<td>32</td>
</tr>
<tr>
<td>10 to 20 years</td>
<td>673</td>
<td>19</td>
</tr>
<tr>
<td>20 to 30 years</td>
<td>647</td>
<td>19</td>
</tr>
<tr>
<td>Entire, 30 year simulation period</td>
<td>745</td>
<td>23</td>
</tr>
<tr>
<td><strong>Base Case’ Scenario (‘high attenuation’)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to 10 years after rehabilitation</td>
<td>958</td>
<td>32</td>
</tr>
<tr>
<td>10 to 20 years</td>
<td>673</td>
<td>19</td>
</tr>
<tr>
<td>20 to 30 years</td>
<td>647</td>
<td>19</td>
</tr>
<tr>
<td>Entire, 30 year simulation period</td>
<td>745</td>
<td>23</td>
</tr>
</tbody>
</table>

* From Hydrobiology (2015)
For the first ten years after rehabilitation, the annual, flow-weighted mean Cu concentration is predicted to be 18 µg/L for the ‘base case’ scenario. This concentration is most representative of ‘wet season’ conditions when 90% of the flow in the river occurs and is 35% lower than the 27.5 µg/L LDWQO for Cu. The flow-weighted concentration is about 56% lower than the flow-weighted mean Cu concentration at gauge GS8150327 for current conditions, i.e. since the gauge was installed in 2010.

From 10 to 20 years after rehabilitation, the flow-weighted Cu concentration in the EBFR decreases to 13 µg/L Cu (or about 53% of the LDWQO) and remains 13 µg/L Cu from 20 to 30 years after rehabilitation.

**Post-Rehabilitation Cu concentrations (‘high attenuation’ Cu transport scenario):**

For the first ten years after rehabilitation, the flow-weighted annual Cu concentration is predicted to be 8 µg/L. This concentration is about 30% of the 27.5 µg/L LDWQO for Cu. From 10 to 20 years after rehabilitation, the mean flow-weighted Cu concentration decreases to 3 µg/L Cu (and then to 2 µg/L Cu from 20 to 30 years).

Note that RGC (2016f) considers the ‘moderate attenuation’ scenario to be more likely to occur than the ‘high attenuation’ scenario because the ‘moderate attenuation’ scenario provides a better representation of copper concentrations and loads under current conditions. However, the ‘high attenuation’ scenario is a plausible alternative scenario that would result in much lower Cu concentrations in the EBFR. Additional geochemical testing of contaminated soils and/or shallow bedrock would be required to further constrain predictions of copper transport in groundwater and loading to surface water after rehabilitation.

To illustrate model sensitivity, SO₄ and Cu concentrations in the EBFR for the ‘upper bound’ and ‘lower bound’ scenarios described in Section 4.1.4 are provided in Table 4-6a,b. These concentrations show that SO₄ concentrations depend somewhat on the condition of water flowing from the Intermediate Pit, but that Cu concentrations are not particularly sensitive to those flows. This is related to the predominance of Cu loads from groundwater to the EBFR from residual plumes near the Main WRD and the Intermediate WRD. Predicted Cu concentrations in the river are therefore more sensitive to the magnitude of residual Cu leaching from the aquifer (see RGC, 2016f) than inputs from leachate collected from the new WSF. SO₄ concentrations in the river are more affected by leachate collected from the new WSF, but predicted SO₄ concentrations for each sensitivity run were much lower than the LDWQO.
Table 4-6a

Predicted Annual SO$_4$ and Cu Loads and Concentrations in the EBFR for the ‘Base Case’ Scenario and Sensitivity Runs (‘moderate attenuation’)

<table>
<thead>
<tr>
<th>Source</th>
<th>$SO_4$ in EBFR</th>
<th>Total Ca in EBFR</th>
<th>Dissolved Cu in EBFR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg/L</td>
<td>ug/L</td>
<td>mg/L</td>
</tr>
<tr>
<td>Observed Contaminant Loads in the East Branch of the Finlay River G38150327 (adjusted to average year), 2010 to 2015</td>
<td>1,807</td>
<td>64</td>
<td>2.1</td>
</tr>
<tr>
<td>Locally-Derived Water Quality Objective (DWQO)*</td>
<td>-</td>
<td>967</td>
<td>-</td>
</tr>
<tr>
<td>Base Case Scenario</td>
<td>0 to 10 years after rehabilitation</td>
<td>958</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>10 to 20 years</td>
<td>673</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>20 to 30 years</td>
<td>647</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>Entire, 30 year simulation period</td>
<td>745</td>
<td>23</td>
</tr>
<tr>
<td>Upper Bound Scenario (20,000 mg/L SO$_4$, 1 mg/L Cu from new WSF)</td>
<td>0 to 10 years after rehabilitation</td>
<td>1130</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>10 to 20 years</td>
<td>855</td>
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<td></td>
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<td>830</td>
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<tr>
<td></td>
<td>Entire, 30 year simulation period</td>
<td>945</td>
<td>28</td>
</tr>
<tr>
<td>Lower Bound Scenario (7500 mg/L SO$_4$, 100 ug/L Cu from new VSF)</td>
<td>0 to 10 years after rehabilitation</td>
<td>923</td>
<td>32</td>
</tr>
<tr>
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<td>627</td>
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</tr>
<tr>
<td></td>
<td>Entire, 30 year simulation period</td>
<td>715</td>
<td>22</td>
</tr>
</tbody>
</table>

