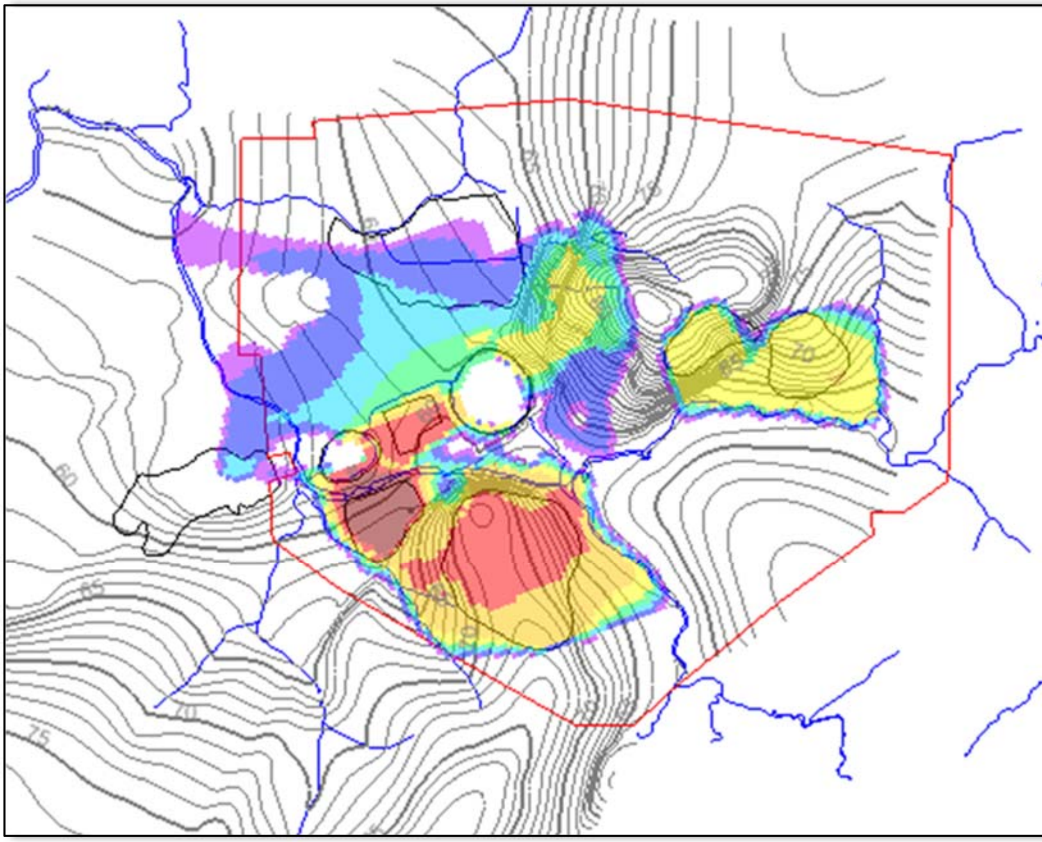
Appendix 28.

Robertson GeoConsultants (2016) *Groundwater Flow and Transport Model for Current Conditions, Rum Jungle*. Report to the Department of Mines and Energy, Northern Territory. PART A

Department of **Primary Industry and Resources**

REPORT NO. 183006/6

GROUNDWATER FLOW AND TRANSPORT MODEL FOR CURRENT CONDITIONS, RUM JUNGLE



Submitted to:

Northern Territory Government

Department of Mines & Energy

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EXECUTIVE SUMMARY

This Robertson GeoConsultants Inc. (RGC) report describes a transient numerical flow and solute transport model for groundwater at the Rum Jungle Mine Site. This modelling was done to support the refinement of the preferred rehabilitation strategy for the site as part of the Rum Jungle Rehabilitation Project. This report was prepared for the Northern Territory (NT) Department of Mines and Energy (DME) by Mr. Neil Robinson and Dr. Christoph Wels with contributions and review by Dr. Paul Ferguson.

Background

In 2012, RGC developed a transient numerical flow model for groundwater. That model was calibrated to groundwater monitoring data collected during the 2010/2011 wet season (RGC, 2012a), and modelling results were used to develop a preliminary contaminant load balance for groundwater and the East Branch of the Finniss River (RGC, 2012b). The flow model was later updated to include the 2011/2012 wet season in order to support an initial assessment of alternative rehabilitation strategies (RGC, 2013). Initial modelling was done to support the DME during its selection of a preferred rehabilitation strategy for the Rum Jungle mine site (DME, 2013).

Since 2012, the DME has continued to monitor groundwater levels and groundwater quality across the site, and has collected additional samples of seepage, pit water, and surface water flows in the East Branch of the Finniss River. Moreover, the DME commissioned two more drilling programs to characterise groundwater conditions in the Copper Extraction Pad area and in the Old Tailings Dam area (RGC, 2015), and completed a number of geotechnical and geophysical investigations of the area near the proposed new Waste Storage Facility (WSF) (RGC, 2016b).

Study Objectives and Scope

The objectives of this study are to:

- Update the Conceptual Site Model (CSM) to reflect current site data.
- Update and re-calibrate the transient numerical flow model.
- Simulate the transport of dissolved sulphate (SO_4) and copper (Cu) in groundwater for historic and current conditions.

This current work provides the basis for additional, predictive flow and solute transport modelling to be done for the site to predict the effects of the implementation of the DME's preferred rehabilitation strategy. That post-implementation modelling work will be described in RGC Report No. 183006/7 entitled '*Environmental Performance Assessment for the Preferred Rehabilitation Strategy*' (RGC, 2016g).

Numerical Methods and Approach

RGC used the U.S. Geological Survey's MODFLOW-NWT finite difference code to construct the groundwater flow model. The code was run transiently in order to simulate seasonal variations in groundwater elevations and flows. Solute transport was simulated using the transport code MT3DMS.

Figure E-1 shows the model domain, the finite difference grid and the monitoring bores used to calibrate the flow and transport model. Figure E-2 shows the boundary conditions of the model, including drain nodes that simulate creeks and streams, and the time-varied constant head nodes that simulate water level changes in the Main, Intermediate and Brown's pits.

The numerical flow model was set up and parameterised to reflect the updated CSM. Specifically, estimated recharge and evapotranspiration rates were applied, and constant head boundaries were set up to reflect pit water elevations and water level elevations in the East Branch of the Finniss River. Hydraulic conductivity (K) and specific yield (Sy) estimates from the previous version of the model were also assigned, or new values from recent slug testing and the 2012 pumping test in the Copper Extraction Pad area were used. Some adjustments to the vertical discretisation of the flow model were made (i.e. additional layers were added), and a new Digital Elevation Model (DEM) from the 2015 LiDAR survey was applied to estimate ground surface elevations (and the corresponding layer depths below).

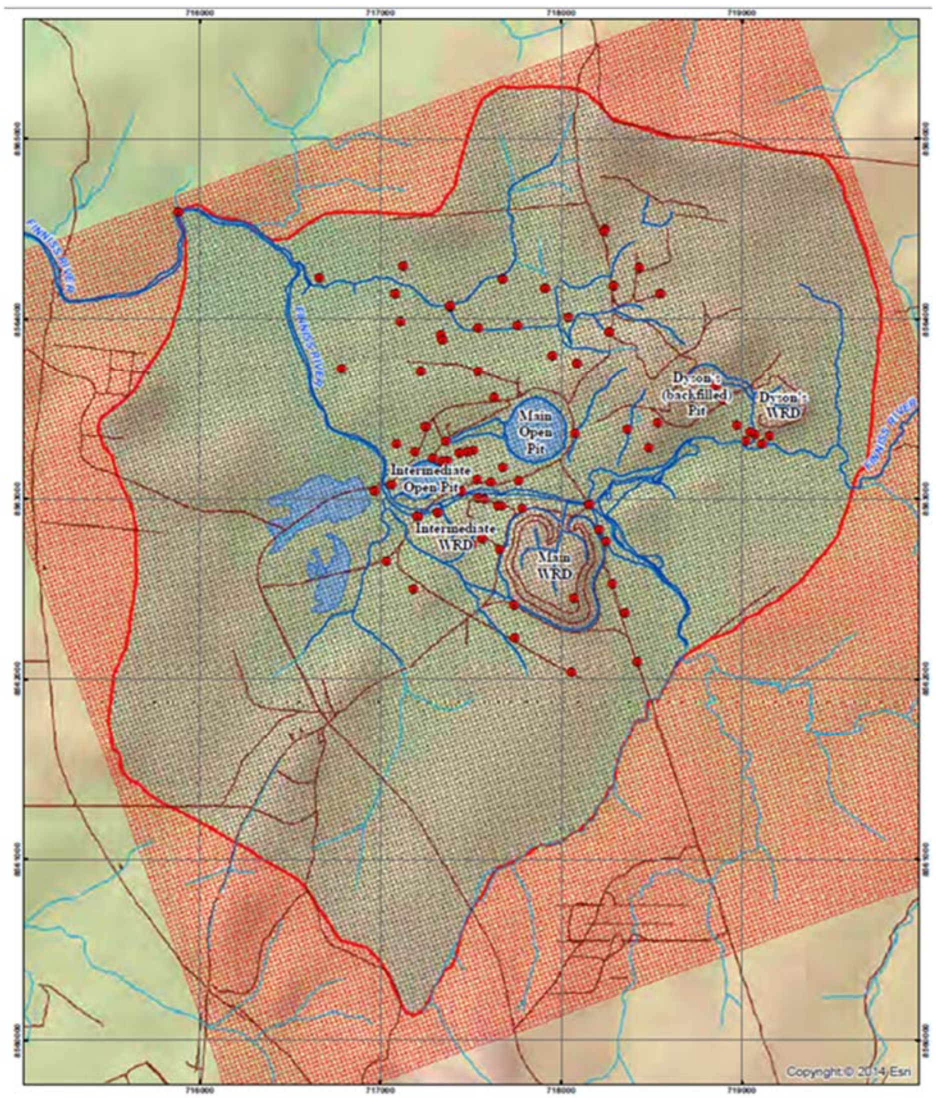

Figure E-1. Model Domain and Finite Difference Grid (black cells represent "active" model domain; red cells are "inactive").

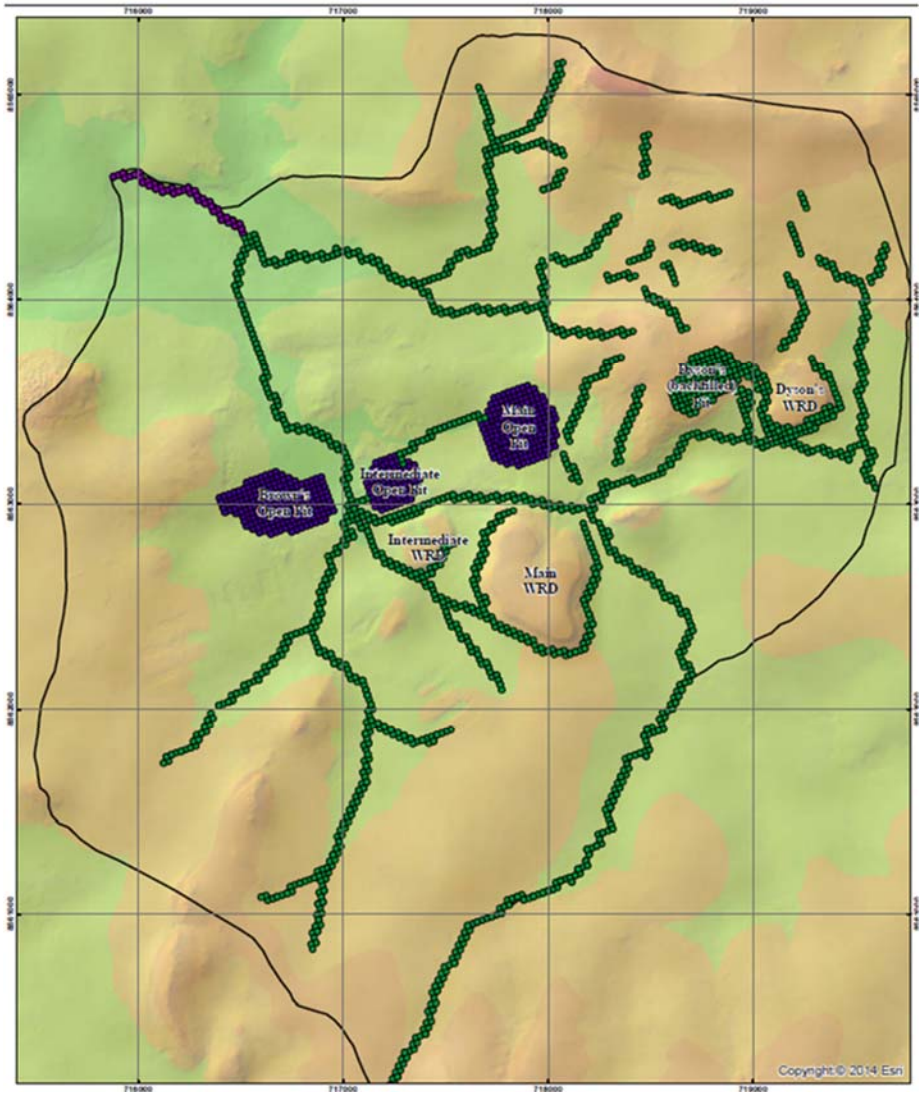

Figure E-2. Model Domain and Boundary Conditions

Flow Model Calibration

RGC calibrated the updated numerical flow model to monthly and semi-monthly groundwater level data collected by the DME from December 2010 to March 2015. Also considered are data from a 2012 pumping test in the Copper Extraction Pad Area, and gauged flows in the East Branch of the Finniss River downstream of the mine site (to gauge GS8150327).

The calibration process involved varying key model parameters (primarily hydraulic conductivity, recharge, and specific yield) in order to fit the simulated groundwater elevations from the model to observed groundwater elevations in calibration bores. The 'goodness of fit' was evaluated visually, and using statistical methods to compare the simulate head distribution in the model to observed conditions.

The simulated heads match the observed groundwater levels very well (with a NRMS error of < 4%) suggesting good calibration to head targets. Furthermore, the simulated monthly groundwater discharges to the lower EBFR fall within the calibration targets.

The calibrated hydraulic properties for overburden and bedrock units generally fall within the range of hydraulic properties determined during conceptual modelling. In general, the highest hydraulic conductivity in overburden was calibrated for laterite (and waste rock) while saprolite is less permeable. Calibrated hydraulic conductivity in bedrock units varied by 3-4 orders of magnitude, depending on lithology and depth. The highest permeability in bedrock was calibrated for the Coomalie dolostone, followed by bedrock of the Whites Formation and Rum Jungle Complex. Calibrated specific yield values in overburden units range from 1% to 10% and in bedrock units from 0.5 to 0.1%.

Simulated Flow Fields and Water Balances

A representative (simulated) flow field for the wet season is shown in Figure E-3. The calibrated groundwater flow model provides a good representation of observed current groundwater flow conditions at the Rum Jungle mine site:

- The model reproduces the observed local flow field, i.e. groundwater flows from highlands to lower areas where it discharges to local drainage lines, the East Branch Finniss River (EBFR), the East Finniss Diversion Channel (EFDC) or the open pits.
- The model reproduces the observed seasonal variations in the water table, ranging from 1-3 m in the low-lying areas and up to 8 m in the upland areas.
- In Dysons area, groundwater flow is predominantly in a southerly direction and seepage from Dysons WRD and Dysons backfilled Pit discharges into the upper EBFR.
- Near the Main WRD, groundwater levels tend to mound into the waste rock (particularly during the wet season).due to preferential recharge over the WRD foot print area and a local high in the bedrock topography. As a result, seepage from the Main WRD flows east towards Fitch Creek and west towards Wandering Creek and the EFDC.
- Near the Intermediate WRD, groundwater flows in a northerly direction with shallow seepage discharging to the EFDC and deeper seepage discharging into the Intermediate Pit.
- In the central mining area, groundwater levels are strongly influenced by water levels in the flooded Main and Intermediate Open Pits. The pits are engineered to receive inflows from the upper EBFR during the wet season, so pit water levels tend to be less variable than groundwater levels in the surrounding aquifer. In the wet season, both flooded pits act as net sinks for groundwater while during the dry season, the pits represent a source of net recharge to groundwater.

The simulated water balance from the calibrated model suggests that the East Branch of the Finniss River and Browns Oxide pit are major groundwater discharge zones. Inflow and outflow to the flooded Main Pit and Intermediate Pit are significantly smaller and vary seasonally.

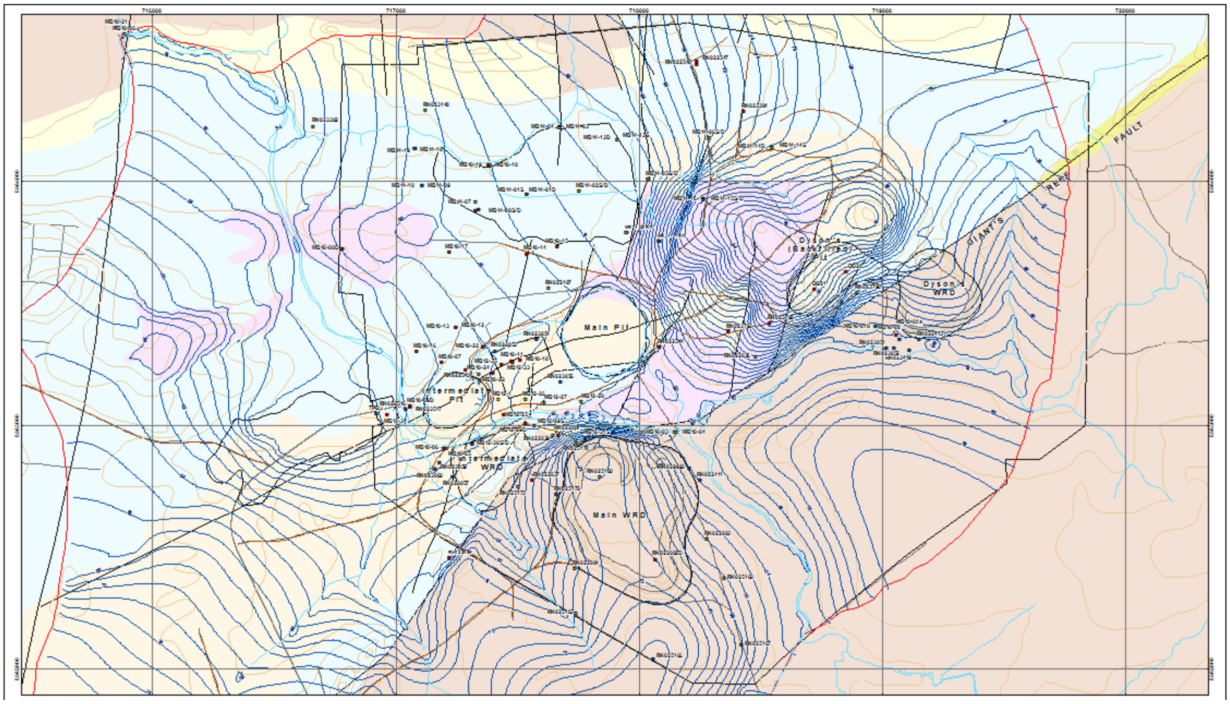

Figure E-3. Simulated Head Contours and Computed Residuals for March 2014 (Wet Season)

Transport Modelling Approach

A solute transport model was developed to simulate historic and current groundwater quality for selected contaminants of concern (i.e. sulphate and copper). The overall objective of the solute transport modelling was to develop a better understanding of the sources, geochemical controls and current extent of water quality impacts in groundwater at the Rum Jungle mine site. In addition, the results of this modelling effort provide a suitable benchmark (and initial conditions) for the prediction of future contaminant transport to assess the environmental effects of the preferred rehabilitation strategy.

A detailed, quantitative calibration of the transport model using historic time trends of groundwater quality at specific monitoring bores was not attempted. Instead, simplified historic and current flow and contaminant loading conditions were assumed and used in the numerical model to simulate current contaminant transport with the aim to reproduce a general, qualitative match to observed current groundwater quality conditions.

Two separate flow and transport models were set up covering different simulation periods:

- “Historic” flow & transport model covering 25 years of pre-rehabilitation conditions (1969 to 1984)
- “Current” flow & transport model covering 30 years of post-rehabilitation conditions (1985 to 2015)

The primary objective of the historic model was to develop suitable initial concentrations for the current transport model (immediately prior to initial rehabilitation in 1984/85).

Simulation of Historic Conditions

To constrain the historic transport model, RGC developed a conceptual load balance that reflects higher recharge to the WRDs and historic seepage water quality data compiled from previous reports (i.e. Davy, 1975). That conceptual model also included several sources of SO_4 and Cu that do not contribute loads to groundwater under current conditions, including tailings in the Old Tailings Dam area and pit water in the Intermediate, and Dysons Pits.

Based on this historic information, the total annual SO_4 and Cu loads in the East Branch of the Finniss River from 1969 to 1984 were 7,220 t/yr SO_4 and 56 t/yr Cu, respectively. RGC estimates that about 60% of these loads reported to the EBFR via groundwater flow, while the other 40% entered the EBFR directly via surface runoff (i.e. from exposed WRDs, contaminated soils and the Old Tailings Dam area) and/or, in the case of Cu, were 'lost' to geochemical reactions (i.e. adsorption and/or precipitation of secondary minerals) in the aquifer system. The source terms (and geochemical reaction terms for Cu) were adjusted in the historic transport model to reproduce those load targets.

Figure E-4 shows the simulated sulphate concentrations for historic conditions, i.e. prior to rehabilitation in 1984/1985. The historic (steady-state) groundwater flow field is also shown for reference (black contour lines). The simulated SO_4 and Cu loads to groundwater prior to rehabilitation were 4,062 t/yr SO_4 and 15-38 t/yr Cu (depending on degree of attenuation). These simulated loads explain up to 90% of the estimated historic loads in groundwater. The simulated SO_4 and Cu concentrations for 1984 were therefore considered to be a reasonable initial condition for the simulation of current conditions (from 1985 to 2015).

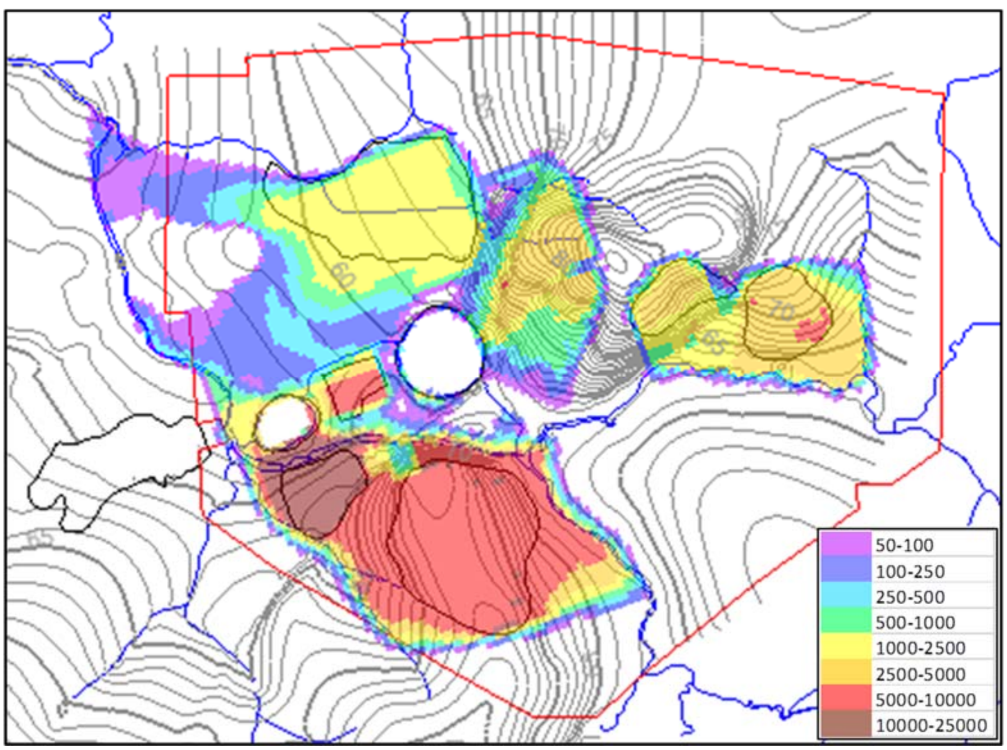

Figure E-4. Simulated 'Historic' SO_4 Concentrations (in mg/L) in Groundwater for Layer 3 (Before Initial Rehabilitation).

Simulated SO_4 Transport (for Current Conditions)

Initial rehabilitation works in the mid-1980s resulted in a significant reduction of contaminant load to groundwater and the receiving surface water (EBFR and tributaries) as a result of removal of certain contaminant sources (Old Tailings Dam, Copper Extraction Pad, contaminated pit water) and rehabilitation of other contaminant sources (e.g. covering of WRDs). RGC estimates that current SO_4 and Cu loads to the EBFR for average precipitation conditions are about 1,840 t/yr SO_4 and 2.7 t/yr Cu, respectively. RGC's conceptual load balance for current conditions was used to develop source terms for the current transport model.

Figure E-5 shows the simulated SO_4 concentrations in groundwater for current conditions with the steady-state flow field. The model predicts few changes in the overall shape of the SO_4 plume near the WRDs, but shows much lower concentrations due to reduced loading of sulphate after rehabilitation of the WRDs. Substantial changes in the SO_4 plume to the north of the central mining area occurred, as the ore stockpiles in the former mill area and tailings in the Old Tailings Dam area were removed from the model (and the area allowed to flush with clean groundwater and rainfall). Residual SO_4 plumes (up to 500 mg/L SO_4 in the footprint of the Old Tailings Dam) remain in this area. Also, groundwater continued to be impacted by contaminated materials near the former mill (which are a secondary source of 1,500 mg/L SO_4 to groundwater near the Main Pit).

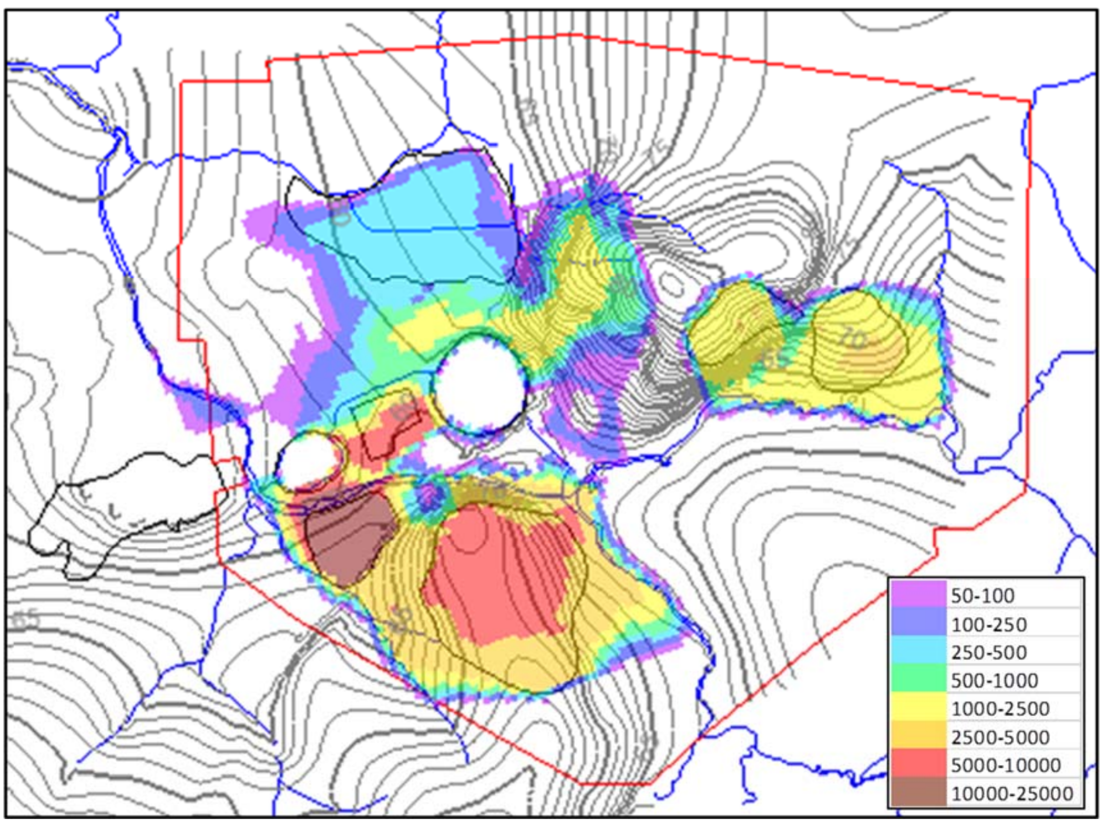

Figure E-5. Simulated 'Current' SO_4 Concentrations (in mg/L) in Groundwater for Layer 3 (Current Conditions).

SO_4 loads from groundwater to the East Branch of the Finniss River have been substantially reduced since 1985 (c. Figures E-4 and E-5). Moreover, the transient time trends for SO_4 indicate that sulphate transport in groundwater reached a new steady-state condition within 5 to 15 years of initial rehabilitation. In other words, historic SO_4 plumes that were present in groundwater before 1984/1985 have been flushed over the last 30 years. This modelling result is consistent with groundwater quality collected since 2010 (which show few changes over time).

Predicted SO_4 loads to the East Branch of the Finniss River (for current conditions) are summarised as follows:

- The total current sulphate load in groundwater discharging to the receiving surface water is predicted to be about 1,439 t/yr. This load represents only about 35% of the historic sulphate load in groundwater, i.e. a threefold decrease.
- The highest proportion of current sulphate load in groundwater is predicted to discharge in the reach of Fitch Creek, EFDC and Wandering Creek impacted by the Main WRD (32%), followed by the reach of EFDC and Wandering Creek near Intermediate WRD (28%).
- Although the current sulphate load to the Upper EBFR (Dysons area) has decreased (relative to pre-rehabilitation), the relative proportion of the total current load has increased to about 14%.
- Similarly, the relative proportion of current sulphate load to the Intermediate Pit (from CEPA and Intermediate WRD) has also increased to about 15%. Sulphate loading to the Main Pit has remained a minor component to total sulphate load (about 5 % of total).
- Sulphate loading to the lower EBFR (including Old Tailings Creek) has significantly declined (from 429 t/yr to 64 t/yr) due to the removal of the historic tailings. The current sulphate load to this reach of the model domain is predicted to be about 5 % of the total sulphate load.

The simulated current SO_4 load to surface water is about 26% higher than the load from RGC's conceptual load balance and about 22% lower than currently observed SO_4 loads in the East Branch of the Finniss River (2010-2015). RGC attributes these discrepancies to diffuse sources of SO_4 to groundwater, including seepage from residual contaminants in the former mill area and Old Tailings Dam area, and other, residually-impacted groundwater. Given the uncertainty in the magnitude of these diffuse sources, the simulated conditions for SO_4 are considered to be a reasonable representation of current conditions, and therefore provide a suitable reference against which to evaluate the effect of future rehabilitation.

Simulated Cu Transport (for Current Conditions)

For copper transport, RGC simulated the following attenuation scenarios:

- 'No Attenuation' (conservative transport).
- '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 types).

More details on the assumptions and numerical implementation of these attenuation scenarios are provided in section 7.3.8 of this report. The simulated copper concentrations in groundwater for these three scenarios illustrating the range of effects of geochemical processes controlling Cu transport in groundwater are shown below in Figure E-6.

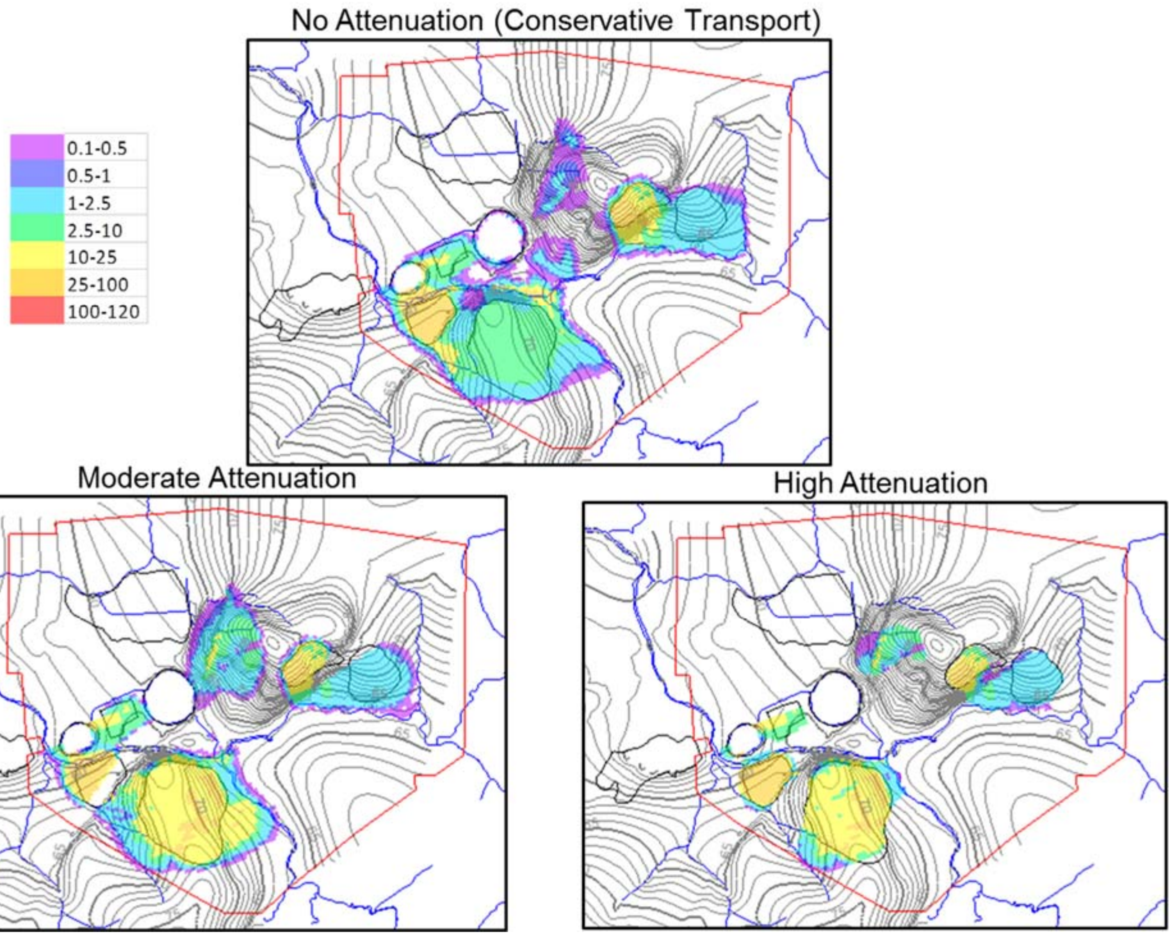

Figure E-6. Simulated 'Current' Cu Concentrations (in mg/L) in Groundwater for Layer 3 (Current Conditions).

Transient transport modelling for the period 1985 to 2015 indicates that the following has occurred as a result of the rehabilitation carried out in the 1980s:

- While a substantial reduction in copper loading for all WRDs (due to cover placement in 1984/85) does not significantly change the spatial extent of the associated copper plumes in groundwater, the copper concentrations in both overburden and bedrock have decreased significantly as a result of reduced loading.
- The removal of the ore stockpiles in the former mill site have reduced the copper load and hence copper concentrations in groundwater in that area (north-east of the Main Pit).
- Removal of the historic tailings from the OTD area has resulted in significant clean-up of the historic copper plume in this area.

A comparison of the copper plume predicted for conservative behaviour (i.e. no chemical attenuation) with the copper plumes simulated for the scenarios of moderate and high attenuation illustrate the influence of geochemical controls on current copper transport. The key observations can be summarised as follows:

- Moderate sorption assumed in the shallow soils (R=3.5 in layers 1 and 2) does not significantly influence copper concentrations in those layers, except near the margin of the plume.
- Strong sorption assumed in bedrock (R=100 in all lithologies except dolostone) significantly delays copper transport in bedrock. In areas where current copper source concentrations have declined, higher residual copper concentrations remain present ("trapped") in deeper bedrock due to slow travel velocities and retardation.
- Chemical precipitation assumed for dolostone (moderate and high attenuation scenarios) and for all other bedrock lithologies (high attenuation scenario) completely removes copper from the aqueous phase, thus effectively eliminating any copper plume in those bedrock units.

The key findings with respect to simulated current copper loads are as follows:

- The total current copper load discharging to the receiving surface water is predicted to range from a low of 1.1 t/yr (high attenuation) to a high of 3.1 t/yr (no attenuation). This represents a 14 to 12-fold reduction in copper load from groundwater to surface water since rehabilitation in the mid-1980s.
- The moderate attenuation scenario predicts only a slightly lower copper load (2.7 t/yr) than the conservative scenario (3.1 t/yr), indicating the relatively small effect of attenuation of copper in bedrock under current conditions.
- Seepage from the Intermediate WRD represents the highest source of current copper load, followed by seepage from the Main WRD, CEPA (to Intermediate Pit) and Dysons WRD/backfilled Pit.
- Residual copper loading from the former mill site and the OTD is not a major source of copper loading for current conditions (for all attenuation scenarios).

Based on a comparison of simulated and observed spatial distribution of copper concentrations in groundwater and load estimates of copper in the EBFR today, the "moderate attenuation" scenario is considered to be the scenario that most closely represents current copper transport at Rum Jungle and should be used for predictive modelling.

However, there is significant uncertainty in reactive transport modelling and the high attenuation scenario (featuring irreversible reaction in bedrock) cannot be ruled out at this time. Furthermore, the "no attenuation" scenario provides a useful (albeit likely unrealistic) reference scenario representing conservative transport. Consequently, these two attenuation scenarios for copper should also be simulated for predictive modelling to evaluate the sensitivity of predicted post-rehabilitation performance to uncertainty in geochemical controls.

Path Forward

The calibrated groundwater flow and solute transport model described here is a suitable tool for predictive modelling of post-rehabilitation groundwater conditions. The following predictive modelling tasks will be undertaken to inform rehabilitation planning:

- Designing the remediation strategy for groundwater in the Copper Extraction Pad area.
- Modelling groundwater inflows to the Main and Intermediate Pits when they are partially de-watered during the construction phase of rehabilitation.
- Modelling future contaminant transport in groundwater as residual plumes are flushed and new loads from backfilled Main Pit and the new WSF report to groundwater.

REPORT NO. 183006/6

GROUNDWATER FLOW AND TRANSPORT MODEL FOR CURRENT CONDITIONS, RUM JUNGLE

Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ACRONYMS AND ABBREVIATIONS

α_L	longitudinal dispersivity
α_T	transverse dispersivity
α_V	vertical dispersivity
β	Irreversible Sorption Reaction Coefficient
AHD	Australian Height Datum
Al	Aluminium
AMD	Acid and Metalliferous Drainage
bgs	below ground surface
BOM	Bureau of Meteorology
CEPA	Copper Extraction Pad Area
CMA	Central Mining Area
Co	Cobalt
COC	Contaminant of Concern
CSM	Conceptual Side Model
Cu	Copper
$CuCO_3$	Copper Carbonate
DEM	Digital Elevation Model
DME	Department of Mines and Energy
DTW	depth-to-water
EC	Electric Conductivity
EMU	Environmental Monitoring Unit
ERI	Electrical Resistivity Imaging
ERISS	Environmental Research Institute of the Supervising Scientist
ET	Evapotranspiration
EBFR	East Branch of the Finniss River
EFDC	East Finniss Diversion Channel
Fe	Iron
GMS	Groundwater Modeling System
GPR	Ground Penetrating Radar
GPS	Global Positioning System
HCO_3	Bicarbonate

Head	hydraulic head (or water level)
K_D	Distribution coefficient (linear sorption)
K	Hydraulic conductivity
K_h	Horizontal hydraulic conductivity
K_v	Vertical hydraulic conductivity
LDWQO	Locally-Derived Water Quality Objective
LiDAR	Light Detection and Ranging
MAE	mean annual lake evaporation
MAET	mean annual evapotranspiration
MAP	mean annual precipitation
Mg	Magnesium
Mn	Manganese
MT3DMS	Modular Three-Dimensional Multispecies Transport Model
NAF	Non-acid forming
n	porosity
n_e	effective porosity
Ni	Nickel
NRMS	normalized root mean squared error
NT	Northern Territory
NWT	Newton Formulation for MODFLOW-2005
OTD	Old Tailings Dam
PAF	Potentially acid forming
Pb	Lead
PVC	polyvinyl chloride
R_f	Retardation factor
RJC	Rum Jungle Complex
RGC	Robertson GeoConsultants Inc.
RN	Registration number (groundwater bores)
Se	Selenium
SMD	soil moisture deficit
SO_4	Sulphate
S_S	Specific Storage

S_y	Specific yield
TDS	Total Dissolved Solids
USGS	United States Geological Survey
WRD	Waste Rock Dump
WSF	Waste Storage Facility
Zn	Zinc

REPORT NO. 183006/6

GROUNDWATER FLOW AND TRANSPORT MODEL FOR CURRENT CONDITIONS, RUM JUNGLE

1 INTRODUCTION

1.1 GENERAL

This Robertson GeoConsultants Inc. (RGC) report describes a transient numerical groundwater flow and solute transport model for current conditions at the Rum Jungle Mine Site. It was prepared in support of the Rum Jungle Rehabilitation Project by Mr. Neil Robinson and Dr. Christoph Wels with contributions and review by Dr. Paul Ferguson. This report is a Stage 5 deliverable under RGC's contract D14-0114 for Phase 5 investigations in support the Rum Jungle Rehabilitation Project.

1.2 TERMS OF REFERENCE

The former Rum Jungle Mine Site is located 105 km by road south of Darwin in the headwaters of the East Branch of the Finniss River. The Rum Jungle Mine 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 1954 and 1971 (Davy, 1975). Acid and Metalliferous Drainage (AMD) at the site has led to significant environmental impacts on local groundwater and the East Branch of the Finniss River and radioactive tailings remain in some areas (Kraatz, 2004).