* From Hydrobiology (2015)

Table 4-6b

Predicted Annual SO$_4$ and Cu Loads and Concentrations in the EBFR for the ‘Base Case’ Scenario and Sensitivity Runs (‘high attenuation’)

<table>
<thead>
<tr>
<th>Source</th>
<th>$SO_4$ in EBFR</th>
<th>Total Ca in EBFR</th>
<th>Dissolved Cu in EBFR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg/L</td>
<td>ug/L</td>
<td>mg/L</td>
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</tr>
</tbody>
</table>

* From Hydrobiology (2015)
5 KEY FINDINGS AND RECOMMENDATIONS

5.1 KEY FINDINGS

5.1.1 Groundwater Flow and Solute Transport Modeling

The calibrated flow and transport model for current conditions ("2016 model") described in RGC (2016f) was modified to assess post-closure conditions and inform the environmental performance of the preferred rehabilitation strategy. The current model was modified to reflect post-rehabilitation conditions, including re-location of the historic WRDs, backfilling the Main Pit, and construction of a WSF.

The future groundwater flow field will differ from the current groundwater flow field in those areas where significant earthworks are planned as part of rehabilitation. The main changes in the groundwater flow field from current conditions:

- Backfilling of the Main Pit will significantly alter the local groundwater flow field in this area. During the dry season, groundwater levels in the backfilled Main Pit are predicted to range from 59 m AHD near the northwestern margin of the backfilled pit to 61 m AHD near the southeastern margin. During the wet season, groundwater is predicted to mound into the domed fill of the backfilled Main WRD (to about 63.5 m AHD).
- Construction of the WSF is predicted to result in an overall decline (of 1 to 3 m) in groundwater levels beneath the facility due to significantly reduced recharge over the footprint of this lined facility.

The simulated SO4 and Cu concentrations for current conditions were used as initial concentrations for prediction of post-closure groundwater quality and contaminant loading to surface water. After rehabilitation, the main sources of SO4 and Cu to groundwater are:

- Residual plumes of SO4 and Cu present in the groundwater system (in overburden and bedrock units). In the case of attenuation, Cu that is currently adsorbed to the solid phase of soils and bedrock will represent a significant secondary residual source of Cu as it desorbs in the future.
- Leachate from the (limed) waste rock backfilled into the Main Pit below the water table.
- Leakage of leachate through the basal liner of the WSF ("basal seepage").

SO4 and Cu concentrations in seepage from the backfilled Main Pit and WSF are predicted to contain 10,000 mg/L SO4 and 0.2 mg/L Cu. The key predicted changes to SO4 transport in groundwater and loading to surface water are:

- Residual SO4 in shallow overburden soils (layers 1 and 2) and shallow bedrock (layer 3) beneath and downgradient of the former WRD areas and other impacted areas (Copper Extraction Pad area, Old Tailings Dam area) are predicted to clean up in 10 to 15 years due
to flushing by local recharge. Residual SO₄ at greater depths in bedrock is predicted to flush more gradually.

- Seepage from the backfilled waste rock in the Main Pit is predicted to result in the development of a new SO₄ plume in less than 5 years:
  - In shallow overburden (layers 1 and 2) the new SO₄ plume is predicted to migrate in a predominantly northwesterly direction and discharge into the realigned EBFR channel.
  - In bedrock (layers 3 to 6) the new SO₄ plume is predicted to migrate preferentially into the Coomalie Dolostone to the north and from there in a southwesterly direction to the Intermediate Pit.
  - A secondary plume (with lower SO₄ concentrations) is also predicted to travel in Coomalie Dolostone from the backfilled Main Pit in a southwesterly direction towards the EFDC.

- A small amount of seepage from the WSF is predicted to generate a new SO₄ plume in the Old Tailings Dam area within about 5 years. The SO₄ plume in shallow laterite is predicted to discharge near the downgradient (western) toe of the WSF. The SO₄ plume in saprolite and shallow bedrock (layers 2 to 3) is predicted to extend from the toe of the WSF to the Old Tailings Dam area and discharge to Old Tailings Creek. The SO₄ plume in deeper bedrock (layers 4 and 5) is predicted to extend to the lower East Branch of Finniss River.

- The total SO₄ load to surface water is predicted to decrease rapidly from about 1400 t/year (current conditions) to about 610 t/year within 5 years after rehabilitation (a 56 % reduction). The long-term SO₄ load to surface water from groundwater (after 30 years) is simulated to be 420 t/year representing a 70% reduction from current conditions.

- The SO₄ load from the backfilled Main Pit (309 t/year) is predicted to be the largest future long-term point source after rehabilitation at Rum Jungle, representing about 74% of the predicted total long-term SO₄ load from the site. In contrast, the future SO₄ load from the new WSF represents only about 15% of the predicted total long-term SO₄ load to surface water.

For Cu transport, three different attenuation scenarios were considered for simulation of post rehabilitation conditions (see RGC, 2016f):

- ‘No Attenuation’ (conservative transport)
- ‘Moderate Attenuation’ (sorption in overburden and bedrock and chemical precipitation in dolostone plus copper removal in limed foot print areas)
- ‘High Attenuation’ (sorption in overburden and shallow bedrock beneath WRDs and chemical precipitation in all bedrock lithologies plus copper removal in limed foot print areas).
RGC considers the ‘moderate attenuation’ scenario to be the scenario that most closely represents current Cu transport at Rum Jungle (RGC, 2016f). The predicted, post-rehabilitation Cu transport for this scenario can be summarized as follows.

- The new waste storage facilities (backfilled Main Pit and WSF) will not represent a significant source of future Cu loads. As a result, residual Cu currently present in groundwater and sorbed to aquifer materials will continue to represent the primary source of future Cu loads to surface water.
- Removal of waste rock and contaminated WRD footprint area soils and liming of the residual footprints in Dysons Area (Dysons WRD and backfilled Dysons Pit) and the Main and Intermediate WRDs is predicted to result in very rapid cleanup of the footprint area (layer 1) and gradual decline in Cu concentrations in the deeper saprolite (layer 2). However, flushing of residual Cu from the underlying bedrock (layers 3 to 6) is predicted to be very slow (much longer than 30 years).
- Cu concentrations in the deeper bedrock (layers 3 to 6) of the Copper Extraction Pad area (CEPA) are predicted to clean up very slowly (i.e. 30+ years due to desorption of Cu from bedrock. Note that Cu in seepage from backfilled waste rock (200 µg/L Cu) in the Main Pit is much lower than the residual Cu present in groundwater in bedrock in the CEPA. Hence, seepage from the backfilled Main Pit will tend to dilute the residual copper plume in the CEPA.
- Seepage rates, and associated Cu load, from the WSF are too small to produce any significant Cu plume or Cu load to Old Tailings Creek and the lower EBFR.
- The total Cu load to surface water is predicted to initially decrease from 2.7 t/year (current conditions) to 1.3 t/year (a 50 % reduction) within 5 years after rehabilitation. This initial reduction is primarily due to above-grade and near-surface Cu sources (waste rock, contaminated soils and foundation material) and liming of the footprint areas.
- Longer-term reduction in Cu loads from groundwater to surface water will be a slow process due to sustenance of Cu concentrations via ongoing desorption from the rock substrate. The total Cu load to surface water after 30 years is predicted to be 1.0 t/year (a 63 % reduction from current conditions).

Future Cu transport was also simulated for the ‘no attenuation’ and ‘high attenuation’ scenarios to evaluate the sensitivity of predicted post-rehabilitation performance to uncertainty in geochemical controls. The influence of attenuation on future Cu transport can be summarized as follows:

- The conservative transport scenario ("No attenuation") is predicted to result in rapid flushing of all residual Cu plumes, in particular in the shallow soils and shallow bedrock (similar to the case of sulphate described above). This scenario produces the highest Cu loads to surface water early on (Years 1 and 2) but Cu loads subsequently fall well below those predicted for
the ‘moderate attenuation’ scenario. After 30 years, the Cu loads for the conservative scenario are predicted to have declined to 0.3 t/year. i.e. 70% lower than the Cu load predicted for the ‘moderate attenuation’ scenario.

- In the ‘no attenuation’ scenario, essentially all of the Cu load represents Cu initially stored in groundwater (‘residual plume’) that is gradually flushed from the aquifer. In contrast, in the ‘moderate attenuation’ scenario, a significant portion of the current total Cu load is gradually released via desorption from the solid phase. This desorption process accounts for the delayed flushing of the Cu plume and overall higher loads over the medium-term time frame to the surface water.

- The ‘high attenuation’ scenario is predicted to generate the lowest Cu loads to surface water throughout the modeling period by removing essentially all of the dissolved Cu load from bedrock except acidic shallow bedrock beneath the re-located WRDs. In this scenario, predicted Cu loads to surface water gradually fall from about 0.5 t/year in Year 1 to 0.15 t/year in Year 30. That is, 85% below the Cu load predicted at year 30 for the ‘moderate attenuation’ scenario.