In 2009, the Northern Territory (NT) Department of Mines and Energy (DME) was tasked with developing a comprehensive rehabilitation strategy for the former Rum Jungle Mine Site. 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.

In June 2010, RGC submitted an initial review of geochemical and hydrogeological data collected since the mid-1980s (RGC, 2010a). That review included an assessment of AMD sources, current groundwater and surface water quality conditions, and the identification of any data gaps that would hinder future rehabilitation planning. RGC completed a second phase of work that including drilling in areas that were under-represented in the existing bore network. This second phase of work was completed between August and December 2010 and included drilling, installation and sampling of 27 new monitoring bores and hydraulic testing of 19 monitoring bores (see RGC, 2011a).

Phase 3 investigations were undertaken after completion of the 2010 drilling program. The first stage of Phase 3 involved the development of a conceptual flow model for the site (see RGC, 2011b), while Stage 2 described numerical modelling based on the field data available to the end of 2011 (see RGC, 2012a). In 2012, fourteen additional monitoring bores were installed in the Central Mining Area (CMA) and in the vicinity of the East Finniss Diversion Channel (EFDC). A pumping test was also conducted in the Copper Extraction Pad area in November 2012. In October and November 2014, RGC supervised the installation of additional 18 monitoring bores were installed within and around the Old Tailings Dam area (RGC, 2015).

1.3 STUDY OBJECTIVES

The objectives of the Phase 5 flow and transport modelling is to simulate current groundwater flow and solute transport at the Rum Jungle Mine Site. Specific objectives are to:

- Compile and interpret groundwater and surface water monitoring data collected from 2010 to 2015.
- Update the Conceptual Site Model (CSM) for the site to reflect additional field work and monitoring data completed since 2012.
- Update and re-calibrate the transient groundwater flow model for current conditions (2010 to 2015).
- Simulate the transport of dissolved sulphate (SO_4) and copper (Cu) in groundwater for historic and current conditions.

This study provides the basis for additional, predictive flow and solute transport modelling for future site conditions, i.e. after implementation of DME’s preferred rehabilitation strategy. That modelling work is described in RGC Report No. 183006/7 entitled ‘*Environmental Performance Assessment for the Preferred Rehabilitation Strategy*’ (RGC, 2016g).

1.4 REPORT ORGANISATION

In addition to this introductory section, this report contains the following sections:

- **Section 2 – Site Description** provides a short description of the location and climate, geology, site layout, hydrology and the groundwater monitoring system.
- **Section 3 – Review of Groundwater Monitoring Data** provides updated descriptions of the groundwater elevation and groundwater quality monitoring data for each area of the Site.
- **Section 4 – Conceptual Site Model** describes the hydrogeological conceptualisation of the site.

- **Section 5 – Model Setup** summarises the numerical methods used to construct the groundwater model of the Rum Jungle Mine Site.
- **Section 6 – Calibration of Groundwater Flow Model for Current Conditions** describes the approach, targets and results of the calibration of the groundwater flow model.
- **Section 7 – Solute Transport Modelling** describes the methods and results of transport modelling (for sulphate and copper) for historic and current conditions.

1.5 SUPPORTING RGC REPORTS

The hydrogeological study described in this report is one of a series of studies completed by RGC during the latest phase of rehabilitation planning for the Rum Jungle mine site. The results of these related studies are summarised in a series of reports which are listed below for ease of reference:

- RGC (2016a), Physical and Geochemical Characterisation of Waste Rock and Contaminated Materials, RGC Report No. 183006/1.
- RGC (2016b), New Waste Storage Facility Investigations, RGC Report No. 183006/2.
- RGC (2016c), Options Assessment for Pit Backfilling, RGC Report No. 183006/3.
- RGC (2016d), Conceptual Water Management and Treatment Plan for Construction Phase of Rehabilitation (Progress Report), RGC Report No. 183006/4.
- RGC (2016e), Groundwater Remediation Strategy for the former Copper Extraction Pad area, RGC Report No. 183006/5.
- RGC (2016f), Groundwater Flow and Transport Model for Current Conditions, RGC Report No. 183006/6.
- RGC (2016g), Environmental Performance Assessment for the Preferred 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 SITE DESCRIPTION

2.1 LOCATION

The Rum Jungle Mine Site is located in Australia's Northern Territory about 105 km by road south of Darwin near the township of Batchelor (Figure 2-1). The Rum Jungle mine site is located within the watershed of the East Branch of the Finniss River which drains into the Finniss River and into the Timor Sea.

Most of the mine site is located within the low-lying flood plain of the East Branch of the Finniss River and its tributaries which experiences flooding during the wet season. The mine lease has a relatively low relief with elevations ranging from about 60m AHD in the flood plain to about 100m AHD along the surrounding ridges.

The region is characterised by a tropical savannah-like climate and vegetation.

2.2 REGIONAL GEOLOGY

The Rum Jungle mineral field is located in northern Australia and contains numerous polymetallic ore deposits, such as the Ranger and Woodcutters ore deposits and the ore deposits associated with the Rum Jungle Mine (i.e. the Main, Intermediate, Dysons, and Brown's Oxide ore deposits).

The Rum Jungle Mine Site is situated in a triangular area of the Rum Jungle mineral field that is bounded by the Giant's Reef Fault to the south and a series of east-trending ridges to the north (Figure 2-2). This triangular area is known as "The Embayment" and it lies on the shallow-dipping limb of a northeast-trending, south-west plunging asymmetric syncline that has been cut by northerly-dipping faults.

The main lithologic units in The Embayment are the Rum Jungle Complex and meta-sedimentary and subordinate meta-volcanic rocks of the Mount Partridge Group. The Rum Jungle Complex consists mainly of granites and occurs primarily along the south-eastern side of the Giant's Reef Fault, whereas the Mount Partridge Group occurs north of the fault and consists of the following sedimentary units (from younger to older): Geolsec Formation, the Whites Formation, the Coomalie Dolostone, and the Crater Formation (Figure 2-3).

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

2.3 SITE LAYOUT

The Rum Jungle Mine Site features the Main, Intermediate and Dysons waste rock dumps (WRDs), the flooded Main and Intermediate Pits, Dysons (backfilled) Pit (or 'landform') and the partially-mined Brown's Oxide Pit (see Figure 2-4). Other notable features shown in Figure 2-4 are the East Finniss Diversion Channel (EFDC), the former Old Tailings Dam (OTD) area along Old Tailings Creek, the former plant site, and the former Copper Extraction Pad area (between the Main and Intermediate Pits).

An aerial photograph of the Rum Jungle Mine Site taken prior to rehabilitation in the 1980s is shown in Figure 2-5. Some minor clean-up operations had been completed in the late 1970s but this photo essentially illustrates the major features of the site as they existed when mining operations ceased in the 1960s. An aerial photograph of the site taken in 2010 is shown in Figure 2-6 for comparison.

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

2.3.1 Main, Intermediate and Dysons Pits

The Main and Intermediate Pits are located in the central mining area (or 'CMA') along the pre-mining course of the East Branch of the Finniss River. These pits were mined out in the 1950s and 1960s and became flooded with contaminated groundwater and seepage when mine de-watering ceased (Davy, 1975). The Main Pit was mined to about 105 m below ground surface (bgs), and was partially backfilled (to approximately 45 m bgs) with tailings and other mine waste in the 1960s. The Intermediate Pit was mined to approximately 57 m bgs and has not been backfilled.

Dysons Pit was mined to a depth of approximately 50 m bgs in the late 1950s. Tailings from the Intermediate ore body were discharged to Dysons Pit from 1961 to 1965 and the pit was later backfilled to near ground surface with additional tailings from the Old Tailings Dam. The surface of the tailings was limed and overlaid with a single layer polypropylene geofabric and a rock blanket comprised of dolomitic material recovered from the Intermediate WRD (SRK, 2012).

Leached low-grade ore and contaminated soils removed from the Copper Extraction Pad area were then placed on top of the rock blanket and the backfilled pit was covered to reduce infiltration and prevent capillary rise of contaminants (Allen and Verhoeven, 1986). Water flowing along the rock blanket currently expresses via a toe drain near the southern edge of the landform. However, based on the results of the drilling investigation completed by SRK, it is possible that the rock blanket has deteriorated to the point that it is no longer functioning as a preferential pathway but more as a barrier.

The Browns Oxide Pit is located west of the central mine area on private property. This pit is relatively shallow (< 30 m bgs) and is at present actively de-watered (but not mined) by HAR Resources.

2.3.2 Waste Rock Dumps

The Main, Intermediate, and Dysons WRDs contain waste rock removed from the open pits during mining operations. The Main WRD is the largest of the three WRDs (30 ha) and is located near the south-eastern boundary of the mine lease adjacent to Fitch Creek. The footprints of the Intermediate and Dysons WRDs are 8 ha and 9 ha, respectively.

Each of the waste rock dumps was covered in the 1980s to reduce rainfall infiltration and oxygen transport into the dumps but the covers have deteriorated since that time. Only the top of Dysons WRD was covered in the 1980s so waste rock is exposed near the edges of the WRD and the condition of the cover is considered particularly poor (Fawcett, 2007).

2.3.3 East Finniss Diversion Channel

The East Branch of the Finniss River (EBFR) was diverted to the EFDC to allow access to the Main and Intermediate ore bodies during mining operations. The EFDC is relatively shallow and has been cut into bedrock south of the Main and Intermediate WRDs. The head of the EFDC is marked by a 'weir structure' immediately west of the confluence of Fitch Creek and the EBFR with its downstream end at the point of outflow from the Intermediate Pit just upstream of the road bridge.

The EFDC currently receives wet season flows from the East Branch of the Finniss River and seepage collected from the Main and Intermediate WRDs. Seepage collected from the eastern edge of the Main WRD is delivered to the EFDC near the 'weir structure' and from the south-western edge via Wandering Creek. Seepage from the Intermediate WRD enters the EFDC directly via a seepage face located about 250 m upstream of the road bridge.

2.3.4 Former Copper Extraction Pad Area

In the 1960s, copper from sub-grade ore (and the oxidised capping) of the Intermediate ore body was extracted via heap leaching on a 'non-permeable' pad located between the Main and Intermediate Pits (Davy, 1975). Contamination of the local soils and local groundwater due to seepage losses was extensive. Most of the contaminated surficial soils were ultimately removed and used to backfill Dysons Pit but residual amounts of contaminated soils and heap leach material remain. Groundwater in bedrock in this area remains highly-contaminated (see RGC, 2011a).

2.3.5 Old Tailings Dam Area

Slurried tailings were discharged to a relatively flat area north of the central mine area during mining operations. Drainages from this area formed a small creek that eventually flowed to the East Branch of the Finniss River (Watson, 1979). As tailings piled up, perimeter walls were built towards the eastern end of the creek to form a series of small dams commonly referred to as the "Old Tailings Dam" (Davy, 1975).

Most of the tailings in this area were removed during reclamation works in the 1980s and the area was limed, re-shaped, and covered to promote the re-establishment of vegetation. Residual tailings do, however, remain present near surface throughout the area (Fawcett, 2007).

2.4 CLIMATIC CONDITIONS

2.4.1 Precipitation

The climate of the Rum Jungle mine site can be generally defined as tropical savannah, characterised by a long dry season from May to October followed by a humid wet season from November to April. A climate database known as SILO (DSITI, 2016) was used to indicate the range of rainfall conditions that can be reasonably expected at the mine site. Table 2-1 provides a monthly summary of the daily rainfall record extracted from SILO database for the Rum Jungle site.

Based on a reconstructed record of 127 years, the study area has a mean annual precipitation (MAP) of 1459 mm/year, and has experienced record minimum and maximum annual rainfalls of 855 mm and 2366 mm, respectively.

Table 2-1.

Estimated Historical Monthly Rainfall Averages and Extremes for the Study Area (based on 1889-2015 SILO database)

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average	332.0	311.4	265.2	77.2	11.9	2.4	1.3	3.5	14.4	57.7	134.0	245.8	1459.1
Min	89.3	67.3	47.6	0.0	0.0	0.0	0.0	0.5	0.0	0.0	41.2	82.5	855.4
Max	778.4	669.0	701.2	474.6	269.9	78.9	61.6	64.9	216.9	217.3	329.5	601.9	2365.9
Count	128	128	128	128	128	127	127	127	127	127	127	127	127

In 2010, DEM established a weather station near the Main WRD that includes a precipitation gauge. Table 2-2 presents the monthly and water year (August to July) rainfall totals for this station. For comparison, recent rainfall data collected at the Batchelor Airport (Station 014272) is also shown. Note that WY 2010/2011 was unusually wet, producing a total precipitation of 2,402 mm (or 65% above MAP). The following three water years had annual total rainfalls that ranged from 6% below to 18% above MAP.

For this hydrogeological study, the complete precipitation record (2010 to 2015) collected at the local weather station was used. Any missing data during this observation period were patched using the precipitation record of the nearby Batchelor Airport station.

Table 2-2.

Recent Rainfall at the Batchelor Airport and the Rum Jungle Mine Site

Wet Season	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Total
Batchelor Airport (Station 014272)													
2007/2008	1	11	88	159	368	318	670	338	36	0	0	0	1989
2008/2009	0	8	40	130	361	224	430	50	0	16	0	0	1259
2009/2010	0	27	29	71	576	422	316	92	155	49	0	3	1740
2010/2011	7	29	162	93	288	555	608	296	354	0	0	0	2392
2011/2012	0	0	110	133	149	326	168	517	29	43	0	0	1475
2012/2013	0	12	59	208	179	274	259	364	67	150	1	0	1573
2013/2014	1	30	64	207	216	543	403	97	53	8	0	0	1622
2014/2015	0	0	11	101	211	377	220	44	-	-	-	-	964
Mean	1	15	70	138	294	380	384	225	108	38	0	0	1653
Gauge near the Main Waste Rock Dump													
2010/2011	0	36	138	84	322	578	697	382	165	0	0	0	2402
2011/2012	0	0	57	112	152	362	230	419	15	30	0	0	1377
2012/2013	0	5	30	138	144	257	237	331	51	185	1	0	1379
2013/2014	5	25	79	193	332	539	373	76	74	33	0	0	1729
2014/2015	0	0	16	72	-	316	255	162	-	-	-	-	821
Mean	1	13	64	120	238	410	358	274	76	62	0	0	1542

2.4.2 Lake Evaporation & Evapotranspiration

The WREVAP model (NHRI, 1985) was applied to climate stations in the region that monitor dew point, air temperatures and sunshine hours to estimate mean annual lake evaporation (MAE) and mean annual (actual) evapotranspiration (MAET). Based on the location of the monitoring stations and the WREVAP model estimates, the mean annual lake evaporation for the Rum Jungle Mine Site is approximately 2,000 mm (5.5 mm/d) and the mean annual actual evapotranspiration is approximately 1,050 mm (2.9 mm/d).

Based on the above estimates of MAP and MAET, the mean annual runoff, i.e. the portion of precipitation running off as stream and/or groundwater flow, would be expected to be roughly 1460-1050=410 mm.

2.5 HYDROLOGY

The Rum Jungle Mine Site is located along the East Branch of the Finniss River about 8.5 km upstream of its confluence with the West Branch of the Finniss River (Figure 2-1). Surface water enters the mine site from the east via the upper East Branch of the Finniss River and from the south-east via Fitch Creek. Before mining, these creeks met near the north-east corner of the Main WRD and subsequently flowed eastward via the natural river course. During mining, the river was diverted to the EFDC to allow access to the Main and Intermediate ore bodies (see 'former river channel' and 'EFDC' on Figure 2-4).

Today, flows from the upper East Branch of the Finniss River and Fitch Creek flow directly into the EFDC and, during high flows, to the Main Pit through a channel near the former Acid Dam. Water then flows from the Main Pit to the Intermediate Pit via a channel that roughly follows the pre-mining river course. Outflow from the Intermediate Pit to the EFDC occurs near the western boundary of the mine site and combined flows from the Main and Intermediate Pits and EFDC continue northward via the natural course of the East Branch of the Finniss River.

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. Early wet season flows in the river ("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 (Taylor et al., 2003).

Flows in the East Branch of the Finniss River are monitored at gauges GS8150200, GS8150327, and GS8150097 (see Figure 2-1). Pertinent features of these gauges are summarised as follows:

- Gauge GS8150200 is located near the road bridge west of the Intermediate Open Pit and drains an area of 53 km^2 that includes the majority of the Rum Jungle Mine site (i.e. the central mining area and Dysons Area, but not the Old Tailings Dam area). Gauge GS8150200 was built in December 1981 and operated initially until August 1988. The gauge was re-established in 1991 and has since been used to monitor surface water quality conditions in the East Branch of the Finniss River immediately downstream of the mine site (see Lawton and Overall, 2002a, for additional details). The East Branch of the Finniss River is thought to be poorly-mixed at this gauge, so water quality data (and loads) are interpreted with caution.
- Gauge GS8150327 is located about 2.5 km downstream of gauge GS8150200 near bores MB10-20 and MB10-21. This gauge was installed in late 2010 and has been operational since 2011. It captures additional flows from Old Tailings Creek and any groundwater discharge from the Old Tailings Dam area.
- Gauge GS8150097 is located about 5 km further downstream of GS8150327. This gauge drains an area of 71 km^2 and captures flows from several tributaries that enter the river downstream of gauge GS8150327. This gauge was constructed in 1965 and has been operational for most of the time since (Lawton and Overall, 2002a). Flows at this location were used to estimate contaminant loads in the East Branch of the Finniss River prior to initial rehabilitation works in the 1980s (Davy, 1975).

2.6 GROUNDWATER MONITORING NETWORK

In August 2010, the DME inventoried the historic monitoring bores at the Rum Jungle Mine Site as part of Phase 1 of the Rum Jungle Rehabilitation Project. This involved searching for each bore that had been assigned a six digit Registration Number (RN) by the NT Government, or that had appeared on a historic (often hand-drawn) figure or map. The DME located 106 of the 121 historic 'RN' bores at the site – each of these bores was photographed and the coordinates of each were taken with a hand-held GPS unit. The depth of each bore and the 'stickup' height above ground surface were also measured during the DME's initial survey in 2010, and the condition of the PVC and protective steel casing were noted.

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). These bores are clustered near the key historic AMD sources (i.e. the WRDs, the pits, etc.), or near the East Branch of the Finniss River. Many of the bores are shallow (i.e. less than 2 m deep), and often screened above the dry season groundwater level at the site. Some of the deeper 'RN' bores, including bore RN022085 and RN023302, are routinely monitored by HAR Resources (so were in good condition in 2010). Most of the historic bores, however, had not been visited since the last post-rehabilitation monitoring report was published in 1998 (see Kraatz, 1998).

43 of the 106 monitoring bores that the DME located in 2010 were suitable for routine groundwater monitoring. The other bores had either been melted by brush fires, or had been damaged or destroyed by previous earthworks at the site. The monitoring bore network at the Rum Jungle Mine Site also includes 64 additional bores that the DME commissioned in 2010, 2012, and 2014 as part of the current Rum Jungle Rehabilitation Project (see Figure 2-7 for locations and Appendix A for further details on their construction). These monitoring bores are referred to as 'MB' bores, with a prefix that indicates the year it was installed (i.e. MB10 bores were installed in 2010). Also, at locations with two monitoring bores (either a pair of nested bores, or two bores very close to one another), the deeper bore is identified with a 'D' and the shallower bore is identified with an 'S'. Each of the MB bores has also been assigned a RN number, but these numbers are not referred to in this report or other RGC reports.

A brief description of the three 'MB' bore series is provided below:

- '<u>MB10 bore series' (26 bores).</u>
    - o The MB10 bores were installed in November and December 2010 as part of RGC's initial investigation of groundwater conditions across the Rum Jungle Mine Site (see RGC, 2011a,b).
    - o Most of the MB10 bores are located in areas of the site that RGC thought were under-represented in the existing bore network (e.g. near Dysons backfilled Pit, or between the Main and Intermediate Open Pits). Of particular interest were areas further downgradient of the existing bores, as the extent of groundwater quality impacts had not been delineated at the time.
    - o The majority of the MB10 bores were installed in holes that were purpose-drilled with an air rotary drill rig. These bores were fitted with 100 mm PVC blanks and machine-slotted PVC. Several bores were installed by retrofitting existing, 'open hole' bores or exploration holes. Bores MB10-9S/D, for instance, were installed in existing bore

RN022108 (an 'open hole' bore that was installed in 1983), and installation of bore MB10-23 involved placing PVC in an open exploration hole near the Intermediate Open Pit (see RGC, 2011a,b).

- 'MB12' bore series (12 bores).
    - The MB12 bores were installed in order to further characterize groundwater conditions in (i) the Copper Extraction Pad area and (ii) the area near the Main and Intermediate WRDs. Several of the MB12 bores were installed near MB10-11 (where severely-impacted groundwater had been identified), and others were installed closer to the EFDC in order to delineated the extent of impacted groundwater (and vertical hydraulic gradients) in this area (see Figure 3-1).
    - One of the bores installed in 2012 was a 30 cm-diameter production bore (PB12-33) that was installed in order to complete a 10-day pumping trial to estimate the hydraulic properties of the bedrock aquifer in the Copper Extraction Pad area. Bore PB12-33 is 32 m deep (and was fitted with a 18 m, stainless steel screen).
- 'MB14' bore series (28 bores).
    - 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). The DME has since elected to move the footprint of the new WSF to higher ground to the east, so many of the MB14 bores are located downgradient of the current WSF footprint (towards the East Branch of the Finniss River).
    - Bores MB14-2 to MB14-6, MB14-13, and MB14-14, and MB14-15 are located within the current WSF footprint and bores MB14-17S/D and MB14-20 are located near the former mill site to the north of the Main Pit.

The bore network at the Rum Jungle Mine Site 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). The exploration holes that are monitored were drilled by HAR Resources since 2010. These are 'open holes' (i.e. no screen) that were initially monitored for the 2012 pumping trial in the Copper Extraction Pad area (and have since been retained in the DME's routine monitoring program). These holes are labelled with the prefix 'OH' in Figure 2-7. They were sampled (by airlifting) in 2012 and the DME has continued to monitor groundwater levels in them as part of routine monitoring (see Section 3.1.2).

3 REVIEW OF GROUNDWATER MONITORING DATA

3.1 GROUNDWATER MONITORING PROGRAMS

3.1.1 Groundwater Level Monitoring

In August 2010, the DME completed an initial, site-wide groundwater level survey of the 43 historic, 'RN' bores that had not been destroyed by previous earthworks or brush fires. This survey involved collecting depth-to-water (DTW) measurements with a water level tape, and then subtracting the DTW from surveyed, top-of-casing elevations to estimate the geodetic groundwater elevation (in m AHD). That August 2010 survey was representative of 'low flow' conditions at the site (during the Dry Season). In December 2010 (after the MB10 bores had been installed), another site-wide groundwater level survey was completed during the so-called 'build up' to the Wet Season.

Since December 2010, the DME has routinely monitored groundwater levels in the 43 historic 'RN' bores, and has incorporated the various MB bores as they have been installed. In 2015, the DME monitored the 43 historic 'RN' bores and 66 additional bores installed over the last five years (see Figure 2-7, and Section 2.6 for further details). Groundwater levels are usually monitored monthly during the dry season, and every two weeks during the wet season (see Figures 3-1 to 3-7 for time trends). Groundwater elevation data for November 2014 (Dry Season) and March 2015 (Wet Season) are presented in Figures 3-8a and 3-8b, respectively.

Seasonally, groundwater levels vary by up to 8 m at higher elevations within the Rum Jungle Mine Site, whereas variations tend to be muted in lowland areas near the East Branch of the Finniss River (and the flooded Main and Intermediate Pits). Further discussion of groundwater level variations (and groundwater quality conditions) within different areas of the site is provided in Sections 3.6 to 3.11.

3.1.2 Groundwater Quality Monitoring

The DME's Environmental Monitoring Unit (EMU) collects water samples twice per year from a selection of monitoring bores (i.e. once in the wet season, and once in the dry season). Prior to sampling, EMU collects manual, depth-to-water measurements, and records the pH, temperature, and electrical conductivity (EC) of groundwater in order to ensure that a representative sample is collected. Water samples are sent to NTEL in Darwin for analysis of major ion and dissolved metal content.

From 2010 to 2015, EMU sampled up to 55 bores during each campaign (i.e. each of the 'MB10' and 'MB12' bores, plus a selection of historic 'RN' bores). The current (2016) program focused on sampling the 'MB14' bores in the Old Tailings Dam area. These bores are being monitored in order to establish pre-rehabilitation, baseline conditions near and within the footprint of the new WSF to the north-east of the Main Pit.

Groundwater quality data collected by the DME since 2010 are provided in Appendix B. Representative, 'wet season' and 'dry season' groundwater quality data (and inferred groundwater elevation contours) are shown in Figures 3-9 to 3-12. These data are further described in Sections 3.6 to 3.11 in order to conceptualize groundwater flow and contaminant transport across the site.

3.2 SURFACE WATER MONITORING

3.2.1 Pit Water Monitoring

Historically, water samples have been collected at different depths in Main and Intermediate Pit in order to characterize the degree of stratification and mixing due to inflows from the East Branch of the Finniss River since 1985 (see Lawton and Overall, 2002a,b). Numerous depth profiling surveys were completed in the 1990s as part of post-rehabilitation monitoring (see Kraatz and Applegate, 1992; Kraatz, 1998), and additional surveys were done more recently in 2008 (see Tropical Water Solutions, 2008) and in 2014 by the DME's EMU.

Since 2010, the DME has also routinely monitored the condition of pit water as it flows from the inlets and outlets of the pits. HAR Resources also routinely collects surface water samples from the east and west sides of the pits as part of their routine monitoring program, and has provided the water quality data to the DME. Pit water levels in the Main and Intermediate Pits are monitored monthly or semi-monthly by the DME. Pit water levels in the Browns Oxide Pit are not routinely monitored, but some data from 2008 to 2011 are available (see RGC, 2012a).

3.2.2 Seepage Monitoring

In April 2009, samples of seepage from the Main WRD and Dysons WRD were collected by the Environmental Research Institute of the Supervising Scientist (ERISS) as part of a preliminary site investigation. RGC then collected samples of seepage from the Main WRD, Intermediate WRD, and Dysons WRD in August 2010 during their initial site visit. Those samples were representative of 'low flow' conditions before the 2010/2011 wet season. Since August 2010, the following seepage samples have been collected:

- Monthly samples of seepage from Dysons WRD and Dysons (backfilled) Pit were collected from January to July 2011 and from February to May 2012. No 'dry season' samples of seepage from Dysons (backfilled) Pit have been collected due to a lack of flow.
- Spot samples of toe seepage from the Main WRD were collected in March 2012, April 2012, and May 2012 near the spot where the drainage channel crosses the main access road (at a station known as at 'MOHSE1'). Another sample was collected from this location in April 2015. Two samples of seepage from the south-west corner of the Main WRD were also collected in April 2015.

- Three samples of seepage from the Intermediate WRD were collected in March 2012. These samples were collected near the northern batter of the Intermediate WRD where seepage accumulates in the EFDC. Some dilution is possible, as the spot where RGC collected a sample of 'basal seepage' in August 2010 was submerged at this time.

Seepage water quality data are provided in Appendix B and discussed further in Section 3.5.

3.2.3 Water Quality Monitoring (East Branch of the Finniss River)

Water quality conditions in the East Branch of the Finniss River are routinely monitored at gauges GS8150200, GS8150327, and GS8150097. Surface water quality data collected since 2010 are provided in Appendix C.

3.3 CONTAMINANTS OF CONCERN

Hydrobiology Inc. developed Locally-Derived Water Quality Objectives (LDWQOs) for the East Branch of the Finniss River in order to ensure the long-term protection of environmental values (see Table 3-1). LDWQOs are defined for several zones along the river. LDWQOs for Zones 2, 3, and 4 are applicable to the East Branch of the Finniss River, whereas LDWQOs for Zone 6 apply to the Finniss River downstream of the confluence between the East Branch of the Finniss River and the West Branch of the Finniss River (at gauge GS8150204).

Table 3-1.

Locally-Derived Water Quality Objectives for EBFR and Finniss River

River Zone	Site/Location	EC µS/cm	SO_4 mg/L	Mg mg/L	Al µg/L	Cu µg/L	Co µg/L	Fe µg/L	Mn µg/L	Ni µg/L	Zn µg/L
East Branch of the Finniss River											
2	Upper EBFR at Dyson's Gauge	2985	1192	86.6	236	60.2	89	300	759	130.4	210.5
2	EBFR at gauge GS8150200	2985	1192	86.6	236	60.2	89	300	795	130.4	210.5
3	EBFR at gauge GS8150327	2985	997	86.6	150	27.5	25.9	300	443	43.1	180
3	EBFR at gauge GS8150097	2985	997	86.6	150	27.5	25.9	300	443	43.1	180
4	EBFR upstream of confluence with Finniss River	427	761	33.2	117	7.9	3.6	300	228	32.5	180
East Branch of the Finniss River											
6	Finniss River at Gauge GS8150204	191	594	33.2	117	3.4	2.8	300	140	20	26.1

See Hydrobiology (2016) for additional details

RGC considers each of the constituents for which LDWQOs have been developed to be a contaminant of potential concern in groundwater. Cu is of particular interest because concentrations of this metal currently exceed LDWQOs for the East Branch of the Finniss River during the wet season (see Hydrobiology, 2016). Other metals, such as Se, may be of interest after rehabilitation is complete but these metals are beyond the scope of this report. Note that SO_4 is discussed here because there is a LDWQO for it, and because RGC considers SO_4 to be a conservative tracer of groundwater movements across the site (and to the East Branch of the Finniss River).

3.4 BACKGROUND WATER QUALITY CONDITIONS

Unimpacted groundwater in the Coomalie Dolostone near the Rum Jungle Mine Site is typically neutral to slightly alkaline (i.e. pH 7 to 8), and characterized by EC values around 500 µS/cm (see Table 3-2 and Tables B-1 and B-2 in Appendix B). Average SO_4 concentrations in unimpacted groundwater are less than 2 mg/L and average Cu concentrations in groundwater range from 0.5 to 1.7 µg/L. Other metals, such as Co, Ni, Pb, and Zn, are also low (i.e. less than 5 µg/L) (see Table 3-2). Fe and Al concentrations are slightly higher by comparison (i.e. up to 200 µg/L), and Mn concentrations at bore RN022085 can reach close to 700 µg/L Mn. These concentrations are considered representative of unimpacted groundwater that resides within the Coomalie Dolostone.

In the Rum Jungle Complex, unimpacted groundwater (at bore RN025168) is characterized by a lower pH (and lower HCO_3 concentrations) than groundwater from the Coomalie Dolostone. These data reflect the lower carbonate content of the Rum Jungle Complex. SO_4 and metal concentrations in groundwater at bore RN025168 are comparable to concentrations in bores RN023140 and RN022085 and are thought to be representative of unimpacted groundwater within the Rum Jungle Complex. There is no information on the composition of unimpacted groundwater in the Geolsec Formation or Whites Formation, but SO_4 and metal concentrations are likely low in both.

Table 3-2.

Background (unimpacted) Groundwater Quality Data for the Coomalie Dolostone and Rum Jungle Complex

	FIELD DATA		LAB DATA			MAJOR IONS (in mg/L)							DISSOLVED METALS (in ug/L)									
Bore ID	pH	EC	pH	Acidity	HCO_3 Alkalinity	HCO_3	SO_4	Cl	Ca	Mg	Na	K	Al	Fe	Cd	Cu	Co	Mn	Ni	Pb	U	Zn
		uS/cm		mg/L	mg/L as CaCO3																	
RN023140 (Dry Season), Coomalie Dolostone																						
No. of samples	8.0	8	6	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8.0	8	8.0
Minimum	7.1	460	7	n/a	177	216	1	3	26	39	2	1	0	2	0.02	0.1	0.1	0.2	0.1	0.0	0.7	0.4
Maximum	8.6	557	8.1	n/a	259	315	4	5	30	46	3	3	10	200	0.20	3.6	0.3	10.5	1.0	0.2	14.2	12.0
Mean	7.5	513	7.6	n/a	212	258	2	3	29	43	3	2	5	63	0.07	1.0	0.2	1.9	0.3	0.1	4.0	2.8
Standard Deviation	0.5	29	0.4	n/a	31	38	1	1	1	2	0	1	3	85	0.08	1.2	0.1	3.5	0.3	0.1	4.5	3.8
80th Percentile	8.1	538	8.1	n/a	251	306	3	5	29	45	3	3	7	200	0.20	2.2	0.3	2.9	0.5	0.1	6.8	4.6
RN023140 (Wet Season), Coomalie Dolostone																						
No. of samples	5.0	5	4	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5.0	5	5.0
Minimum	7.1	472	7.7	n/a	187	228	1	2	25	43	3	1	0	2	0.02	0.1	0.1	1.3	0.1	0.0	0.7	0.7
Maximum	8.0	564	7.9	n/a	236	288	2	5	31	45	3	1	11	200	0.20	5.7	0.2	2.5	0.4	1.1	0.9	2.2
Mean	7.5	513	7.9	n/a	213	260	2	4	28	44	3	1	5	52	0.06	1.7	0.1	1.7	0.2	0.3	0.7	1.3
Standard Deviation	0.5	34	0.1	n/a	21	26	0	1	2	1	0	0	5	83	0.08	2.3	0.1	0.5	0.1	0.5	0.1	0.6
80th Percentile	8.0	555	7.9	n/a	236	287	2	5	31	45	3	1	11	164	0.16	4.9	0.2	2.4	0.3	0.9	0.9	2.1
RN022085 (Dry Season), Coomalie Dolostone																						
No. of samples	8.0	8	7	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Minimum	7.1	366	6.9	n/a	144	176	0.4	2	23	25	2	0.3	1	20	0.02	0.1	0.5	121	0.3	0.0	0.6	2.1
Maximum	8.0	530	7.9	n/a	199	243	2	5	39	34	2	2	120	200	0.20	1.3	6.8	679	4.4	0.7	7.8	5.6
Mean	7.3	420	7.4	n/a	169	206	1	3	30	28	2	1	18	70	0.07	0.6	2.5	295	1.6	0.2	2.8	3.1
Standard Deviation	0.3	56	2.6	n/a	23	29	1	1	6	4	0	1	41	81	0.08	0.5	2.0	176	1.2	0.2	3.0	1.2
80th Percentile	7.6	486	7.8	n/a	197	241	2	3	37	33	2	2	29	200	0.20	1.1	4.0	415	2.3	0.4	7.1	4.1
RN022085 (Wet Season), Coomalie Dolostone																						
No. of samples	3.0	3	3	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Minimum	7.0	484	7.3	n/a	184	224	0.1	2	35	34	2	0	2	20	0.02	0.4	0.6	306	0.2	0.0	1.9	0.5
Maximum	7.3	520	7.5	n/a	197	240	1	2	40	36	2	1	3	20	0.02	0.6	0.7	637	0.4	0.1	4.7	2.1
Mean	7.1	508	7.4	n/a	190	232	0.4	2	37	35	2	0.4	2	20	0.02	0.5	0.7	453	0.3	0.0	3.0	1.4
Standard Deviation	0.2	21	0.1	n/a	7	8	0.3	0.1	3	1	0.1	0.2	1	0.0	0.00	0.1	0.1	169	0.1	0.0	1.5	0.8
80th Percentile	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
RN025168 (Wet Season), Rum Jungle Complex																						
RN025168	6.1	366	-	-	95	116	2	-	0.2	2	-	-	21	200	0.2	4	2	9	2	2.2	0.4	5

3.5 CONTAMINANT SOURCES TO GROUNDWATER

3.5.1 Seepage from the WRDs and Dysons (backfilled) Open Pit

Seepages from the WRDs are acidic (pH < 4.5) and characterized by high concentrations of SO_4 and dissolved metals due to the oxidation of sulphide-containing waste rock. Table 3-3 summarises seepage water quality and some pertinent groundwater quality collected near the WRDs and Dysons (backfilled) Pit since 2009. All of the seepage water quality data collected since 2009 is provided in Tables B-3 and B-4 of Appendix B.

Some key aspects of the seepage water quality data are summarised here:

- Seepage from the Intermediate WRD is characterized by the highest concentrations of SO_4 and dissolved metals (i.e. 13,800 mg/L SO_4 and 34,900 µg/L Cu in August 2010). These high concentrations are consistent with the high sulphide content of the PAF-I and PAF-II waste rock within the Intermediate WRD (see RGC, 2016a).
- SO_4 and metal concentrations in seepage from the Main WRD are typically lower than in seepage from the Intermediate WRD (i.e. 4,000 to 5,000 mg/L SO_4 and ~4,000 µg/L Cu compared to 13,800 mg/L SO_4 in basal seepage from the Intermediate WRD). These lower concentrations are consistent with the overall average moderate sulphide content of waste rock in the Main WRD (it contains all three PAF types plus substantial NAF material). The lower concentrations may also be the result of some dilution of primary seepage by shallow groundwater near the toe of the Main WRD, where seepage is collected from a shallow channel.
- Seepage from Dysons WRD is characterized by 3,000 to 5,000 mg/L SO_4 which is about the same as in seepage from the Main WRD. However, metal concentrations in seepage from Dysons WRD are much lower than in seepage from the Main WRD, which is consistent with the low sulphide (and metals) content of PAF-III (and NAF) waste rock in Dysons WRD. The predominance of PAF-III and NAF waste rock in Dysons WRD is related to the mining of Dysons ore body exclusively for uranium (and not a suite of metals) (see RGC, 2016a).
- Metal concentrations in seepage from Dysons (backfilled) Pit are comparable to those in seepage from the Intermediate WRD. Seepage from Dysons (backfilled) Pit only occurs during the wet season when water levels within the pit rise into the shallow backfill materials that were placed in the pit. High metal concentrations are related to the high copper content of the heap leach material (and contaminated soils) that were placed in Dysons Pit in 1984/1985. RGC (2016a) classifies these materials as PAF-I waste rock. It is therefore suggested that they should be re-located to the Main Pit during rehabilitation in order to reduce future AMD.

Table 3-3.

Seepage and Groundwater Quality near the Existing (Historic) WRDs and Dysons (backfilled) Pit, 2008 to 2014

Location/Sample Type	n	Season	Field pH	Field EC, uS/cm	SO_4, mg/L	Al, ug/L	Fe, ug/L	Cu, ug/L	Co, ug/L	Mn, ug/L	Ni, ug/L	U, ug/L	Zn, ug/L
Main WRD													
Toe seepage (August 2010), NE	1	Dry	3.7	6,000	5,190	12,900	4,800	4,400	5,180	11,100	3,840	568	7,140
Toe seepage (2009 to 2012), NE	3	Wet	3.7	4,780	4,445	10,445	3,505	3,955	4,200	7,290	3,428	86	7,018
Standard Deviation (σ):			0.3	1,690	622	1,871	945	317	748	2,567	435	73	764
Toe seepage (April 2015), SW	1	Wet	4.3	4,390	-	2,310	40	2,610	1,330	1,980	1,150	190	2,430
Toe seepage (April 2015), SW	1	Wet	4.3	5,660	-	3,370	40	1,340	2,450	3,200	2,010	207	4,030
Toe seepage (April 2015), NE	1	Wet	3.7	8,180	-	72,700	310,000	11,300	31,700	41,000	29,600	657	64,200
Intermediate WRD													
Basal seepage (August 2010)	1	Dry	3.3	12,600	13,800	199,000	349,000	34,900	74,700	84,300	64,900	1,840	156,000
Toe seepage (March 2012), Seep 1	1	Wet	3.8	4,192	5,870	20,500	58,100	5,600	21,700	28,600	15,100	228	22,000
Toe seepage (March 2012), Seep 2	1	Wet	3.5	660	5,630	42,800	133,000	7,150	21,200	28,600	16,800	363	32,000
Toe seepage (March 2012), Seep 3	1	Wet	3.7	639	6,290	44,900	165,000	9,660	27,800	35,300	23,800	441	48,700
Bore MB12-30S (February 2014)	1	Wet	4.2	4,731	2,770	22,600	74,900	10,900	12,700	18,100	11,000	167	15,200
Bore MB12-30S (April 2015)	1	Wet	4.4	5,547	3,840	38,000	145,000	17,800	20,000	34,900	16,000	480	29,100
Dyson's WRD													
Toe seepage (April 2009)	1	Dry	2.9	4,851	3,430	154,000	49,000	188	648	10,700	2,100	1,980	265
Toe seepage (August 2010)	1	Dry	3.7	4,520	2,710	87,600	5,800	157	395	5,060	1,240	1,170	175
Toe seepage (2011 to 2012)	9	Wet	4.3	1,481	934	8,654	1,028	2,423	5,699	14,134	4,420	154	195
Standard Deviation (σ):			0.1	475	430	3,752	810	1,672	3,413	8,378	2,523	52	81
Dyson's (backfilled) Open Pit													
Toe seepage (December 2011)	1	Dry	3.8	4,549	2,990	-	-	29,000	22,700	51,500	19,700	1,590	860
Toe seepage (2011 to 2012)	7	Wet	3.6	3,437	2,250	22,350	4,865	29,714	24,014	52,514	19,157	1,321	870
Standard Deviation (σ):			0.3	719	782	9,137	5,152	10,145	8,162	17,265	6,096	468	284
MB10-1b (November 2010)	1	Dry	3.5	4,066	2,720	18,300	400	31,700	24,700	48,000	19,800	1,800	

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

3.5.2 Pit Water

Water quality data for the Main and Intermediate Open Pits in 2010 and 2011 are provided in Table 3-4. Low concentrations of SO_4 and total metals in shallow pit water reflect annual flushing by the East Branch of the Finniss River through the pits. Note that concentrations are higher in the dry season due to evapo-concentration, and that Cu concentrations in the Intermediate Open Pit are higher than in the Main Open Pit. RGC attributes these higher concentrations in the Intermediate Open Pit to inputs from groundwater in the Copper Extraction Pad area.

Table 3-4.

Shallow Pit Water Quality Data, 2010 and 2011

Depth m	Date	pH	EC, uS/cm	SO_4, mg/L	Al, ug/L	Cu, ug/L	Fe, ug/L	Mn, ug/L	Ni, ug/L	Zn, ug/L
Main Open Pit (eastern side)										
0	Aug-10	-	-	64	56	45	420	780	64	22
0	Sep-10	-	-	67	26	32	120	720	59	32
0	Oct-10	-	-	63	9	22	370	550	59	19
0	May-11	-	-	11	130	48	180	290	36	11
0	Aug-11	-	-	29	100	120	34	1,300	100	43
Main Open Pit (western side)										
0	Aug-10	-	-	63	67	47	410	780	62	22
0	Sep-10	-	-	64	34	34	100	720	58	27
0	Oct-10	-	-	63	13	23	120	590	63	20
0	Feb-11	-	-	33	740	1,200	220	460	180	30
Intermediate Open Pit (eastern side)										
0	Aug-10	-	-	65	61	82	210	340	63	28
0	Sep-10	-	-	69	55	76	110	310	55	32
0	Oct-10	-	-	67	25	57	100	260	55	24
0	May-11	-	-	11	140	71	190	210	37	15
0	Aug-11	-	-	32	64	84	97	310	61	21
Intermediate Open Pit (western side)										
0	Aug-10	-	-	63	72	100	290	340	65	24
0	Sep-10	-	-	68	46	70	80	310	54	32
0	Feb-11	-	-	15	30	110	180	410	55	23
0	May-11	-	-	68	120	59	140	270	58	22

Total concentrations

Historic pit water quality, including samples collected at different depths before and after rehabilitation in the 1980s, is provided in Table 3-5 and Table 3-6. Immediately before pit water from the Main Pit was pumped and treated in 1985, pit water was highly-acidic (pH 2.5) and characterized by 8,200 mg/L SO_4 and 55,000 µg/L Cu (see Table 3-5). Pit water from the Intermediate Pit was slightly less acidic by comparison and characterized by lower SO_4 concentrations, but Cu concentrations were comparable to concentrations in the Main Pit (Table 3-6). After pit water from the Main Pit was treated (and the Intermediate Open Pit initially flushed), concentrations in pit water were substantially reduced (and have been further reduced in shallow pit water by annual flushing from the East Branch of the Finniss River.

Untreated water that once characterized the entire water column still appears to reside at the bottom of the Main Pit. In 1990, the top of the highly-impacted layer of untreated water in the Main Pit 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 (see Table 3-5 and Table 3-6).

This trend suggests that a proportion of the contaminated water is being entrained (or “eroded”) each year as the pit is flushed by inflows from the East Branch of the Finniss River. In 2008, the volume of the lens of impacted bottom water in the Main Pit was likely about 100 ML (assuming it was 5 m thick). This volume was estimated 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.

At the bottom of the Intermediate Pit, there is a lens of water that is more impacted than shallow pit water, but it is not characterized by high metals or reduced pH (only elevated EC and SO_4). The absence of highly elevated metals is likely related to (i) the absence of stratification in this pit before pit water was treated, and (ii) the approach to treatment in 1985, which involved induced mixing by aeration from the bottom of the pit (see Allen and Verhoeven, 1986). Shallow pit water in the Intermediate Open Pit does, however, often 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 pit. This is consistent with the groundwater flow field for this area of the site (and previous modelling results) that indicate some groundwater discharge to the pit from upgradient.

Table 3-5.

Historic Pit Water Quality Data (Main Open Pit)

Depth m	Date	pH	EC, uS/cm	SO_4, mg/L	Al, ug/L	Cu, ug/L	Fe, ug/L	Mn, ug/L	Ni, ug/L	Zn, ug/L
Pit water quality for the first 15 years after mining operations ceased (Davey, 1975), total metal concentrations										
0	1959	4.8	-	180	-	3,700,000	-	2,700,000	-	-
50	1959	4.8	-	200	-	4,000	-	2,800	-	-
0	1969	2.7	-	4,750	-	52,000	-	86,000	-	-
0	1970	2.8	-	6,000	-	53,000	-	115,000	-	-
0	1974	2.4	-	5,700	-	56,000	-	150,000	-	-
50	1974	2.2	-	9,200	-	60,000	-	220,000	-	-
Typical water quality immediately prior to rehabilitation (from Mining and Processing Engineering Services report), dissolved metal concentrations										
15	Aug-85	2.5	-	8,200	230,000	55,000	430,000	230,000	14,000	6,000
Pit water quality in 1990 (from Henkel, 1991b), dissolved concentrations										
0	Oct-90	4.6	640	300	-	830	-	4,400	-	240
2	Oct-90	4.8	630	300	-	770	-	4,200	-	220
12	Oct-90	4.7	630	310	-	800	-	4,200	-	230
14	Oct-90	4.6	640	300	-	890	-	4,300	-	220
20	Oct-90	4.6	640	310	-	880	-	4,300	-	220
22	Oct-90	3.0	6,600	4,900	-	22,000	-	120,000	-	4,100
24	Oct-90	3.0	7,900	6,400	-	44,000	-	180,000	-	6,100
26	Oct-90	2.9	8,500	7,600	-	54,000	-	200,000	-	6,400
28	Oct-90	2.9	8,600	7,700	-	55,000	-	210,000	-	6,900
30	Oct-90	2.9	8,600	8,200	-	56,000	-	210,000	-	6,900
Pit water quality in 1991 (from Henkel, 1991b), dissolved metal concentrations										
0	May-91	6.5	170	63	-	130	-	630	-	10
2	May-91	6.0	170	66	-	180	-	640	-	50
12	May-91	6.5	170	65	-	150	-	640	-	40
14	May-91	6.5	170	66	-	70	-	630	-	30
20	May-91	6.0	220	94	-	340	-	1,100	-	30
22	May-91	5.7	240	100	-	460	-	1,300	-	110
24	May-91	4.7	380	260	-	950	-	3,000	-	180
26	May-91	2.9	8,000	6,500	-	46,000	-	184,000	-	6,400
28	May-91	2.9	8,300	7,500	-	57,000	-	220,000	-	6,900
30	May-91	2.9	8,200	7,700	-	59,000	-	240,000	-	6,600
36	May-91	2.9	8,300	7,700	-	61,000	-	230,000	-	7,000
Pit water quality in April 1998 (from Lawton and Overall, 2002), dissolved metal concentrations										
0	Apr-98	6.8	157	61	90	100	460	310	60	40
5	Apr-98	6.5	172	-	130	100	440	340	60	50
10	Apr-98	6.1	110	41	180	100	350	320	60	30
15	Apr-98	5.7	115	-	130	100	190	460	60	40
20	Apr-98	5.4	151	64	130	200	60	740	90	40
25	Apr-98	5.4	171	-	140	200	70	780	80	50
30	Apr-98	4.4	274	137	1,880	800	130	2,450	230	110
31	Apr-98	4.1	458	-	5,200	1,300	210	4,420	370	180
32	Apr-98	3.7	993	-	14,800	3,100	870	17,650	1,010	420
33	Apr-98	3.8	7,168	-	215,000	54,000	378,000	244,000	18,550	5,490
34	Apr-98	3.8	7,478	-	226,000	60,000	404,000	269,000	16,700	7,400
35	Apr-98	3.8	7,558	8,270	236,000	62,000	420,000	254,000	19,000	7,750
Depth profiling in May 2008 (by Tropical Water Solutions Pty Ltd.), dissolved metal concentrations										
0	May-08	-	-	60	112	95	440	50	73	24
5	May-08	-	-	60	163	108	700	50	74	24
30	May-08	-	-	60	172	110	740	50	74	24
36	May-08	-	-	63	214	120	1,000	50	77	26
41	May-08	-	-	7,710	170,000	38,000	851,000	219,000	12,300	6,200
43	May-08	-	-	7,810	107,000	26,000	1,160,000	220,000	10,400	5,200

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

Table 3-6.

Historic Pit Water Quality Data (Intermediate Open Pit)

Depth m	Date	pH	EC, uS/cm	SO_4, mg/L	Al, ug/L	Cu, ug/L	Fe, ug/L	Mn, ug/L	Ni, ug/L	Zn, ug/L
Pit water quality before treatment (Davey, 1975), total metal concentrations										
15	Aug-85	3.5	-	3100	60,000	60,000	2,000	60,000	14,000	7,000
Pit water quality in 1990 (from Henkel, 1991b), dissolved concentrations										
0	Oct-90	4.9	900	460	-	1,200	-	2,100	-	340
1	Oct-90	4.5	900	460	-	1,100	-	2,100	-	320
15	Oct-90	4.7	890	450	-	1,100	-	2,000	-	310
17	Oct-90	4.7	890	460	-	1,100	-	2,000	-	320
21	Oct-90	4.7	890	460	-	1,100	-	2,100	-	320
23	Oct-90	4.7	890	460	-	1,100	-	2,100	-	320
25	Oct-90	4.7	3600	2500	-	730	-	1,700	-	590
27	Oct-90	4.8	3800	2700	-	620	-	1,900	-	640
29	Oct-90	5.2	4000	2800	-	370	-	1,500	-	420
Pit water quality in 1991 (from Henkel, 1991b), dissolved metal concentrations										
0	May-91	6.6	180	71	-	380	-	830	-	70
2	May-91	4.6	190	76	-	420	-	820	-	90
12	May-91	5.9	180	73	-	240	-	830	-	100
14	May-91	6.3	180	73	-	390	-	840	-	40
20	May-91	6.1	190	76	-	380	-	880	-	40
22	May-91	5.5	250	110	-	470	-	1,200	-	70
24	May-91	5.2	380	220	-	540	-	1,500	-	170
26	May-91	5.4	3600	2800	-	550	-	3,600	-	530
28	May-91	6.1	3700	3100	-	170	-	4,400	-	320
30	May-91	6.4	3700	3100	-	150	-	4,300	-	390
Pit water quality in April 1998 (from Lawton and Overall, 2002), dissolved metal concentrations										
0	Apr-98	6.9	143	53	220	200	370	380	110	30
5	Apr-98	6.7	141	-	210	100	380	370	100	30
10	Apr-98	6.5	130	48	210	100	330	370	80	20
15	Apr-98	5.6	124	-	150	200	30	660	90	40
20	Apr-98	5.5	125	51	160	200	20	660	90	40
25	Apr-98	5.4	137	-	160	200	30	720	130	40
30	Apr-98	5.3	161	71	180	300	60	910	150	60
31	Apr-98	5.0	240	-	330	400	60	1,190	190	100
32	Apr-98	4.7	418	-	480	600	60	1,650	300	200
33	Apr-98	4.5	1104	-	1,140	1,100	110	3,540	980	950
34	Apr-98	4.8	2278	-	1,550	1,100	16,050	9,600	1,830	2,010
35	Apr-98	4.7	3478	2410	350	100	25,000	9,750	1,140	740
Depth profiling in May 2008 (by Tropical Water Solutions Pty Ltd.), dissolved metal concentrations										
0	May-08	-	-	45	103	103	160	316	61	19
15	May-08	-	-	45	138	115	220	312	60	18
31	May-08	-	-	101	33	76	60	638	86	48

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

3.5.3 Other Contaminant Sources to Groundwater

From 1965 to 1971, a so-called 'heap leach experiment' was conducted in order to extract Cu from ore mined from the Intermediate deposit. According to Davy (1975), losses of pregnant liquor during the experiment from unlined channels and storage ponds were substantial. Seepage lost during the experiment contained up to 1,200,000 µg/L Cu (see Table 3-7).

Impacts by this seepage (i.e. pregnant liquor) have been identified in several bores within the Copper Extraction Pad area (i.e. MB10-23 and MB12-35, amongst others). This water (and any Cu that adsorbed to the aquifer in the 1970s during the initial exposure period) likely remains a substantial source of contaminants to groundwater downgradient. This impacted groundwater likely reports to the Intermediate Pit, and thereby explains higher Cu concentrations in the Intermediate Pit than in the Main Pit (see Table 3-4, and further discussion in Section 3.5.2).

Table 3-7.

Condition of Seepage Lost to Groundwater during the Heap Leach Experiment, 1964 to 1971

Waste Unit	Sampling Date	pH	EC, uS/cm	SO_4 mg/L	Al, ug/L	Fe, ug/L	Cu, ug/L	Co, ug/L	Mn, ug/L	Ni, ug/L	U, ug/L	Zn, ug/L
Seepage losses during the Copper Heap Leach Experiment, 1964 to 1971												
Acid to sulphide pile	n/a	2.2	-	-	-	3,600,000	150,000	-	-	-	-	-
Liquor from sulphide pile	n/a	1.2	-	-	-	3,000,000	660,000	-	-	-	-	-
Liquor from oxide pile	n/a	1.7	-	-	-	2,800,000	1,200,000	-	-	-	-	-
Barren liquor from launders	n/a	2.1	-	-	-	4,600,000	160,000	-	-	-	-	-
MB10-23 (screened 13 to 25 m bgs in the Coomalie Dolostone)												
MB10-23	23-Dec-10	3.5	6,940	5,190	37,700	13,000	506,000	73,700	143,000	56,400	404	10,500
MB10-23	10-Oct-13	3.9	6,540	4,670	10,200	29,200	488,000	57,500	122,000	43,000	110	7,890
MB10-23	31-Aug-11	3.6	7,120	5,320	27,800	20,500	635,000	71,000	160,000	58,100	325	10,600
MB10-23	20-Oct-14	4.1	4,852	3,810	7,130	37,400	561,000	50,300	124,000	39,900	109	7,190
MB10-23	10-Oct-12	3.9	6,980	5,060	15,700	34,200	661,000	71,200	155,000	53,800	198	9,820
MB10-23	10-Feb-11	3.5	7,200	5,290	35,900	19,800	587,000	71,300	152,000	57,600	371	11,900
MB10-23	28-Feb-12	3.9	9,510	7,670	29,400	47,700	857,000	120,000	237,000	92,600	222	17,000
MB10-23	13-Feb-13	4.0	8,800	7,320	20,500	33,200	758,000	109,000	220,000	83,000	164	15,500
MB10-23	6-Feb-14	4.0	6,190	4,630	14,800	38,200	651,000	69,600	153,000	52,700	173	9,950
MB10-23	24-Apr-15	4.0	7,876	3,510	16,900	36,500	785,000	84,700	178,000	63,500	203	12,000
No. of samples		10	10	10	10	10	10	10	10	10	10	10
Minimum		3.5	4,852	3,510	7,130	13,000	488,000	50,300	122,000	39,900	109	7,190
Maximum		4.1	9,510	7,670	37,700	47,700	857,000	120,000	237,000	92,600	404	17,000
Mean		3.8	7,201	5,247	21,603	30,970	648,900	77,830	164,400	60,060	228	11,235
Standard Deviation		0.2	1,310	1,334	10,576	10,435	121,080	21,567	37,751	16,367	104	3,066
80th Percentile		4.0	8,615	6,920	34,600	38,040	779,600	104,140	211,600	79,100	362	14,800
MB12-35 (screened 22 to 34 m bgs in the Coomalie Dolostone)												
MB12-35	8-Nov-12	4.6	10,390	9,120	5,310	127,000	442,000	116,000	379,000	93,000	23	195,000
MB12-35	8-Oct-13	4.2	10,400	8,180	16,200	89,100	472,000	79,300	272,000	70,300	59	10,600
MB12-35	20-Oct-14	4.4	9,420	8,500	12,500	79,100	511,000	90,000	330,000	80,300	93	11,600
MB12-35	28-Feb-13	4.5	10,820	8,700	9,240	68,320	481,000	96,700	342,000	87,800	41	14,500
MB12-35	21-Feb-14	4.2	9,380	7,470	15,800	92,200	516,000	86,700	310,000	76,500	55	11,100
No. of samples		5	5	5	5	5	5	5	5	5	5	5
Minimum		4.2	9,380	7,470	5,310	68,320	442,000	79,300	272,000	70,300	23	10,600
Maximum		4.6	10,820	9,120	16,200	127,000	516,000	116,000	379,000	93,000	93	195,000
Mean		4.4	10,082	8,394	11,810	91,144	484,400	93,740	326,600	81,580	54	48,560
Standard Deviation		0.2	646	619	4,597	22,119	30,287	13,931	39,532	8,997	26	81,876
80th Percentile		4.5	10,736	9,036	16,120	120,040	515,000	112,140	371,600	91,960	86	158,900

Red numbers indicate that the concentration was below the indicated detection limit

3.6 GROUNDWATER CONDITIONS IN DYSONS AREA

3.6.1 Groundwater Levels and Inferred Flow Field

Groundwater in Dysons Area generally flows in a southerly direction from higher elevations immediately north of Dysons (backfilled) Pit towards the upper East Branch of the Finniss River (see Figures 3-8a,b). Groundwater does not appear the flow west beyond Dysons Area, as the ridge to the west of Dysons (backfilled) Pit appears to be a flow divide. Also of interest is the observation that groundwater does not 'mound' beneath Dysons WRD as it does beneath the Main WRD (see Section 3.7).

Seasonally, groundwater levels in bores screened in bedrock to the west of Dysons (backfilled) Pit fluctuate by up to 6 m (i.e. bores RN022036 and RN023792) (see Figure 3-1). Fluctuations are similar in magnitude at bore DO21, which is screened in shallow backfill and tailings near the centre of Dysons (backfilled) Pit. At bore DO20 (and bore RN023790), water levels fluctuate to a lesser degree (i.e. 2 to 3 m) than at bores RN022036 and RN023792.

Bore DO20 is screened in shallow backfill and tailings in Dysons Pit, and bore RN023790 is screened in bedrock to the south of the backfilled pit. Bore RN023790 is screened in bedrock beneath the surficial drainage channel that runs from the southern batter of Dysons (backfilled) Pit to the upper East Branch of the Finniss River. This channel (which is screened by bore MB10-1b) receives seepage flows from a drain within Dysons (backfilled) Pit.

Further south, groundwater level fluctuations are more subdued in bores screened in alluvium near the upper East Branch of the Finniss River. During the wet season, groundwater levels in this area often rise to near ground surface, indicating groundwater discharge to the river channel from upgradient areas. Conversely, groundwater elevations often drop below the invert elevation of the river, and therefore suggest water losses from the groundwater system by evaporation and plant transpiration.

3.6.2 Groundwater Quality

Seepage from Dysons (backfilled) Pit and Dysons WRD are the two sources of AMD in Dysons Area. Seepage from both sources is acidic (pH 3 to 4), and characterized by high concentrations of SO_4 and dissolved metals (see Table 3-8). Metal concentrations are particularly high in seepage from Dysons (backfilled) Pit. These contaminants originate from contaminated soils and spent heap leach material that was used to backfill the shallow zones of the pit (see Section 3.5.1).

Table 3-8.

Representative Groundwater Quality Data for Selected Bores in Dysons Area

Bore ID	Screened Lithology	Screened Interval, m bgs	Sampling Date	FIELD DATA		MAJOR IONS			DISSOLVED METALS (in ug/L)									
				pH	EC uS/cm	SO_4	Ca	Mg	Al	Fe	Cd	Cu	Co	Mn	Ni	Pb	U	Zn
Dyson's WRD																		
Toe seepage	n/a	n/a	Apr-09	2.9	4,851	3,430	-	-	154,000	49,000		188	648	10,700	2,100		1,980	265
Toe seepage	n/a	n/a	Aug-10	3.7	4,520	2,710	-	-	87,600	5,800		157	395	5,060	1,240		1,170	175
Toe seepage	n/a	n/a	2011 to 2012	4.3	1,481	934	-	-	8,654	1,028		2,423	5,699	14,134	4,420		154	195
Near Dyson's WRD																		
MB10-1a	Saprolite	1.4 to 3.4	Mar-11	5.1	841	1,150	134	216	161	1,000	0.4	78	1,290	5,670	1,290	2.1	48	71
MB10-2	Rum Jungle Complex	12.7 to 18.7	Nov-10	6.8	2,350	1,110	186	134	73	200	0.2	178	1,130	2,760	927	4.0	158	50
RN023413	Laterite	1.3 to 1.8	Oct-11	3.5	2,389	2,730	178	439	54,000	133,000	0.5	679	442	8,450	1,340	65.2	202	201
RN023419	Alluvium	1.2 to 1.7	Apr-09	-	9,860	8,660	299	976	666,000	29,600	-	2,610	2,830	29,700	7,360	-	4,540	815
Dyson's (backfilled) Open Pit																		
Toe seepage	n/a	n/a	Dec-11	3.8	4,549	2,990	-	-	-	-		29,000	22,700	51,500	19,700		1,590	860
Toe seepage	n/a	n/a	2011 to 2012	3.6	3,437	2,250	-	-	22,350	4,865		29,714	24,014	52,514	19,157		1,321	870
Near or within Dyson's (backfilled) Pit																		
DO20	Tailings	16.0 to 19.0	Sep-11	5.2	8,720	6,580	450	1,230	22	435,000	0	0	4,550	56,500	1,460	0	6	124
DO21	Shallow backfill and tailings	14.7 to 17.7	Sep-11	4.7	5,510	3,850	302	679	2,130	145,000	9	3,660	11,400	67,100	8,140	2	622	1,550
MB10-1b	Alluvium	2.2 to 3.7	Mar-11	5.1	782	343	49	56	128	200	0.2	469	312	642	256	2.3	26	32
RN023790	Geolsec Formation	10.0 to 16.0	Sep-10	7.0	996	271	77	73	2	200	0.2	0	-	1	0.3	0.1	2	10
West of Dyson's Area (towards the Main Pit)																		
RN022036	Geolsec Formation	7.0 to 12.0	Sep-10	6.6	416	3	12	41	2	200	0.2	1	-	7	1	0.1	1	40
RN023792	Geolsec Formation	20.0 to 26.0	Sep-10	7.3	463	3	25	40	2	200	0.2	0	-	158	0.1	0.1	2	5
RN023793	Whites Formation	13.2 to 19.2	Sep-10	5.9	1,236	444	5	149	347	400	0.2	4	4	4	6	0.9	0.4	15

Values that are accompanied by a range of dates are average values for that period (see Table 3-3)

Shallow backfill materials in Dysons Pit are unsaturated for most of the year, but they are typically inundated at the onset of the wet season when water levels near and within Dysons Pit rise above the tailings surface (i.e. ~77.5 m AHD near the north-east pit wall). When this occurs, contaminants are flushed from the interior of the pit and highly-contaminated seepage expresses from a toe drain near bore RN023790. From there, seepage flows at surface to the upper East Branch of the Finniss River via a drainage channel that is screened by bore MB10-b. Most of the vegetation near or within this channel has died back, and salts are commonly observed to accumulate in the dry season (after the channel has dried up for the year).

Seepage from Dysons WRD is characterized by similar concentrations of SO_4 as seepage from Dysons (backfilled) Pit, but metal concentrations are much lower by comparison (i.e. ~2,500 µg/L Cu) (Table 3-8). Monitoring bores RN023413 and RN023419 are both impacted primarily by seepage from Dysons WRD. These bores are screened in the alluvial channel of the upper East Branch of the Finniss River. Bore MB10-2 is screened relatively deep (i.e. 12.7 to 18.7 m bgs) in the Rum Jungle Complex near Dysons WRD. 2,350 mg/L SO_4 is a typical concentration for this bore, and suggests that the SO_4 plume that emanates from Dysons WRD extends to at least 15 m bgs (see Figures 3-9a,b).

Cu concentrations at bore MB10-2 are relatively low in comparison to seepage. This suggests that Cu is retarded to some extent in the aquifer, and hence does not penetrate as deep as SO_4 (which is assumed to be transported conservatively in groundwater). No information on the condition of groundwater deeper than 18 m or so in Dysons Area is available. Conceptually though, it is possible that deeper groundwater in Dysons Area is impacted by SO_4 and some, more conservatively-transported metals (e.g. Zn). Cu concentrations in deep groundwater are thought to be low, however, but additional drilling would be needed to confirm this.

Groundwater west of Dysons (backfilled) Pit (at bores RN022036 and RN023792) is not impacted by AMD. These data indicate that the contaminant loads from the mine waste units in Dysons Area report to the East Branch of the Finniss River via shallow groundwater discharge (and that neither Dysons WRD or Dysons Pit are sources of contaminants to the central mining area). This is consistent with the inferred flow field for Dysons Area, which indicates southerly flows towards the Upper East Branch of the Finniss River. Some impacts are observed at bore RN023793 (located west of bore RN023792 towards the Main Open Pit). Impacts to groundwater near RN023793 are likely attributable to some localized mine waste in this area (not from Dysons Area).

3.7 GROUNDWATER CONDITIONS NEAR THE MAIN AND INTERMEDIATE WRDS

The Main WRD is located to the south of the Giant's Reef Fault, and therefore underlain by granites of the Rum Jungle Complex. The Crater Formation is present between the EFDC and the north-west perimeter of the Main WRD. Monitoring bores RN022082S/D are screened directly beneath the Main

WRD whereas numerous other monitoring bores are screened along the perimeter of the WRD towards the Intermediate WRD or towards Fitch Creek (see Figure 2-7 for bore locations).

The Intermediate WRD is underlain by the Rum Jungle Complex, Coomalie Dolostone and Whites Formation. Monitoring bores do not exist within the Intermediate WRD footprint, although several are located to the west, north and south-east. Groundwater levels and inferred flow fields near these WRDs are described in Section 3.7.1, and groundwater quality data are discussed in Section 3.7.2.

3.7.1 Groundwater Levels and Inferred Flow Field

Figures 3-10a,b show the inferred groundwater flow field in the vicinity of the Main and Intermediate WRDs. Groundwater flow generally follows topography, i.e. groundwater moves from the higher elevations in the southern-most portion of the mine lease (near bore RN025166) toward Fitch Creek and the former floodplain of the East Branch of the Finniss River. Pre-mining topography within the WRD footprints, particularly bedrock topography, likely also has a controlling influence on groundwater flow.

Groundwater levels at monitoring bore RN022082D indicate that groundwater mounds beneath the Main WRD throughout the year. This is due to the shallow depth and relatively low K of bedrock underlying the Main WRD and the relatively high recharge rate to groundwater from the WRD compared to the surrounding aquifer. No monitoring bores are located within the footprint of the Intermediate WRD, but groundwater elevations at surrounding monitoring bores do not suggest any mounding beneath this WRD. This may be due to the pre-mining bedrock topography underlying the WRD, as well as the presence of the more permeable Coomalie Dolostone and moderately-permeable Whites Formation beneath the Intermediate WRD.

Groundwater level time trends for bores near the Main WRD are shown in Figures 3-2a to 3-2d. Key findings are summarised as follows:

- Year-round groundwater mounding under the Main WRD in the granitic bedrock is indicated by groundwater elevations observed at monitoring bores RN022082S and RN022082D. The approximately 0.4 m higher heads observed in RN022082D compared to RN022082S indicate an upward gradient. The relatively small change in groundwater elevation from wet season to dry season (approximately 0.5 m) suggests significant seasonal attenuation of recharge within the Main WRD due to high storage capacity of the waste rock.
- A very similar muted seasonal response is observed in monitoring bores RN022411 and RN029993, located along the north-eastern toe of the Main WRD (near Fitch Creek). Here groundwater elevations are near or at surface in the wet season and only decline to slightly more than 1 m below ground surface in the dry season. An aerial photograph from 1952, before the Main WRD existed, suggests the presence of a creek or drainage feature from within the Main WRD footprint to Fitch Creek in this area. This topographical low likely

represents a preferential pathway for seepage from the Main WRD which could maintain near-surface groundwater elevations throughout the year.

- Along the western toe of the Main WRD, monitoring bores RN025172, RN30001 and RN30002 groundwater elevations are also at or near surface during the wet season and showed limited recession during the dry season, suggesting sustained seepage from the Main WRD.
- Significantly higher seasonal variations (up to 5 m) are observed at monitoring bores MB12-31S and RN25170, located at the north-western toe of the Main WRD. Very similar seasonal trends are observed in other monitoring bores located at greater distance from the Main WRD to the west (e.g. RN25165) and east of the Main WRD (e.g. RN22083 RN25168), suggesting that this area is more influenced by natural recharge than seepage from the Main WRD (possibly due to topographic controls).
- The highest seasonal groundwater level variations in the area are observed in more distant monitoring bores RN025167, RN025166, and RN02165 (6-7 m fluctuation). All of these more distant bores are located well outside the influence of the Main WRD and are representative of natural recharge conditions to the local bedrock aquifer.

The seasonal response of groundwater levels in proximity of the Intermediate WRD during the 2010 to 2015 monitoring period is presented on Figure 3-2c and can be summarised as follows:

- Groundwater levels along the upgradient (south-eastern) toe of the Intermediate Dump (at RN025173 and RN022037) varied seasonally by about 3 m. These seasonal hydrographs are characteristic of groundwater levels in the weathered granite of the Rum Jungle Complex in this reach of the Site and do not suggest significant influence by seepage from the Intermediate WRD.
- Monitoring bores MB12-30S and MB12-30D are located upgradient along the EFDC showed smaller seasonal variations of up to approximately 2 m in the deep monitoring bore and 2.5 to 3 m in the shallow monitoring bore. The shallow groundwater may fluctuate more due to more direct recharge or surficial runoff.
- Groundwater levels immediately north of the Intermediate WRD along the EFDC (at monitoring bore MB12-29S screened in laterite) showed a faster response during the onset of the wet season, with up to 4 m water table fluctuation. This well is located in close proximity of an inferred fault (and known seepage area from the Intermediate WRD). Preferential groundwater discharge along a bedrock structure and/or preferential discharge of seepage in this area may explain the rapid groundwater level changes at MB12-29S.
- Groundwater levels further downgradient to the west (RN023060) and north-west (MB10-05 and MB10-06) of the Intermediate WRD varied approximately 1 to 1.5 m between the wet and dry seasons. Groundwater levels in the deeper bore (MB10-6) screened in weathered schist of the Whites Formation (MB10-6) is consistently higher than in the overlying

overburden (MB10-5) indicating an upward gradient and groundwater discharge into the EFDC and/or Intermediate Pit.

3.7.2 Groundwater Quality

A selection of representative groundwater quality data for bores near the Main and Intermediate WRDs is provided in Table 3-9 (see also Figures 3-10a,b). Groundwater beneath the Main WRD (at monitoring bores RN022082S/D) is characterized by very high SO_4 and metals concentrations. Groundwater quality conditions have improved somewhat since the WRD was covered in the mid-1980s due to reduced infiltration and a likely reduction in basal seepage loads to groundwater (RGC, 2011b).

Groundwater east of the Main WRD (at monitoring bore RN022083) is moderately-acidic and characterized by SO_4 concentrations that are higher than in current toe seepage from the Main WRD. These high concentrations suggest that impacts to groundwater may be related to seepage from the Main WRD before initial rehabilitation in 1984/1985 when much higher SO_4 concentrations were observed (i.e. 90,000 to 120,000 µg/L Cu; see Table 3-7). This implies that deep groundwater beneath the Main WRD could be characterized by a stronger, residual SO_4 plume, and that shallow groundwater in the area could be characterized by a weaker SO_4 plume that is sustained by current seepage. This scenario is consistent with high SO_4 concentrations at bore RN022084 (which, like bore RN022083, is screened from 10 to 16 m bgs and characterized by SO_4 concentrations that are higher than in current seepage from the Main WRD) and lower SO_4 concentrations in numerous shallow bores nearby (e.g. bore RN022417).

Cu concentrations in groundwater from bore RN022083 are relatively low. These data suggest that a SO_4 plume emanates beyond bore RN022083 towards Fitch Creek, but that a Cu plume has not yet reached this area due to retardation in the aquifer. On the opposite side of the Main WRD (at bore RN022084), Cu concentrations are much higher (i.e. 15,400 µg/L Cu in February 2011; see Table 3-9). Cu (and SO_4) concentrations are also very high near the north-east toe of the Main WRD (near the spot where the main access road crosses Fitch Creek). High Cu concentrations in this area, and near the south-western toe of the Main WRD, suggest that the majority of Cu loads from the Main WRD report to the shallow aquifer in these two areas (and not to the deep aquifer towards RN022083 or the EFDC to the north of the Main WRD). This is consistent with groundwater flow field near the Main WRD, which suggests groundwater moves away from the Main WRD to the south-west and north-east (see Figures 3-10a,b).

Groundwater further from the Main WRD (at monitoring bores RN022037 and RN025173) is characterized by high SO_4 concentrations, but groundwater is only slightly acidic and metals concentrations are much lower than in groundwater closer to the Main WRD; these data and prevailing hydraulic gradients in this area therefore suggest a north-westerly direction of seepage flow from the Main WRD towards the eastern toe of the Intermediate WRD.

Table 3-9.

Representative Groundwater Quality Data for Selected Bores near the Main WRD

Bore ID	Screened Lithology	Screened Interval, m bgs	Sampling Date	FIELD DATA		MAJOR IONS			DISSOLVED METALS (in ug/L)									
				pH	EC uS/cm	SO_4	Ca	Mg	Al	Fe	Cd	Cu	Co	Mn	Ni	Pb	U	Zn
Main WRD																		
Toe seepage	n/a	n/a	Aug-10	3.7	6,000	5,190			12,900	4,800		4,400	5,180	11,100	3,840		568	7,140
Toe seepage	n/a	n/a	2009 to 2012	3.7	4,780	4,445			10,445	3,505		3,955	4,200	7,290	3,428		86	7,018
Main WRD (East)																		
RN022411	Alluvium	0.3 to 1.5	Apr-09	3.6	5,200	3,430	119	729	20,400	2,800	18	4,190	4,750	13,500	4,150	22	1,010	5,250
RN022417	Rum Jungle Complex (wtr)	0.4 to 2.5	Apr-09	-	4,825	3,230	278	534	47,300	1,800	24	20,100	4,310	5,510	4,800	44	1,420	6,680
RN022082D	Rum Jungle Complex	37.0 to 52.0*	Feb-11	4.0	10,150	7,640	471	1,630	4,710	16,000	22	1,380	3,720	12,800	4,080	3	271	6,610
RN029993	Clay	1.0 to 7.2	Feb-11	5.5	10,230	8,240	266	1,940	1,020	34,400	7	1,680	1,760	22,900	1,240	5	161	1,560
RN022083	Rum Jungle Complex	10.0 to 16.0	Feb-13	6.1	15,560	14,200	317	3,530	136	28	0.6	1,730	32	3,150	24	0.5	9	27
RN025168	Rum Jungle Complex (wtr)	6.5 to 9.5	Apr-09	6.1	37	2	0	2	21	200	0.2	4	2	9	2	2.2	0	5
Main WRD (Southwest)																		
RN022084	Rum Jungle Complex	10 to 16	Feb-11	3.7	11,430	9,090	213	2,100	16,800	4,400	65	15,400	11,500	45,400	8,870	41	3,800	17,100
RN030002	Rum Jungle Complex	1.0 to 8.4	Oct-10	3.8	8,930	8,440	401	1,980	9,860	6,200	63	8,940	6,850	19,800	5,890	51	1,820	15,700
RN029997	Quartz gravels	1.0 to 3.3	Oct-10	5.2	10440	8,880	197	2,160	265	400	8	659	414	10,900	795	5	268	980
RN029999	Quartz gravels	1.0 to 7.8	Oct-10	3.8	2865	1,660	198	282	7,810	-	9	4,570	1,270	3,050	1,060	14	515	2,800
RN030004	Sandstone	1.5 to 2.9	Aug-10	7.2	1760	1,760	122	450	19	200	0.2	2	258	6,390	110	0	97	48
RN025165	Rum Jungle Complex	5.2 to 8.2	Oct-10	6.2	335	98	2	28	18	3,800	-	12	3	337	2	0.7	1	55
Main WRD (Northwest)																		
RN025170	Whites Formation	5.9 to 8.9	Oct-10	7.2	1054	326	7	131	661	400	-	4	2	52	3	2.6	2	35
MB12-31S	Laterite	1.7 to 7.7	Oct-14	7.2	1350	122	19	182	27	20	0.0	73	2	38	3	0.1	192	7
RN022081	Coomalie Dolostone	40.7 to 43.9	Dec-14	7.3	1914	789	110	198	5	558	0.0	1	1	293	1	0.0	29	0.1
RN022039	Coomalie Dolostone	12.0 to 18.0	Feb-14	5.7	72	9	3	4	59	66	0.0	11	1	16	2	0.6	1	16
Main WRD (West)																		
RN022037	Rum Jungle Complex (wtr)	16.0 to 22.0	Aug-10	5.7	5270	5,360	70	1,430	37	200	0.6	181	125	403	81	0.8	47	150
RN025172	Rum Jungle Complex	1.7 to 4.7	Aug-10	6.4	4053	2,960	288	552	15	1,600	1	2	1040	1,650	618	0	49	411
Main WRD (North)																		
RN025169	Laterite	2.8 to 5.8	Feb-13	6.5	416	110	7	41	30	20	0.2	18	2	72	3	0.1	1	6
RN025171	Laterite	2.8 to 5.8	Feb-13	5.7	5460	3,860	105	938	191	1,020	1.6	1,770	733	2,830	644	1.2	3	558
MB10-4	Rum Jungle Complex	9.3 to 15.3	Aug-11	6.8	2435	1,150	98	271	13	20	0.2	7	1	32	1	0.2	15	4

* Below the surface of the Main WRD

Values that are accompanied by a range of dates are average values for that period (see Table 3-3)

Near the Intermediate WRD, AMD impacts to groundwater appear to be confined to the area immediately adjacent to the WRD (see Figures 3-10a,b). This is consistent with the lack of mounding around this WRD (and the rather weak horizontal hydraulic gradients that are related to this absence of mounding). These data suggest the majority of contaminant loads from the Intermediate WRD report to shallow groundwater immediately beneath the WRD and to the seepage face along the EFDC. This is consistent with high SO_4 and metal concentrations in shallow groundwater at bores MB12-30S and RN023057 (near the western toe) (Table 3-10).

Also of interest are low Cu concentrations at bore MB10-30D – this bore is screened in deeper bedrock beneath the Intermediate WRD and shows mainly impacts by SO_4 (i.e. only 100 µg/L Cu). Lower Cu concentrations at this depth suggest that the downward movement of a Cu plume is retarded to some extent by the sorption of Cu to aquifer materials and the lower solubility of Cu at higher pH.

Table 3-10.

Representative Groundwater Quality Data for Selected Bores near the Intermediate WRD

Bore ID	Screened Lithology	Screened Interval, m bgs	Sampling Date	FIELD DATA		MAJOR IONS			DISSOLVED METALS (in ug/L)									
				pH	EC uS/cm	SO_4	Ca	Mg	Al	Fe	Cd	Cu	Co	Mn	Ni	Pb	U	Zn
Intermediate WRD Toe seepage	n/a	n/a	Aug-10	3.3	12,600	13,800			199,000	349,000		34,900	74,700	84,300	64,900		1,840	156,000
Intermediate WRD (North)																		
MB12-30S	Whites Formation/waste rock	1.5 to 7.5	Apr-15	4.4	5,547	3,840	276	669	38,000	145,000	52.0	17,800	20,000	34,900	16,000	5.8	480	29,100
MB12-30D	Whites Formation	12.3 to 18.3	Apr-15	6.2	14,197	11,600	449	2,870	54	5,570	6.0	101	648	1,890	527	0.4	17	1,060
RN023057	Whites Formation (wtr)	1.8 to 2.6	Apr-09	-	4,702	3,280	179	655	8,070	40,800	-	7,150	6020	9,200	7130	-	218	4640
RN023060	Whites Formation (wtr)	4.2 to 5.1	Feb-12	6.5	1,317	525	85	113	28	32	0.2	7	37	760	45	0.1	2	8
MB10-5	Laterite/fill	2.0 to 5.0	Nov-10	6.6	1,358	463	55	106	53	200	1.0	19	997	2,850	749	7.5	15	800
MB10-6	Whites Formation	13.5 to 25.5	Nov-10	7.2	1,952	931	232	126	19	200	0.2	3	1	577	1	30.7		
MB12-25	Whites Formation	12.9 to 18.9	Nov-12	6.5	2,760	1,530	242	273	67	20	0.2	6	2	46	2	0.1	1	13
MB12-29D	Coomalie Dolostone	14.9 to 17.9	Nov-12	7.3	1,882	835	112	147	45	20	0.2	9	12	4,280	25	0.1	12	8
Intermediate WRD (Southeast)																		
RN025173	Rum Jungle Complex	5.1 to 8.1	Aug-10	6.1	4,616	3,800	45	962	232	200	0	40	16	4,170	161	0	3	45
RN022037	Rum Jungle Complex	16.0 to 22.0	Feb-12	6.1	6,840	5,220	78	1,320	86	1,160	1.3	247	280	600	184	0.8	43	186

3.8 GROUNDWATER CONDITIONS NEAR THE FLOODED PITS

3.8.1 Groundwater Levels and Inferred Flow Field

Groundwater flow fields in the central mining area suggest a strong influence by the flooded Main and Intermediate Pits on groundwater levels. Under wet season (high flow) conditions, the Main Pit represents a local discharge zone for groundwater from the north. i.e. groundwater flows from that area into the pit. The Intermediate Pit represents a local discharge zone for groundwater flowing from the south and south-east in the dry season, and from the north-east in the wet season. In the dry season, the Main and Intermediate Pits generally act as sources of recharge to the surrounding aquifer, when groundwater elevations to the north and east of the pits decline below the pit lake elevations.

Near the former Copper Extraction Pad area, groundwater flows westward towards the Intermediate Pit (see Figures 3-11a,b). The fault that hosts mineralization at the site lies between the Main and Intermediate Pits and may represent a preferential pathway for groundwater. Logging at several monitoring bores, including MB10-11, MB12-33 and MB12-35 describe high yields and sands and gravels at depths of approximately 15 m to 32 m below ground surface within Whites Formation, suggesting that the fault was encountered at these locations and that it is in-filled with more permeable (alluvial?) materials. However, the presence of persistently high metal concentrations in groundwater at monitoring bores MB10-10 and MB10-23 suggests that the fault is not significantly more permeable than the surrounding fractured bedrock.

Preferential flow paths due to fracturing and/or chemical dissolution (“karst” features) also characterize groundwater flow within the Coomalie Dolostone (which is intersected by both the Main and Intermediate Pits). Specifically, the northern third of the Intermediate Pit intersects the Coomalie Dolostone whereas this unit is inferred to intersect the southern portion of the Main Pit.