A sensitivity analysis of limited extent was completed to assess the influence of transport parameters on the predicted contaminant loads from groundwater to surface water.

- SO\textsubscript{4} transport is significantly influenced by the effective porosity. A higher effective porosity results in slower flushing of the residual SO\textsubscript{4} plume. A twofold increase in effective porosity increases the total SO\textsubscript{4} mass to surface water by up to 65%.

- Cu transport and loads to surface water are not significantly influenced by the change in transport parameters. This lack of sensitivity is a result of the dominating control of chemical reactions assumed for the ‘moderate attenuation’ scenario. In other words, Cu transport is much more sensitive to the uncertainty in chemical attenuation than uncertainty in transport parameters.

### 5.1.2 Post-Rehabilitation Loads to Surface Water and Water Quality Predictions

The Intermediate Pit is predicted to receive 535 t/year SO\textsubscript{4} and 0.44 t/year Cu post-rehabilitation. Simulated, post-rehabilitation loads from groundwater are the largest sources of SO\textsubscript{4} and Cu to the pit (i.e. 60% of the SO\textsubscript{4} load and 93% of the Cu load). Leachate collected from the WSF accounts for 34% of the SO\textsubscript{4} load to the pit, but only 1% of the Cu load.

To simulate the precipitation of dissolved Cu from pit water, a 100 µg/L Cu solubility limit was applied. This concentration is based on (i) the solubility of Cu at near-neutral to alkaline pH conditions and (ii) observed pit water quality since 2010. About 36% (0.16 t/year Cu) of the Cu load that reports to the Intermediate Pit is predicted to precipitate from pit water if the 100 µg/L Cu solubility limit is applied.
Most of this precipitated mass would remain in the pit as sludge, and the residual dissolved Cu load would report to the EBFR via outflows from the Intermediate Pit during the wet season.

Similarly, for the EBFR, solubility limits of 20 µg/L Cu and 50 µg/L Cu were applied during dry season and the wet season, respectively. These solubility limits are based on observation of dissolved Cu concentrations in the EBFR at GS8150097 (as too few dissolved Cu concentrations are available at GS8150327). Dissolved Cu concentrations at GS8150097 clearly suggest lower dissolved Cu concentration under lower flow conditions, possibly due to the predominance of particulate Cu under these conditions. Moreover, the data suggest an upper limit for dissolved Cu at the circum-neutral pH conditions in the EBFR (as per the solubility curve for Cu).

Predicted loads to the EBFR for 30 years post rehabilitation are summarized below:

- For SO₄, a load of 749 t/year SO₄ is predicted to report to the EBFR at gauge GS9150327. 72% (535 t/year) of the SO₄ load is delivered to the EBFR via the Intermediate Pit. This load is related to groundwater discharge to the Intermediate Pit and flows of leachate from the WSF (see above). 27% (202 t/year) of the load is related to the discharge of residual, AMD-impacted groundwater directly to the EBFR (mainly from the footprints of the Main WRD and Intermediate WRD). The remaining 1% is from upstream EBFR flows through the EFDC. 749 t/year SO₄ in the EBFR is about 60% lower than the ~1800 t/year SO₄ load that was observed in the EBFR from 2010 to 2015.

- For Cu, 1.06 t/year Cu is predicted to report to the EBFR at gauge GS8150327. 73% of this Cu load is related to residual, AMD-impacted groundwater that reports directly to the EBFR from the former footprints of the Main and Intermediate WRDs. 26% is delivered to the EBFR via the Intermediate Pit and 1% is from upstream EBFR flows through the EFDC. 50% of the Cu load to the EBFR (0.5 t/year Cu) reports to gauge GS8150327 in the form of dissolved Cu. This dissolved Cu load is about 60% lower than the dissolved Cu load in the EBFR at gauge GS8150327 from 2010 to 2015.

Assuming loads from the 'high attenuation' Cu transport scenario, 0.29 t/year Cu reports to the EBFR at gauge GS8150327. This load is only 27% of the Cu load from the 'moderate attenuation' scenario because Cu loads to the river from groundwater are much lower. These estimates indicate that post-rehabilitation Cu concentrations in the EBFR will be determined mainly by Cu loads from residual, AMD-impacted groundwater. The predicted load of dissolved Cu at gauge GS8150327 over the 30-year simulation period was 0.2 t/year (or 60% lower than the dissolved Cu load from the 'moderate attenuation' scenario).