A strong hydraulic connection between the Intermediate Pit and the Coomalie Dolostone was demonstrated by a ‘large-scale’ pumping test conducted in late 2008 by HAR Resources (tenement holders of the Browns Oxide Mine Site).

The groundwater flow field suggests that most impacted groundwater from the central mining area discharges into the Intermediate Pit and mixes with relatively unimpacted pit water under the high flow conditions shown in Figures 3-11a,b. The pit water from the Intermediate Pit then continues westward towards the East Branch of the Finniss River primarily via the pit overflow but also as groundwater along the fault structure and within the more permeable Coomalie Dolostone.

Figures 3-3a to 3-3d illustrate seasonal time trends in groundwater levels and pit water levels for the central mining area near the Main Pit and the Intermediate Pit. The key observations may be summarised as follows:

- Monitoring bores located in proximity of the Main Pit and screened in Whites Formation (e.g. RN22544) show similar seasonal trends as observed in the Main Pit (about 2 m seasonal fluctuations) suggesting good hydraulic connection. In contrast, groundwater in the Coomalie dolostone to the north of the Main Pit (e.g. RN22107) shows significantly larger seasonal fluctuations (up to 6 m), including higher peaks and lower troughs, implying limited hydraulic connection.
- Monitoring bores located in the reach between the two pits (primarily screened in Whites Formation) show very similar seasonal trends as observed in the Main and the Intermediate Pit (about 2 to 2.5 m seasonal fluctuations) suggesting that the bedrock aquifer in this area is well connected to the two pits and controlled by pit water levels.
- Monitoring bores located in immediate proximity of the Intermediate Pit and screened in Coomalie dolostone (e.g. RN022543, MB10-9S/D, and MB10-24) all follow the seasonal water level trends observed in the Intermediate Pit very closely indicating very good hydraulic connection.
- The hydraulic influence of the Intermediate Pit is still clearly evident in monitoring bores MB10-07 and MB10-16, located further north-west of the Intermediate Pit. However, seasonal groundwater level fluctuations are significantly higher in the Coomalie dolostone further upgradient (to the north-east) of the Intermediate Pit (e.g. at MB10-12, MB10-13 and MB10-22), illustrating the diminishing hydraulic influence of the Intermediate pit. The higher seasonal variations are primarily a result of higher peaks during the wet season indicating higher recharge in the Coomalie dolostone to the north than in the central mining area.

3.8.2 Groundwater Quality

Representative groundwater quality data for bores near the flooded Main and Intermediate Pits and near the former Copper Extraction Pad area are summarized in Table 3-11. Groundwater in this area can contain very high Cu concentrations that are related to seepage losses while ore from the Intermediate ore body was heap leached in the 1970s. For instance, groundwater from bore MB12-35 typically contains about 500,000 µg/L Cu in the dry season, and up to 857,000 µg/L Cu during the wet season (see Tables B-31 and B-37 in Appendix B). For comparison, seepage lost to the groundwater system in the 1970s was thought to contain up to 1,200,000 µg/L Cu (see Table 3-7).

Table 3-11.

Representative Groundwater Quality Data for Selected Bores near the Main and Intermediate Open Pits

Bore ID	Screened Lithology	Screened Interval, m bgs	Sampling Date	FIELD DATA		MAJOR IONS			DISSOLVED METALS (in ug/L)									
				pH	EC uS/cm	SO_4	Ca	Mg	Al	Fe	Cd	Cu	Co	Mn	Ni	Pb	U	Zn
Bores neart the Main Pit																		
RN022544	Whites Formation	35.2 to 44.5	22-Sep-10	7.5	3,624	3,880	472	768	22	2,000	0.2	1	145	10,100	30	0.2	325	10
RN022107	Coomalie Dolostone	12.8 to 14.8	1-Oct-13	7.8	2,107	976	117	186	14	724	0.1	0	1	2,230	1	0.1	1	1
Bores near the former Copper Extraction Pad																		
MB12-35	Coomalie Dolostone	22.1 to 34.1	20-Oct-14	4.4	9,420	8,500	407	1,480	12,500	79,100	20	511,000	90,000	330,000	80,300	15	93	11,600
MB10-23	Coomalie Dolostone	13.0 to 25.0	28-Feb-12	3.9	9510	7,670	339	1,150	29,400	47,700	25.6	857,000	120,000	237,000	92,600	9.3	222	17,000
MB10-23	Coomalie Dolostone	13.0 to 25.0	10-Oct-13	3.9	6,540	4,670	228	666	10,200	29,200	20.0	488,000	57,500	122,000	43,000	10.0	110	7,890
MB10-11	Whites F. (sand-filled cavity)	31.5 to 34.5	21-Oct-14	5.4	6,150	5,180	426	951	428	1,490	10.2	77,200	51,100	144,000	42,700	1.0	24	6,870
PB12-33	Whites Formation	14.1 to 32.1	21-Oct-14	5.4	5,600	4,580	337	892	243	946	6.7	63,200	40,200	85,100	25,700	1.4	5	4,920
MB10-24	Coomalie Dolostone	4.0 to 16.0	23-Oct-14	3.5	1,801	1,050	82	147	24,300	560	4.4	52,600	5,180	18,300	5,110	15.4	162	1,370
MB10-10	Whites Formation	16.0 to 32.0	21-Oct-14	6.6	1,881	756	57	260	10	1,800	0.0	6	111	220	19	0.0	85	2
MB10-22	Coomalie Dolostone	12.6 to 24.6	3-Oct-13	7.7	1,619	627	57	161	34	496	0.0	1	2	402	1	0.1	7	4
Bores near the Intermediate Pit (or immediately north)																		
RN022543	Coomalie Dolostone	23.0 to 33.0	29-Oct-14	7.7	2,318	1,340	140	297	7	20	0.2	8	3	81	4	0.1	3	3
MB10-7	Coomalie Dolostone	9.0 to 18.0	24-Oct-14	7.3	2,813	1,450	149	320	25	2	0.0	3	0	2	1	0.1	6	10
MB10-16	Coomalie Dolostone	13.5 to 22.5	16-Dec-10	6.8	4,407	2,580	320	473	30	200	0	0.1	-	594	22	-	3	10
MB10-12	Coomalie Dolostone	12.6 to 24.6	11-Oct-12	7.2	4,172	2,360	299	460	10	10	0.1	5	1	2	1	0.1	6	3
MB10-13	Coomalie Dolostone	48.8 to 60.8	18-Oct-12	7.9	321	20	16	25	19	2	0.0	11	10	28	8	0.2	1	3
Bores near the EFDC (north side)																		
MB12-25	Whites Formation	12.9 to 18.9	29-Oct-14	6.6	2,537	1,570	247	288	6	60	0.2	57	6	64	8	0.1	2	7
MB12-26	Whites Formation	9.0 to 11.0	29-Oct-14	6.4	1,821	973	180	178	2	16	0.0	69	6	98	4	0.0	1	6
MB12-27	Coomalie Dolostone	8.7 to 11.7	30-Oct-14	7.3	1,025	302	67	63	6	92	0.0	15	1	599	1	0.4	33	1
MB12-28	Coomalie Dolostone	9.4 to 15.4	30-Oct-14	6.9	985	337	77	89	4	58	0.0	23	1	194	2	0.0	1	3
Bores west of the Intermediate Pit																		
MB10-9S	Coomalie Dolostone	23.4 to 29.4	28-Oct-14	7.4	434	350	58	78	12	220	0.0	3	19	474	11	0.1	9	3
MB12-34	Coomalie Dolostone	48.7 to 60.7	28-Oct-14	7.2	2,745	1,630	223	328	10	652	0.2	2	32	1,060	34	0	8	5
MB10-9D	Coomalie Dolostone	46.3 to 62.3	28-Oct-14	6.9	4,670	3,270	346	697	18	2,350	0.2	46	393	5,420	144	0.1	316	38
RN023516	Alluvium	3.1 to 3.9	28-Sep-12	5.5	518	197	24	36	10	174	0.5	59	129	552	134	1.3	1	172

Near the Intermediate Open Pit (at bore RN022543), and immediately north of the Intermediate Pit (at bores MB10-7 and MB10-16), groundwater is characterized by elevated SO_4 concentrations, but concentration of Cu and other metals are low. Low Cu and metal concentrations are also observed to the south of the Copper Extraction Pad at bores MB12-25 to MB12-28. These data suggest that groundwater affected by historic seepage losses is confined to the area between the Main and Intermediate Pits. However, the extent of the Cu plume in the CEPA is still not well-delineated due to the absence of bores in the former foot print of the CEPA. In addition, there are few bores deeper than 35 m, so the depth of the Cu plume is not well-defined either.

Groundwater quality at MB10-09S is relatively unimpacted by AMD (i.e. 400 to 500 mg/L SO_4, and low Cu concentrations). Deeper groundwater from monitoring bore MB10-09D is more impacted by comparison, but concentrations of Cu and other metals are still relatively low. At bore MB12-34, which was installed beyond the East Branch of the Finniss River in 2012 (towards the Browns Oxide Pit), groundwater is less impacted that at MB10-9D (i.e. 1500 to 2000 mg/L SO_4, and non-detectable Cu concentrations). Generally speaking, these data suggest that a SO_4 plume affects the area to the west of the Intermediate Open Pit (near the East Branch of the Finniss River), but that a Cu plume remains upgradient.

3.9 GROUNDWATER CONDITIONS NEAR THE BROWNS OXIDE PIT

3.9.1 Groundwater Levels and Inferred Flow Field

Groundwater levels near the Browns Oxide Pit are monitored by HAR Resources and selected data were incorporated into this report. Figure 3-7 shows the time trends of selected monitoring bores in proximity of the Browns Oxide Pit. Groundwater levels at bores TPB4 and TPB5 are known to mimic changes in the pit lake elevation in the Browns Oxide Pit due to strong hydraulic connection between the pit and the surrounding aquifer. In contrast, groundwater levels in the nearby monitoring bore RN023137 (screened in the White’s Formation) showed a much more modest decrease. This much more muted response is inferred to be a result of the greater distance from the pit perimeter and the lower permeability of the local bedrock (Whites Formation).

The strong hydraulic connection between Brown’s Oxide Pit and monitoring bore TPB5 is well demonstrated. The 2012 to 2015 groundwater elevation data provided by HAR (for TPB5) is therefore a suitable proxy for the actual pit lake levels. Note that groundwater levels at TPB5 and more recently installed MB12-34 show similar seasonal trends as observed in the Intermediate Pit and the nearby (impacted) monitoring bore MB10-09D. However, the groundwater levels near the Browns Oxide Pit are consistently lower (by about 1 to 2 m) throughout the year than in the Intermediate Pit indicating the potential for groundwater flow from the Rum Jungle site towards the Brown’s Oxide Pit. Continued dewatering of the Browns Oxide Pit is likely inducing this hydraulic gradient and migration of impacted groundwater to the west.

3.9.2 Groundwater Quality

Groundwater quality data for bores TPB4 and TPB5 suggest that groundwater near the Browns Oxide Pit is unimpacted by ARD. Groundwater from bore TPB4, for instance, contains non-detect levels of SO_4 and background metals concentrations. Bore TPB5 is located east of the Browns Oxide Pit closer to the East Finniss River. As few bores are located in this area, the extent of a SO_4 plume in this area is not well-constrained. Groundwater quality data for bore MB12-34 does, however, suggest some impacts by SO_4 in this area, but few impacts by Cu or other metals (see Section 3.8.2).

3.10 GROUNDWATER CONDITIONS IN THE OLD TAILINGS DAM AREA

3.10.1 Groundwater Levels

The Old Tailings Dam area is characterized by the laterite/saprolite/Coomalie Dolostone profile. The results of the 2014 hydrogeological investigation in this area indicate that the groundwater aquifer in the Coomalie Dolostone is at least partially confined by lower permeability saprolite overlying it (RGC, 2015). During the wet season, an unconfined aquifer forms in the more highly permeable laterite overlying the saprolite and flows horizontally along the top of the saprolite and vertically downward to the Coomalie Dolostone.

Seasonal groundwater fluctuations in the Old Tailings Dam area are essentially unaffected by the Main and Intermediate Pits and respond only to direct recharge, recharge in the uplands to the east and drainage towards the East Finniss River and, to a lesser degree, its tributaries like Old Tailings Creek. Observed groundwater elevations from November 2014 to March 2015 indicate that seasonal groundwater fluctuations are typically in the range of 4 to 7 m with the largest seasonal fluctuations in the eastern portion.

During the monitoring period, a downward hydraulic gradient was typically present at most nested monitoring bore pairs. This is clearly demonstrated at monitoring bores MB14-02S/D, MB17S/D and MB14-20S/D where near-continuous groundwater elevations were recorded from January to April 2015 (see Figures 3-5a to 3-5c). Near Old Tailings Creek, however, this downward gradient is either absent most of the time (monitoring bores MB10-18 and MB10-19) or very weak (MB14-03 and MB14-04), likely due to incision of the saprolite by the creek and/or the upward gradients that occur due to the discharge of groundwater at the creek.

The seasonal response in groundwater levels in the Old Tailings Dam area during the 2010 to 2015 monitoring period are shown on Figures 3-4a to 3-4e and can be summarized as follows:

- Seasonal groundwater levels in the highlands to the east and north east of the Old Tailings Dam area vary up to 8 m between the wet and dry seasons. This area includes monitoring bores RN023304, RN022547, RN022548, MB14-14S/D, MB14-15S/D and MB14-16. At the shallow monitoring bores MB14-06S, MB14-14S groundwater elevations rise close to surface during the wet season.

- Seasonal groundwater levels in the hill slope immediately east of the Old Tailings Dam area fluctuate with less amplitude than in the highlands. Although the 2014 monitoring bores were only monitored during one wet/dry transition, groundwater levels measured at monitoring bores MB14-17S/D, MB14-05S/D, and MB14-13S/D suggest the seasonal fluctuations are in the range of 6 to 7 m
- Seasonal groundwater levels observed at monitoring bores installed in the flood plain of the Old Tailings Dam area and to the west of the Old Tailings Dam area vary in the range of 4 to 6 m. The amplitude of the seasonal fluctuations decreases from east to west north of a line roughly defined by monitoring bores MB14-20S/D and MB10-08S/D, and west of monitoring bores MB14-02/D and MB14-13S/D. The reduced seasonal fluctuations are primarily a result of flooding in this low-lying topography during the wet season (limited water table rises) and/or discharge to the nearby Old Tailings Creek.

3.10.2 Groundwater Quality

Groundwater quality data for bores near the Old Tailings Dam area are summarized in Table 3-12. Groundwater at higher elevations towards the northern site boundary (at bores RN022547 and RN022548) is not impacted by AMD (i.e. 1 to 2 mg/L SO_4, and 1 µg/L Cu). Unimpacted groundwater is also observed to the north of Old Tailings Creek at bore RN023140.

Generally, groundwater throughout the Old Tailings Dam area is characterized by elevated concentrations of SO_4, Cu, and other metals. However, concentrations are relatively low, and likely reflect residual impacts from when tailings covered this area, and some seepage from residual tailings and other mine waste that remains in the area (see Figure 3-12a,b). Low concentrations of Cu, and other metals, are likely related to the presence of Coomalie Dolostone throughout this area of the site. Groundwater in the Coomalie Dolostone is well-buffered by carbonate dissolution, and therefore the concentrations of most metals have been reduced by precipitation of metal hydroxides and/or other pH-controlled processes that affect solute concentrations in groundwater (e.g. adsorption, co-precipitation reactions, etc.).

Bores MB14-17S/D and MB14-20S/D are notable exceptions to this trend, as groundwater from these bores is characterized by at least 1,000 mg/L SO_4 and high concentrations of Cu (i.e. up to 62,600 µg/L Cu) (see Table 3-12). These bores are located within the former mill area to the north of the Main Pit. Contaminated soils and waste rock were identified in this area during the 2014 test pitting program, and these materials are the likely source to groundwater at MB14-17S/D and MB14-20S/D. These materials will be removed during rehabilitation, so local groundwater quality conditions may improve.

Table 3-12.

Representative Groundwater Quality Data for bores in the Old Tailings Dam Area and Further Downstream near the East Branch of the Finniss River

Bore ID	Screened Lithology	Screened Interval, m bgs	Sampling Date	FIELD DATA		MAJOR IONS			DISSOLVED METALS (in ug/L)									
				pH	EC uS/cm	SO_4	Ca	Mg	Al	Fe	Cd	Cu	Co	Mn	Ni	Pb	U	Zn
Bores to the northwest of the Main Pit																		
RN022547	Coomalie Dolostone	17.0 to 23.0	15-Feb-12	6.8	210	1	7	12	19	9,900	0.1	1	3	4,740	2	0.0	6	9
RN022548	Coomalie Dolostone	27.9 to 30.5	16-Feb-12	7.4	840	2	18	39	27	2,580	0.2	1	1	86	1	0.1	5	1
RN023304	Coomalie Dolostone	20.9 to 26.4	1-Mar-12	7.1	1538	579	146	112	29	44	0.2	1	0.1	5	0.1	0.1	1	1
MB14-17S	Fill/Lat./Geolsec Formation	2.1 to 7.1	1-Apr-15	5.1	1949	1,080	127	154	501	50	28.0	62,600	15,800	6,510	11,000	85.2	10,900	8,310
MB14-17D	Geolsec Formation	21.0 to 28.0	1-Apr-15	5.2	2178	1,300	144	204	1,690	20	29.2	52,700	18,400	8,160	11,700	31.6	12,100	8,450
MB14-20S	Saprolite	2.0 to 8.0	31-Mar-15	4.8	2106	1,120	141	172	2,160	60	21.2	33,600	10,500	7,720	6,660	4.1	2,990	6,290
MB14-20D	Coomalie Dolostone	21.0 to 27.0	31-Mar-15	6.1	2387	1,190	167	180	17	10	18.2	8,300	9,550	7,180	5,770	0.3	297	6,050
MB14-05D	Coomalie Dolostone	21.6 to 27.6	21-Apr-15	7.5	570	103	34	40	17	2	0.02	36	1	3	1	0.0	24	2
MB14-06D	Coomalie Dolostone	18.0 to 24.0	2-Apr-15	7.5	328	44	28	19	29	2	0.02	28	0.5	2	1	0.0	22	3
MB14-15D	Geolsec Formation	21.0 to 42.0	1-Apr-15	7.1	1374	446	89	120	36	2	0.1	138	5	181	7	0.2	1,300	7
Bores in the former Old Tailings Dam area																		
MB14-01D	Coomalie Dolostone	25.8 to 31.8	23-Apr-15	7.4	563	109	37	37	20	2	0.02	0.2	0.1	2	0.1	0.3	1	1
MB14-01S	Saprolite	2.0 to 6.5	23-Apr-15	7.4	571	107	39	37	28	2	0.0	1	0.2	4	0.2	0.7	1	1
MB14-02S	Rum Jungle Complex	2.0 to 8.0	2-Apr-15	6.0	288	96	18	17	10	2	1.6	2,040	498	695	550	0.3	29	623
MB14-02D	Coomalie Dolostone	23.1 to 29.1	2-Apr-15	7.2	501	105	28	31	14	2	0.4	369	121	134	142	0.1	22	150
MB14-03	Saprolite	17.8 to 22.8	23-Apr-15	7.4	556	16	36	43	9	2	0.02	38	0.1	5	0.4	0.0	2	1
MB14-04	Saprolite	2.3 to 8.3	23-Apr-15	7.6	540	113	39	32	21	2	0.0	18	0.3	9	1	0.1	5	4
MB10-18	Saprolite/alluvium	2.0 to 8.0	15-Feb-12	7.3	714	104	50	38	14	2	0.0	3	0.1	21	0.2	1.3	1	17
MB10-19	Coomalie Dolostone	12.5 to 24.5	15-Feb-12	7.5	618	81	46	37	17	2	0.0	1	0.0	14	0.1	0.4	1	6
MB14-18	Coomalie Dolostone	11.0 to 17.0	4-Dec-14	7.3	617	19	38	46	17	20	0.2	15	1	6	1	0.1	1	2
MB14-19	Saprolite	2.0 to 6.2	22-Apr-15	7.0	1475	458	98	117	18	2	0.1	156	3	99	5	0.1	59	16
MB14-09	Coomalie Dolostone	10.0 to 16.0	22-Apr-15	6.7	996	329	87	65	12	2	0.1	50	4	2,490	8	0.0	9	10
MB14-08S	Lat./Sap./Coomalie Dolostone	2.0 to 5.0	22-Apr-15	7.2	521	93	30	10	13	2	0.2	79	27	752	69	0.0	6	31
MB14-08D	Coomalie Dolostone	17.5 to 23.5	22-Apr-15	7.2	910	229	58	32	14	2	0.1	45	1	144	4	0.0	37	4
MB14-10	Saprolite	2.2 to 5.2	22-Apr-15	6.7	1055	351	100	66	11	2	0.0	73	1	88	2	0.0	12	9
MB14-13S	Lat./Sap./Coomalie Dolostone	2.0 to 8.0	23-Apr-15	6.3	227	44	14	13	76	48	0.0	28	1	14	4	0.1	1	9
MB14-13D	Coomalie Dolostone	13.0 to 18.0	23-Apr-15	6.9	284	44	23	14	8	2	0.02	20	0.3	4	1	0.0	3	2
MB14-15S	Geolsec Formation	11.0 to 14.0	1-Apr-15	6.1	195	35	4	14	11	4	0.5	533	156	330	107	0.4	726	155
MB14-06S	Siltstone	2.0 to 8.0	2-Apr-15	6.5	225	53	8	17	10	2	0.1	134	5	69	7	0.0	10	64
MB14-16	Laterite/Fill	2.0 to 7.0	23-Apr-15	5.3	94	17	3	5	20	12	1.0	827	171	48	120	0.5	5	340
RN023302	Coomalie Dolostone	9.5 to 12.5	15-Feb-12	7.2	543	1	33	42	12	2	0.0	6	0.1	4	0.4	1.6	1	2
MB10-20	Alluvium	2.9 to 6.9	27-Feb-14	5.4	59	3	1	2	35	1,150	0.02	6	2	33	4	0.2	0.2	8
MB10-21	Rum Jungle Complex	12.0 to 32.0	27-Feb-14	6.9	387	24	22	13	20	2	0.02	7	0.0	1	0.1	0.1	2	12

3.11 GROUNDWATER CONDITIONS DOWNSTREAM NEAR EBFR

3.11.1 Groundwater Levels and Inferred Flow Field

The East Branch of the Finniss River is a groundwater discharge zone for the Old Tailings Dam area, and modestly-impacted groundwater from the east and unimpacted groundwater from the west discharges directly into the river and/or into the underlying alluvial sediments. Groundwater levels at bores screened near the East Branch of the Finniss River are shown in Figure 3-6.

Groundwater levels at bore MB10-21 were only monitored during the 2010/2011 wet season, whereas groundwater levels at bore MB10-20 have been monitored routinely by the DME since 2010. While both were monitored, downward gradients were observed during the early portion of the wet season (from December to mid-February), and then upward gradients were observed during the period of receding flows at the end of the wet season. The upward gradient persisted until the end of the monitoring of monitoring bore MB10-21.

Seasonal variations in groundwater levels in immediate proximity of the East Branch of the Finniss River (a regional discharge zone for groundwater) are significantly lower than observed further from the river (i.e. only 2 m or so between dry and wet season, compared to 3 to 5 m at bores RN23302 and RN23140). Figure 3-6 shows the water level in the EBFR monitored periodically from 2010 to 2015 at the mid-stream gauge station near MB10-20 and MB10-21 not shown in Figure 3-7.

When the groundwater elevations are higher than the river levels, groundwater is discharging to the EBFR. When river levels are higher than groundwater levels, groundwater is being recharged by the EBFR. The available data indicates that the aquifer is recharged by the EBFR during the early part of the wet season while groundwater discharges to the EBFR during the rest of the wet season. For much of the dry season, groundwater is below the EBFR and the river is dry. Based on the available data, it can be inferred that the invert of the EBFR is approximately 52 m AHD at the gauge and therefore there is no flow in the EBFR when river levels near this elevation are reported. As well, some of the river level measurements are clearly in error, such as during December to April 2013 when no rise in river level is recorded.

3.11.2 Groundwater Quality

Detailed water quality surveys conducted in the mid-1990s suggest that the area immediately downstream of gauge GS8150200 is a discharge zone for groundwater (Lawton and Overall, 2002a; RGC, 2011b). This scenario is consistent with comments from Davy (1975) and the local groundwater flow field shown on Figure 3-12. Specifically, modestly-impacted groundwater is thought to discharge from the bedrock aquifer to the eastern side of the EBFR and unimpacted groundwater is thought to discharge to the western side (RGC, 2011b).

At bore MB10-20 (near gauge GS8150327), SO_4 and Cu concentrations are low (and lower still in deeper bedrock screened by MB10-21). These data suggest only minor contaminant loads (if any) bypass the gauge, implying that any load from the mine site is subsumed into the estimated load in the East Branch of the Finniss River. This is consistent with findings from Moliere et al. (2007), wherein loads at GS8150200 and GS8150097 were found to be the same once the flow records for each gauge were properly adjusted.

4 CONCEPTUAL SITE MODEL

4.1 OVERVIEW

A Conceptual Site Model (CSM) is a simplified representation of the essential features of a hydrogeologic system that provides the basis for numerical simulations of groundwater flow. In 2011, RGC developed a conceptual model for the Rum Jungle mine site based on the information available at that time which included (RGC, 2011b).

The CSM for the Rum Jungle mine site is updated herein based on new data that has become available since 2011, including:

- borehole logs for monitoring bores installed in 2014;
- the results of a geophysical investigation conducted in 2015;
- the results of a pumping test conducted in November 2012 in the CMA;
- groundwater level time trends from 2011 to April 2015 (including those observed in more recently installed bores in 2012 and 2014); and
- groundwater and seepage water quality data collected since 2011.

The following sub-sections provide a summary of all the previously available and new data. The CSM is updated where necessary based on the available information.

4.2 MODEL DOMAIN

Figure 4-1 shows the boundaries of the model domain for the Rum Jungle Mine Site. These boundaries enclose an area of approximately 14.1 km^2 or about 20% of the total catchment area of the EBFR at gauge GS8150097. This gauge is located about 6 km downstream of gauge GS8150327, a gauge installed in 2010 that defines the downstream limit of the model boundary.

The boundaries of the model domain (shown in red) were defined by local topographic highs and low-lying drainage features, i.e. cross-boundary flows into the groundwater system are assumed to be negligible. Note that the area west of the East Branch of the Finniss River towards the Browns Oxide Pit is included in the model domain because the development of this mine, and pumping at the pit, may influence the local groundwater flow and contaminant transport on the Rum Jungle mine site.

Some minor groundwater flow may enter the model domain along Fitch Creek and the Upper Branch of the East Finniss River. However, these inflows are assumed to be negligible relative to the overall water balance due to the absence of significant gradients and depth of alluvium.

Similarly, groundwater outflow (“underflow”) leaving the model domain at the downstream boundary along the East Branch of Finniss River (beneath gauge GS8150327) is assumed to be negligible. Instead, it is assumed that all groundwater is forced to discharge into the EBFR at this location due to bedrock outcropping in this area.

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

4.3 LOCAL GEOLOGY

Groundwater flow and contaminant transport at the Rum Jungle mine site occurs predominantly in shallow residual soils derived from local bedrock and underlying moderately to slightly weathered, fractured bedrock. Hydraulic properties and geochemical controls of these geological units differ significantly and, consequently, knowledge of the local geology, including spatial distribution of the different bedrock units within the model domain and their extent of weathering is required to predict groundwater flow and contaminant transport.

As part of this model update, earlier geological interpretations were reconciled with more recent drilling and geophysical field work (RGC, 2015 and 2016b). Figure 4-2 shows an updated map of the surficial bedrock geology of the Rum Jungle mine site (originally prepared by Lally, 2003). A NW-SE geological section through the Brown's oxide project at the Rum Jungle site is shown in Figure 4-3. Rocks of the entire Mount Partridge Group have been folded, faulted and metamorphosed to greenschist facies during the 1880 Ma Barramundi orogeny but the original stratigraphic succession has been preserved (McCready et al., 2004). Brittle failure associated with deformation has produced a number of faults, some of which follow the northeast-southwest structural trend.

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

Additional hydrogeological and geophysical field programs were undertaken in 2014/2015 to better define the upper soil/bedrock profile (RGC, 2015 and 2016b). Figure 4-2 shows the alignment of several geological and geophysical sections completed as part of this work and summarized below.

Figure 4-4 shows the geological cross-section A-A' which runs east-west through the Old Tailings Dam area. The cross-section illustrates the typical profile common to the Old Tailings Dam area of laterite and well developed saprolite (~10m) overlying weathered Coomalie Dolostone. The contact with Coomalie Dolostone and Geolsec Formation contact is visible at the eastern end of the cross-section, showing the Coomalie Dolostone undercutting the Geolsec Formation at monitoring bore MB14-05S/D.

Figure 4-5 shows the geological cross-section B-B’ which extends in a north-easterly direction from the Main Pit in a north-easterly direction up the hill side towards monitoring bores MB14-15S/D and MB14-16. The contact between Whites Formation and Geolsec Formation is inferred to be dipping to the north-east. The Geolsec profile on the hill side shows a relatively thick laterite zone (~5 m) directly overlying highly weathered bedrock. A well-developed saprolite layer (as observed in the dolostone to the west) was not observed in the Geolsec formation. Drilling and test pitting in this area (former plant site) indicated the presence of a thin layer (~1-2 m) of residual mine waste (“fill”).

Geophysical lines using Ground Penetrating Radar (GPR) and Electrical Resistivity Imaging (ERI) techniques were completed in 2015 to evaluate karst features and geological unit boundaries (RGC, 2016b). None of the methods proved successful in identifying karst features (i.e. cavities). However, ERI was able to identify geological boundaries (and associated structures) as well as the water table.

Figures 4-6 to 4-8 show three representative ERI profile plots with cooler colours representing materials with lower resistivity and warmer colours represent materials with higher resistivity. Overlain on the profiles are summary stratigraphic logs of boreholes and test pits at their approximate locations along the alignments.

Resistivity Line 1 (Figure 4-6) runs immediately south of the Main Pit in a generally east-west direction and was intended to investigate the extent of Coomalie Dolostone in this area. It indicates that the Coomalie Dolostone dips under the Geolsec Formation to the east at an angle of approximately 80° and Whites Formation to the west vertically. This is consistent with logging at monitoring bore RN022039 which indicates Geolsec Formation overlying Coomalie Dolostone.

Resistivity Line 3 (Figure 4-7) runs approximately parallel to and south of cross-section A-A’. The geophysical results support the geological interpretation from drilling, showing the Coomalie Dolostone dipping under the Geolsec Formation. The profile in the west comprises laterite/saprolite over weathered Coomalie Dolostone which becomes less weathered with depth. The bottom of the surficial pockets of high resistivity at a number of locations along the profile corresponds well with the groundwater level in the test pits and monitoring bores. The low resistivity response (blue) in the weathered rock layers below is thought to be due to high moisture content, becoming more resistive with less weathering with depth. In the eastern part of Line 3 is Geolsec Formation, with an inferred weathering profile of less than 10 m. The low resistivity response in this unit is attributed to the high iron content in this material.

Resistivity Line 6 is oriented north to south along an approximate line from monitoring bore RN022547 to monitoring bore MB14-15 (Figure 4-8). In general, the upper profile is inferred to comprise laterite/saprolite material with varying moisture content. There was general correlation with the resistivity and groundwater observations in the test pits and monitoring bores, whereby the dry to moist shallow soils showed high resistivity response and saturated soils (below groundwater surface) showed low resistivity response. The bedrock geology is inferred to be mostly Coomalie Dolostone but the ERI response is different to that for this unit elsewhere (lower resistivity). This could potentially be because it has been altered to Tremolite Schist in this area - a product of contact metamorphism. The resistivity survey shows the contact between Whites Formation and tremolite schist (altered Coomalie Dolostone) in the vicinity of monitoring bore MB14-06. In the middle, near test pit TP15-10, a structure is apparent that may be a fold in Whites Formation or a dolostone pinnacle.

During additional surficial mapping conducted in 2015 along the EFDC, Geolsec Formation was observed in the EFDC channel, as well as Coomalie Dolostone and Whites Formation. This information, with the results of the geophysical results south of the Main Pit, was available during model calibration in preliminary form and was used to update the conceptual geological model between the Main WRD and the Main Pit.

4.4 HYDROSTRATIGRAPHIC UNITS

The hydrostratigraphic units at the mine site are divided into unconsolidated (overburden) and consolidated (bedrock) units. The units and sub-units are discussed in detail in the subsections below, including the material hydraulic properties. Figure 4-9 presents a simplified illustration of the hydrostratigraphic units at the mine site as well as ranges of hydraulic conductivities estimated for each. Table 4-1 presents the results of hydraulic testing conducted during the 2010, 2012 and 2014 hydrogeological investigations. Figure 4-10 presents a box and whisker plot of the hydraulic conductivity (K) testing results showing the full range of the data, the geometric mean, and the 25th and 75th percentiles for each sub-unit.

Table 4-1.

Hydraulic Testing Summary

Monitoring Bore ID	Screen Interval (m BGS)	Test Method	Hydraulic Conductivity (m/s)
Laterite		***Geometric Mean =***	***2E-05***
MB10-08S	5 - 14	Slug Test	2E-06
MB14-16	2 - 7	Slug Test	2E-06
MB14-17S	2 - 7	Slug Test	5E-06
MB14-20S	2 - 8	Slug Test	1E-05
2014-TPA-01	4.3	Infiltration Test	2E-04
2014-TPA-02	4.4	Infiltration Test	1E-04
2014-TPA-10	5.5	Infiltration Test	8E-05
Saprolite		***Geometric Mean =***	***2E-06***
MB10-01a	1.4 - 3.4	Slug Test	9E-07
MB10-20	3 - 7	Slug Test	3E-06
MB14-02S	2 - 8	Slug Test	4E-06
MB14-04	2 - 8	Slug Test	7E-07
Whites Formation		***Geometric Mean =***	***3E-06***
MB10-06	13 - 26	Slug Test	4E-05
MB14-14D	24 - 29	Slug Test	8E-07
MB12-35	22 - 34	Pumping Test (DD)	1E-05
		Pumping Test (TR)	3E-06
MB10-10	16 - 32	Slug Test	4E-07
		Pumping Test (DD)	8E-06
		Pumping Test (TR)	6E-06
MB10-11	31 - 34	Pumping Test (DD)	3E-06
		Pumping Test (TR)	2E-06
MB12-33	14 - 32	Pumping Test (TR)	2E-06
Geolsec Formation		***Geometric Mean =***	***2E-07***
MB10-08D	20 - 23	Slug Test	1E-05
MB14-15S	11 - 14	Slug Test	4E-07
MB14-15D	21 - 42	Slug Test	2E-08
MB14-17D	21 - 29	Slug Test	8E-09
Rum Jungle Complex		***Geometric Mean =***	***3E-06***
RN022083	11 - 17	Slug Test	9E-06
RN022084	10 - 16	Slug Test	3E-06
RN023792	20 - 26	Slug Test	1E-05
RN025165	5.2 - 8.2	Slug Test	2E-07
RN025170	5.9 - 8.9	Slug Test	2E-06
RN025173	5.2 - 8.2	Slug Test	4E-06
Coomalie Dolostone		***Geometric Mean =***	***2E-05***
MB10-07	9 - 18	Slug Test	1E-05
MB10-09D	46 - 62	Slug Test	2E-04
MB10-12	13 - 25	Slug Test	3E-06
MB10-13	49 - 61	Slug Test	1E-05
MB10-14	16 - 18	Slug Test	7E-05
MB10-17	20 - 26	Slug Test	5E-04
MB10-22	12 - 24	Slug Test	2E-07
MB14-01D	26 - 32	Slug Test	7E-05
MB14-02D	23 - 29	Slug Test	6E-04
MB14-03	18 - 23	Slug Test	2E-05
MB14-05D	22 - 28	Slug Test	1E-05
MB14-06D	18 - 24	Slug Test	2E-06
MB14-08D	18 - 24	Slug Test	8E-06
MB14-09	10 - 16	Slug Test	2E-03
MB14-13D	13 - 18	Slug Test	5E-05
MB14-18	11 - 17	Slug Test	5E-05
MB14-20D	21 - 27	Slug Test	8E-07

DD = Distance Drawdown

TR = Theis Recovery

4.4.1 Unconsolidated Materials

Unconsolidated materials consist of laterite, saprolite, alluvium and waste materials that have been used as fill or are stored in the WRDs.

- Alluvium is comprised of riverine sands and gravels that occur near the EBFR, including deposits along the EBFR pre-mining channel between the flooded Main and Intermediate Pits. Alluvium deposits up to 9 m thick were observed at monitoring bore MB10-22 in the CMA along the former course of the EBFR, however, alluvial deposits encountered are typically less than 5 m in thickness. Alluvium in the EFDC is assumed to be negligible as it cuts into bedrock and deposits of transported material along the channel are thin and discontinuous. No hydraulic testing is available for alluvium but it is inferred to be relatively high (i.e. $5x10^{-5}$ to $5x10^{-4}$ m/s)
- Laterite (and fill materials) that comprises the shallow soil unit extending through the Old Tailings Dam area to the East Branch of the Finniss River, as well as in parts of the CMA (monitoring bores MB12-25 to MB12-29, inclusive) was encountered at thicknesses of up to 8 m. Slug testing results for monitoring bores screened in laterite and fill indicate K values ranging from 2×10^{-6} m/s to 1×10^{-5} m/s. Infiltration testing conducted during the 2014 geotechnical test pitting program at test pits indicate K values ranging from 8×10^{-5} m/s to 2×10^{-4} m/s. The geometric mean of all available hydraulic testing results for laterite is 2×10^{-5} m/s
- Saprolite soils that underlie the shallow fill and laterite soils in the Old Tailings Dam area were encountered with thicknesses of up to 8 m but are typically in the range of 2 to 5 m thick. Saprolite was not observed overlying the Geolsec or Whites Formations or the Coomalie Dolostone south of the CMA. Saprolite soils are expected to have K values that are lower than the underlying (moderately to slightly) weathered Coomalie Dolostone. Slug testing at monitoring bores screened in saprolite suggest K values ranging from 7×10^{-7} to 4×10^{-6} m/s with a geometric mean of $2x10^{-6}$ m/s.

Soils testing of laterite and saprolite samples collected from the Old Tailings Dam area during a test pitting program in 2014 indicate grain sizes typical of silts and clays which suggest relatively high porosities and low specific yields. However, samples collected during a test pitting program in 2015 indicate coarser laterite of sand and gravel at higher elevations to the east of the Old Tailings Dam area suggesting higher specific yields. S_y values for clays have been estimated by Morris and Johnson (1967) to range from 0% to 6%, with coarser particles increasing S_y to 12%.

Based on the laboratory reported moisture contents of three laterite samples from the Old Tailings Dam area, S_y is estimated to range from 4% to 9% with an average of 7%. The laboratory results for one sample from the highlands indicated a S_y of 11%. Note that these estimates are also based on assumed dry densities and the assumption that the moisture contents represent specific retention (i.e. gravity drained conditions). If they are over-dried due to evaporation, the actual S_y would be lower than estimated. If the soils are not fully drained, the estimates of S_y would be lower than actual.

Based on the estimated range of S_y from laboratory testing and the literature values, an S_y of 5% was assigned to unconsolidated materials with a potential range from 1% to 10%. Specific yield for unconsolidated materials was further refined during model calibration.

Porosity (n) of fined grained soils like clay can be as high as 50% (Heath 1983). The laboratory analyses for coarse and fine laterites suggest a range of porosity from 37% to 39%. However, the effective porosity (n_e) is typically much lower, but higher than the specific yield. Effective porosity for unconsolidated materials was therefore assumed to be twice the highest potential S_y, giving an assumed n_e of 20%.

4.4.2 Bedrock

Initially, the bedrock aquifer at the Rum Jungle mine site was subdivided into the four main bedrock units (see Figure 4-9):

- Rum Jungle Complex (granite)
- Whites Formation (black shale/schist)
- Geolsec Formation (Quartz breccia)
- Coomalie Dolostone (dolostone//tremolite)
- Crater Formation (sandstone)

These bedrock units were further subdivided by the degree of weathering/fracturing which tends to decrease with depth.

As part of the 2010 and 2014, slug testing was conducted at several monitoring bores screened in bedrock to assess hydraulic conductivity. Slug testing was also conducted at historical monitoring bores during the 2010 investigation. During the 2012 investigation, a pumping test was conducted in the CMA and the results were used to assess hydraulic conductivity (K) of bedrock in this area. On the basis of these investigations, the bedrock unit properties are as follows:

- The Rum Jungle Complex is present along the south-eastern side of the Giant's Reef Fault (and hence underlies the Main and Dysons WRDs) and also outcrops at the north-west extreme of the model domain in the vicinity of monitoring bores MB10-20 and MB10-21. The slug testing conducted in the Rum Jungle Complex indicates that the upper-most 30 m is relatively permeable, suggesting weathering and/or fracturing. Slug testing in monitoring bores screened in granitic bedrock of the RJC indicate a K ranging from 2×10^{-7} to 1×10^{-5} m/s with a geometric mean of 3×10^{-6} m/s. Although hydraulic testing results at greater depths are not available, it is assumed that the K of the Rum Jungle Complex decreases significantly with increasing depth (as bedrock becomes less weathered, and hence more competent)

- The Whites Formation hosts the main mineralization at the mine site and hence occurs in the CMA, in Dysons Area, and in the vicinity and west of Brown's Oxide Pit. Slug testing conducted in Whites Formation indicate K ranging from 4×10^{-7} to 4×10^{-5} m/s. K values inferred from a pumping test conducted in the CMA in 2012 range from 2×10^{-6} to $1x10^{-5}$ m/s. The geometric mean of all available hydraulic testing results for this unit is 3×10^{-6} m/s.
- The Geolsec Formation extends from immediately north of the Main WRD eastward to Dysons (backfilled) Pit, wrapping around the CMA and extending northward to the vicinity of monitoring bores MB14-15S/D. Isolated areas of Geolsec Formation are also present underlying the East Branch of the Finniss River to the west of the Old Tailings Dam area and north of the CMA. Slug testing conducted in the Geolsec formation indicates K ranges from 8×10^{-9} to 1×10^{-5} m/s with a geometric mean of 4×10^{-8} m/s[1]. It is assumed that the Geolsec Formation hydraulic conductivity decreases with increasing depth
- Coomalie Dolostone underlies most of the East Branch of the Finniss River downstream of gauge GS8150200 as well as the entire Old Tailings Dam area extending from the CMA beyond Old Tailings Creek. Coomalie Dolostone is also present immediately south of the CMA, extending from the southern perimeter of the Main Pit south-westward beneath the Intermediate WRD and beyond monitoring bore RN022085. Approximately one third to one half of the northern perimeter of the Intermediate Pit cuts into the Coomalie Dolostone while a smaller proportion of the southern perimeter of the Main Pit cuts into it at shallow depth. Slug testing conducted at 13 monitoring bores screened in the Coomalie Dolostone indicate a K ranging from 2×10^{-7} to 2×10^{-3} m/s with a geometric mean of 2×10^{-5} m/s
- Crater Formation has been mapped by Davy (1975) under the north-west corner of Main WRD near the Giant's Reef Fault. It is also mapped along the northern extreme of the Coomalie Dolostone. The Crater Formation was not encountered in any bores and therefore hydraulic testing data is not available. However, it is expected to have a relatively low K compared to the other bedrock formations at the Site

No measurements of storage properties were available for the various bedrock units. Instead, representative storage values had to be assigned based on the literature and experience. Based on our experience at the nearby Woodcutters site, all bedrock units were assigned a specific yield of 0.005 and a specific storage (S_s) of $1x10^{-6}$. Effective porosity is assumed to be 1%, i.e. twice the assumed specific yield.

4.4.3 Waste Rock and Tailings Properties

Waste rock in the waste rock dumps is assumed to have relatively high permeability and specific yield. As well, the vertical anisotropy is expected to be higher than bedrock at the Mine Site. Based

[1] The slug result for monitoring bore MB10-08D is suspect and was excluded to compute the geometric mean.

on earlier modelling results (RGC, 2012a) the waste rock in the Main and Intermediate WRDs was assigned a hydraulic conductivity of $6x10^{-5}$ m/s while the waste rock in Dysons WRD was assigned a conductivity of $6x10^{-6}$ m/s. The vertical anisotropy was assumed to be Kh/Kv=10.

These assumed values are in reasonable agreement with the range of K values estimated for waste rock from Rum Jungle ($5x10^{-7}$ m/s to $1x10^{-5}$ m/s) based on more recent laboratory testing (O'Kane Consultants, pers. Comm.). This laboratory testing also suggested that the specific yield of waste rock could be in the range of 11% to 16% while total porosity ranged from 26% to 30%, depending on the level of compaction.

No hydraulic testing data is available for the tailings backfilled in the Main Pit and Dysons Pit. However, based on experience elsewhere, the tailings can be expected to have a relatively low hydraulic conductivity, in the order of $1x10^{-7}$ to $1x10^{-8}$ m/s, due to the fine grained nature of the tailings. In addition, tailings tend to have some vertical anisotropy (in the order of 5 to 20) due to the placement on a beach.

The tailings in Dysons Pit were discharged from the western pit perimeter, likely resulting in some hydraulic segregation along the beach from west to east. It is therefore likely that the western portion is generally coarser-grained (higher K) then the eastern portion (lower K). Consequently, the tailings in Dysons backfilled Pit were subdivided into a western and eastern portion in the model. The hydraulic properties (K, S_y) of the tailings in each zone were then calibrated using the water table time trends observed in monitoring bores DO20 and DO21.

The tailings in the Main Pit are assumed to have a K value on the order $1x10^{-8}$ m/s and an S_y similar to the fine tailings in the eastern half of Dysons backfilled pit. A vertical anisotropy of 10 is assumed for the backfill tailings at both the Main and Dysons Pits.

4.5 STRUCTURAL CONTROLS ON GROUNDWATER FLOW

4.5.1 Faults

There are several faults cutting across the study area with a south-west to north-east to north-south trend (see Figure 4-2). Some of these faults are connected to the Main and Intermediate Pits and may potentially influence the direction of groundwater flow. The low grade metamorphism associated with the fault zones could also potentially influence the hydraulic properties and groundwater flow (potentially acting as a flow barrier or as a preferred flow path).

A particularly prominent north-east trending fault runs from the area near bore MB10-14 across the former Copper Extraction Pad area to the Intermediate WRD. Very high airlift yields (~50 L/s) encountered during the drilling of monitoring bore MB10-14 (and at bore RN022107) suggests that secondary permeability in this area is very high due to either the presence of a fracture zone near the fault and/or dissolution channels at shallow depth in the Coomalie Dolostone. Note that this fault eventually coincides with the location of the seepage face that characterizes the north-western toe of the Intermediate WRD. It is therefore conceivable that this seepage face is structurally controlled.

The fault that runs between the Main and the Intermediate Pits is thought to represent a preferential pathway for groundwater and hence, impacted groundwater may flow south-west along the fault towards the Intermediate Pit. Note, however, that the presence of carbonaceous, highly-weathered shale of the Whites Formation may limit preferential movement of (highly-contaminated) groundwater in this area to greater depths (say >15-30 m) where the bedrock is less weathered and more competent. The persistence of high copper concentrations in this area after several decades suggests that groundwater flows are not significantly higher than areas outside of this fault zone.

4.5.2 Cavities and Karst Features

During the drilling investigations conducted at the Rum Jungle Mine Site in 2010, 2012 and 2014, several cavities were encountered in the Coomalie Dolostone. The cavities encountered may be related to faults, however, the potential exists that the cavities represent karst formations. Like faults, karst formations can locally influence groundwater flow.

Preferential pathways can exist or form depending on the interconnectivity of karst voids, both horizontally and vertically. Where high interconnectivity of voids exists, relatively high flows to discharge areas (creeks) can occur. Karst voids in the saprolite can also induce flows of nominally perched, shallow groundwater to the deeper, confined aquifer in the underlying Coomalie Dolostone. Preferential pathways due to karst formations can therefore induce rapid migration of tailings impacted groundwater.

During the 2014 hydrogeological investigation, voids generally described as sand filled fractures, were encountered at monitoring bores MB14-02D (screened from 23.1 to 29.1 m bgs) and MB14-09 (screened from 10 to 16 m bgs). K values estimated from hydraulic testing at these monitoring bores were greater than $1x10^{-3}$ m/s, approximately two orders of magnitude higher than the average of all results. The K values for voids encountered during the 2010 investigation at monitoring bores MB10-09D (screened from 46.3 to 62.3 m bgs) and MB10-17 (screened from 20 to 26 m bgs) were lower than the 2014 void results, but still an order of magnitude higher than the geometric mean. Although the continuity of the voids encountered in the aquifer during the hydrogeological investigations is difficult to assess, the effect on hydraulic conductivity and the potential range of depth where they can occur is well demonstrated at these monitoring bores.

Although K values were not shown to be as significantly elevated, voids were encountered at other monitoring bores such as MB14-01D, MB14-07, MB14-11&12, MB10-13, MB10-14 and MB10-19, as well as south of the CMA at monitoring bores MB12-27 and MB12-28. This suggests that karst voids must be expected to be present throughout the Coomalie Dolostone in the study area.

4.6 GROUNDWATER RECHARGE

Because the model domain is defined by topographic highs and lows (i.e. no flow boundaries), cross-boundary groundwater flows into the model domain are considered negligible. Therefore, rainfall is the only external source of recharge to the model domain[2].

Groundwater recharge occurs mainly during the wet season. The amount of precipitation that infiltrates the ground as recharge varies depending on the ground surface (bedrock versus unconsolidated soils), the ground slope, and the rate of precipitation (flooded versus non-flooded conditions).

4.6.1 Recharge by Rainfall to Undisturbed Areas

Previous studies have estimated that only 10% of incident rainfall to natural ground surfaces in humid areas of the Northern Territory recharges the groundwater as the remainder of incident rainfall is lost via evapotranspiration and surface runoff (Aquaterrra, 1999, RGC, 2012a). To estimate site-specific recharge, the water table fluctuation method from Healy and Cook (2002) was applied. This method involves interpreting the water table response to individual precipitation events in order to estimate the percentage of incident precipitation that infiltrates and recharges the aquifer.

Figures 4-11 to 4-13 show observed groundwater elevation trends observed during the 2015 wet season (between February 15 and April 2, 2015) at monitoring bores MB14-02S, MB14-17S and MB14-20S. The groundwater level rise was related to precipitation measured at the Mine Site during the same observation period to estimate recharge. Using an assumed specific yield for laterite and saprolite of 5%, recharge was estimated to range from 19% (MB14-20S) to 30% (MB14-02S) of precipitation with an average of 24%.

The monitoring bores used for this analysis are located in areas of relatively thick overburden (7 m to 13 m). Recharge rates can be expected to be lower in areas where overburden is thin due to the lower capacity of the near surface bedrock to store infiltration before runoff is induced.

4.6.2 Recharge by Rainfall to the WRDs

Infiltration rates into the waste rock dumps are expected to be higher than infiltration to groundwater via natural ground surfaces, in particular prior to initial rehabilitation in the mid-1980s when the waste rock dumps were uncovered. Daniel et al. (1982) estimated that 50 to 60% of annual rainfall percolated through the Main WRD before rehabilitation. Cover placement as part of rehabilitation works in 1984/1985 reportedly reduced infiltration to 5 to 10% of annual rainfall by the late 1990s. However, the covers are known to have eroded over time reducing their effectiveness. In addition,

[2] The only other source of recharge to the groundwater system is recharge from the flooded Main Pit and Intermediate Pit during the wet season when the pit water levels rise temporarily above the surrounding groundwater level.

there is some doubt regarding the reliability of the lysimeter data interpreted in historic reports (Taylor et al., 2003; Phillip and O'Kane, 2006).

Based on previous investigations and preliminary contaminant load estimates from RGC (2011b), a net infiltration rate of 25% of incident rainfall was estimated for the Main and Intermediate WRDs. A net infiltration of 50% of incident rainfall was estimated for Dysons WRD because the cover placed on this dump during rehabilitation works in the mid-1980s was reportedly of lower quality and did not cover the entire dump surface area.

4.6.3 Recharge from the Flooded Pits

Groundwater flow into and out of the Main and Intermediate Pits occurs throughout the year. However, during the dry season when groundwater elevations in the Coomalie Dolostone to the north of the pits decline below the pit lake elevations, both pits become net sources of recharge to the aquifer. The Intermediate Pit cuts into the highly permeable Coomalie Dolostone along its northern perimeter and is therefore expected to be a potentially higher source for groundwater recharge than the Main Pit which is generally surrounded by the less permeable Whites Formation.

4.7 EVAPOTRANSPIRATION AND SOIL MOISTURE DEFICIT

Evapotranspiration will remove water from the shallow groundwater system using two different mechanisms: (i) evaporation from water bodies (e.g. flooded open pits or saturated soils where the groundwater table reaches the ground surface) and (ii) transpiration by vegetation which extracts groundwater from the root zone.

Using a regional analysis, mean annual lake evaporation at the Rum Jungle mine site has been estimated is approximately 2,000 mm (5.5 mm/d) and the mean annual actual evapotranspiration is approximately 1,050 mm (2.9 mm/d) (see section 2.4.2).

Evaporation from the flooded pit lakes has an influence on the groundwater flow system during the dry season when the pit lakes do not receive any recharge (from direct precipitation of the Upper EBFR or the surrounding aquifer) and lake evaporation draws down the pit lake elevation.

Based on the lake elevation data for the Main and Intermediate Pits for the dry seasons of 2011 to 2014, an average rate of decline of 5.3 mm/d for the Main Pit and 6.6 mm/d for the Intermediate Pit is calculated. These seasonal declines are in reasonable agreement with the estimated potential lake evaporation rate of 5.5 mm/d for the Mine Site[3].

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[3] The greater rate of seasonal decline in pit lake elevation in the Intermediate Pit vis-à-vis the Main Pit (delta= 1.3 mm/d) is significant and is inferred to be indicative of higher net seepage losses from the Intermediate Pit to the surrounding bedrock aquifer, in particular the high-K dolostone to the north. The observed incremental decline in pit lake elevation (1.3 mm/d) represents a net seepage flow out of the Intermediate Pit of approximately 0.5 L/s.

Evaporation from the pit lakes was not modelled explicitly in the groundwater model. Instead, the observed decline in pit lake elevations was modelled implicitly by assigning seasonally varying pit lake elevations to the constant heads representing the flooded pits.

Of particular interest in this groundwater study is the rate of actual evapotranspiration from woodlands (primarily eucalyptus trees) which can represent a significant source of groundwater extraction during the dry season. Ecological studies in the study area support the above estimates of actual evapotranspiration. A study conducted by the Department of Lands, Planning and Environment (DLPE, 2000), reported evapotranspiration rates of 7 mm/d for the Berry Creek catchment and 5 mm/d in adjacent catchments. At Howard Springs, approximately 35 km south-east of Darwin, Hutley et al (2000) determined an average evapotranspiration rate of 2.6 mm/d. At a site near Darwin, O'Grady et al. (1999) concluded that due to groundwater exploitation by tree roots, transpiration rates were higher during the dry season than during the wet season.

In the conceptual model, evapotranspiration losses are treated differently in the dry season and the wet season. During the wet season, evapotranspiration losses from the shallow groundwater system are offset by recharge of precipitation. The temporal discretization of the model (monthly time steps) does not warrant an explicit simulation of those highly transient near-surface processes. Instead, evapotranspiration losses are implicitly accounted for by reducing the recharge to groundwater from actual precipitation rates observed during model calibration (see above).

During the dry season, evapotranspiration is assumed to be active in areas of dense vegetation of the Rum Jungle mine site, typically located in low-lying flood plains where groundwater levels tend to be near-surface for extended periods into the dry season (for example in the upper EBFR near Dysons WRD). For the conceptual site model, evapotranspiration is therefore only considered for densely vegetated areas (based on 2010 aerial photography) during the dry season (during months of no recharge).

The conceptual site model assumes a potential range of evapotranspiration rates of 1 to 7 mm/d with an average rate of 2 mm/d and an extinction depth of 4 m. These evaporation parameters were later modified as part of model calibration.

During the dry season, evapotranspiration tends to dry the surficial soils below the drainable porosity (or S_y) typically reached by gravity drainage alone resulting in a soil moisture deficit (SMD). Due to this deficit, a portion of the initial precipitation at the beginning of the wet season is required to "wet up" the soil before the aquifer responds, i.e. before the soils re-saturate and the groundwater table rises.

The amount of SMD can be expected to vary depending on local soil conditions and preceding dry season conditions. For the nearby Woodcutters mine site, Aquaterra (1999) had estimated that up to 200 mm of precipitation could be required to wet up the surficial soils at the start of the wet season. Based on a review of detailed water level responses observed at monitoring bore RN022081 during the 2010/2011 wet season the SMD for the Rum Jungle Mine Site was estimated to be a minimum of 102 mm.

For the conceptual site model, the SMD to be applied at the start of the wet season was initially assumed to range from 100 to 200 mm depending on preceding climate conditions. These initial estimates of SMD are subject to further model calibration.

4.8 GROUNDWATER FLOW REGIME

4.8.1 Inferred Groundwater Flow Field

Groundwater at the Mine Site flows from upland areas to lower elevation areas that correspond to the current course of the East Branch of the Finniss River and its pre-mining course in the central mining area. During the wet season, groundwater discharges to numerous smaller tributary creeks to the EBFR such as Fitch Creek, Wandering Creek and Old Tailings Creek, as well as unnamed creeks and man-made drainage features. During the dry season all drainages dry up and groundwater levels typically fall below the creek inverts. While groundwater flow may still converge along major drainage lines (e.g. EBFR) groundwater flow may pass beneath smaller drainage lines (e.g. the EFDC) to other, more downgradient discharge areas (e.g. the Intermediate Pit).

In general, downward hydraulic gradients are observed in upland areas during the wet season when high precipitation events recharge the shallow, more permeable laterite soils overlying less permeable saprolite and/or weathered/fractured bedrock. Throughout the wet season, these shallow soils remain saturated and act as preferred shallow flow paths towards the nearest drainage line or creek. At the same time, strong downward gradients provide recharge through the less-permeable saprolite into the moderately to highly permeable fractured bedrock.

Detailed monitoring of nested monitoring bores near the EBFR and Old Tailings Creek indicate upward gradients from shallow bedrock to surficial soils (alluvium and/or laterite) throughout most of the late wet season and subsequent dry season. These upward gradients represent groundwater discharge to the EBFR and Old Tailings Creek when groundwater elevations reach the inverts of the creeks. Such upward gradients are characteristic of local and regional groundwater discharge zones typically observed in the flood plains of larger creeks and rivers.

However, downward gradients have been observed during the onset of the wet season (typically November, December and January) both in the Old Tailings Creek area (e.g. at MB10-18 and MB10-19) and near the EBFR (at MB10-20 and MB10-21 during the 2010/2011 wet season (see Figure 3-4e and Figure 3-6, respectively). These downward gradients early in the wet season are inferred to be caused by a faster response in the shallow soils (relative to deeper bedrock) due to (i) direct precipitation, (ii) preferential shallow recharge from the side hills (in more permeable laterite and/or alluvium) and/or (iii) surface runoff from the upstream catchment during precipitation events.

Along most of the EFDC reach, upward gradients are observed between the bedrock and the overlying saprolite year-round. The EFDC is cut into bedrock and does not have underlying alluvial soils and therefore groundwater flow from upstream along the channel does not occur. As well, the EFDC does not carry flow from upstream during the early wet season. Hence, downward gradients do not occur along the EFDC.

Groundwater flow within the study area is also affected by the Main, Intermediate and Dyson WRDs. Preferential infiltration into the WRDs and hence above-average recharge to the underlying aquifer can result in local groundwater mounding. Monitoring beneath the Main WRD suggests groundwater is mounding up to 2 m above natural ground surface beneath the Main WRD.

Monitoring bores are not present within the footprints of the Intermediate or the Dyson WRD. However, the presence of toe seepage along the toes of these WRDs suggests that groundwater is mounded (or perched) beneath these WRDs, at least during the wet season. Of particular interest is the presence of a well-defined seepage face which discharges highly impacted seepage from the Intermediate WRD directly into the EFDC. Monitoring of groundwater levels at nested monitoring bores MB12-30S and MB12-30D, located in immediate proximity of this seepage face, shows downward gradients year-round (contrary to other reaches along the EFDC). These year-round downward gradients suggest year-round seepage from the foot print of the Intermediate WRD some of which recharges the deeper bedrock aquifer.

Groundwater mounding beneath the foot print of the WRDs can result in radial flow, as observed near the Main WRD. This flow pattern will result in divergent flow of impacted groundwater (radially away from the WRD perimeter) and will enhance spreading of contaminants from the foot print of the WRDs in the groundwater system. Radial flow is not evident near the Intermediate WRD, possibly due to the higher permeability of the underlying bedrock units (Whites and Coomalie Dolostone).

In the vicinity of the Main, Intermediate and Dysons WRDs, the amplitude of seasonal groundwater fluctuations observed at nearby monitoring bores are less than at distant monitoring bores in undisturbed areas of the Mine Site. The groundwater levels recorded at monitoring bores RN022082S and RN022082D, screened directly beneath the Main WRD, show the least seasonal fluctuation observed anywhere at the Mine Site. An increase in the amplitude of seasonal fluctuations with distance from the Main and Intermediate WRDs is observable. This suggests that WRDs have relatively high storage, which will dampen the high recharge during the wet season and will continue to release seepage held in storage within the WRD throughout most of the dry season (as evidenced by toe seepage year-round).

4.8.2 Influence of Main and Intermediate Pits

The Main and Intermediate Pits cut deeply into the bedrock aquifer in the CMA and therefore have a potential to interact significantly with groundwater in adjacent zones of the bedrock aquifer. During active mining (and de-watering), both pits represented major sinks for groundwater and the bedrock aquifer in the CMA likely featured a significant cone of depression. However, the Main and Intermediate Pits have been flooded now for 40 to 50 years and groundwater levels have reached post-mining steady-state conditions. Note that a cone of depression may, however, still characterize the area near the Browns Oxide Open Pit as it is actively de-watered.

The Main and Intermediate Pits have a strong influence on the groundwater flow field which can act as sources or sinks for groundwater depending on the pit water level and water levels in the surrounding aquifer. A comparison of the Main and Intermediate Pit water levels to groundwater levels in the surrounding aquifer (see Figure 3-7 and Figures 3-8a,b) suggest that the Main and Intermediate Pits tend to receive flows of groundwater during the wet season but act primarily as sources of water to the groundwater system during the dry season. Higher flows from the Intermediate Pit than the Main Pit are expected due its strong hydraulic connection to the Coomalie Dolostone and the partial backfilling of the Main Pit with low-K tailings which has likely sealed the deeper pit walls from the surrounding bedrock aquifer.

The pit lakes also have an effect of dampening the seasonal fluctuation of groundwater elevations throughout the CMA. While seasonal fluctuations in levels in undisturbed areas distant from the pits vary on the order of 5 m or more, fluctuations are limited to less than 3 m in the CMA.

4.8.3 Influence of Browns Oxide Pit

The Browns Oxide Open Pit is the shallowest of the three open pits (< 30 m deep) but it is expected to interact significantly with the groundwater system at the Rum Jungle Mine Site because it is actively de-watered by HAR Resources. As a result, the Browns Oxide Open Pit represents a local sink for groundwater (see Coffey, 2006) and likely induces a more south-westerly flow of groundwater west of the Intermediate Pit near the East Branch of the Finniss River. Note that information on the groundwater system in proximity of the Browns Oxide Open Pit is generally more limited with monitoring data for several monitoring bores only available for a brief observation period in 2011 and for only one monitoring bore available on a monthly basis from January 2012 to March 2015.

4.8.4 Groundwater Discharge to the East Branch of the Finniss River

The East Branch of the Finniss River is the primary discharge point for surface water and groundwater in the model domain. All surface drainages within the domain, whether natural or anthropogenic, ultimately report to the EBFR.

Flow in the EBFR can be broken into four key periods:

- Build Up (November/December)
- Wet Season (January through April)
- Receding Flows (May/June)
- Dry Season (July to October)

Flow rates in the EBFR downstream of the CMA are measured at gauges GS8150200 (near the road bridge) and at Gauge GS8150327 located approximately 700 m downstream of the confluence of Old Tailings Creek and the EBFR. The difference between flow rates measured at the two gauges at any time provides an estimate of the flow of groundwater and surface water (drainages tributary to the EBFR and overland flow) into the EFBR between the gauges. The area draining into the gauged reach of the EBFR includes the Old Tailings Dam area immediately north of the CMA, the area west of the EBFR and south of Brown's Oxide Pit, and the watershed of an unnamed creek downstream of the confluence of Old Tailings Creek.

The model domain includes all drainage features flowing into the EBFR with the exception of the unnamed creek downstream of Old Tailings Creek. Assuming similar precipitation patterns, the unnamed creek watershed contributes approximately 43% of the flow in the gauged reach of the EBFR, based on the area of the watershed. The remaining flows are assumed to represent both surface runoff and groundwater flows from the model domain.

To provide a calibration target for groundwater flows, it was assumed that groundwater flow represents between 10% and 25% of average monthly discharge observed in EBFR. Figure 4-14 shows the estimated upper and lower bounds for groundwater flows to the EBFR based on stream gauging data from May 2011 to June 2014.

4.9 CONCEPTUAL GROUNDWATER BUDGET

4.9.1 Approach and Assumptions

As an initial assessment of the water balance for the domain defined for the numerical model, inflows and outflows were estimated for the major hydrogeological features at the Site. These include the Main, Intermediate and Brown's Pits, the upstream and downstream reaches of the East Branch of the Finniss River, the East Finniss Diversion Channel, Fitch Creek and recharge.

The flows in and out of the pits and the river reaches were estimated using simple Darcy calculations based on weighted hydraulic conductivities, typical wet and dry season hydraulic gradients in the vicinity of the features, and assumed aquifer thicknesses. The hydraulic conductivities were weighted using typical material thicknesses and the ranges of hydraulic conductivities estimated from hydraulic testing conducted during the field studies. Additional allowance was made for lithological changes along a given reach, such as the Geolsec Formation and Crater Formation adjacent to the downstream reach of the EBFR.

Aquifer thickness was assumed to be 45 m in all cases with the exception of the EFDC where an aquifer thickness of 15 m was assumed. Essentially, it was assumed that all groundwater in the aquifer from both sides of the river channel would discharge to the river. In the case of the EFDC, groundwater discharge was assumed to originate from the south side only.

For recharge on natural terrain, the available literature and field testing indicates a range of 10% to 30% of incident precipitation throughout most of the Site. Based on previous analysis, recharge at the Main, Intermediate and Dyson WRDs likely ranges from 25% to 50% of incident precipitation. Although it is known that the recharge rate varies across the Site depending on several factors (eg overburden thickness and slope) this simplified analysis assumed a uniform recharge for both the upper and lower bounds shown in Table 4-2.

Evapotranspiration is accounted for to some extent in the use of net recharge. However, for areas of relatively dense forest throughout the Mine Site, including reaches of the EFDC, the upstream and downstream EBFR, parts of Fitch Creek and Old Tailings Creek, it is likely that transpiration by the deeply rooted trees is an additional significant outflow for the Site during the dry season. It has been included in the analysis assuming a potential range of 1 mm/d to 7 mm/d.

4.9.2 Estimated Flows

The results of the initial conceptual groundwater budget are presented in Table 4-2. Results suggest that recharge by rainfall is by far the dominant inflow. In general, the primary outflow boundary for the model domain is discharge to surface drainage including reaches of the EBFR and Fitch Creek. The actual outflow via evapotranspiration, and specifically transpiration, depends on the area of the model domain where it is significant.

The inflow and outflow estimates for the Main Pit suggest a net inflow (out of the model domain) of approximately 1 L/s while estimates for the Intermediate Pit suggest a net outflow (into the model domain) up to 4 L/s.

Table 4-2.

Conceptual Groundwater Budget for the Rum Jungle Mine Site

Component	Flow (L/s)		Comment
	Lower Bound	Upper Bound	
Inflows			
Recharge by rainfall (undisturbed areas)	54	163	Assuming 1307 mm rainfall and percentage recharge ranging from 10% to 30%
Recharge by rainfall (mine waste units)	4.7	10	Assuming 1307 mm rainfall and 25 to 50% recharge to mine waste units
Flows from the Main Pit	0.4	4	Assuming dry season gradients, 45 m aquifer thickness, and K = 1E-6 to 1E-5 m/s
From the Intermediate Pit	0.7	11	Assuming dry season gradients, 45 m aquifer thickness, and K = 1E-5 to 9E-5 m/s
Total:	60	188	
Outflows			
Evapotranspiration	6.0	44	Assumed range of 1 mm/d to 7 mm/d, 6 months of the year, all significantly treed areas
To the Main Pit	1.0	5	Assuming wet season gradients, 45 m aquifer thickness, and K = 2E-6 to 1E-5 m/s
To the Intermediate Pit	0.4	2	Assuming wet season gradients, 45 m aquifer thickness, and K = 2E-6 to 1E-5 m/s
To the Browns Oxide Pit	10	25	Best judgement from previous model results and preliminary water level surveys
To the upper EBFR	6.0	27	Assuming wet season gradients, 45 m thick aquifer, and K = 2E-6 to 1E-5 m/s
To Fitch Creek	2.4	12	Assuming wet season gradients, 45 m thick aquifer, and K = 2E-6 to 1E-5 m/s
To the EFDC	2.4	12	Assuming wet season gradients, 15 m thick aquifer, and K = 2E-6 to 1E-5 m/s
To the EBFR d/s of gauge GS8150200	12	57	Assuming wet season gradients, 45 m thick aquifer, and K = 2E-5 to 9E-5 m/s
Total:	41	184	

Note 1: Flows to the flooded Pits and tributaries of the East Branch of the Finniss River were estimated via Darcy flow calculations

Note 2: Net rainfall is mean annual rainfall minus soil moisture deficit of 150 mm/yr

4.10 CONTAMINANT TRANSPORT IN GROUNDWATER

4.10.1 Contaminants of Concern (COC)

Hydrobiology Inc. developed LDWQOs for the East Branch of the Finniss River (see Section 3.3). Cu is of particular interest for this report because concentrations currently exceed LDWQOs for the East Branch of the Finniss River during the wet season (see Hydrobiology, 2015). SO_4 is also discussed here in order to establish conservative transport rates in groundwater (and because there is a LDWQO for it).

4.10.2 Background Groundwater Quality

Unimpacted groundwater at the Rum Jungle Mine Site is typically neutral to slightly alkaline (pH 7 to 8), and characterized by low concentrations of SO_4 (<5 mg/L) and dissolved metals (i.e. less than 5 µg/L) (see Section 3.4). Unimpacted groundwater occurs mainly in peripheral areas near the lease boundaries as groundwater in Dysons Area, near the Main and Intermediate WRDs, the central mining area, and the Old Tailings Dam area is variably-impacted by AMD.

4.10.3 Geochemical Controls on Solute Transport in Groundwater

In the sub-surface, RGC assumes that SO_4 behaves conservatively in groundwater. This implies that SO_4 is not removed or retarded in groundwater by geochemical reactions or adsorption, and is therefore transported at a rate that is equivalent to the linear velocity of groundwater. Locally, this assumption may not be valid due to the precipitation of secondary minerals, such as Fe- and/or Al hydroxide sulphates. However, at the regional scale of the transient flow model, these changes in SO_4 concentrations are likely small, and would not affect the overall conclusions drawn from the solute transport modelling.

Dissolved metals, such as Cu, cannot be assumed to behave conservatively in groundwater because their mobility is often hindered by geochemical reactions along a flow path. Of particular interest is the reduced mobility (and hence slower rate of transport) that is caused by metals adsorbing to aquifer materials or precipitating to form secondary minerals. These mechanisms are often pH dependent, and not only retard the movement of metals in groundwater, but also provide a future source of metals to groundwater if the metals are eventually released by desorption or if they begin to dissolve.

For Cu, groundwater and soil chemistry strongly influence the speciation of Cu (and, in turn, how it behaves along a flowpath). For instance, in aerobic, alkaline systems, $CuCO_3$ is the dominant, soluble copper species. The cupric ion (Cu^{2+}), and hydroxide complexes, i.e. $CuOH^+$ and $Cu(OH)_2$, are also common under these conditions. Each of these copper species can form strong complexes with humic acids, and the affinity of Cu for these acids increases as pH increases. Moreover, Cu adsorption to hydrous iron oxides that precipitate from groundwater also increases at higher pH.

Together, these factors explain the high retardation factors that are often assigned to Cu under near-neutral-to-alkaline conditions.

According to RGC (2016a), the concentrations of metals in leachate from waste rock samples from the WRDs at the Rum Jungle Mine Site are likely controlled by the solubilities of hydroxide and carbonate phases in waste rock, and by the adsorption of metal ions to both the primary bulk solid phases (e.g. chlorite, muscovite) and to secondary, precipitated Fe and Al hydroxide phases. These controlling processes (solubility and adsorption) are a function of pH, with the extent of metal precipitation and metal adsorption typically increasing as the pH increases from an acidic initial condition, to near-neutral or alkaline pH conditions (i.e. along a ‘pH adsorption edge’).

Adsorption is likely to be the more important process at lower metal concentrations (i.e. in groundwater, as opposed to seepage), and when the pH of pore water initially increases from a more acidic starting value (near areas where AMD is released to groundwater). The latter typically occurs over a 1 to 2 unit pH range for the types of alumino-silicate phases that dominate the mineralogy of the wastes at the Rum Jungle Mine Site (see RGC, 2016a). The exact range of pH values that defines the ‘pH adsorption edge’, which reflects range of processes that act to remove metals from pore water at a site or in a WRD.

Regardless, the key finding is that Cu will be removed from groundwater (and would reside on aquifer materials until it desorbs, or becomes irreversibly adsorbed by ageing). This is consistent with observed groundwater quality impacts at the Rum Jungle Mine Site, which show that Cu concentrations are very high in groundwater near the WRDs, but are much lower (if not absent) from groundwater downgradient (see below).

Figures 4-15a and 4-15b show the inferred spatial extent of sulphate and copper, respectively. Note that Cu concentrations are particularly high near the Main WRD due to the low buffering capacity of the underlying Rum Jungle Complex. Groundwater affected by seepage from the Main WRD generally moves eastward towards Fitch Creek or westward towards the Intermediate WRD 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 with some bypass in deeper bedrock towards the Intermediate Pit.

In Dysons Area, highly-impacted groundwater resides in the shallow bedrock aquifer near Dysons WRD and south of Dysons (backfilled) Pit and ultimately discharges to the upper East Branch of the Finniss River. 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 SO_4 concentrations characterize groundwater north of the central mine reach but metal concentrations in this area are low. This suggests that metals are naturally attenuated in groundwater due to the high buffering capacity of the Coomalie Dolostone and the low solubility of most metals under near-neutral pH conditions. Major ions, such as 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).

Not represented in the conceptual contaminant plumes are preferential flow paths along karst channels and cavities that could accommodate higher contaminant concentrations (and loads) in groundwater due to less surface area/attenuation capacity.

4.10.4 Estimated Contaminant Loads in the East Branch of the Finniss River

RGC estimated contaminant loads in the East Branch of the Finniss River from 2010 to 2015 in order to constrain a conceptual contaminant load balance for groundwater and the East Branch of the Finniss River (see Section 4.9.2). Estimated contaminant loads at gauges GS8150200, GS8150327, and GS8150097 are summarized in Tables 4-3 to 4-6. Historic loads compiled from previous reports, including Davy (1975), Moliere et al. (2007), and Allen and Verhoeven (1986), are provided for comparison. Further description of how contaminant loads from 2010 to 2015 were estimated, and some key findings are provided below.

For the five wet seasons since 2010, RGC estimated the loads of SO_4, Cu, and Zn at each gauge using instantaneous flow measurements[4] and a database of surface water quality data provided by the DME. Flows at each gauge are not measured at a consistent frequency (i.e. not every 15 minutes, for instance), and there are comparatively few water samples collected during the periods of interest (i.e. hundreds of samples from 2010 to 2015, compared to many thousands of flow measurements). RGC therefore computed daily flows for each gauge and then used a regression analysis to patch the historic concentration record.

[4] Loads at gauge GS8150327 for the 2010/2011 wet season (i.e. July 1st, 2010, to June 30th, 2011) couldn't be estimated because this gauge was installed in late 2010 (so the flow record is incomplete for that year).

Table 4-3.

Estimated Contaminant Loads in the East Branch of the Finniss River at Gauge GS8150200

Wet Season	Rainfall, mm/yr	Flow, BL/yr	Flow-Weighted [SO_4], mg/L	SO_4 Load, t/yr	Flow-Weighted [Cu], µg/L		Estimated Copper Loads, t/yr		Flow-Weighted [Zn], µg/L		Zinc (Zn) Load, t/yr	
					Total	Dissolved	Total	Dissolved	Total	Dissolved	Total	Dissolved
Post-Rehabilitation Conditions, 1993 to 1998, from Moliere et al. (2007)												
1993/1994	1,367	22	100	2,201	528	202	11.6	4.4	302	58	6.6	1.3
1994/1995	1,580	28	111	3,114	363	215	10.2	6.0	335	315	9.4	8.8
1995/1996	996	10	162	1,616	629	169	6.3	1.7	423	340	4.2	3.4
1996/1997	1,716	67	73	4,884	240	110	16.1	7.4	125	101	8.4	6.8
1997/1998	1,688	42	101	4,237	365	90	15.3	3.8	230	131	9.7	5.5
No. of years	5	5	5	5	5	5	5	5	5	5	5	5
Minimum	996	10	73	1,616	240	90	6.3	1.7	125	58	4.2	1.3
Maximum	1,716	67	162	4,884	629	215	16.1	7.4	423	340	9.7	8.8
Mean	1,469	34	109	3,210	425	157	11.9	4.7	283	189	7.7	5.2
Standard Deviation	298	22	32	1,362	153	55	4.0	2.2	112	129	2.3	2.9
80th Percentile	1,710	62	152	4,755	608	212	16.0	7.1	405	335	9.6	8.4
Current Conditions, 2010 to 2015 (RGC estimates)												
2010/2011	2,759	69	33	2,287	33	-	2.3	-	41	-	2.9	-
2011/2012	1,593	24	45	1,057	45	-	1.1	-	65	-	1.6	-
2012/2013	1,113	15	66	1,014	66	-	1.0	-	108	-	1.7	-
2013/2014	1,806	39	40	1,581	40	-	1.6	-	57	-	2.2	-
2014/2015	1,142	20	57	1,115	57	-	1.1	-	88	-	1.7	-
No. of years	5	5	5	5	5	-	5	-	5	-	5	-
Minimum	1,113	15	33	1,014	33	-	1.0	-	41	-	1.6	-
Maximum	2,759	69	66	2,287	66	-	2.3	-	108	-	2.9	-
Mean	1,683	33	48	1,411	48	-	1.4	-	72	-	2.0	-
Standard Deviation	671	22	13	540	13	-	0.5	-	26	-	0.6	-
80th Percentile	2,568	63	64	2,146	64	-	2.1	-	104	-	2.8	-

Table 4-4.

Estimated Contaminant Loads in the East Branch of the Finniss River at gauge GS8150327

Wet Season	Annual Rainfall, mm	Flow, BL/yr	Flow-Weighted [SO_4], mg/L	SO_4 Load, t/yr	Flow-Weighted [Cu], µg/L		Estimated Copper Loads, t/yr		Flow-Weighted [Zn], µg/L		Zinc (Zn) Load, t/yr	
					Total	Dissolved	Total	Dissolved	Total	Dissolved	Total	Dissolved
2010/2011	2,759	-	-	-	-	-	-	-	-	-	-	-
2011/2012	1,593	31	72	2,204	88	-	2.7	-	58	-	1.8	-
2012/2013	1,113	22	90	1,949	67	-	1.4	-	68	-	1.5	-
2013/2014	1,806	46	54	2,462	94	-	4.3	-	53	-	2.4	-
2014/2015	1,142	23	83	1,886	70	-	1.6	-	65	-	1.5	-
No. of years	5	4	4	4	4	-	4	-	4	-	4	-
Minimum	1,113	22	54	1,886	67	-	1.4	-	53	-	1.5	-
Maximum	2,759	46	90	2,462	94	-	4.3	-	68	-	2.4	-
Mean	1,683	30	75	2,125	80	-	2.5	-	61	-	1.8	-
Standard Deviation	671	17	36	977	38	-	1.6	-	28	-	0.9	-
80th Percentile	2,568	46	90	2,462	94	-	4.3	-	68	-	2.4	-

Table 4-5.

Estimated Contaminant Loads in the East Branch of the Finniss River at Gauge GS8150097 (Before Initial Rehabilitation)

Wet Season	Rainfall, mm/yr	Flow, BL/yr	Flow-Weighted [SO_4], mg/L	SO_4 Load, t/yr	Flow-Weighted [Cu], µg/L		Estimated Copper Loads, t/yr		Flow-Weighted [Zn], µg/L		Zinc (Zn) Load, t/yr	
					Total	Dissolved	Total	Dissolved	Total	Dissolved	Total	Dissolved
Conditions Prior to Rehabilitation, 1971 to 1984, from NT DME's 1986 Final Rehabilitation Report												
1969/1970	896	7	471	3,300	6,286	-	44	-	-	-	-	-
1970/1971	1,611	33	364	12,000	2,333	-	77	-	727	-	24	-
1971/1972	1,542	31	213	6,600	1,645	-	51	-	613	-	19	-
1972/1973	1,545	26	212	5,500	1,731	-	45	-	615	-	16	-
1973/1974	2,000	-	-	8,700	-	-	95	-	-	-	30	-
1982/1983	1,121	10	-	-	2,421	-	23	-	526	-	5	-
No. of years	6	5	-	5	-	-	6	-	-	-	5	-
Minimum	896	7	-	3,300	-	-	23	-	-	-	5	-
Maximum	2,000	33	-	12,000	-	-	95	-	-	-	30	-
Mean	1,453	21	-	7,220	-	-	56	-	-	-	19	-
Standard Deviation	390	14	-	4,176	-	-	26	-	-	-	11	-
80th Percentile	1,844	33	-	11,340	-	-	88	-	-	-	29	-

Table 4-6.