Using the predicted SO₄ and dissolved Cu loads in the EBFR at gauge GS8150327, monthly (flow weighted) concentrations were computed to allow a comparison with LDWQOs. The key findings are summarized below:
For the first 10 years after rehabilitation, the flow-weighted SO$_4$ concentration in the EBFR is 32 mg/L SO$_4$. This is less than 50% of the flow-weighted SO$_4$ concentration from 2010 to 2015 (and less than 3% of the 997 mg/L SO$_4$ LDWQO. After ten years, the flow-weighted SO$_4$ concentration in the river is 19 mg/L SO$_4$ or less.

With respect to Cu, the annual, flow-weighted mean Cu concentration is predicted to be 18 µg/L for the first 10 years after rehabilitation (assuming the ‘moderate attenuation’ Cu transport scenario). This concentration is 56% lower than the flow-weighted mean Cu concentration at gauge GS8150327 since the gauge was installed in 2010, and 35% lower than the 27.5 µg/L LDWQO for Cu. From 10 to 30 years after rehabilitation, the flow-weighted Cu concentration in the EBFR decreases to 13 µg/L Cu, less than 50% of the LDWQO.

Assuming the ‘high attenuation’ Cu transport scenario, the flow-weighted annual Cu concentration is predicted to be 8 µg/L for the first 10 years after rehabilitation. This concentration is 70% lower than the 27.5 µg/L LDWQO for Cu. From 10 to 30 years after rehabilitation, the mean flow-weighted Cu concentration decreases to less than 3 µg/L Cu.

### 5.2 Recommendations

#### 5.2.1 Field Studies and Laboratory Testing

The following field and laboratory studies are recommended during Stage 2.5 of the Rum Jungle Rehabilitation Planning Project:

- Determine the physical and geochemical properties of tailings from the Main Pit in order to estimate a geochemical source term for these tailings after they are placed in the WSF. This will likely involve drilling to collect tailings samples and then completing a series of sequential leach extraction tests on raw tailings and neutralised tailings. These data could then be interpreted in order to derive a geochemical source term for tailings (as was done for waste rock in RGC (2016a).

- Estimate site-specific Rf values for Cu and other metals for which there are LDWQOs (i.e. Mg, Al, Co, Fe, Mn, Ni, and Zn). This study will involve test pitting and/or drilling to collect samples of laterite and bedrock from areas where Cu concentrations are elevated in groundwater (e.g. the Copper Extraction Pad area, WRD footprints, etc.). Sequential leach extraction tests will then be done to estimate the number of pore volumes required to desorb Cu, and other metals, from the solids samples.

- Complete laboratory testing and/or field trials to evaluate the efficacy of liming of clean fill to neutralise and reduce metal concentrations in contaminated groundwater.

#### 5.2.2 Modeling

- Use the groundwater model to evaluate water management of the Main Pit during rehabilitation and its effect on post rehabilitation water quality:
o Evaluate the effect of Main Pit dewatering (required for backfilling of the pit) on groundwater flow and contaminant transport during rehabilitation.

- Evaluate passive and ‘active’ reflooding of the backfilled Main Pit and its effect on contaminant transport and loading to surface water post rehabilitation.

- Optimize the design of Main Pit backfill (placement of PAF vs NAF or clean fill, barrier layers, etc) with the aim to minimize shallow contaminant loading to the re-aligned EBFR channel (using the updated flow and transport model).

- Update the contaminant transport to reflect site-specific $R_f$ values for laterite and bedrock, and extend to scope of the transport modeling to include other contaminants for which there are LDWQOs (i.e. Mg, Al, Co, Fe, Mn, Ni, and Zn).

- Complete additional sensitivity runs to assess the influence of liming of WRD footprint areas (and uncertainty in its efficacy) on future Cu transport and loading to surface water.

- Develop a limnological model for the Intermediate Pit in order to refine the approach to seepage management after rehabilitation (i.e. depth of seepage discharge, etc.) and estimate pit water concentrations of each contaminant for which there is a LDWQO.

### 5.2.3 Post-Rehabilitation Monitoring Programs

A post-rehabilitation Adaptive Management Plan (AMP) should be developed for surface water quality. The different components of this plan would be implemented in the event that there are issues meeting LDWQOs. The AMP will contain "early warning" trigger values and changes to routine monitoring and management of pit water and surface water at gauge GS8150327 that will be associated with meeting key, post-rehabilitation Operation, Maintenance, and Surveillance (OMS) objectives. The post-rehabilitation groundwater monitoring program needs to be finalized. Figure 5-1 shows proposed groundwater monitoring locations near the WSF, former WRD footprints, and near the backfilled Main Pit.
6 CLOSURE

Robertson GeoConsultants Inc. is pleased to submit this report entitled ‘Environmental Performance Assessment for the Preferred Rehabilitation Strategy, Rum Jungle’ to the Northern Territory Department of Mines and Energy.