Estimated Contaminant Loads in the East Branch of the Finniss River at Gauge GS8150097 (After Initial Rehabilitation)

Wet Season	Rainfall, mm/yr	Flow, GL/yr	Flow-Weighted [SO_4], mg/L	SO_4 Load, t/yr	Flow-Weighted [Cu], µg/L		Estimated Copper Loads, t/yr		Flow-Weighted [Zn], µg/L		Zinc (Zn) Load, t/yr	
					Total	Dissolved	Total	Dissolved	Total	Dissolved	Total	Dissolved
Post-Rehabilitation Conditions, 1993 to 1998, from Moliere et al. (2007)												
1983/1984	1,704	48	-	-	583	-	28	-	188	-	9	-
1984/1985	1,112	12	-	-	769	-	9.0	-	342	-	4.0	-
1985/1986	910	11	-	-	351	-	4.0	-	263	-	3.0	-
1986/1987	1,222	13	217	2,870	424	424	5.6	5.6	205	205	2.7	2.7
1987/1988	1,064	6	195	1,230	508	508	3.2	3.2	317	317	2.0	2.0
1988/1989	1,600	35	113	3,940	154	154	5.4	5.4	126	126	4.4	4.4
1989/1990	900	3	245	760	581	581	1.8	1.8	516	516	1.6	1.6
1990/1991	1,590	41	99	4,000	368	74	14.9	3.0	183	148	7.4	6.0
1991/1992	1,002	7	177	1,260	535	394	3.8	2.8	380	366	2.7	2.6
1993/1994	1,367	24	93	2,242	519	187	12.5	4.5	219	179	5.2	4.3
1994/1995	1,580	33	89	2,946	316	134	10.4	4.4	173	149	5.7	4.9
1995/1996	996	9	148	1,332	328	189	2.9	1.7	335	282	3.0	2.5
1996/1997	1,716	89	50	4,451	134	48	11.9	4.3	86	69	7.7	6.2
1997/1998	1,688	45	102	4,575	261	91	11.7	4.1	144	123	6.5	5.5
1998/1999	1,888	53	69	3,682	154	26	8.2	1.4	103	71	5.5	3.8
1999/2000	1,712	46	66	3,023	22	22	1.0	1.0	99	18	4.5	0.8
No. of years	16	16	13	13	16	13	16	13	16	13	16	13
Minimum	900	3	50	760	22	22	1.0	1.0	86	18	1.6	0.8
Maximum	1,888	89	245	4,575	769	581	28.0	5.6	516	516	9.0	6.2
Mean	1,378	30	128	2,793	375	218	8.4	3.3	230	198	4.7	3.6
Standard Deviation	342	23	76	1,632	201	193	6.8	1.9	120	148	2.2	2.1
80th Percentile	1,709	47	200	4,090	562	441	12.2	4.7	339	327	7.0	5.6
Current Conditions, 2010 to 2015 (RGC estimates)												
2010/2011	2,759	115	36	4,173	61	49	7.0	5.6	37	27	4.3	3.2
2011/2012	1,593	35	47	1,656	61	42	2.1	1.5	43	34	1.5	1.2
2012/2013	1,113	18	69	1,236	61	30	1.1	0.5	56	47	1.0	0.8
2013/2014	1,806	53	43	2,280	61	43	3.3	2.3	41	32	2.2	1.7
2014/2015	1,142	25	59	1,481	63	33	1.6	0.8	51	42	1.3	1.1
No. of years	5	5	5	5	5	5	5	5	5	5	5	5
Minimum	1,113	18	18	1,236	61	30	1.1	0.5	37.3	27.4	1.0	0.8
Maximum	2,759	115	115	4,173	63	49	7.0	5.6	55.7	47.4	4.3	3.2
Mean	1,683	49	49	2,165	61	39	3.0	2.1	45.8	36.6	2.1	1.6
Standard Deviation	671	39	39	1,187	1	8	2.4	2.0	7.5	8.2	1.3	0.9
80th Percentile	2,568	103	103	3,795	63	47	6.2	4.9	54.8	46.4	3.9	2.9

No quantitative assessment of the error associated with load estimates was made, as loads are intended to be comparative (and average loads for several years were used to calibrate RGC's conceptual load balance).

For interest, RGC estimated total and dissolved Cu and Zn loads at gauge GS8150097, but only estimated total loads at gauges GS8150200 or GS8150327. Dissolved loads at gauge GS81050200 are, however, available for five years in the 1990s when loads were being estimated by the DME as part of routine monitoring (see Table 4-3). Total Cu loads in the East Branch of the Finniss River are typically much higher than dissolved Cu loads. RGC attributes higher total Cu loads to the contribution of particulate Cu loads in the total load estimate.

Total Cu (and Zn) loads are interpreted throughout this report because it is assumed that particulate loads (and dissolved loads) both originate from WRD seepage or seepage from Dysons (backfilled) Pit (i.e. particulate matter is thought to be mainly solid precipitates that form when seepage enters the river). These precipitates form in the river where seepage enters the river, or they accumulate in the river channel during the dry season and are re-suspended under higher flow conditions. Note that total and dissolved Zn loads are similar to one another because the solubility of Zn is less sensitive to pH changes than Cu solubility is, so fewer precipitates that contain Zn form in the river, or adjacent to it in the dry season.

Key findings from a review of contaminants loads in the East Branch of the Finniss River are summarized here:

- **Before initial rehabilitation, 1969 to 1983**. The average Cu load in the East Branch of the Finniss River at gauge GS8150097 was 56 t Cu/year and the average Zn load was 19 t Zn/year. The average annual SO_4 load for this period was 7,220 t SO_4/year (see Table 4-5). No information on loads upstream of this gauge is available for this time period because neither gauge GS8150200 nor GS8150327 had been built. Davy (1975) suggests that the majority of the load in the East Branch of the Finniss River 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. Seepage from the ore stockpile in the Copper Extraction Pad area contributed substantial loads to groundwater, but these loads did not report to the East Branch of the River (see Section 4.9.2 for further details).
- **After initial rehabilitation, 1984 to 2000.** Rehabilitation works were begun in 1984, and completed by mid-1985. Rehabilitation primarily involved (i) the re-location of tailings from the Old Tailings Dam area, (ii) treatment of pit water in the Main Pit (and flushing the Intermediate Pit), and (ii) re-shaping and covering the WRDs to reduce rainfall infiltration (see Allen and Verhoeven, 1986). SO_4, Cu, and Zn loads at GS8150097 were substantially reduced by rehabilitation (i.e. the average Cu load in the river after rehabilitation was 85%

lower than the average, pre-rehabilitation Cu load of 56 t Cu/year). SO_4 and Zn loads after rehabilitation were reduced by about 60% and 75%, respectively (see Table 4-6).

- **Current Conditions, 2010 to 2015.** The average SO_4 and Cu loads in the East Branch of the Finniss River at gauge GS8150097 are estimated to be 2,165 t SO_4/year and 3.0 t Cu/year, respectively (see Table 4-6). The annual Zn load for this period is 2.1 t Zn/year. Upstream at gauge GS8150327, average loads of 2,125 t SO_4/year and 2.5 t Cu/year were estimated for the five years since 2010 (see Table 4-4). For comparison, only 1,411 t SO_4/year (and 1.4 t Cu/year) was estimated for gauge GS8150200 over this period (see Table 4-3). Gauge GS8150200 is located immediately downstream of the zone where the East Branch of the Finniss River is thought to be poorly-mixed (with inflowing water from Intermediate Pit). Moreover, this gauge is located upstream of the Old Tailings Dam area, so it does not capture additional loads of SO_4 that report to the river via groundwater.

Further discussion of current and historic contaminant loads in the East Branch of the Finniss River is provided in Section 4.8.2, wherein conceptual load balance for pre-rehabilitation conditions and conditions since 2010 are developed.

4.10.5 Conceptual Contaminant Load Balance Model

RGC developed a conceptual contaminant load balance model in order to explain contaminant loads to the East Branch of the Finniss River before and after initial rehabilitation in 1984/1985. The contaminant load balance model for pre-rehabilitation conditions was calibrated to average load estimates from 1969 to 1984, whereas the load balance for current conditions was calibrated to estimated loads from 2010 to 2015.

Prior to rehabilitation, Davy (1975) identified the following sources of AMD to groundwater and the East Branch of the Finniss River:

- Seepage from the Main WRD.
- Seepage from the Intermediate WRD.
- Seepage from the Dysons WRD.
- Seepage from the Dysons (backfilled) Pit.
- Flows from the flooded Main Pit
- Flows from the flooded Intermediate Pit
- Flows from the flooded Dysons Pit

Water quality data for these historic sources are summarized in Table 4-7. These data were compiled from historic reports, including Davy (1975), and various monitoring reports issued by the DME. Recent seepage monitoring data, and pertinent groundwater quality data, are included for reference.

Table 4-7.

Current and Historic Sources of AMD to Groundwater and the East Branch of the Finniss River

Waste Unit	Sampling Date	pH	EC, uS/cm	SO_4 mg/L	Al, ug/L	Fe, ug/L	Cu, ug/L	Co, ug/L	Mn, ug/L	Ni, ug/L	U, ug/L	Zn, ug/L
Pit water quality immediately before treatment/site rehabilitation (samples from 15 m below pit lake surface)												
Main Pit	Aug-85	2.5	-	8,200	230,000	430,000	55,000		230,000	14,000		6,000
Intermediate Pit	Aug-85	3.5	-	3,100	60,000	2,000	60,000		60,000	14,000		7,000
Toe seepage along the eastern toe of the Main WRD (near Fitch Creek)												
Toe seepage (S1)	19-Mar-74	3.6	-	-	-	-	95,000	-	28,000	-	-	40,000
Toe seepage (S2)	19-Mar-74	3.4	-	-	-	-	114,000	-	56,000	-	-	133,000
Toe seepage (S5)	19-Mar-74	3.5	-	-	-	-	118,000	-	43,000	-	-	51,000
Toe seepage (S5)	7-Mar-74	3.4	-	-	-	-	110,000	-	36,000	-	-	45,000
Toe seepage (S4)	7-Mar-74	3.6	-	-	-	-	90,000	-	34,000	-	-	35,000
Toe seepage (S4)	19-Mar-74	3.5	-	-	-	-	93,000	-	32,000	-	-	36,000
Toe seepage	6-Aug-10	3.7	6,000	5,190	12,900	4,800	4,400	5,180	11,100	3,840	568	7,140
Toe seepage	26-Apr-12	3.8	4,579	3,830	8,870	3,080	3,650	3,510	5,670	2,950	473	6,400
Toe seepage	21-May-12	3.3	2,213	4,050	9,110	3,540	3,880	3,740	6,530	3,170	466	6,480
Shallow bore (< 1 m) in Fitch Creek alluvial channel, near Main WRD												
Bore RN022411	27-Oct-83	-	10,980	9,800	-	-	84,000	-	25,000	-	-	67,000
Bore RN022411	15-May-85	-	9,500	8,890	-	-	35,000	-	23,000	-	-	25,000
Bore RN022411	6-Apr-09	3.6	5190	3,430	-	-	4,190	-	13,500	-	-	19,100
Seepage from the Intermediate WRD												
Seepage from Intermediate WRD	19-Mar-74	3.0	-	34,000	-	-	760,000	-	150,000	-	-	150,000
Seepage from Intermediate WRD	6-Aug-10	3.3		13,800	199,000	349,000	34,900	74,700	84,300	64,900	1,840	156,000
Seepage from Dyson's WRD												
Toe seepage	16-Mar-11	4.3	1,106	579	9,020	2,740	4,630	3,100	7,380	2,590	155	134
Toe seepage	13-Apr-11	4.2	1,356	766	14,900	1,880	5,040	4,110	9,770	3,380	224	231
Toe seepage	10-May-11	4.2	1,579	1,020	11,800	560	3,800	6,340	14,900	4,930	217	257
Shallow bore screened in alluvium near the Upper East Branch of the Finniss River												
Bore RN023413	26-Mar-85	-	9,500	8,800	-	-	300	-	49,000	-	-	650
Bore RN023413	7-Apr-09	3.1	5,310	3,780	123,000	126,000	182	667	12,100	2,040	340	320
Shallow bore screened in alluvium near the Upper East Branch of the Finniss River												
Bore RN023419	15-Feb-85	-	12,100	13,100	-	-	7,500	-	55,000	-	-	8,000
Bore RN023419	9-Apr-09	2.8	9,860	8,660	666,000	29,600	2,610	2,830	29,700	7,360	4,540	815
Bores screened in tailings used to backfill the pit (in 1984)												
DO20	7-Sep-11	5.2	8,720	6,980	-	-	0.1	-	60,800	-	-	124
DO21	7-Sep-11	4.7	5,510	4,020	-	-	3,660	-	67,100	-	-	1,550
Seepage losses during the Copper Heap Leach Experiment, 1964 to 1971												
Acid to sulphide pile	n/a	2.2	-	-	-	3,600,000	150,000	-	-	-	-	-
Liquor from sulphide pile	n/a	1.2	-	-	-	3,000,000	660,000	-	-	-	-	-
Liquor from oxide pile	n/a	1.7	-	-	-	2,800,000	1,200,000	-	-	-	-	-
Barren liquor from launders	n/a	2.1	-	-	-	4,600,000	160,000	-	-	-	-	-
Seepage from tailings in the Old Tailings Dam												
Simulated (leach test)	n/a	-	-	15,400	-	-	290,000	-	-	-	-	-

Some recent data are provided for reference

Of particular interest from Table 4-7 are the much higher concentrations of SO_4 and dissolved metals in historic seepage from the Main and Intermediate WRDs than are observed today (i.e. more than 90,000 µg/L Cu in seepage from the Main WRD in 1974, compared to less ~5,000 µg/L Cu today). Also note the high concentrations of SO_4 and dissolved metals in (i) pit water immediately before it was treated in 1985, and (ii) the condition of seepage lost during the heap leach experiment in the Copper Extraction Pad area (from 1964 to 1971) (see Davy, 1975, for additional details).

To explain historic SO_4 and Cu loads in the East Branch of the Finniss River before rehabilitation, RGC estimated annual contaminant loads as the product of annual recharge (in ML) and the likely SO_4 and Cu concentration in seepage from a particular source based on data from Table 4-7. For the WRDs (which were un-covered), RGC assumed that 50% of annual rainfall infiltrated to groundwater. Other assumed recharge values (i.e. for the Old Tailings Dam area, for instance) are provided in Table 4-8.

Table 4-8.

Contaminant Loads to Groundwater and the East Branch of the Finniss River (Before Rehabilitation), 1969 to 1984

Source	Area, m^2	SO_4,	Cu,	Recharge,	Recharge (or Flow),	SO_4 Load,	Cu Load,
		mg/L	ug/L	mm	ML	t/yr	t/yr
Estimated Contaminant Loads to Groundwater (before rehabilitation)							
Seepage from the Main WRD	330,000	10,000	100,000	650	215	2,145	21
Seepage from the Intermediate WRD	80,000	25,000	225,000	650	52	1,300	12
Seepage from Dyson's WRD	90,000	5,000	7,500	650	59	293	0.4
Seepage from Old Tailings Dam	275,000	5,000	30,000	400	110	550	3
Seepage from former mill area	54,000	5,000	60,000	144	8	39	0.5
Seepage from Copper Extraction Pad area (shallow)	34,000	2,500	7,500	264	9	22	0.1
Sub-total:	**863,000**	**n/a**	**n/a**	**n/a**	**452**	**4,349**	**37**
Estimated Losses from Groundwater							
Geochemical reactions (e.g. precipitation), 30% for Cu	n/a	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						**7,220**	**56**

Surface water loads to the East Branch of the Finniss River were not well-constrained prior to rehabilitation, so loads were estimated as the difference between the observed loads in the river and estimated loads to groundwater. For instance, the SO_4 load from surface water from the Old Tailings Dam area and the flooded pit was estimated to be 2,871 t/year (or about 40% of the annual load in the East Branch of the Finniss River). This same approach was used for Cu, but 30% of Cu was assumed to be lost in the sub-surface by adsorption to aquifer materials and/or the precipitation of Cu hydroxides from groundwater (due to increasing pH conditions along the flowpath).

In general, the load balance in Table 4-8 is consistent with load estimates from Davy (1975) for the 1973/1974 wet season, and further refinement was unnecessary because the historic loads were only intended to constrain conditions immediately prior to rehabilitation in 1984/1985 (and thereby establish the initial site condition for transport modelling.

Under current conditions, the only sources of AMD to shallow groundwater and the East Branch of the Finniss River are the three (covered) WRDs and Dysons (backfilled) Pit. Conceptual load balances for current conditions are provided in Table 4-9a,b. For these load balances, annual recharge to the Main and Intermediate WRDs was assumed to be 25% of annual rainfall. 50% of annual rainfall was assumed to infiltrate through Dysons WRD (as this WRD was only partially covered), and 10% infiltration was assumed for Dysons (backfilled) Open Pit.

Percentage recharges for the WRDs are based on a load balance for the East Branch of the Finniss River that is based on the 2012 low-flow seepage survey (see RGC, 2012b), and some professional judgment regarding the likely infiltration rates to waste rock with a thin, degraded cover. Note that loads from Table 4-9a correspond to an annual rainfall of 1735 mm (the average rainfall for 2010 to 2015), whereas loads in Table 4-9b correspond to MAP (1459 mm).

Together, seepage from the three WRDs and Dysons (backfilled) Pit account for an estimated 1,147 t SO_4/year and 2.2 t Cu/year to the East Branch of the Finniss River assuming average annual rainfall (see Table 4-9b). Diffuse sources, such as contaminated soils and severely-impacted groundwater in the Copper Extraction Pad area, account for an additional 694 t SO_4/year and 0.6 t Cu/year. Loads from these sources report mainly to the Intermediate Open Pit via groundwater, and their magnitude corresponds well to loads from the Intermediate Pit at gauge GS8150212 (at the outlet of the Intermediate Pit).

Table 4-9a.

Estimated Contaminant Loads to Groundwater and the East Branch of the Finniss River, 2010 to 2015

Source	Area, m^2	SO_4, mg/L	Cu, ug/L	Recharge, mm	Recharge (or Flow), ML	SO_4 Load, t/yr	Cu Load, t/yr
Estimated Contaminant Loads to Groundwater (2010 to 2015), 1735 mm rainfall							
Seepage from the Main WRD	330,000	5,000	5,000	392	129	647	0.6
Seepage from the Intermediate WRD	80,000	15,000	35,000	392	31	471	1.1
Seepage from the Dyson's (backfilled) Pit	61,000	2,500	30,000	174	11	26	0.3
Seepage from Dyson's WRD	90,000	2,500	2,500	784	71	176	0.2
Seepage from former mill area	54,000	1,500	30,000	264	14	21	0.4
Seepage from Copper Extraction Pad area (shallow)	34,000	5,000	7,500	264	9	45	0.1
Sub-total:	**649,000**	**n/a**	**n/a**	**n/a**	**265**	**1,387**	**2.7**
Diffuse sources (e.g. contaminated soils, liquor, etc.)	n/a	n/a	n/a	n/a	n/a	778	0.5
TOTAL:		n/a	n/a	n/a	n/a	2,165	3.2
Observed Contaminant Loads in the East Branch of the Finniss River Mean Annual Loads, 2010 to 2015						**2,165**	**3.2**

Table 4-9b.

Estimated Contaminant Loads to Groundwater and the East Branch of the Finniss River, Current Conditions ('Average Year')

Source	Area, m^2	SO_4,	Cu,	Recharge,	Recharge (or Flow),	SO_4 Load,	Cu Load,
		mg/L	ug/L	mm	ML	t/yr	t/yr
Estimated Contaminant Loads to Groundwater (2010 to 2015), 1459 mm rainfall							
Seepage from the Main WRD	330,000	5,000	5,000	330	109	544	0.5
Seepage from the Intermediate WRD	80,000	15,000	35,000	330	26	396	0.9
Seepage from the Dyson's (backfilled) Pit	61,000	2,500	30,000	146	9	22	0.3
Seepage from Dyson's WRD	90,000	2,500	2,500	659	59	148	0.1
Seepage from former mill area	54,000	1,500	30,000	144	8	12	0.2
Seepage from Copper Extraction Pad area (shallow)	34,000	5,000	7,500	144	5	24	0.0
Sub-total:	**649,000**	**n/a**	**n/a**	**n/a**	**216**	**1,147**	**2.2**
Diffuse sources (e.g. contaminated soils, liquor, etc.)	n/a	n/a	n/a	n/a	n/a	694	0.6
TOTAL:		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**

4.10.6 Transport Parameters

No direct or indirect measurements of the parameters, effective porosity and dispersivity, that control solute transport are available for the study area. For effective porosity, RGC used values twice as high as the specific yield values provided in Section 4.3 as a default conceptualization of the system.

For dispersivity, RGC acknowledged the scale-dependent nature of dispersion and estimated longitudinal dispersivity (α_L) by using a well-known published empirical plot of longitudinal dispersivity versus the scale of the study (Xu and Eckstein, 1995). Based on experience at other sites, the transverse (α_T) and vertical (α_V) dispersivity values were estimated using typical ratios of α_L/α_T and α_L/α_V of 100 and 1000, respectively. Accordingly, dispersivity values of 10 m, 0.1 m and 0.01 m were selected for α_L, α_T, and α_V, respectively, for the conceptual transport model.

For retardation factors (R_f), RGC assumed that values for lateritic soils from Brazil (from de Matos et al., 2001) were representative of laterite and other soils. De Matos et al. (2001) estimated R_f for Cu, as well as Cd, Pb, and Zn for soils using leaching columns. The average R_f for Cu in the nine soils was 3.5. RGC assumed R_f = 3.5 for laterite (and saprolite) to simulate Cu transport.

5 MODEL SETUP

5.1 MODELLING OBJECTIVES

A numerical groundwater flow model was constructed to simulate transient groundwater conditions at the Rum Jungle Mine Site from August 2010 to March 2015. This numerical flow model is a mathematical representation of the conceptual model presented in Section 4 that enables a quantitative analysis of groundwater flow and seepage from mine waste units at Rum Jungle.

5.2 KEY ASSUMPTIONS

The conceptual site model (CSM) was represented in a numerical model using the following simplifying assumptions:

- The aquifer system at the Rum Jungle Mine Site can be subdivided into hydrostratigraphic units that represent either mine waste (i.e. waste rock and/or tailings) or the naturally-occurring bedrock aquifer and overburden units.
- Each hydrostratigraphic unit can be represented as a single model layer with representative hydraulic properties (i.e. permeability, anisotropy, storage) and recharge can be estimated as a proportion of incident rainfall.
- Water movement in the hydrostratigraphic units follows Darcy's law and hence can be modelled using the 'equivalent porous medium' approach, i.e. the use of effective (or 'bulk') hydraulic properties to approximate conditions in the aquifer.
- The flooded Main, Intermediate and Brown's Oxide Pits can be represented by 'specified head boundaries' that are equivalent to observed water levels in the pit lakes during the simulation period.
- Shallow creeks and seepage areas within the model domain can be adequately represented by drain nodes that have been set below the ground surface and receive flows from the surrounding aquifer.
- Sections of the East Branch of the Finniss River downstream of Old Tailings Creek can be represented by 'specified head boundaries' that are nearly equivalent to observed groundwater levels in monitoring bores near the river.

These assumptions and other aspects of the numerical representation of the conceptual model are explained in more detail in the sub-sections below.

5.3 CODE SELECTION

RGC used the USGS code MODFLOW-NWT to construct the groundwater flow model (see Niswonger et al., 2011 for details on this code). Solute transport was simulated using the transport code MT3DMS which uses the flow solution developed in MODFLOW (Zheng and Wang, 1999). The model was setup in GMS v.10.0.9, a widely-used software package that provides a full suite of options to pre/post-process numerical models (Aquaveo, 2016).

MODFLOW was run transiently and hence recharge was applied on a month-by-month basis over the course of the simulation period. A transient model was used to simulate the pronounced seasonality in groundwater levels (and flows) at the site. This approach provides greater accuracy and confidence in model calibration as well as in prediction of various rehabilitation options.

For the current model, all drainage features (i.e. groundwater discharge to rivers, drainage lines, seepage faces, etc.) were modelled using the drain (DRN) package. Also used were the recharge (RCH), time-variant specified head (CHD), and evapotranspiration (EVT1) packages which are described further in subsequent sections.

Groundwater extraction due to pumping of private production bores was assumed to be negligible at the scale of the model domain.

5.4 MODEL DOMAIN

Boundaries of the numerical model domain are shown in Figure 5-1. The model domain was defined by local topographic highs and low-lying drainage features which represent no-flow boundaries. This approach implicitly assumes that cross-boundary flows into or out of the groundwater system could be assumed to be negligible. For this reason, net recharge by rainfall and inflows from the flooded Main and Intermediate Pits are the only sources of water to the groundwater system within the model domain, whereas any outflows are accounted for by groundwater discharge and evapotranspiration. Boundary conditions and drain nodes are shown in Figure 5-2.

5.5 GRID DESIGN AND SPATIAL DISCRETIZATION

The numerical model domain was spatially discretised into a uniform grid with cell dimensions of 25 m by 25 m (see Figure 5-1). The thickness of the cells varies depending on lithology. The model is composed of 7 layers and extends from a maximum elevation of approximately 100 m AHD to a minimum elevation of -90 m AHD.

Surface topography from a recent Lidar survey was used to define the top of Layer 1, including the WRDs and Dysons (backfilled) Pit. Figure 5-3 shows a plan view of current ground elevations across most of the model domain. Various section views of the model domain are provided in Figures 5-4a-e.

Layer 1 represents shallow overburden at the site, including laterite, fill and waste rock and has a minimum thickness of 2 m. Layer 2 represents saprolite (where present). The top of bedrock (i.e. bottom of layer 2) was based on an interpolation of top of bedrock elevations observed at historical and new bores. In undisturbed areas of the site the overburden profile was assumed to comprise 40 % laterite (layer 1) and 60% saprolite (layer 2).

In areas with overburden less than approximately 5 m thick, layer 2 is assigned bedrock properties and has a minimum thickness of 3 m.

Layers 3 through 5 represent shallow, partially weathered and fractured bedrock and have minimum thicknesses of 5 m, 15 m, and 25 m. Layers 6 and 7 represent deeper, fresh and typically low permeability bedrock and have minimum thicknesses of 60 m or greater.

Within the model domain all cells are active with the exception of the cells in Layers 1 through 5 representing mined-out portions of the Main, Intermediate and Brown's Oxide Pits. The approximate depths of the pit were duplicated as closely as possible given the limited vertical discretization in the model. The Main Pit and Intermediate Pit were excavated into fresh bedrock to depths of approximately 105 m and 57 m bgs respectively (layer 5 and layer 6, respectively). However, the Main Pit was subsequently backfilled with tailings to a depth of about 47 m bgs which are explicitly included in the model (in layer 6). Brown's Oxide Pit was only mined in the upper weathered bedrock and is represented in the model to a depth of approximately 20 m (in Layers 1, 2 and 3).

5.6 TEMPORAL DISCRETIZATION

The simulation period was temporally discretised into 80 stress periods, each representing one month. The period of interest is the calibration period from December 2010 to March 2015. An additional 26 stress periods were added prior to December 2010 to approach initial conditions consistent with the assumed recharge conditions.

Initial heads for the first stress period were taken from the output for a wet season month from an earlier simulation. Because the first stress period has no recharge and is run to steady-state, 200 mm/month was applied.

5.7 RECHARGE

Recharge to the groundwater model is defined as the amount of precipitation which reaches the water table. The recharge model applied here is similar to that used in earlier modelling studies at Rum Jungle (and nearby Woodcutters), i.e. recharge for each monthly time step is assumed to represent a fixed percentage of the incident precipitation during this month. In addition, recharge to the groundwater system can only occur after initial "wetting up" of the unsaturated soils/saprolite during the early portion of the wet season. The amount of precipitation required to wet up the initially dry soils are referred to as "soil moisture deficit" (see section 4.7).

Monthly recharge to the numerical model was calculated in two steps. First, the estimated SMD (initially 102 mm/d) was subtracted at the beginning of each wet season before recharge was applied to the model. This seasonal "soil moisture deficit" was considered subject to variation during calibration. Next, a fixed percentage of the SMD-adjusted precipitation was applied as recharge to the numerical model.

Recharge rates were initially assumed to be uniform representing 25% of the monthly (SMD adjusted) precipitation rate across the entire model domain. This initial percentage estimate of local recharge was subsequently adjusted during model calibration.

Figure 6-10 shows the initial distribution of recharge zones adopted from the earlier model. This distribution was based primarily on knowledge of surficial geology at that time. These recharge polygons and their local recharge rate were subsequently modified during model calibration to better match observed water levels or reduce excessive heads (see Section 6.4 for more details).

Previous calculations completed for contaminant loadings from the WRDs indicated recharge rates of 15% for Dysons (Backfilled) Pit, 25% for the Main and Intermediate WRDs and 50% for Dysons WRD. These earlier estimates of recharge (or "net percolation") through the existing cover over the mine waste facilities are still considered valid and therefore, were not varied during calibration of the numerical model.

5.8 EVAPOTRANSPIRATION

An initial evapotranspiration rate of 2 mm/d was applied in areas of dense forestation (see Figure 6-11) with an extinction depth of 4 m. The evapotranspiration rate was modified as required in each area during calibration. Evapotranspiration was applied only during months of no precipitation (ET is implicitly accounted for in the use of "net" recharge).

5.9 INTERNAL SOURCES AND SINKS

5.9.1 Time Variant Constant Head Boundaries

Model cells immediately surrounding the flooded Main and Intermediate Pits (in Layers 3, 4, and 5) and cells in layer 6 representing bedrock and/or backfilled tailings beneath the pit floor were assigned specified heads equal to the geodetic elevation of the water level in the pit lakes using a time variant constant head boundary (see Table 5-1). Note that surface flow within the flooded pits themselves is not simulated by the groundwater model so cells representing the flooded portion of the pits were set to be inactive.

For some monitoring periods, lake levels were missing or reported measurements did not appear to be accurate. In those cases, estimates of pit lake elevations were made based on groundwater elevations at nearby monitoring bores.

Table 5-1.

Specific Heads for the Flooded Pits and the East Branch of the Finniss River

Wet Season	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Main Pit												
2010/2011	59.5	59.4	59.3	59.8	60.2	60.5	60.8	61.1	60.4	60.1	59.9	59.8
2011/2012	59.7	59.5	59.4	59.3	59.3	59.4	60.4	60.3	60.2	60.0	59.9	59.8
2012/2013	59.5	59.3	59.1	59.0	59.1	59.2	59.5	60.1	60.1	59.9	59.9	59.9
2013/2014	59.7	59.6	59.5	59.4	59.6	60.0	61.2	60.0	59.9	59.9	59.8	59.6
2014/2015	59.5	59.3	59.1	59.0	59.1	60.4	59.9	60.2	-	-	-	-
Intermediate Pit												
2010/2011	57.3	57.2	56.9	57.4	57.9	58.5	58.7	58.9	58.4	58.0	57.7	57.5
2011/2012	57.3	57.2	57.1	57.1	57.0	57.1	58.1	58.3	58.0	57.9	57.6	57.2
2012/2013	57.0	57.0	56.9	56.9	56.9	56.9	56.9	58.0	58.0	57.8	57.9	57.7
2013/2014	57.5	57.3	57.2	57.0	57.1	58.0	58.9	58.0	57.9	57.8	57.7	57.4
2014/2015	57.2	57.0	57.0	57.0	57.0	58.4	58.1	58.2	-	-	-	-
Brown's Pit												
2010/2011	55.2	55.2	55.2	55.2	55.2	55.2	56.4	58.6	58.2	57.4	55.5	55.7
2011/2012	55.9	55.9	55.9	55.7	55.2	55.7	56.2	56.0	56.6	55.7	54.6	54.8
2012/2013	54.8	54.7	54.7	54.6	54.1	54.5	54.8	55.0	55.4	55.4	55.2	54.9
2013/2014	54.8	54.9	54.8	54.9	55.1	56.0	56.4	56.5	55.7	55.0	55.0	55.3
2014/2015	55.1	55.0	55.3	54.0	55.1	55.6	55.9	56.3	-	-	-	-
Finniss River Downstream												
2010/2011	51.9	51.8	51.5	51.8	52.2	52.8	53.2	52.9	52.7	52.5	52.2	52.0
2011/2012	51.9	51.8	51.5	51.8	51.9	52.8	53.1	52.9	52.6	52.2	51.9	51.8
2012/2013	51.7	51.5	51.2	51.1	51.5	52.0	52.5	52.9	52.6	52.2	52.0	51.7
2013/2014	51.5	51.3	51.1	51.7	52.1	52.3	52.7	52.3	52.1	51.9	52.0	51.9
2014/2015	51.4	51.1	51.0	50.9	51.5	53.0	52.9	52.9	-	-	-	-

Heads in cells along the edge of the Browns Oxide Open Pit were assigned based on water level data collected by HAR Resources (J. Hill, personal communication). Specifically, pit water levels and groundwater levels at monitoring bore TPB5 were used to represent the pit lake via a time variant constant head boundary (see Figure 5-2). Note that the water level in the Browns Oxide pit varies primarily as a result of de-watering (as opposed to seasonal variations in rainfall and river flow) and hence the pattern in water levels differs from that of the Main and Intermediate Pits.

The water level in Brown's Oxide Pit remained depressed below model layers 1 and 2 so time variant constant heads were only placed in Layer 3 around the pit. In addition, a time variant constant head polygon was used throughout the entire footprint of the pit in Layer 4.

5.9.2 Drains

Relatively shallow creeks, engineered drainage features, and areas where seepage is known to express itself at ground surface are represented by drain nodes in Layers 1 and 2 of the model (see Figures 5-2). The East Branch of the Finniss River and the EFDC are relatively deep and are known to incise through surficial soils (Layers 1 and 2) into shallow bedrock. Therefore, the drain nodes for these features are applied to Layer 3 as well as Layers 1 and 2. Drain nodes can only receive groundwater discharge from the simulated groundwater system and are characterized by a geodetic elevation and a conductance that represents the ease with which water can flow to the drain from the surrounding aquifer.

In general, drain elevations across the model domain were set to 0.2 m below ground surface based on the DTM provided by DME and drain conductances were set to one or two orders of magnitude higher than K values for the surrounding aquifer. In other words, groundwater discharge was assumed to be solely controlled by the permeability of the surrounding aquifer material.

All shallow surface drainages, including Fitch Creek, Wandering Creek, and Old Tailings Creek, were simulated by drains in layers 1 and 2. All larger surface drainages, including the East Branch of the Finniss River and the EFDC were extended into model layer 3.

In addition, drains were placed in Layer 1 and 2 along the edges of the waste rock dumps and Dysons (backfilled) Pit to allow discharge of shallow seepage along the side slopes of the mine waste units (or the rock drain in the case of Dysons backfilled pit).

The East Branch of the Finniss River represents a major discharge zone for groundwater across the study area and was represented by drains from Dysons Area and downstream to the confluence of Old Tailings Creek with the EBFR. From Old Tailings Creek to the downstream terminus of the EBFR in the model domain, time variant constant heads were assigned based on groundwater levels observed at monitoring bore MB10-20 (see Table 5-1). Note that the value of the specified head is slightly lower than the observed groundwater level due to some assumed head losses in the aquifer between the monitoring bore and the river.

5.9.3 Pumping Bores

Pumping bores were simulated in the model by using the original multi-node well package (“MNW1”) available in MODFLOW. Pumping bores were used to assess rehabilitation of the copper contamination in the Copper Extraction Pad Area, assess interception scenarios for Main Pit dewatering and to simulate the 2012 pumping test in the CMA.

5.10 SOLVER AND CONVERGENCE CRITERIA

For the simulation of groundwater flow the MODFLOW-NWT package was used. To solve the flow equation, the GMSRES Matrix solver was used with a head convergence criterion (HEADTOL) of 0.0001 m, a flux (FLUXTOL) convergence criterion of 0.005 m^3/s and a maximum number of outer iterations (MAXITEROUT) of 1500. All other settings were kept at their default, including 0.00001 m thickness for adjusting coefficients to zero and SIMPLE solver settings.

In order to compute pathlines (for MODPATH) the HDRY option was turned on such that dry cells at convergence are set to inactive cells.

6 CALIBRATION OF GROUNDWATER FLOW MODEL FOR CURRENT CONDITIONS

The transient groundwater flow model for the Rum Jungle mine site was calibrated for the observation period December 2010 to March 2015 (“current conditions”). The following sections provide a description of the calibration methods and results, including a comparison of simulated and observed heads and flows and calibrated model parameters. This section also summarizes results of a model validation exercise and sensitivity analysis.

6.1 CALIBRATION METHODS

6.1.1 Approach

A trial-and-error calibration procedure was adopted. Material properties (K, S_s and S_y), as well as recharge and evapotranspiration rates were varied until a satisfactory match of simulated and observed spatial and temporal variations in groundwater levels was achieved (flow calibration). Where required, the zonation of K, recharge and evapotranspiration were also adjusted or additional zones introduced.

The principle of parsimony was followed during the course of the calibration, i.e. an effort was made to maintain the model complexity to a minimum. The effects of incremental changes to the flow calibration were assessed by visually comparing observed and simulated time trends.

6.1.2 Flow Targets

Measurements of flow in the EBFR at gauging stations GS8150200 and GS8150327 were used to determine the total amount of runoff and groundwater flow to the EBFR between the stations (see Section 4.6.5).

For the purpose of this study, the model was considered adequately calibrated if the simulated groundwater flow to the EBFR in the reach between gauging station GS8150200 (at the bridge near the Intermediate Pit) and GS8150327 (model domain boundary) falls within the estimated upper and lower bounds shown in Figure 4-14.

6.1.3 Groundwater Level Targets (2010 to 2015)

The groundwater flow model for “current conditions” was calibrated against groundwater elevations observed in the period December 2010 to March 2015. The following monitoring bore groups and their specific monitoring periods were available and used for model calibration:

- Historical “RN” monitoring bores installed prior to 2010 and monitored from December 2010 to March 2015
- MB10 series of monitoring bores installed by RGC in 2010 and monitored from December 2010 to March 2015

- MB12 series of monitoring bores installed by RGC in 2012 and monitored from November 2012 to March 2015
- MB14 series of monitoring bores installed by RGC in 2014 and monitored from November 2014 to March 2015.

In total, 96 monitoring bores were available for transient calibration of the Rum Jungle flow model.

6.1.4 2012 Pumping Test

In addition to the long-term monthly groundwater elevation monitoring, the results of a pumping test conducted in November 2012 in the CMA were used to refine the calibration between the Main and Intermediate Pits. The pumping test was conducted from November 22 to November 29, 2012 with monitoring bore MB12-33 used as the pumping well. The drawdown measured at several monitoring bores during the test provided calibration targets for a refined calibration of hydraulic properties (K, S_s, S_y) of the surrounding bedrock units (primarily schist of the Whites formation).

The results of analytical interpretation and transient model calibration to this pumping test are summarized in Appendix D and discussed in section 6.4.3 (under “Whites Formation”).

6.2 GOODNESS-OF-FIT

The goodness-of-fit of the simulated flow field (head solution) to observed groundwater levels was evaluated in three ways:

- Computation of calibration statistics for a representative wet season and dry season
- Checking for spatial bias in residuals for a representative wet season and dry season, and
- Visual inspection of simulated versus observed seasonal time trends in groundwater levels.

These calibration results are described in more detail below.

6.2.1 Calibration Statistics

The goodness-of-fit of the calibrated flow model was statistically evaluated by computing standard calibration statistics for a dry season (November 2014) and wet season (March 2015). Although the 2014/2015 wet season was the driest of the monitoring period up to the end of March, 2015, it was chosen for the statistical analysis because it is the only wet season with a complete data set that included the monitoring bores installed in 2014.

Figures 6-1a,b show scatter plots of simulated versus observed heads and relevant calibration statistics. The observed and simulated head and computed error (“residuals”) for the various monitoring bores for these two observation periods are available in Appendix E.

The calibration of a numerical model is typically considered good if the normalized root mean square of the errors (NRMS) is less than 5%. The calculated NRMS values for the dry and wet season data sets presented in Figures 6-2a,b are 3.6% and 3.2%, respectively. The computed NRMS values are well below the target NRMS of 5% suggesting good calibration to head targets.

The respective dry and wet season residual means are 0.49 m and -0.16 m, respectively. These statistics and visual inspection of the scatter plots suggest that the calibrated model tends to overpredict heads in the dry season. In contrast, the model only slightly underpredicts heads during the wet season. However, the residuals do not show any systematic bias across the observed head range and lie on average within the acceptable target range of +/- 1 m.

The calibration statistics and the residual error scatter plots indicate that the head calibration for the numerical model is statistically acceptable for the purpose of this study.

6.2.2 Spatial Bias of Head Residuals

Figures 6-2a,b show the simulated head contours (layer 3) and computed residuals at the various monitoring bores used for model calibration for the dry season and wet season, respectively. Residuals which fall within the target range for head calibration of +/- 1 m are shown in green. Any residuals falling above or below this target range are highlighted in red.

For the dry season conditions shown in Figure 6-2a, all but one of the 21 residuals greater than 1 m are positive. Of the 26 wet season residuals shown on Figure 6-2b greater than 1 m, 18 are negative. Again, this suggests that the model has a tendency to overpredict heads during the dry season. And slightly underpredicts heads during the wet season.

For both the wet and dry seasons, the eastern area of the Old Tailings Dam area and the adjacent hillside to the east (near monitoring bores MB14-17 and MB14-15) show the greatest number of residual errors greater than 1 m. The western portion of Dysons Backfilled Pit and the ridge immediately west of it, also have residuals greater than 1 m for both seasons. Otherwise, residuals are typically less than 1 m throughout the majority of the model domain in both the wet and dry seasons.

The abovementioned areas with higher head residuals tend to be areas with higher topographic relief and/or deeper water tables which tend to result in high seasonal amplitudes in groundwater levels. In general, those areas were more difficult to calibrate due to the absence of topographic constraints (such as drainage lines or creeks) and/or presence of strong vertical gradients which could be indicative of preferential lateral flow (potentially in perched laterite).

Nevertheless, the spatial bias in head residuals is considered acceptable for the purpose of this study.

6.2.3 Simulated versus Observed Time Trends of Groundwater Levels

Simulated versus observed seasonal time trends of groundwater levels for selected monitoring bores in different reaches of the Rum Jungle mine site, covering the entire calibration period (December 2010 to March 2015), are illustrated in Figures 6-3 to 6-9. A compilation of calibration time trend plots for all monitoring bores grouped by study reaches are provided in Appendix F. In all plots the dashed line indicates the ground surface elevation and the plot border is colour coded to illustrate the main lithology screened (orange=GF: grey = WF; red = RJC; blue= CD) by the monitoring well.

The following observations can be made from an inspection of these plots:

- In general, the heads simulated of the calibrated flow model match the seasonal variations in observed groundwater levels very well, including the sharp rise in groundwater levels typically observed during the wet season and the long, gradual recession during the dry season. However, the calibrated model tends to underpredict high seasonal amplitudes observed in areas with higher topographic relief.
- Seasonal trends of groundwater levels in shallow soils near the toe of Dysons WRD (RN23413) and in the flood plain of nearby Upper EBFR (RN23419) are reproduced very well (Figure 6-3). Seasonal trends observed within the backfilled Dysons Pit (DO20, DO21) and in shallow bedrock downgradient of Dysons Pit (RN23790) are also well-matched (Figure 6-3).
- Field observations indicated significant differences in the magnitude (amplitude) of seasonal groundwater level fluctuations near the Main WRD, ranging from < 1 m beneath the Main WRD (at RN22082D), 3-4 m near the toe of the Main WRD (RN22084, RN22083), and up to 6-7m upgradient (south) of the Main WRD (RN25167). The simulated groundwater level trends generally match this pattern very well (Figure 6-4). However, some local discrepancies were observed suggesting local heterogeneity not accounted for in the model (e.g. at RN25165, see Appendix F).
- In proximity of the Intermediate WRD, observed groundwater levels showed only moderate seasonal fluctuations in the order of 2-3 m. The simulated groundwater levels match the observed time trends very well in all shallow and deeper bores located near the toe of the Intermediate WRD (Figure 6-5).
- Seasonal fluctuations in groundwater levels in the central mining area (including the Copper extraction area (CEPA)) between the Main and Intermediate Pits are strongly controlled by (known) seasonal fluctuations in pit lake elevations. These seasonal pit lake elevations are input to the model as time-variant changing head boundaries into the model, and as a result, the groundwater model provides a very good match to those observed trends (Figure 6-6).
- Simulated groundwater elevations at monitoring bores screened in the Coomalie Dolostone to the north of the CMA consistently under predict the peaks during the wet season (e.g. at monitoring bore MB10-12, Figure 6-6). This bias during the wet season is likely caused by local variations in recharge and/or hydraulic properties in the Coomalie Dolostone which are not represented in the numerical model.
- Groundwater levels in the Old Tailings Dam area show significant seasonal fluctuations, ranging from 4 to 7 m depending on location. The simulated groundwater elevations fit the observed elevations generally very well for most monitoring bores in the Old Tailings Dam Area (Figure 6-7). However, notable discrepancies were observed at the nested well pair

MB10-18 and MB10-19. Simulated heads for the shallow bore (MB10-18) underpredict the observed peaks and overpredict the observed peaks in the deeper bore (MB10-19). These discrepancies are in part due to the fact that this area floods during the wet season, a process which cannot be properly simulated with a groundwater model. In addition, the vertical anisotropy may be too high in this area restricting groundwater discharge from the deeper bedrock layer into the shallow alluvium and Old Tailings Creek during the wet season.

- Groundwater levels in the north-eastern area of the site (north-east of the CMA and east of the Old Tailings area) show among the highest seasonal fluctuations (up to 8 m) across the site. This area is located upgradient and at higher elevation than the CMA and Old Tailings Area. The simulated groundwater levels match the recent time trends observed in this reach reasonably well (Figure 6-8). However, the model does not reproduce the observed variations in peak groundwater levels in response to different wet season inputs very well (e.g. note lower peaks observed in the relatively dry wet season 2013 at RN22547 and RN 23304).
- Seasonal fluctuations in groundwater levels to the west of the Old Tailings area near the EBFR range from a high of 7 m (at MB10-08D) to as low as 3 m (at RN23302). The model tended to underestimate the seasonal fluctuations in this area (Figure 6-9), likely due to the proximity of these bores to the EBFR which shows much lower seasonal variations (see below).
- Groundwater levels in immediate proximity of the EBFR (at MB10-20 and MB10-21) near the downstream boundary show the lowest seasonal fluctuations (about 2 m). The model reproduces the seasonal trends near the EBFR very well as these bores were used to constrain the time-variant head boundary in the lower EBFR (Figure 6-9).

6.3 SIMULATED WATER BALANCE

6.3.1 Calibrated Recharge

Recharge was calibrated in the model as a percentage of monthly precipitation which was first adjusted to account for initial wetting up of the soils, i.e. to replenish the soil moisture deficit (“SMD”) developed during the preceding dry season.

Initially, a constant soil moisture deficit of 102 mm was used based on conceptual and earlier numerical modelling. However, model calibration indicated that a much better fit to the seasonal heads would be obtained by adjusting the SMD for the different model years.

Table 6-1 shows the monthly precipitation observed at the site and the adjusted net precipitation used for computing the monthly recharge. The calibrated SMDs ranged from a low of 102 mm for the 2014/2015 water year to a high of ~275 mm for the water years 2010/2011 and 2011/2012. The calibrated SMDs for the remaining water years was around 150 mm.

Table 6-1.

Net Rainfall Used to Compute Recharge

Wet Season	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Total
Total rainfall													
2010/2011	0	36	138	84	322	578	697	382	165	0	0	0	2402
2011/2012	0	0	57	112	152	362	230	419	15	30	0	0	1377
2012/2013	0	5	30	138	144	257	237	331	51	185	1	0	1379
2013/2014	5	25	79	193	332	539	373	76	74	33	0	0	1729
2014/2015	0	0	16	72	-	316	255	162	-	-	-	-	821
Net rainfall													
2010/2011	0	0	0	0	302	**378**	**497**	382	165	0	0	0	1724
2011/2012	0	0	0	0	49	362	230	419	15	30	0	0	1105
2012/2013	0	0	0	18	144	257	237	331	51	185	1	0	1224
2013/2014	0	0	0	147	332	**425**	373	76	74	33	0	0	1460
2014/2015	0	0	0	0	197	316	255	162	-	-	-	-	930

Model calibration also indicated that net precipitation had to be further adjusted for months of very high (intense) precipitation. Trial and error indicated that the model produced extensive flooding using default values of ~25% recharge for months with precipitation greater than 500 mm. During periods of very high (intense) precipitation it is likely that the recharge rate as a percentage of incident precipitation declines when groundwater levels rise to surface. To allow for higher runoff rates (and lower % recharge) during these periods, the monthly net precipitation used to compute recharge was reduced for those months with high precipitation (see highlighted values in Table 6-1).

Based on the assessment of recharge discussed in Section 4.4.2 above, recharge was initially assigned as 25% of net rainfall across the entire model domain. Recharge rates for the Main, Intermediate and Dysons waste rock dumps were assumed to be of 25%, 25%, and 50% of the net rainfall, respectively.

Recharge rates at individual recharge zones were calibrated based on groundwater elevations at monitoring bores within and near the zones, and the degree of flooding occurring during wet seasons. In general, areas of known or suspected thin overburden appeared to require reduced recharge rates. The only area where recharge was increased above 25% of incident precipitation was the Old Tailings Dam area and the areas immediately adjacent to the east and west.

Figure 6-10 shows the calibrated recharge rates for each recharge zone in the numerical model. As can be seen, the highland areas at the north-eastern and south-western extents of the numerical model typically required reductions in recharge rates to 5% to 20% of incident precipitation with 15% being typical. Although field data for most of these areas are not available, aerial photographs suggested that overburden may be thin and with the sloped topography, the percentage of runoff is likely higher in these areas than in others. The model also predicted flooding in these areas beyond what is indicated by flood mapping for the Mine Site. In order to reduce the simulated flooding in these areas, recharge rates were reduced, typically to 15% of incident precipitation.

6.3.2 Evapotranspiration

During the dry season, evapotranspiration was applied to several areas with dense vegetation (see Figure 6-11). The highest rates were applied at the upstream reaches of the EBFR from Dysons Area to the EFDC where rates ranged from 3.5 mm/d to 5 mm/d. Along the EFDC, a rate of 2 mm/d was applied and 1.5 mm/d was applied along sections of Fitch Creek. The EBFR downstream of the CMA, as well as much of Old Tailings Creek and the forested area adjacent to the north of the CMA were assigned an ET rate of 1.5 mm/d. Forested areas to the south-west of the Main WRD and north of Dysons Area were also assigned ET rates of 1.5 mm/d.

6.3.3 Modelled Inflows and Outflows

To calculate the water balance for the numerical model, flow output was averaged from January 2011 to December 2014.

Table 6-2 presents the average water balance for this 4-year simulation period.

The sources of inflow to the model include recharge and the time variant constant heads in the Main, Intermediate and Brown's Oxide pits, as well as the time variant constant heads used for the EBFR downstream of Old Tailings Creek. Outflows include groundwater discharges to drains, the time variant constant heads and evapotranspiration. Flows in and out of storage as groundwater levels rise and fall seasonally represent additional sources of outflow and inflow to the groundwater system, respectively.

The total simulated 4-year average inflow to the model is 179.47 L/s and the total outflow is 179.49 L/s. The water balance error for the calibrated transient model is very small (i.e. 0.02 L/s or 0.04%).

Table 6-3a/b provide a further breakdown of the simulated inflows and outflows by specific areas and site features of interest.

Natural recharge to all areas accounts for approximately 94% of the model inflow. The remaining inflows to the model are from the Main, Intermediate and Brown's Oxide pits. The significantly higher inflow to the groundwater system of 5.8 L/s from the Intermediate Pit can be attributed to the presence of high K Coomalie Dolostone along much of its northern perimeter. Brown's Oxide Pit is also cut well into the Coomalie Dolostone, however, ongoing pumping of the pit maintains it as a net sink for groundwater. The Main Pit is only exposed to the high K Coomalie Dolostone at shallow depths along its south-western perimeter, hence the relatively low average inflow to the groundwater system from the Main pit of 1.8 L/s.

Table 6-2.

Average Water Balance (Jan. 2011 to Dec. 2014)

Component	Flow L/s
Inflows	
Recharge to undisturbed areas	121.5
Recharge to mine waste units	6.3
Time Variant Constant Heads (Pits)	5.0
Time Variant Constant Heads (EFBR D/S)	0.1
Storage	46.6
Total:	179.47
Outflows	
Evapotranspiration	9.9
Drains	83.8
Time Variant Constant Heads (Pits)	24.4
Time Variant Constant Heads (EFBR D/S)	16.2
Storage	45.2
Total:	179.49

Table 6-3a.

Inflow Contributions of Site Features

Component	Flow L/s
Inflows	
Recharge to undisturbed areas	121.5
Recharge to mine waste units	6.3
Inflows from the Main Pit	1.8
Inflows from the Intermediate Pit	5.8
Inflows from Brown's Oxide Pit	0.6
Total:	135.9

Table 6-3b.

Outflows to Site Features

Component	Flow L/s
Outflows	
Evapotranspiration	9.9
To the Main Pit	3.6
To the Intermediate Pit	3.1
To the Browns Oxide Pit	17.7
To the upper EBFR	14.9
To Fitch Creek	5.6
To the EFDC	2.3
To Wandering Creek	4.8
To Old Tailings Creek	10.4
To the EBFR d/s of gauge GS8150200	35.9
Other unnamed creeks and tributaries	27.0
Total:	135.2

Groundwater discharge to the EBFR and its tributaries represents about 75% of all simulated outflows from the calibrated model. Groundwater discharge to the three open pits represents an additional 18% of the simulated outflow and ET covers the remaining 7%.

The simulated water balance of the calibrated model is generally consistent with the conceptual water balance, i.e. the simulated average annual inflows and outflows fall within the upper and lower ranges estimated during conceptual modelling (Table 4-1). The simulated average recharge in the calibrated model of 121.5 L/s falls approximately halfway between the estimated lower and upper bound of recharge for the conceptual water balance (61 to 182 L/s, respectively). The simulated average groundwater discharge to the EBFR and its tributaries in the calibrated model (124.4 L/s) also falls within the conceptual range, although it is closer to the upper limit of 153 L/s.

6.3.4 Comparison to Flow Calibration Targets

Figure 6-12 shows the simulated groundwater discharge into the EBFR between gauging stations GS8150200 and GS8150327 immediately downstream of the CMA. Also shown are the upper and lower bounds for groundwater discharge representing 25% and 10% of total stream flow, respectively (see Section 4.6.5).

The simulated groundwater flows to the EBFR generally fall within the estimated upper and lower bounds during the wet season from December to June. The calibrated groundwater recharge rates in the numerical model in the catchment of the EBFR downstream of the CMA range from 15% to 30% with an approximate average of 25%. As a result, the simulated stream flows are expected to track closest to the upper bound (25%). This is observed during the early and late wet seasons. However, during the wettest periods when flows are the highest the simulated discharge rates are closer to the lower bound (10%). This likely reflects an actual decrease in infiltration rates that occurs during periods of high precipitation when groundwater levels rise to surface and the aquifer is near capacity. The proportion of streamflow due to surface runoff is higher during these periods.

In the numerical model, groundwater heads above the tops of cells in Layer 1 represent areas where the aquifer has reached capacity and infiltration of precipitation has ceased. This condition represents flooding and overland flow. Overland flow to streams is not included in the groundwater flow calculations and therefore during periods of flooding, the flow predictions for the lower reach of the EBFR tend toward the 10% lower bound.

During the dry season, the numerical model “over-predicts” discharge to the EBFR. Note, however, that groundwater discharge is predicted to occur downstream of the confluence of Old Tailings Creek with the EBFR where the EBFR is represented in the model by time variant constant heads. In contrast, simulated dry season flows in the EBFR between gauge GS8150200 and Old Tailings Creek where the EBFR is represented by drain nodes typically decline to less than 2 L/s.

During the dry season, the elevations assigned to the constant head nodes along the lower EBFR are lower than the actual invert of the EBFR (as observed in the field). In other words, the simulated discharge to these constant heads represents groundwater flow in the alluvium and shallow bedrock underlying the EBFR rather than discharge to surface.

Additional studies would be required to determine whether the alluvium/bedrock along the EBFR channel is capable of transmitting the predicted dry season groundwater baseflow (~20-30 L/s).

6.4 CALIBRATED MATERIAL PROPERTIES

Figures 6-13a to 6-13g show the zonation of calibrated hydraulic conductivity (K) across the model domain resulting from the parameterization and re-calibration of the model, for all seven model layers. Figures 6-14a/b show the calibrated specific yield (S_y) for Layers 1 and 2. The material property zones for each layer are numbered. The material properties, including horizontal hydraulic conductivity (K), vertical and horizontal anisotropies, specific storage and specific yield corresponding to each material property zone are presented in Tables G1 through G7 in Appendix G.

Represented in the model are laterite, saprolite, Whites Formation, Geolsec Formation, Rum Jungle Complex, Crater Formation, Coomalie Dolostone and mine waste (waste rock and tailings). The calibrated values used for each and a comparison with measured field values are detailed below.

6.4.1 Mine Waste and Contaminated Soils

Mine waste represented in Layer 1 includes waste rock placed above natural ground in the waste rock piles (Dysons, Main and Intermediate WRD) and contaminated soils in the backfilled Dysons Pit.

Waste Rock

- Waste rock in the Intermediate and Main WRDs were assigned a K_h value of $6x10^{-5}$ and a vertical anisotropy of 10 based on earlier studies. S_y values of 0.1 and 0.15 were calibrated for the Intermediate and Main WRDs, respectively. A K_h value of $5x10^{-6}$ m/s was applied to Dysons WRD based on earlier modelling. A S_y value for Dysons WRD of 0.07 was assigned through calibration.
- The K_h value for waste rock in Dysons WRD falls within the range estimated by O'Kane (see Section 4.3.3) while the K_h used for waste rock in the Main and Intermediate WRDs is higher than the O'Kane estimates. However, a vertical anisotropy of 10 (i.e. K_h = 10 x K_v) due to layered construction and compaction was also assumed for all three WRDs and therefore the K_v value is within the O'Kane range.
- The calibrated S_y values for the Main and Intermediate WRDs are essentially within the range estimated by O'Kane (0.11 to 0.16). The calibrated S_y for the waste rock in Dysons WRD is lower than the O'Kane estimate but it should be noted that calibration of S_y for the Intermediate and Dyson WRDs was based on head responses at monitoring bores in bedrock outside the WRD footprints and therefore represents, to some degree, an effective S_y for the WRD and the surrounding bedrock.

Tailings and Contaminated Soils

- The K_h and S_y of the tailings used to backfill Dysons Pit were calibrated after dividing the pit into a western and eastern portion, representing coarser and finer tailings. The calibrated K_h of the coarser tailings of the western half of the pit had calibrated K_h values of $1x10^{-6}$ m/s for Layers 2 and 3 and $8x10^{-7}$ m/s and $1x10^{-7}$ m/s for Layers 4 and 5, respectively. The calibrated K_h of the finer tailings (slimes) of the eastern half of the pit was $1x10^{-7}$ m/s in Layer 2 while the K_h for Layer 3, 4 and 5 was $8x10^{-8}$ m/s. The calibrated S_y of the tailings ranged from 0.02 in the western half to 0.04 for the eastern half.
- The contaminated soil cap placed above tailings in Dysons backfilled Pit was assigned a uniform K_h of $3x10^{-6}$ m/s and S_y of 0.035. A vertical anisotropy of 10 was applied to the entire pit backfill (soils and tailings). The recalibrated specific yield for contaminated soils was lower (0.035) than for waste rock (0.07 to 0.15) which is consistent with the finer grain size of the contaminated soils compared to waste rock.
- Tailings discharged into the deeper portion of the Main Pit (Layer 6) were assigned the same hydraulic parameters as those calibrated for the finer tailings portion in the Dysons backfilled Pit, i.e. K_h = $8x10^{-8}$ m/s, anisotropy of 10 and S_y=0.03.

6.4.2 Unconsolidated Materials

Across the undisturbed areas, Layer 1 is comprised primarily of laterite and fill soils. The calibrated K_h for those soils ranges from $1x10^{-5}$ m/s to $1x10^{-4}$ m/s. In some areas such as near Dysons Pit, K_h is as low as $1x10^{-6}$ m/s. The field hydraulic testing for laterites/shallow soils indicated a range of $2x10^{-6}$ m/s to $1x10^{-4}$ m/s, which agrees very well with the calibrated values. The calibrated specific yield (S_y) values range from 0.01 to 0.075. The lowest S_y values of 0.01 were calibrated for upland areas where residual soils and/or bedrock of the Geolsec formation are present. The calibrated values for S_y generally fall within the range of S_y determined for the clay-rich laterite during conceptual modelling (0.01 to 0.1).

Layer 2 of the numerical model typically represents saprolite and shallow, highly weathered bedrock. Saprolite was typically logged in areas to the north of the CMA and in Dysons Area. The calibrated K_h values for Layer 2 in this area ranged from $5x10^{-7}$ to $5x10^{-6}$ m/s with S_y ranging from 0.01 to 0.07. Hydraulic testing at four locations at the Site indicated a K_h range of $7x10^{-7}$ m/s to $4x10^{-6}$ m/s. The S_y of saprolite was originally assumed to range from 0.01 to 0.10.

6.4.3 Bedrock Units

Model layers 3 to 7 typically represent bedrock of different lithological units and varying degrees of weathering. The lithology of the various model zones was determined based on the surficial geology and local drilling information (see Section 4.3.2). Similarly, the degree of weathering (and hence default hydraulic properties) was assumed to decrease with depth, with some adjustment of the depth of weathering according to lithology.

The calibrated hydraulic properties are discussed further below by lithology.

Rum Jungle Complex

- The Rum Jungle Complex (granite) is primarily present in the southern portion of the model (south of the Giant Reef Fault), but is also present at the downgradient (northern) boundary of the model (near the East Branch of the Finniss River). This bedrock unit is generally represented in Layers 3 to Layer 7 although in areas of thin overburden it is also represented in Layer 2.
- In Layer 2 near the EBFR and immediately south-west of Dysons WRD, high K_h values of $3x10^{-5}$ m/s were required for the RJC which is likely due to a high degree of weathering. A relatively low specific yield of 0.01 was required for calibration in this area which is consistent with thin overburden.
- In Layers 3 and 4, the calibrated K_h for RJC typically ranges from $1x10^{-6}$ m/s to $7x10^{-6}$ m/s. The calibrated K_h decreased with depth, ranging from $4x10^{-7}$ m/s to $2x10^{-6}$ m/s in Layer 5 and with uniform values of $1x10^{-7}$ m/s and $5x10^{-8}$ m/s assigned to Layers 6 and 7, respectively. The S_y for the Rum Jungle Complex was 0.005 in all layers except Layer 7 where it was 0.001.
- The calibrated range of K_h values of RJC bedrock units agree reasonably well with the field hydraulic testing available for this unit (K_h range of $2x10^{-7}$ m/s to $1x10^{-5}$ m/s).

Geolsec Formation

- Bedrock of the Geolsec Formation is represented in the numerical model in Layers 3 through 7. Model calibration indicated that bedrock of the Geolsec Formation is generally less permeable than that of the RJC, at least in the upper partially weathered and/or fractured zone. The calibrated K_h in all model layers ranged from $1x10^{-8}$ m/s to $5x10^{-7}$ m/s. Up to one order of magnitude higher values were used immediately north of the Main Pit and near the East Branch of the Finniss River.
- The calibrated range of K_h values of Geolsec bedrock units agree reasonably well with the (limited) field hydraulic testing available for this unit (a K_h range of $9x10^{-9}$ m/s to $4x10^{-7}$ m/s for two depths at one location).

Coomalie Dolostone

- The K_h of the Coomalie Dolostone to the north of the CMA ranges from $3x10^{-5}$ m/s to $7x10^{-5}$ m/s in Layers 3, 4 and 5 and was assigned a uniform K_h of $5x10^{-6}$ m/s and $1x10^{-7}$ m/s in Layers 6 and 7, respectively. To the south of the CMA, the Coomalie Dolostone was assigned a lower K_h value of $1x10^{-5}$ m/s in Layers 3, 4 and 5, but the same K_h values as the northern Coomalie Dolostone in the deeper Layers 6 and 7.
- Hydraulic testing results for the Coomalie Dolostone in the vicinity of the Old Tailings area varied widely from $2x10^{-7}$ m/s to $2x10^{-3}$ m/s with a geometric mean of $2x10^{-5}$ m/s. The relatively high effective hydraulic conductivity values calibrated for the Coomalie Dolostone are at the high end of the range of field data, however 6 out of 17 hydraulic test results for the Coomalie Dolostone indicated K values of $7x10^{-5}$ m/s or higher. It should also be noted that given the potential for Karst channels in the Dolostone, a relatively high effective K_h is not unreasonable.
- To the north-east in the vicinity of monitoring bores RN022547, N022548 and RN023304, bore logging indicated that the Coomalie Dolostone in the area was altered. During calibration, a K_h value of $1x10^{-5}$ m/s, significantly lower than in the Old Tailings Dam area, was required to provide a reasonable match to time trend heads.
- Although the S_y assigned to the Coomalie Dolostone itself was 0.005, the calibrated S_y for the overlying laterite (Layer 1) and saprolite (Layer 2) was 0.033. To the north-east, overburden overlying the altered Coomalie Dolostone required a calibrated S_y of 0.05 in Layer 1 and 0.01 in Layer 2. Bore logging in this area suggests that overburden is thin in this area and hence, Layer 2 was assumed to represent bedrock. Field sampling of soils conducted in 2015 also indicated coarser overburden material in the north-east uplands, which suggests a higher S_y than the clay-like laterites and saprolites encountered in the flats within and around the Old Tailings area. The resulting calibrated S_y values for Coomalie Dolostone areas are consistent with field observations.

Whites Formation

- The calibrated K_h of bedrock units of the Whites Formation in the CMA was $2x10^{-6}$ m/s in Layers 3, 4 and 5, $1x10^{-7}$ m/s in Layer 6 and $5x10^{-8}$ m/s in Layer 7. The value of $2x10^{-6}$ m/s was arrived at by calibrating to the pumping test in the CMA (at monitoring bore MB10-10) conducted in November, 2012 (Appendix G). This value is at the low end of the range of $2x10^{-6}$ m/s to $8x10^{-6}$ m/s calculated from the recovery data at several monitoring bores following the test. Note that the recovery data for monitoring bores closest to the pumped bore also indicated a K_h of $2x10^{-6}$ m/s (Appendix G). A slug test conducted at monitoring bore MB10-12 indicated a K_h of $4x10^{-7}$ m/s. A value of $5x10^{-6}$ m/s east of the Main Pit was used to calibrate the area around monitoring bore RN022544.
- To the east of the CMA, calibrated K_h of Whites Formation ranged from $5x10^{-7}$ m/s to $1x10^{-6}$ m/s in Layer 3, and $1x10^{-7}$ m/s to $8x10^{-7}$ m/s in Layers 4 and 5. The K_h in Layers 6 and 7 were a uniform $1x10^{-7}$ m/s and $5x10^{-8}$ m/s, respectively. To the west of the CMA, a K_h range of $4x10^{-6}$ m/s to $5x10^{-6}$ m/s was used for Layers 3, 4 and 5 while Layers 6 and 7 were assigned lower K_h values of $1x10^{-7}$ m/s and $5x10^{-8}$ m/s, respectively.
- The range of K_h values for bedrock of the Whites Formation generally agrees with the range of K_h values obtained through hydraulic testing in this formation ($8x10^{-7}$ m/s to $4x10^{-5}$ m/s).

Crater Formation

- Although field testing of the Crater Formation has not been conducted, it is expected to be of relatively low hydraulic conductivity. Surficial mapping suggests that Crater Formation is present at, and to some degree under, the northern toe of the Main WRD. This is consistent with the K_h value of $1x10^{-7}$ m/s required to match the observed groundwater elevations at monitoring bore MB12-31S.

6.5 MODEL VALIDATION (2008 PIT DE-WATERING TRIAL)

In late 2008, HAR Resources conducted a large-scale de-watering trial that involved drawing down the water level in the Intermediate Pit and monitoring groundwater levels at monitoring bores RN022107, RN022108 (currently MB10-09S/D), and RN022081. Continuous water level monitoring with data loggers was conducted at monitoring bores RN022108 and RN022081 at 12-hour and 6-hour intervals, respectively.

The calibrated groundwater flow model was used to simulate this earlier pit-dewatering trial as partial model validation.

Aspects of the pit de-watering trial that are pertinent to model validation are summarized as follows:

- The water level in the Intermediate Pit was pumped down to 46 m AHD (or ~10 to 12 m below its typical level) over a 3.5-month period from August 29 to December 18, 2008.
- Groundwater levels at monitoring bore RN022108 (located approximately 60 m to the west of the Intermediate Pit) declined in tandem with the water level in the Intermediate Pit, having

an elevation typically 0.1 m to 0.3 m higher until December 16, 2008. A strong hydraulic connection between the pit and the area around monitoring bore RN022108 is expected considering the relatively high hydraulic conductivity of the Coomalie Dolostone (>1x10^{-5} m/s).

- Groundwater levels at bore RN022107 (located approximately 500 m to the north east of the Intermediate Pit) declined by 1.0 m from September 1 to December 4, 2008. Based on groundwater elevation measurements during the 2010 to 2015 monitoring period, water levels typically decline approximately 0.8 m to 0.9 m from late August to late November which suggests that very little drawdown likely occurred at this monitoring bore due to pit dewatering.
- Groundwater levels at monitoring bore RN022081 (located approximately 350 m south of the Intermediate Pit) declined approximately 0.48 m between August 29 and December 16, 2008. During the 2010 to 2015 monitoring period, groundwater levels dropped 0.20 to 0.32 m in the period early September to late November. As well, data logger data recorded at the monitoring bore in 2009 indicates an approximate drop of 0.36 m from early September to early December. This suggests that it is likely that groundwater levels at monitoring bore RN022081 were drawn down slightly due to the pit dewatering.
- On December 16, two days before the cessation of dewatering, continuous groundwater elevation monitoring at monitoring bores RN022108 and RN022081 indicated increasing groundwater elevation despite continued dewatering of the Intermediate Pit. At the end of dewatering, the water level at monitoring bore RN022108 was approximately 1.1 m higher than the pit lake level. Precipitation records for Batchelor Airport indicate relatively high precipitation from December 9 to December 15, 2008 which likely accounts for the increasing water levels on December 16. This suggests that groundwater elevations in this area are heavily influenced by recharge.
- Electrical conductivity (EC) values for groundwater collected from bore RN022108 during the dewatering trial increased from ~400 μS/cm at the start of the test to 2,600 μS/cm when dewatering ceased in December 2008. The EC of groundwater pumped near the end of dewatering is consistent with samples collected from deep monitoring bore MB10-09D after retro-fitting while the EC of groundwater collected during the early stages is consistent with samples collected from shallow monitoring bore MB10-09S. This suggests that more heavily impacted groundwater at depth is being drawn toward the Intermediate Pit during dewatering more quickly than less impacted shallow groundwater. This is consistent with the relatively high K measured at monitoring bore MB10-09D.

To simulate the Intermediate Pit dewatering, lake elevations for both the Main and Intermediate Pits measured during the 2008 dewatering period were applied to the time varied constant heads at the pits in the numerical model for 2012 year of the current simulation. The year 2012 was chosen as it provided the closest match of heads at the beginning of the dewatering simulation. Note that monitoring bore RN022108 was a 55 m deep open-hole bore in 2008 but has since been retrofitted with nested monitoring bores MB10-09S and MB10-09D. For the dewatering trial, the screen of monitoring bore MB10-09D was extended to emulate the open monitoring bore RN022108.

A record of lake elevation at Brown's Oxide Pit during the dewatering test is not available, as well as a record of dewatering activities. The time varied constant heads in the current simulation for the period September through December 2012 decline from 54.6 to 54.09 m AHD and were not modified for the dewatering simulation.

The simulated groundwater flow field at the end of the dewatering trial (December 18, 2008) is presented in Figure 6-15. Time trends of simulated and observed groundwater levels for monitoring bores RN02108, RN022107 and RN022081 are shown in Figures 6-16.

The flow field shown on Figure 6-15 represents the maximum simulated drawdown and the maximum extent of the capture zone. The capture zone extends from the Intermediate Pit north to the vicinity of the Geolsec Formation around monitoring bore MB10-08D, to the north-east to approximately monitoring bore MB10-14, and to the general area between Brown's Oxide Pit and the Geolsec Formation. To the south of the Intermediate Pit, groundwater gradients are increased within the Whites Formation. The lower K Geolsec Formation to the north and north-west limit the capture zone.

The simulated drawdown of groundwater levels at monitoring bore RN022108 matches the observed drawdown in the early stages of dewatering but gradually under estimates drawdown as the simulation progresses. This is likely due to two issues:

- It is understood that the lake level in Brown's Oxide dropped during the dewatering of the Intermediate Pit, but actual elevations are not available for the simulation. The constant heads used at Brown's Oxide Pit in the model act to prevent the simulated water levels from declining with the level of the Intermediate Pit.
- The area immediately west of the Intermediate Pit in the vicinity of monitoring bore RN022108 is a faulted area as well as an area of extreme weathering of the Coomalie Dolostone. It is likely that a highly conductive bedrock structure connects this bore to the Intermediate Pit, providing a much stronger hydraulic connection than currently modelled.

Though the factors noted above prevent an ideal drawdown simulation at monitoring bore RN022108, the calibrated numerical model still produced a reasonable prediction. A strong hydraulic connection between the area around the monitoring bore and the Intermediate Pit is demonstrated by the model.

As shown on Figure 6-16, the numerical model slightly over-predicts the effect of the Intermediate Pit dewatering on groundwater levels at monitoring bore RN022107. It is likely that the Coomalie Dolostone in the vicinity of the monitoring bore, or a section of the Dolostone between the Intermediate Pit and the monitoring bore, has a lower hydraulic conductivity than represented in the numerical model. This would tend to reduce the hydraulic connection between the pit and the area to the north-east. A second potential cause of the over-prediction of drawdown may be differences in precipitation/recharge between the 2012 simulation year and 2008. Higher recharge would increase groundwater elevations and potentially offset the effects of dewatering drawdown.

At monitoring bore RN022081, the model predicts very limited drawdown as observed during the dewatering trial. In other words, the weak hydraulic connection between the monitoring bore RN022081 and the Intermediate Pit is well represented in the numerical model.

Overall, the calibrated model provided a reasonable match with field observations from the dewatering trial, demonstrating strong hydraulic connection of the Intermediate Pit to nearby RN22108 (screened in Whites Formation) and moderate connection to more distant RN22107 screened in Coomalie Dolostone to the north-east. This validation process suggests that the current calibrated model is a reasonable approximation of current flow conditions at the Rum Jungle Mine Site and can be used to predict the response of the groundwater system for rehabilitation planning.

6.6 SENSITIVITY ANALYSIS

6.6.1 Approach

Due to the uncertainty in key model input parameters, a sensitivity analysis was completed to evaluate the sensitivity of the calibrated model to variations in parameter values.

This analysis was carried out by systematically changing the following parameters:

- Hydraulic conductivity.
- Natural recharge.
- Specific yield of overburden and bedrock.
- Specific storage.
- Evapotranspiration.

Each model input parameter was adjusted, one at a time, up or down from the calibrated value and within a plausible range. The model was rerun transiently for the calibration period (2010-2015) using this adjusted (“perturbed”) set of model parameters. In the case of evapotranspiration, rather than adjusting rates, the EVT Package in GMS was completely disabled for a single simulation.

For each sensitivity run, simulated time trends for heads were plotted and calibration statistics for November 2014 (dry season) and March 2015 (wet season) recomputed to evaluate the goodness-of-fit. As well, predicted flows to the EFDC and the EFBR downstream of gauge GS8150200 were compared to calibrated model flow estimates.

6.6.2 Sensitivity Runs

A total of 11 sensitivity runs were conducted as part of the sensitivity analysis for current conditions. Table 6-4 presents the calibration statistics for each sensitivity run as well as the statistics for the calibrated model. Plots showing the time trends for groundwater elevations for the upper and lower sensitivity bounds, the calibrated time trends and observed elevations at 20 monitoring bores across the Site are also presented in Appendix H.

Table 6-4.

Calibration Statistics for Sensitivity Analyses

Run ID	Description	Calibration Statistics (Dry Season)				Calibration Statistics (Wet Season)			
		ME (m)	MAE (m)	RMSE (m)	NRMSE (%)	ME (m)	MAE (m)	RMSE (m)	NRMSE (%)
N834	Calibration Run	0.43	0.68	0.90	3.51%	-0.14	0.69	0.92	3.20%
Sensitivity to Hydraulic Conductivity (K)									
N834_K_LC	Decrease K in all units by a half order of magnitude	2.68	2.69	3.54	13.76%	1.81	1.89	2.57	8.94%
N834_K_UC	Increase K in all units by a half order of magnitude	-2.07	2.24	3.56	13.81%	-1.70	1.77	2.44	8.51%
Sensitivity to Recharge									
N834_Rech_LC	Decrease Recharge (/2)	-0.40	0.79	1.12	4.37%	-1.53	1.65	2.12	7.39%
N834_Rech_UC	Increase Recharge (x2)	0.98	1.06	1.48	5.76%	1.16	1.26	1.66	5.79%
Sensitivity to Overburden Specific Yield (Sy)									
N834_Sy_LC_OB	Decrease Overburden Specific Yield (/2)	-0.85	1.05	1.38	5.35%	0.15	0.74	1.03	3.57%
N834_Sy_UC_OB	Increase Overburden Specific Yield (x2)	1.46	1.50	1.93	7.50%	-0.41	0.78	1.06	3.68%
Sensitivity to Bedrock Specific Yield (Sy)									
N834_Sy_LC_BR	Decrease Bedrock Specific Yield (/2)	0.24	0.63	0.84	3.26%	-0.11	0.70	0.94	3.27%
N834_Sy_UC_BR	Increase Bedrock Specific Yield (x2)	0.64	0.80	1.09	4.25%	-0.19	0.69	0.92	3.19%
Sensitivity to Specific Storage (Ss)									
N834_Ss_LC	Decrease Specific Storage by an order of magnitude	0.40	0.67	0.88	3.43%	-0.13	0.69	0.92	3.20%
N834_Ss_UC	Increase Specific Storage by an order of magnitude	0.69	0.82	1.11	4.30%	-0.21	0.69	0.93	3.24%
Sensitivity to Evapotranspiration									
N834_No_ET	Remove evapotranspiration	0.86	0.98	1.23	4.79%	-0.06	0.69	0.92	3.20%

ME - Residual mean error
MAE - Absolute residual mean error

Table 6-5 presents the predicted flows to the EBFR downstream of stream gauge GS8150200 and the EFDC for the sensitivity runs. Plots showing predicted groundwater flows to the EBFR and the EFDC are also available in Appendix F as Figures F9.

Table 6-5.

EBFR Downstream and EFDC Flows for Sensitivity Analyses

Run ID	Description	EBFR D/S (L/s)	EFDC (L/s)
N834	Calibration Run	47.8	2.4
Sensitivity to Hydraulic Conductivity (K)			
N834_K_LC	Decrease K in all units by a half order of magnitude	42.7	2.0
N834_K_UC	Increase K in all units by a half order of magnitude	62.1	2.6
Sensitivity to Recharge			
N834_Rech_LC	Decrease Recharge (/2)	27.4	1.6
N834_Rech_UC	Increase Recharge (x2)	92.0	3.8
Sensitivity to Overburden Specific Yield (Sy)			
N834_Sy_LC_OB	Decrease Overburden Specific Yield (/2)	48.5	2.4
N834_Sy_UC_OB	Increase Overburden Specific Yield (x2)	47.3	2.5
Sensitivity to Bedrock Specific Yield (Sy)			
N834_Sy_LC_BR	Decrease Bedrock Specific Yield (/2)	47.8	2.4
N834_Sy_UC_BR	Increase Bedrock Specific Yield (x2)	47.7	2.4
Sensitivity to Specific Storage (Ss)			
N834_Ss_LC	Decrease Specific Storage by an order of magnitude	47.8	2.4
N834_Ss_UC	Increase Specific Storage by an order of magnitude	47.6	2.4
Sensitivity to Evapotranspiration			
N834_No_ET	Remove evapotranspiration	51.5	2.7

6.6.3 Results

Based on the calibration statistics shown on Table 6-4, the numerical model is most sensitive to variations in horizontal hydraulic conductivity and recharge, with the specific yield of the overburden being significant to a lesser degree for the dry season statistics. The normalized root mean square (NRMS) is greater than 5% for all sensitivity cases with the exception of the dry season for recharge. The lower degree of sensitivity to recharge in the dry season is not unexpected since there is no recharge applied in the dry season.

Assuming a requirement for an NRMS less than 5%, specific yield of bedrock, specific storage and the removal of evapotranspiration are not significant parameters for calibration. The NRMS for all sensitivity cases for these parameters remained below 5%.

The groundwater elevation time trends presented in Appendix H demonstrate that generally, the upper bound of K_h induces heads lower than observed, while the lower bound values induce heads higher than observed. The time trends for monitoring bores RN029993 (between Fitch Creek and the Main WRD), MB10-06 and RN023060 (both near Intermediate WRD), MB10-23 (immediately east of the Intermediate Pit) and MB12-28 (north of the EFDC) indicate the least sensitivity to K_h. Time trends for monitoring bores distant from the CMA (e.g. RN023790, RN022547 and MB14-19) showed high sensitivity to variations in K_h.

The sensitivity results for recharge showed similar, though less pronounced sensitivity to variations in values. Time trends for monitoring bores such as RN023790, RN025168, and MB14-06D, located well outside the CMA, varied significantly between the upper and lower bounds while the differences at monitoring bores RN029993, MB10-06 and MB10-23, located within or near the CMA, were much smaller.

Variations in the S_y of the overburden had little effect on the peak groundwater elevations of the time trends, as suggested by the calibration statistics in Table 6-4. However, the calibration statistics and the time trends in Appendix H show that the dry season troughs are sensitive to S_y with elevations differences greater than 4 m observed at some monitoring bore. Again, the strongest sensitivity is observed outside of the CMA (e.g. monitoring bores RN022547 and MB14-06D).

As indicated by the results on Table 6-5, average annual flows to the EBFR and EFDC are insensitive to changes of S_y (both overburden and bedrock) and S_s. A difference of only 1.1 L/s (~2% of calibrated flow) at the EBFR due to S_y of overburden is the largest difference between upper and lower bounds, with a 0.1 L/s difference at the EFDC (~4% of calibrated flow) is indicated by the sensitivity analyses. The S_y of bedrock, as well as specific storage (S_s), affect the estimates of flow to the EBFR by less than 1% and induce no measurable difference in flow estimates to the EFDC.

The EBFR and EFDC flows are sensitive to changes in K_h, but far more so to recharge. The difference in estimated average flows to the EBFR with an order of magnitude difference in K_h between the upper and lower bounds is approximately 40% of the estimated calibrated flow. However, the difference in estimated average flows between the upper and lower bounds of recharge is approximately 140% of calibrated flow. While the flow to the EFDC varies by approximately 25% with K_h, flow differences of approximately 90% are estimated for recharge.

The removal of evapotranspiration from the numerical model affects heads and flows in the dry season and the early wet season. This is expected since ET is only applied during the dry season. Table 6-4 and the groundwater elevation time trends presented in Appendix H show that during the wet season heads are generally unchanged and the NRMS is the same as the calibrated model. The dry season heads are higher with an NRMS higher than calibrated but still less than 5%. Average annual flows to the EBFR and EFDC increase approximately 8% and 12%.

6.6.4 Implications of the Sensitivity Analysis

The results of the sensitivity analyses indicate that the calibration of the numerical model is most sensitive to horizontal hydraulic conductivity (K_h), recharge, and to a lesser degree, the specific yield (S_y) of overburden. Groundwater elevation time trends and calibration statistics (e.g. NRMS) become unacceptable as the lower and upper bounds of recharge and K_h are approached in both the dry and wet seasons, while the dry season calibration becomes unacceptable as the S_y for overburden is approached. The specific storage (S_s) of all units and the S_y of bedrock do not produce unacceptable results when varied along plausible ranges of values.

Although evapotranspiration is necessary to calibrate groundwater elevation time trends to observed, particularly during the dry season, it is not strictly necessary to achieve a statistically acceptable calibration. Estimated average annual flows to the EBFR and the EFDC increase approximately 8% and 12% without ET from the calibrated model estimates. Considering the lack of actual field measurements of groundwater flow to the EBFR and EFDC, ET is not considered a critical component of the flow model.

7 SOLUTE TRANSPORT MODELING

7.1 TRANSPORT MODELLING OBJECTIVES

The overall objective of the solute transport modelling described herein was to develop a better understanding of the sources, geochemical controls and current extent of water quality impacts in groundwater at the Rum Jungle mine site.

Specific transport modelling objectives include:

- Simulate the fate of selected COCs (sulphate and copper) in groundwater for current hydraulic and geochemical conditions
- Delineate the spatial extent and associated mass of COCs in the local aquifer system
- Estimate the current contaminant loads to surface water (open pits, EFDC, EBFR).

In addition, the results of this modelling effort provide a suitable benchmark (and initial conditions) for the prediction of future contaminant transport to assess the environmental effects of the preferred rehabilitation strategy.