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,

Prepared by:

Dr. Paul Ferguson
Senior Geochemist

Dr. Christoph Wels
Principal Hydrogeologist

Reviewed by:

Dr. David Jones
Principal (DR Jones Environmental Excellence)
7 REFERENCES


Appleyard, S. (1983), Groundwater investigations at Rum Jungle April to December 1983. Water Division; Department of Transport and Works.


Plumb, K.A (1979), Structure and tectonic style of the Precambrian shields and platforms of northern Australia. Tectonophysics 58(3/4) p291-325


RGC (2012b), Phase 3 (Stage 3 Report) – Contaminant Load Balance and Surface Water Quality Assessment for the Rum Jungle, NT, May 2012, Report No. 183003/2


RGC (2016g), Environmental Performance Assessment for the Final Rehabilitation Strategy, RGC Report No. 183006/7.


Worden (2006), Geology and geochronology of the Palaeoproterozoic Pine Creek Orogen, Evolution and Metallogenesis of the Northern Australian Craton Conference, June 2006.
FIGURES
General Layout of the Rum Jungle Mine Site

Client: Rum Jungle Rehabilitation Planning
Project No: 183006
Report No: 183006/7
Last Update: 13 Jun 2016
Mean Monthly Rainfall for periods
(a) 1889 to 2015, and (b) 2010 to 2015
Estimated Daily Flows in the East Branch of the Finniss River at Gauge GS8150097:

(a) July 1st 2014 to July 1st 2015,
(b) July 1st 2010 to July 1st 2011 (2010/2011 water year), and
(c) July 1st 2014 to July 1st 2015 (2014/2015 water year)
Contaminant Loads to the East Branch of the Finniss River at Gauge Stations GS8150200, GS8150327 and GS8150097 for Sulphate, Copper and Zinc
Conceptual Cross-Section for Dyson’s (backfilled) Pit

- Contaminated soils & heap leach material
- Tailings from the Old Tailings Dam
- Tailings deposited in the 1960s
- Toe drain
- Rock blanket (dolomitic)
- Cover
Pie Charts
NAF and PAF Distribution
Conceptual Copper Plume in Groundwater (Current Conditions)

Ruins Jungle Mine Site

Cu Zones (in µg/L)
- > 50,000
- 25,000 - 50,000
- 20,000 - 25,000
- 15,000 - 20,000
- 10,000 - 15,000
- 5,000 - 10,000
- 2,500 - 5,000
- 1,000 - 2,500
- 500 - 1,000
- 100 - 500
- 10 - 100
- < 10

Legend
- Well Location, Number & Cu Value (µg/L)
- Cu Contour
- Drainage
- Pit/WRD Outline
- Mine Site Boundary

Project: New Waste Storage Facility Investigation

Figure 2-9b

Report: RDG 183006/7

Last Update: Jul 14, 2016

Drawn: L.R.
Water Quality along the East Branch of the Finniss River
at Gauge Stations at the Lease Boundary (EB), Fitch Creek at the Lease Boundary (FC),
Dyson’s Gauge Station (DYS), GS8150200 (G200), GS8150327 (G327), and GS8150097 (G097)
Water Quality along the East Branch of the Finniss River
at Gauge Stations at the Lease Boundary (EB), Fitch Creek at the Lease Boundary (FC),
Dyson’s Gauge Station (DYS), GS8150200 (G200), GS8150327 (G327), and GS8150097 (G097)
Sulphate Source Terms for Future Transport Model
Copper Source Terms for Future Transport Model

Values in mg/L
Initial Sulphate Concentrations (in mg/L) for Future Model (after Rehabilitation)
Initial Sulphate Concentrations (in mg/L) for Future Model (after Rehabilitation)
Initial Copper Concentrations (in mg/L) for Future Model (after Rehabilitation) No Attenuation
Initial Copper Concentrations (in mg/L) for Future Model (after Rehabilitation)

No Attenuation

Client: Northern Territory Government
Project: Rum Jungle Rehab. Project
Report No: 183006/7
Original File: CuInitConc-Cons.pptx
Last Update: Jun 13, 2016

- Layer 5
- Layer 6
- Layer 7
Initial Copper Concentrations (in mg/L) for Future Model (after Rehabilitation) Moderate Attenuation
Initial Copper Concentrations (in mg/L) for Future Model (after Rehabilitation) Moderate Attenuation
Initial Copper Concentrations (in mg/L) for Future Model (after Rehabilitation)

High Attenuation

Layer 1

Layer 2

Layer 3

Client: Rum Jungle Rehab. Project

Figure: 3-6a

Report No: 183006/7

Original File: CuInitConc–HiRxn.pptx

Project No: 183006

Last Update: Jun 13, 2016
Layer 7 clean

Initial Copper Concentrations (in mg/L) for Future Model (after Rehabilitation)
High Attenuation
Simulated Monthly Groundwater Balance by Model Reach

- **Dyson’s Pit**
- **Dyson’s WRD**
- **Main WRD**
- **Intermediate WRD**
- **Main Pit**
- **Intermediate Pit**
- **Brown’s Oxide Pit**
- **Waste Storage Facility**
- **Lower EBFR**

**Legend:**
- Recharge
- Drains
- Cst H (net)

Client: Rum Jungle Rehab. Project
Project No: 183006
Report No: 183006/7
Last Update: Jun 08, 2016

Original File: Zonebudget (CW Edits).xlsx

Figure: 3-8
Simulated Model Wide Monthly Groundwater Balance & Model Zones
Simulated Sulphate Concentrations (in mg/L)
in Layer 1 at 5, 10, 15 and 30 Years
after Rehabilitation
Simulated Sulphate Concentrations (in mg/L) in Layer 2 at 5, 10, 15 and 30 Years after Rehabilitation

Client: Northern Territory Government
Project: Rum Jungle Rehab. Project
Original File: SO4 June 3.pptx & SO4 June 3.pptx

Simulated Sulphate Concentrations (in mg/L)
in Layer 2 at 5, 10, 15 and 30 Years
after Rehabilitation

Year 5
Year 10
Year 15
Year 30
Simulated Sulphate Concentrations (in mg/L) in Layer 3 at 5, 10, 15 and 30 Years after Rehabilitation.
Simulated Sulphate Concentrations (in mg/L) in Layer 4 at 5, 10, 15 and 30 Years after Rehabilitation
Simulated Sulphate Concentrations (in mg/L) in Layer 5 at 5, 10, 15 and 30 Years after Rehabilitation
Simulated Sulphate Concentrations (in mg/L) in Layer 6 at 5, 10, 15 and 30 Years after Rehabilitation
Simulated Transient Sulphate Mass Fluxes to Surface Water after Rehabilitation
Simulated Copper Concentrations (in mg/L) in Layers 1 and 2 at 15 and 30 Years after Rehabilitation

Moderate Attenuation

Year 15

Layer 1:

Year 30

Layer 2:
Simulated Copper Concentrations (in mg/L) in Layers 3 and 4 at 15 and 30 Years after Rehabilitation

Moderate Attenuation
Simulated Copper Concentrations (in mg/L) in Layers 5 and 6 at 15 and 30 Years after Rehabilitation

Moderate Attenuation

Client: Northern Territory Government
Project: Rum Jungle Rehab. Project
Report No: 183006/7
Last Update: Jun 07, 2016

Original File: SO4 June 5.pptx & SO4 June 3.pptx

Figure: 3-12c
Simulated Copper Concentrations (in mg/L) in Layer 1 at 30 Years after Rehabilitation
All Attenuation Scenarios
Simulated Copper Concentrations (in mg/L)
in Layer 2 at 30 Years after Rehabilitation
All Attenuation Scenarios

No Attenuation

Moderate Attenuation

High Attenuation

Figure: 3-13b

Client: Northern Territory Government
Department of Resources, Planning and Energy

Project: Rum Jungle Rehab. Project
Report No: 183006/7
Last Update: Jun 07, 2016

Original File: Cu6June6.pptx
Simulated Copper Concentrations (in mg/L) in Layer 3 at 30 Years after Rehabilitation
All Attenuation Scenarios

No Attenuation

Moderate Attenuation

High Attenuation

Client: [Client Information]
Project: Rum Jungle Rehab. Project
Figure: 3-13c

Last Update: Jun 07, 2016

Robertson GeoConsultants Inc

Report No: 183006/7
Project No: 183006
Simulated Copper Concentrations (in mg/L) in Layer 4 at 30 Years after Rehabilitation

All Attenuation Scenarios

No Attenuation

Moderate Attenuation

High Attenuation
Simulated Copper Concentrations (in mg/L) in Layer 5 at 30 Years after Rehabilitation

All Attenuation Scenarios

No Attenuation

Moderate Attenuation

High Attenuation

Client: Northern Territory Government

Project: Rum Jungle Rehab. Project

Original File: CuJune6.pptx

Last Update: Jun 07, 2016
Simulated Copper Concentrations (in mg/L) in Layer 6 at 30 Years after Rehabilitation

All Attenuation Scenarios

No Attenuation

Moderate Attenuation

High Attenuation
Simulated Transient Copper Mass Flux to Surface Water after Rehabilitation

Dyson’s Reach

No Attenuation

Moderate Attenuation

High Attenuation

Copper Flux to Creeks (t/yr)
Simulated Transient Copper Mass Flux to Surface Water after Rehabilitation

Main WRD Reach

Client: Northern Territory Government
Project: Rum Jungle Rehab. Project
Report No: 183006/7
Original File: Time trends 2016-2045.xlsx
Last Update: Jun 07, 2016

Figure: 3-14b
Simulated Transient Copper Mass Flux to Surface Water after Rehabilitation
Intermediate WRD Reach

Client: Northern Territory Government
Project: Rum Jungle Rehab. Project
Report No: 183006/7
Last Update: Jun 07, 2016
Simulated Transient Copper Mass Flux to Surface Water after Rehabilitation

Main Pit Reach

No Attenuation

Moderate Attenuation

High Attenuation
Simulated Transient Copper Mass Flux to Surface Water after Rehabilitation

Intermediate Pit Reach

No Attenuation

Moderate Attenuation

High Attenuation
Simulated Transient Copper Mass Flux to Surface Water after Rehabilitation Waste Storage Facility Reach

Client: Project: Rum Jungle Rehab. Project
Project No: 183006
Report No: 183006/7
Last Update: Jun 07, 2016

Figure: 3-14f

- No Attenuation
- Moderate Attenuation
- High Attenuation
Simulated Transient Copper Mass Flux to Surface Water after Rehabilitation

Lower EBFR Reach

No Attenuation

Moderate Attenuation

High Attenuation
Simulated Transient Copper Mass Flux to Surface Water after Rehabilitation
Total for All Reaches

No Attenuation

Moderate Attenuation

High Attenuation
Sulphate Sensitivity Runs
Simulated Transient Total Mass Flux to Surface Water after Rehabilitation

Figure: 3-15
Copper Sensitivity Runs
Simulated Transient Total Mass Flux to Surface Water after Rehabilitation

Client: Northern Territory Government
Project: Las Tortolas Phase 2 Work
Report No: 183006/7
Project No: 183006
Last Update: Jun 10, 2016

Project: Las Tortolas Phase 2 Work
Report No: 183006/7
Last Update: Jun 10, 2016

Original File: Cu-Sensitivity Run Time Trends - REV1.xlsx

Figure: 3-16
Predicted Sulphate Concentrations in the Intermediate Pit Post Rehabilitation

Client: Rum Jungle Rehabilitation Planning
Report No: 183006/7
Original File: Section4.pptx
Last Update: 17 Jun 2016

Figure: 4-1a
SO4 Conc in Intermediate Pit

SO4 Concentration (mg/L)

2016 Feb 01 2017 Feb 01 2018 Feb 01 2019 Feb 01 2020 Feb 01 2021 Feb 01 2022 Feb 01 2023 Feb 01 2024 Feb 01 2025 Feb 01 2026 Feb 01 2027 Feb 01 2028 Feb 01 2029 Feb 01 2030 Feb 01 2031 Feb 01 2032 Feb 01 2033 Feb 01 2034 Feb 01 2035 Feb 01 2036 Feb 01 2037 Feb 01 2038 Feb 01 2039 Feb 01 2040 Feb 01 2041 Feb 01 2042 Feb 01 2043 Feb 01 2044 Feb 01 2045 Feb 01 2046 Feb 01
Predicted Dissolved Copper Concentrations in the Intermediate Pit Post Rehabilitation
Dissolved Cu Concentration as a Function of Daily Instantaneous Discharge, EBFR at GS8150327

- Wet Season: >0.5 m³/s
- Dry Season: <0.5 m³/s

\[ y = 23.482x^{0.2137} \]

\[ R^2 = 0.5262 \]

Figure: 4-2
Estimated Flow-Weighted Mean Sulphate Concentrations
In the Intermediate Pit Post Rehabilitation
Estimated Flow-Weighted Mean Copper Concentrations in the East Branch of the Finniss River after Rehabilitation

Client: Northern Territory Government
Project: Las Tortolas Phase 2 Work
Report No: 183006/7
Last Update: Jun 17, 2016

Figure: 4-3b

<table>
<thead>
<tr>
<th>Client</th>
<th>Figure: 4-3b</th>
</tr>
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<tr>
<td>Project: Las Tortolas Phase 2 Work</td>
<td>183006</td>
</tr>
<tr>
<td>Report No: 183006/7</td>
<td>Last Update: Jun 17, 2016</td>
</tr>
</tbody>
</table>
Recommended Groundwater Monitoring Locations

Post-Rehabilitation

Elevation (m AHD)

- 102 - 111.5
- 94 - 102
- 86 - 94
- 80 - 86
- 74 - 80
- 70 - 74
- 67 - 70
- 60 - 67
- 54.5 - 60
- 2 - 54.5

Legend:
- Proposed Monitoring Bore Location
- Existing Monitoring Bore
- Simulated Head Contour (m AHD)
- Model Domain Boundary
- Mine Site Boundary

Projection: GDA 1994 MGA Zone 52
Scale 1:11,000

Existing Monitoring Bore
Proposed Monitoring Bore Location
Simulated Head Contour (m AHD)
Model Domain Boundary
Mine Site Boundary

Ohio L.R.  

Figure: 5-1  

Drawn: L.R.