7.2 MODELLING APPROACH

A detailed, quantitative calibration of the transport model using historic time trends of groundwater quality at specific monitoring bores was not attempted in this study because of (i) the complexity and uncertainty in historic conditions (climate, source terms), (ii) limited historic water level and water quality data available for model calibration, and (iii) numerical challenges in accurately simulating solute transport in complex, heterogeneous aquifer systems (in particular fractured and/or karstic bedrock).

Instead, simplified historic and current flow and contaminant loading conditions were assumed and used in the numerical model to simulate current contaminant transport with the aim to reproduce a general, qualitative match to observed current groundwater quality conditions.

The main hydraulic conditions at the Rum Jungle mine site have essentially remained unchanged since completion of rehabilitation works in the 1980s. Furthermore, limited historic groundwater quality monitoring suggests that groundwater quality has also been relatively stable for at least the last 5 to 10 years (see Section 3). This would imply that contaminant loading has been reasonably constant over this time period as well and the groundwater system at Rum Jungle has been approaching hydraulic and geochemical steady-state conditions.

Consequently, a simplified flow and transport model was developed to represent current conditions with the following key assumptions:

- The net recharge in the calibrated flow model (see section 6) was modified to represent long-term average precipitation conditions (steady-state flow with a mean annual precipitation of 1484 mm/yr).

- Historic impacts in the aquifer resulting from historic sources prior to rehabilitation works in 1984/85 (e.g. uncovered WRDs, Copper Extraction Pad, Old Tailings Dam) were estimated by simulating "historic conditions" (from 1960 to 1984) and included as initial source terms but allowed to dilute/disperse over time.
- Contaminant loading of COCs to the environment from remaining contaminant sources after completion of earlier rehabilitation works in 1984/85 (primarily seepage from WRDs, backfilled Dysons Pit, backfilled Main Pit etc.) were assumed constant for simulation of "current conditions" (from 1985 to 2015) using current loading estimates.

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

7.3 Numerical Methods

7.3.1 General

Two separate flow and transport models were set up covering different simulation periods:

- "Historic" flow & transport model covering 25 years of pre-rehabilitation conditions (1969 to 1984).
- "Current flow & transport model covering 30 years of post-rehabilitation conditions (1985 to 2015)

The primary objective of the historic model was to develop suitable initial concentrations for the current transport model (immediately prior to rehabilitation). To this end, a simplified (steady-state) groundwater flow field and rough estimates of historic (pre-rehabilitation) source terms for sulphate and copper were used. This historic model significantly simplifies actual historic conditions and therefore does not attempt to reproduce the detailed, historic evolution of contaminant plumes. Therefore, only simulated conditions at the end of this simulation (for 1984) are presented and discussed further in this report.

The objective of the current model was to explain current groundwater quality (sulphate and copper) at the Rum Jungle mine site. To this end, the current (steady-state) groundwater flow field and estimates of current source terms for sulphate and copper were used. An in-depth calibration of the current transport model was beyond the scope of this study. However, an attempt was made to provide a reasonable match to (i) observed sulphate and copper loads in the EBFR and (ii) inferred sulphate and copper plumes in the local groundwater system.

7.3.2 Code Selection

The USGS code MODFLOW-NWT (Niswonger et al, 2011) was used to construct the groundwater flow model and the transport code MT3DMS (Zheng and Wang, 1999) was used to construct the solute transport model for sulphate and copper. The model was set up in GMS v.10.0.9, a widely-used software package that provides a full suite of options to pre/post-process numerical models (Aquaveo, 2016).

7.3.3 Steady-state Flow Field

To simplify and speed up transport modelling, the historic and current transport models were run using a steady-state flow solution representing long-term average precipitation and hence recharge conditions. Average recharge conditions were obtained by averaging the calibrated net precipitation (after adjustment of SMD and excess rainfall, see Table 4-1) for the period January 2012 to December 2014. The average total precipitation for this 3-year period was 1484 mm/yr which is close to the MAP for the site (1457 mm/year). The average net precipitation used for this 3-year period was 1296 mm/yr. The average recharge to the historic and current steady-state model was calculated by applying the calibrated % recharge (Figure 6-10) to this average net precipitation value.

Evapotranspiration was also not simulated for the simplified steady-state flow solution.

The time-variant heads representing the flooded pits and the lower EBFR in the transient flow model were converted to fixed constant heads. The constant head value for these water bodies was also computed by averaging the (known) time-variant heads for the 3-year calibration period.

Finally, in the steady-state flow solution for the historic transport run the Brown's Oxide Pit was removed since this pit did not exist prior to 1984.

7.3.4 Time Discretization

The model was set up in two phases. The first phase ("historic" transport model) was set up to run for a period of 25 years prior to rehabilitation, i.e. nominally the period from January 1960 to December 1984. The historic model was run as a steady state flow, transient transport simulation with 25 annual transport time steps. The second phase ("current" transport model) was set up to run for a period of 30 years post-rehabilitation, i.e. the period from January 1985 to December 2015. The current model was run as a steady state flow, transient transport simulation with 30 annual transport time steps.

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

7.3.5 Boundary Conditions

All external boundary condition used in the flow model (Section 5.4) remained unchanged for the transport model. All external boundaries of the model domain represent no-flow boundaries with the exception of the most downgradient (northern) boundary representing the EBFR which is represented by a constant head.

No flow boundaries also represent a barrier to solute transport, i.e. no mass flux occurs across a no-flow boundary. Any groundwater exiting along a prescribed head boundary is assigned the simulated sulphate (or copper) concentration in the respective boundary cells, i.e. an equivalent sulphate (or copper) mass is removed from the boundary cell.

7.3.6 Transport Parameters

The transport model was parameterized using the same spatial zonation and calibrated hydraulic properties developed for the flow model (see Sections 5 and 6). The two additional transport parameters required to solve the transport equation are effective porosity (n_e) and dispersivity (α).

Initial estimates of effective porosity were spatially distributed in the model using the same approach as outlined above for hydraulic parameters. Based on experience elsewhere, effective porosity was assumed to be two times the value of the calibrated specific yield (see section 6.4).

Dispersivity was assumed to be independent of aquifer type and a uniform distribution was assumed across all model zones/layers using the following dispersivity values:

- Longitudinal dispersivity (α_L): 10.0 m
- Transverse dispersivity (α_T): 0.1 m
- Vertical dispersivity (α_V): 0.01 m.

7.3.7 Source Terms

The key point sources of SO_4 and Cu to groundwater for historic and current conditions at the Rum Jungle mine site include:

- Dysons WRD and backfilled Dysons Pit.
- Main and Intermediate WRDs.
- Copper Extraction Pad Area.
- Former Mill and Ore Stockpile Area.
- Old Tailings Dam.

In addition, highly contaminated pit water in the Main Pit and Intermediate Pit represented a potential source of SO_4 and Cu to groundwater prior to rehabilitation in 1984/85 (historic model only). However, in the steady-state flow model (average recharge), only the Intermediate Pit provides some seepage (in the north-western portion) to groundwater. The remainder of the Intermediate Pit and the entire Main Pit represent a sink for groundwater flow. Hence, only seepage from the north-western portion of the Intermediate Pit for the historic model was considered.

Based on a review of historic and current seepage water quality and reconciliation of contaminant loads observed in the receiving surface water, source concentrations and associated loads were estimated for historic and current conditions (see Section 4.10).

Table 7-1 and Table 7-2 summarize the source concentrations and numerical implementation of these sources in the transport model for historic and current conditions, respectively.

Table 7-1.

Sulphate and Copper Source Terms for Historic Transport Model (Pre-Rehabilitation)

Source	Area (m^2)	Type	Concentration (mg/L)	Layer(s)	Recharge (mm/yr)	Load (t/yr)
Historic SO4 Source Term Properties						
Main WRD	285,000	Constant	10,000	1 - 2	653	1862
Intermediate WRD	73,000	Constant	25,000	1 - 2	653	1192
Dyson'sWRD	94,000	Constant	5,000	1 - 2	653	307
CEPA	28,000	Constant	7,500	2 - 5	261	55
Main Pit						
Intermediate Pit		Constant	2,500	2 - 5		
Dyson's (backfilled) Pit	61,000	Constant	2,500	1	196	30
Old Tailings Dam	271,000	Constant	2,500	1 - 2	391	265
Mill Area	54,000	Constant	5,000	1 - 2	325	88
					Total Load =	3798
Historic Cu Source Term Properties						
Main WRD	285,000	Constant	100	1 - 2	653	18.6
Intermediate WRD	73,000	Constant	225	1 - 2	653	10.7
Dyson'sWRD	94,000	Constant	7.5	1 - 2	653	0.5
CEPA (Deep)	10,000	Constant	300	4 - 5	261	
CEPA (Shallow)	45,000	Constant	50	2	261	0.6
Main Pit						
Intermediate Pit		Constant	60	2 - 5		
Dyson's (backfilled) Pit	61,000	Constant	8	1 - 5	196	0.1
Old Tailings Dam	241,000	Recharge Conc	30	1 - 2	391	2.8
Mill Area	54,000	Constant	60	1 - 2	325	1.1
					Total Load =	34.4

Table 7-2.

Sulphate and Copper Source Terms for Current Transport Model (1985 - 2015)

Source	Area (m^2)	Type	Concentration (mg/L)	Layer(s)	Recharge (mm/yr)	Load (t/yr)
Current SO4 Source Term Properties						
Main WRD	285,000	Constant	5,000	1 - 2	325	463
Intermediate WRD	73,000	Constant	15,000	1 - 2	325	356
Dyson'sWRD	94,000	Constant	2,500	1 - 2	653	154
CEPA (Deep)	10,000	Constant	7,500	4 - 5	261	20
CEPA (Shallow)	45,000	Constant	5,000	2 - 5	261	59
Main Pit		Constant	2,000	6		
Intermediate Pit						
Dyson's (backfilled) Pit	61,000	Constant	2,500	1 - 2	196	30
Old Tailings Dam	241,000	Recharge Concentration	500	1	391	47
Mill Area NW	47,000	Recharge Concentration	1,500	1	391	28
Mill Area SE	158,000	Recharge Concentration	1,500	1	325	77
Mill Area SW	3,000	Recharge Concentration	1,500	1	261	1
					Total Load =	1234
Current Cu Source Term Properties						
Main WRD	330,000	Constant	5	1 - 2	325	0.54
Intermediate WRD	80,000	Constant	35	1 - 2	325	0.91
Dyson'sWRD	90,000	Constant	3	1 - 2	653	0.15
CEPA (Deep)	6,800	Constant	75	4 - 5	261	0.13
CEPA (Shallow)	34,000	Constant	7.5	2	261	0.07
Main Pit		Constant	30	6		
Intermediate Pit						
Dyson's (backfilled) Pit	50,000	Constant	30	1	196	0.29
Old Tailings Dam	400,000	N/A	N/A	N/A	N/A	N/A
					Total Load =	2.09

Figures 7-1a/b and 7-2a/b show the source terms implemented in the numerical model for historic and current conditions, respectively. The majority of contaminant sources were represented in the transport model using constant concentrations applied to the respective foot print area. In this approach, MT3DMS keeps the solute concentration in the respective model nodes fixed at the specified concentration. In the case of surficial contaminant sources (e.g. WRDs) this approach is equivalent to specifying a source concentration in recharge[5]. For selected, surficial contaminant sources (e.g. Old Tailings Dam area, mill area), a constant concentration was applied to recharge for the current model.

[5] The use of constant concentrations (as opposed to specified concentrations applied to recharge) was preferred because MT3D can only apply solute loads via recharge to the aquifer in MODFLOW-NWT if the uppermost cell is "wet". However, many contaminant source areas include "dry" cells in layer 1.

7.3.8 Geochemical Reactions

SO_4 is assumed to be non-reactive (“conservative”), i.e. no geochemical reactions are assumed to influence sulphate transport along the groundwater flow path (see Section 4.10).

Based on experience at other sites and limited information at Rum Jungle solute transport, copper transport in groundwater can be expected to be influenced by geochemical reactions, including:

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

Sorption refers to the mass transfer process between the solute dissolved in groundwater (aqueous phase) and the solute sorbed on the porous medium (solid phase). For the purpose of this study, sorption was assumed to be a linear reversible process which is represented in the transport model by the retardation equation:

$$R = 1 + \rho_b / n * K_d$$

Where ρ_b is the bulk density (in kg/L), n is the porosity and K_d is the distribution coefficient (slope of linear isotherm) in L/kg.

Chemical precipitation of copper (due to buffering of ARD) was simulated in the numerical model by applying a first-order irreversible kinetic reaction (ß) to bedrock units. The rate constant was applied to both dissolved and sorbed concentrations and set to ß = 1 s^{-1}. This rate constant was sufficiently high that essentially all dissolved copper in solution is removed from the groundwater system.

Detailed site-specific information on geochemical controls for copper at Rum Jungle was not available to quantify the relative proportion of these attenuation mechanisms and/or parameterize these reaction models. Instead, a range of “attenuation scenarios” for copper were simulated to illustrate and bracket the potential influence of these geochemical controls on historic and current copper transport in groundwater and loading to the receiving surface water.

The following three attenuation scenarios were simulated for copper:

- No attenuation (conservative transport)
- Moderate Attenuation
- High Attenuation

For the conservative base case, the chemical reaction package in MT3DMS was turned off such that no sorption and no chemical reaction was modelled (i.e. R=1; ß=0).

For the scenario of “moderate attenuation”, all overburden was assigned a retardation factor of 3.5 to represent weak sorption (see section 4.6.3) and all bedrock (other than Coomalie Dolostone) was assigned a retardation factor of 100 to represent strong sorption. In addition, all model zones representing Coomalie Dolostone were assigned a first-order reaction rate of ß = 1 s^{-1}. Figures 7-3 and 7-4 show the spatial distribution of respective K_D and ß values assigned to the numerical model for the moderate attenuation scenario[6].

For the scenario of "high attenuation", all overburden (model layers 1 and 2) and shallow bedrock (model layer 3) underlying mine waste units (except Coomalie dolostone underlying the Old Tailings Dam area) was assigned a retardation factor of 3.5 and all other bedrock (all lithologies including dolostone) was assigned a first-order reaction of ß = 1 s^{-1}. Figure 7-5 shows the spatial distribution of ß values assigned to the bedrock units across the model domain for the high attenuation scenario.

7.3.9 Initial Concentration

For the historic model, an initial background concentration of 0 mg/L SO_4 (and 0 mg/L Cu) was applied over the entire domain in every variable-head cell. It is acknowledged that this is a highly simplified assumption. However, this assumption does not significantly influence the final solution of the historic model (of primary interest here) because the sulphate and copper plumes approach steady-state in less than 25 years.

For the current model, the simulated sulphate (or copper) concentrations simulated by the historic model for the final time step (end of 1984) were used as initial concentrations.

7.3.10 Solver and Convergence Criteria

The matrix equation for groundwater flow was implemented using the Upstream Weighting (UPW) package and solved using the Newton (NWT) solver developed specifically for MODFLOW-NWT. All seven model layers were defined as convertible by setting the LAYTYP array to >0. Iteration control and model convergence were constrained by setting up the maximum head change (HEADTOL), maximum flux difference (FLUXTOL), and maximum number of outer iterations (MAXITEROUT) to 0.005 m, 5 L/s, and 1500, respectively.

For transport, the matrix equation was implemented using the basic transport package (BTN5 in GMS). The advection component of the advection-dispersion ("ADE") equation was solved using the standard finite difference method with upstream weighting, while the dispersion and sinks/sources components were solved implicitly with the generalized conjugate gradient solver ("GCG"), using the Symmetric Successive Over Relaxation (SSOR) preconditioner and a maximum relative concentration change (CCLOSE) of 10^{-4}.

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[6] Bulk density values assumed in the model to compute retardation factors ranged from 1,600 kg/m^3 for overburden to 2,400-2,800 kg/m^3 for bedrock (depending on lithology).

7.4 SIMULATION OF SULPHATE TRANSPORT

7.4.1 Historic Conditions

Figures 7-6a/b show the simulated sulphate concentrations for historic conditions, i.e. prior to rehabilitation in 1984/1985. The historic (steady-state) groundwater flow field is also shown for reference (black contour lines).

The model predicts the presence of several distinct historic sulphate plumes caused by historic seepage from the different known (or inferred) mine waste units present prior to rehabilitation in the mid 1980's:

- In Dysons Area, the SO_4 plume reaches peak concentrations of about 5,000 mg/L SO_4; this plume discharges to the Upper EBFR and smaller northern tributaries.
- In proximity of Main and Intermediate WRD, the sulphate plume reaches peak concentrations of 10,000 and 25,000 mg/L SO_4, respectively. The sulphate plume from the Main WRD discharges to Fitch Creek to the east, Wandering Creek to the south-west and the EBFR to the north. To the west, the sulphate plume merges with the (more concentrated) plume from the Intermediate WRD and discharges to the EBFR and to the Intermediate Pit.
- In the copper extraction pad area, sulphate concentrations are assumed to be highly elevated (7,500 mg/L) to significant depth in bedrock (layers 2-5) because of historic leach operations. This plume is limited to the immediate foot print of the CEPA and discharges into the Intermediate Pit.
- Seepage from the former mill area and associated ore stockpiles (to the north-east of the Main Pit) is predicted to migrate in a south-westerly direction towards the Main Pit. Simulated peak concentrations of sulphate in this mill site plume reach 5,000 mg/L in overburden soils.
- Seepage from the historic tailings placed in the OTD Tailings Dam area (with an estimated source concentration of 2,500 mg/L) is predicted to have produced a historic sulphate plume of significant spatial extent, covering the former foot print area of the OTD and significant portions of the Coomalie dolostone aquifer to the west. The majority of the sulphate plume (primarily in overburden) discharges to Old Tailings Creek while a smaller proportion (in deeper bedrock) discharges directly to the EBFR (between gauging stations GS8150200 and GS8150327).

The historic flow and transport model was used to compute the historic mass fluxes ("loads") of sulphate to the receiving surface water. Table 7-3 summarizes the simulated historic sulphate loads (in t/yr) for different model reaches.

Table 7-3.

Simulated Sulphate Loads from Groundwater to Surface Water

Reach	Historic SO_4 Load		Current SO_4 Load	
	t/yr	%	t/yr	%
Dyson's Reach	364	9%	202	14%
Main WRD	1664	41%	461	32%
Intermediate WRD	1156	28%	408	28%
Main Pit	109	3%	74	5%
to Intermediate Pit	339	8%	211	15%
Brown's Oxide Pit	-	-	18	1%
OTD Reach	124	3%	22	2%
Lower EBFR (d/s of Intermediate Pit)	305	8%	42	3%
TOTAL:	4062	100%	1439	100%

The predicted historic sulphate loads may be summarized as follows:

- The total historic sulphate load discharging to the receiving surface water is predicted to be about 4,062 t/yr.
- The highest proportion of this sulphate load was predicted to discharge in the reach of Fitch Creek, EFDC and Wandering Creek impacted by the Main WRD (41%), followed by the reach of EFDC and Wandering Creek near Intermediate WRD (28%).
- Historic sulphate load to the Upper EBFR (Dysons area) and the lower EBFR (including Old Tailings Creek) are predicted to be significantly smaller (9% and 11% of the total load).
- The historic sulphate flux to the Intermediate Pit (about 8% of total) is higher than to the Main Pit (3% of total) because of discharge of highly impacted groundwater from the CEPA and the Intermediate WRD.

The simulated historic load balance for sulphate (Table 7-3) agrees reasonably well with the conceptual load balance for historic conditions discussed in Section 4-10 and summarized in Table 4-8. The simulated historic sulphate load (4,062 t/yr) explains about 93% of the historic sulphate load in groundwater estimated using conceptual modelling (4,349 t/yr). Furthermore, the respective simulated sulphate loads discharging to surface water near major point sources (primarily WRDs) agree reasonably well with historic load estimates for those point sources. The historic model is therefore considered to provide a reasonable approximation of historic sulphate conditions in groundwater experienced at the Rum Jungle mine site prior to rehabilitation works in the mid-1980s.

7.4.2 Current Conditions

Figures 7-7a,b show the simulated sulphate concentrations for current conditions. The current (steady-state) groundwater flow field is also shown for reference (black contour lines). The model predicts the following significant changes to sulphate concentrations in groundwater for current conditions vis-à-vis historic, pre-rehabilitation conditions:

- A reduction in sulphate loading for all WRDs (due to cover placement in 1984/85) does not significantly change the spatial extent of the associated sulphate plumes in groundwater. However, sulphate concentrations in both overburden and bedrock decrease significantly as a result of reduced loading.
- The removal of the ore stockpiles in the former mill site have reduced the sulphate load and hence sulphate concentrations in groundwater in that area (north-east of the Main Pit). However, contaminated soils remaining in this area (and other areas between the Main Pit and the OTD) represent a secondary source of sulphate (~1,500 mg/L) which produces a secondary sulphate plume.
- Removal of the historic tailings from the OTD area has resulted in significant clean-up of the historic sulphate plume in this area. However, a residual sulphate plume is predicted to be present in the former OTD foot print area (~500 mg/L SO_4) due to ongoing seepage from residual tailings not removed during rehabilitation works.

The current flow and transport model was used to compute the mass fluxes (“loads”) of sulphate to the receiving surface water. Figure 7-8 shows the simulated transient mass fluxes of sulphate reporting to different reaches of the EBFR (and tributaries) for the 30-year modelling period (1985 to 2015). An inspection of these transient time trends indicates that sulphate transport in the groundwater system approach new steady-state conditions reflecting post-rehabilitation sulphate loading within 5-15 years depending on the transport distance and local hydraulic conditions. In other words, historic sulphate plumes present prior to rehabilitation works in the mid-1980s (e.g. in the Old Tailings Dam area) are predicted to have been “flushed out” over the last 30 years. This modelling result is consistent with field observations which have not shown significant changes in groundwater quality in in recent years of monitoring (section 3).

Table 7-3 summarizes the simulated sulphate loads (in t/yr) for different model reaches for current conditions (nominally 2015). The predicted current sulphate loads may be summarized as follows:

- The total current sulphate load in groundwater discharging to the receiving surface water is predicted to be about 1,439 t/yr. This load represents only about 35% of the historic sulphate load in groundwater, i.e. an almost threefold decrease.
- The highest proportion of current sulphate load in groundwater is predicted to discharge in the reach of Fitch Creek, EFDC and Wandering Creek impacted by the Main WRD (32%), followed by the reach of EFDC and Wandering Creek near Intermediate WRD (28%).
- Although the current sulphate load to the Upper EBFR (Dysons area) has decreased (relative to pre-rehabilitation), the relative proportion of the total current load has increased to about 14%.

- Similarly, the relative proportion of current sulphate load to the Intermediate Pit (from CEPA and Intermediate WRD) has also increased to about 15%. Sulphate loading to the Main Pit has remained a minor component to total sulphate load (about 5 % of total).
- Sulphate loading to the lower EBFR (including Old Tailings Creek) has significantly declined (from 429 t/yr to 64 t/yr) due to the removal of the historic tailings. The current sulphate load to this reach of the model domain is predicted to be about 5 % of the total sulphate load.

The simulated current load balance for sulphate (Table 7-3) agrees reasonably well with the conceptual sulphate load balance for current conditions described in Section 4-10 and summarized in Table 4-8. The simulated current sulphate load (1,439 t/yr) is about 26% higher than the current sulphate load in groundwater estimated using known point sources (1,138 t/yr) but is about 22% lower than observed sulphate loading to the EBFR (1,840 t/yr).

The discrepancy between those estimates is attributed to “diffuse” sources such as seepage from residual contamination in the CEPA, the Old TDF and other areas with contaminated soils and/or residual mine waste. Given the uncertainty in the magnitude of these diffuse sources, the simulated conditions for SO4 are considered to be a reasonable representation of current conditions, and therefore provide a suitable reference against which to evaluate the effect of future rehabilitation.

7.5 SIMULATED COPPER TRANSPORT

7.5.1 Overview

As described earlier, transport of copper in groundwater is influenced by geochemical reactions, specifically sorption and chemical precipitation. In the absence of site-specific geochemical information on copper attenuation at Rum Jungle a range of “attenuation scenarios” for copper were simulated to illustrate and bracket the potential influence of these geochemical controls on historic and current copper transport in groundwater and loading to the receiving surface water.

The following three attenuation scenarios were simulated for copper (see section 7.3.8 for details):

- No Attenuation (conservative Base Case)
- Moderate Attenuation (sorption in overburden and bedrock and chemical precipitation in dolostone)
- High Attenuation (sorption in overburden and shallow bedrock beneath WRDs and chemical precipitation in all bedrock lithologies.

The following sections describe and compare the simulated historic and current copper transport for the above three attenuation scenarios.

7.5.2 Historic Conditions

Figures 7-9a-g show the simulated copper concentrations for the three attenuation scenarios for historic conditions, i.e. prior to rehabilitation in 1984/1985. The historic (steady-state) groundwater flow field is also shown for reference (black contour lines).

For the conservative scenario ("no attenuation"), the model predicts similar distinct historic copper plumes as described above for sulphate associated with the historic seepage from the different known (or inferred) mine waste units present prior to rehabilitation in the mid 1980's:

- In Dysons area, the copper plume reaches peak concentrations of about 8 mg/L Cu; this plume discharges to the Upper EBFR and smaller northern tributaries.
- In proximity of Main and Intermediate WRD, the copper plume reaches peak concentrations of 100 and 225 mg/L Cu, respectively. The copper plume from the Main WRD discharges to Fitch Creek to the east, Wandering Creek to the south-west and the EBFR to the north. To the west, the copper plume merges with the (more concentrated) plume from the Intermediate WRD and discharges to the EBFR and to the Intermediate Pit.
- In the copper extraction pad area, copper concentrations are assumed to be highly elevated (up to 300 mg/L Cu) to significant depth in bedrock (layers 2-5) because of historic leach operations. This copper plume is limited to the immediate foot print of the CEPA and discharges into the Intermediate Pit.
- Seepage from the former mill area and associated ore stockpiles (to the north-east of the Main Pit) is predicted to migrate in a south-westerly direction towards the Main Pit. Simulated peak concentrations of copper in this mill site plume reach 60 mg/L in overburden soils.
- Seepage from the historic tailings placed in the OTD Tailings Dam area (with an estimated source concentration of 30 mg/L Cu) is predicted to produce a historic copper plume of significant spatial extent, covering the former foot print area of the OTD and significant portions of the Coomalie dolostone aquifer to the west. The majority of the copper plume (primarily in overburden) discharges to Old Tailings Creek while a smaller proportion (in deeper bedrock) discharges directly to the EBFR (below gauging station 200).

A comparison of the conservative copper plume with the copper plumes simulated for the scenarios of moderate and high attenuation illustrate the influence of geochemical controls on historic copper transport. The key observations can be summarized as follows:

- Moderate sorption assumed in the shallow soils (R_f=3.5 in layers 1 and 2) does not significantly influence copper concentrations in those layers, except near the margin of the plume. Travel times in the shallow soils tend to be short (< 2-5 years) and a threefold increase in travel time (retardation) does not significantly delay the plume advance over a 25-year modelling period.

- Strong sorption assumed in bedrock (R_f=100 in all lithologies except dolostone) significantly delays copper transport in bedrock, effectively limiting the high strength copper plume to the immediate footprint of the different mine waste units.
- Chemical precipitation assumed for dolostone (moderate and high attenuation scenarios) and for all other bedrock lithologies (high attenuation scenario) completely removes copper from the aqueous phase, thus effectively eliminating any copper plume in groundwater in those bedrock units. In the moderate attenuation scenario, this affects primarily the copper plume in the Old Tailings Dam area. In the high attenuation scenario, copper is precipitated out in all bedrock units (except in shallow bedrock (layer 3) beneath mine waste units where historic leaching is assumed to have depleted any buffering capacity).

Limited groundwater quality data is available for these historic conditions and historic monitoring did not cover important areas such as the CEPA and OTD area. A definitive calibration of the historic copper transport model and a selection of an attenuation scenario based on the spatial distribution of the simulated historic copper plume was therefore not feasible. However, the moderate and high attenuation scenarios are considered more realistic than a fully conservative scenario based on our conceptual understanding of the geochemical processes controlling copper.

The historic flow and transport model was used to compute the historic mass fluxes (“loads”) of copper to the receiving surface water. Table 7-4 summarizes the simulated historic copper loads (in t/yr) for the three different attenuation scenarios.

Table 7-4.

Simulated Copper Load from Groundwater to Surface Water - Historic Conditions

Reach	No Attenuation		Moderate Attenuation		High Attenuation	
	t/yr	%	t/yr	%	t/yr	%
Dyson's Reach	0.6	2%	0.3	1%	0.2	1%
Main WRD	16.6	42%	12.4	67%	11.1	69%
Intermediate WRD	10.4	27%	3.2	17%	2.4	15%
Main Pit	1.2	3%	0.6	3%	0.4	2%
to Intermediate Pit	4.5	12%	0.9	5%	0.8	5%
OTD Reach	1.3	3%	1.2	6%	1.2	7%
Lower EBFR (d/s of Intermediate Pit)	4.4	11%	0.0	0%	0.0	0%
TOTAL:	39	100%	19	100%	16	100%

The simulated historic copper loading to surface water may be summarized as follows:

- The total historic copper load discharging to the receiving surface water is predicted to range from a low of 16 t/yr (high attenuation) to a high of 39 t/yr (no attenuation). The difference in the copper mass reporting to the receiving surface water indicates the extent of copper mass removed from the aqueous phase by sorption and precipitation:
    - o 20 t/yr for moderate attenuation

- 23 t/yr for high attenuation

  Note that a high retardation factor in bedrock (R_f=100 assumed for the moderate attenuation scenario) is almost as effective as a fully irreversible reaction in bedrock (assumed in the high attenuation scenario) in removing copper mass.

- In all three attenuation scenarios, the highest proportion of the historic copper load discharges to Fitch Creek and the reaches of EFDC and Wandering Creek impacted by the Main WRD (42-69%), followed by the reach of EFDC and Wandering Creek near Intermediate WRD (15-27%).
- In contrast, historic copper load to the Upper EBFR (from Dysons WRD and Dysons Pit) is predicted to be minor (~2% of total) due to the assumed lower copper source concentrations.
- Copper loading to the open pits and lower EBFR varied significantly depending on the attenuation scenarios:
  - In the moderate and high attenuation scenarios, historic copper loading to the Main Pit and Intermediate Pit are relatively small due to sorption and/or precipitation of copper in bedrock (3-5% of total). Furthermore, copper loading to the Old Tailings Creek and lower EBFR (from the OTD) is relatively minor (6-7%) due to assumed precipitation in the Coomalie dolostone.
  - In contrast, the conservative "no attenuation" scenario, predicts significant copper loading to the Intermediate Pit (12% of total) from CEPA and Intermediate WRD. In addition, loading from the OTD to the lower EBFR (via transport through Coomalie dolostone) also represents a significant contribution to the total historic Cu load (14%).

The simulated total historic copper load entering the groundwater system (~39 t/yr) agrees very well with the total copper load from historic sources (37 t/yr) estimated by the conceptual load balance for historic conditions discussed in Section 4-10 and summarized in Table 4-8.

However, the actual copper load reporting to surface water via groundwater can be expected to be substantially smaller due to chemical attenuation of copper along the flow path. In the conceptual load balance for copper an estimated 30% was assumed to be lost due to chemical attenuation. However, this value represents only an initial "educated guess". Copper loads to the EBFR via surface sources (e.g. surface runoff from exposed tailings and WRDs, copper loads from acidic pit lakes) represent significant (but difficult to quantify) additional sources which make it difficult to constrain the "loss term" for copper.

The numerical model indicates that chemical attenuation may account for up to 23 t/yr (or 59% of the total copper source load). Both attenuation scenarios described above are considered plausible scenarios while a fully conservative scenario is considered unlikely.

7.5.3 Current Conditions

Figures 7-10a-g show the simulated copper concentrations for current conditions. The current (steady-state) groundwater flow field is also shown for reference (black contour lines). The model predicts the following significant changes to copper concentrations in groundwater for current conditions vis-à-vis historic, pre-rehabilitation conditions:

- A reduction in copper loading for all WRDs (due to cover placement in 1984/85) does not significantly change the spatial extent of the associated copper plumes in groundwater. However, copper concentrations in both overburden and bedrock decrease significantly as a result of reduced loading.
- The removal of the ore stockpiles in the former mill site have reduced the copper load and hence copper concentrations in groundwater in that area (north-east of the Main Pit).
- Removal of the historic tailings from the OTD area has resulted in significant clean-up of the historic copper plume in this area.

A comparison of the conservative copper plume with the copper plumes simulated for the scenarios of moderate and high attenuation illustrate the influence of geochemical controls on current copper transport. The key observations can be summarized as follows:

- Moderate sorption assumed in the shallow soils (Rf=3.5 in layers 1 and 2) does not significantly influence copper concentrations in those layers, except near the margin of the plume. Travel times in the shallow soils tend to be short (< 2-5 years) and a threefold increase in travel time (retardation) does not significantly delay the plume advance over a 30-year modelling period.
- Strong sorption assumed in bedrock (R_f=100 in all lithologies except dolostone) significantly delays copper transport in bedrock. In areas where current copper source concentrations have declined, higher residual copper concentrations remain present ("trapped") in deeper bedrock due to slow travel velocities and retardation.
- Chemical precipitation assumed for dolostone (moderate and high attenuation scenarios) and for all other bedrock lithologies (high attenuation scenario) completely removes copper from the aqueous phase, thus effectively eliminating any copper plume in those bedrock units. In the moderate attenuation scenario, this affects primarily the copper plume in the OTD area. In the high attenuation scenario, copper is precipitated out in all bedrock units (except in shallow bedrock (layer 3) beneath mine waste units where historic leaching is assumed to have depleted any buffering capacity).

A detailed calibration of the copper transport model against currently observed copper concentrations was beyond the scope of this study. However, the scenario of moderate attenuation is judged to provide the best overall match to the copper concentrations currently observed in the groundwater system. The conservative scenario tends to predict higher copper concentrations in deeper bedrock (especially at greater distance from the mine waste units) than is inferred (based on limited monitoring in deep bedrock). In contrast, the high attenuation scenario tends to underpredict copper concentrations in bedrock, in particular in granites and Geolsec where elevated copper concentrations are observed even at moderate depth in bedrock.

The current flow and transport model was used to compute the current mass fluxes (“loads”) of copper to the receiving surface water. Figure 7-11 shows the simulated mass fluxes of copper to different reaches of the EBFR (and tributaries) for the 30-year modelling period (1985 to 2015). An inspection of these transient time trends indicates that copper concentrations in the groundwater system are approaching new steady-state conditions reflecting post-rehabilitation copper loading within 5-30 years depending on the transport distances and degree of attenuation. In other words, much of the historic copper plumes present prior to rehabilitation works in the mid-1980s (e.g. in the Old Tailings Dam area) would have been “flushed out” over the last 30 years.

Note that residual copper concentrations from historic (higher) loading are predicted to remain “trapped” in the deeper bedrock layers (for both the conservative and moderate attenuation scenarios) due to the low travel velocity in those bedrock units. However, the copper load in deeper bedrock represents a relatively small contribution to current copper loads discharging to surface water. The predicted slow flushing of copper in less permeable, deeper bedrock may explain the elevated copper concentrations still seen today in selected monitoring bores in deeper bedrock near the Main WRD and in the CEPA (see section 3).

Table 7-5.

Simulated Copper Load from Groundwater to Surface Water - Current Conditions

Reach	No Attenuation		Moderate Attenuation		High Attenuation	
	t/yr	%	t/yr	%	t/yr	%
Dyson's Reach	0.52	17%	0.29	11%	0.20	18%
Main WRD	0.62	20%	0.70	26%	0.33	30%
Intermediate WRD	0.97	32%	1.20	45%	0.29	26%
Main Pit	0.09	3%	0.07	3%	0.01	0%
to Intermediate Pit	0.82	27%	0.39	15%	0.28	25%
Brown's Oxide Pit	0.04	1%	0.00	0%	0.00	0%
OTD Reach	0.00	0%	0.01	0%	0.01	1%
Lower EBFR (d/s of Intermediate Pit)	0.013	0%	0.009	0%	0.004	0%
TOTAL:	3.08	100%	2.66	100%	1.12	100%

Table 7-5 summarizes the simulated current copper loads (in t/yr) for the three attenuation scenarios. The simulated current copper loading to surface water may be summarized as follows:

- The total current copper load discharging to the receiving surface water is predicted to range from a low of 1.1 t/yr (high attenuation) to a high of 3.1 t/yr (no attenuation). This represents a 14 to 12-fold reduction in copper load from groundwater to surface water since rehabilitation in the mid-1980s.

- The moderate attenuation scenario predicts only a slightly lower copper load (2.7 t/yr) than the conservative scenario (3.1 t/yr), indicating the relatively small effect of attenuation of copper in bedrock under current conditions.
- Seepage from the Intermediate WRD represents the highest source of current copper load, followed by seepage from the Main WRD, CEPA (to Intermediate Pit) and Dysons WRD/backfilled Pit.
- Residual copper loading from the former mill site and the OTD are not predicted to be a major source of copper loading for current conditions (for all attenuation scenarios).

The simulated current copper load from groundwater to surface water predicted for the moderate attenuation scenario (2.7 t/yr) agrees very well with the observed total copper load in the EBFR (2.7 t/yr) (see Table 4-9b). The total copper load predicted for the conservative (no attenuation) scenario (3.1 t/yr) is only slightly higher suggesting that the mass of copper currently removed by chemical reactions is predicted to be relatively small. In other words, the conservative scenario cannot be ruled out based on current copper loading in the EBFR.

In contrast, the predicted current copper load for the high attenuation scenario (1.1 t/yr) is significantly lower than currently observed. In other words, the conceptual load balance for copper does not support this high attenuation scenario.

Based on a comparison of simulated and observed spatial distribution of copper concentrations in groundwater and load estimates of copper in the EBFR today, the moderate attenuation scenario is considered to be the scenario that most closely represents current copper transport at Rum Jungle.

8 CONCLUSIONS

8.1 KEY FINDINGS

A hydrogeological study was completed to characterize current groundwater conditions at the Rum Jungle mine site. This study included the following components:

- Compile and interpret groundwater and surface water monitoring data collected from 2010 to 2015.
- Update the Conceptual Site Model (CSM) for the site to reflect additional information from hydrogeological investigations conducted in 2012 and 2014 and geotechnical investigations conducted in 2014 and 2015.
- Update and recalibrate the existing groundwater flow model (RGC, 2012b) for the observation period 2010 to 2015
- Develop a solute transport model and simulate transport of dissolved sulphate (SO_4) and copper (Cu) in groundwater for historic and current conditions.

The key findings of this study are summarized below.

8.1.1 Review of Groundwater Monitoring Data

Groundwater levels and water quality at the Rum Jungle Mine Site have been routinely monitored by the DME since early 2011 using an extensive network of monitoring bores. The key findings from a review of this monitoring data are as follows:

- The observation period covers a significant range of precipitation conditions, including an unusually wet year (2010/2011) producing a total precipitation of 2,402 mm (or 65% above MAP) and a dry year (2014/2015) with a total rainfall of 1,320 mm (or 10% below MAP).. The three intervening water years had annual total rainfalls that ranged from 6% below to 18% above MAP.
- Groundwater levels showed significant seasonal fluctuations with up to 8 m seasonal amplitude in upland areas and 2-3 m seasonal amplitude in lowland areas. Groundwater level hydrographs responded to individual precipitation events but seasonal fluctuations were generally similar from year to year despite large difference in wet season totals.
- Groundwater levels typically fall below the EBFR and its tributaries during the dry season resulting in limited, if any, groundwater discharge during the dry season. However, year-round seepage from the WRDs has resulted in groundwater mounding and year-round discharge of contaminated seepage along the toe of the WRDs.
- Groundwater quality conditions at the site appear to be relatively stable, as few changes in groundwater or seepage water quality have occurred since 2010. Some differences in groundwater quality are evident between the dry and wet seasons, but the changes are small compared to the large fluctuations in groundwater levels.

- In Dysons Area, highly-impacted groundwater resides in the shallow bedrock aquifer near Dysons WRD and south of Dysons (backfilled) Pit. Impacted groundwater in Dysons Area reports primarily to the upper East Branch of the Finniss River via shallow bedrock and unconsolidated sediments. Seepage from shallow backfill in Dysons Pit is the key source of Cu and other metals in Dysons Area, whereas Dysons WRD contributes only small metal loads (and moderate loads of SO_4).
- In the central mining area, the highest concentrations of SO_4 and dissolved metals occur in groundwater near the Main WRD. These high concentrations are due to large loads of SO_4 and metals from waste rock in the Main WRD, and the relatively low buffering capacity of the Rum Jungle Complex beneath and around the Main WRD.
- In the Copper Extraction Pad area, very high Cu concentrations are observed in groundwater (i.e. up to 850,000 µg/L Cu). Groundwater is also acidic (pH < 4.5) and characterized by 3,500 to 8,500 mg/L SO_4. The most impacted groundwater appears to occur along a major fault that runs across the Copper Extraction Pad area. RGC attributes these high Cu concentrations to losses of pregnant liquor from the heap leach operation in the 1970s. High concentrations persist today because groundwater is either hydraulically isolated, or Cu that initially adsorbed to aquifer materials is now being released (desorbed) and/or maintaining high concentrations (by chemical dissolution reactions).
- Near the former processing plant (north of the Main Pit), 50,000 to 60,000 µg/L Cu was identified in groundwater from two bores installed in 2014 (MB14-17S and MB14-20S). RGC attributes these high concentrations to ongoing seepage from buried ore and/or waste rock in this area (as opposed to historic seepage losses from surface). These high concentrations are likely confined to a small area, but there are too few bores to properly delineate the extent of impacted groundwater.
- North of the central mining area (near the Old Tailings Dam area), SO_4 concentrations in groundwater are typically less than 500 mg/L SO_4, and dissolved Cu concentrations are only slightly elevated (i.e. less than 100 µg/L). Historic sulphate and copper plumes are inferred to have been flushed from this area due to high recharge and high permeability in this area. Also, copper is assumed to be attenuated (precipitated) in the well-buffered Coomalie Dolostone.

8.1.2 Conceptual Site Model

The Conceptual Site Model (CSM) for the Rum Jungle mine site was updated using results of additional field investigations (primarily in the CMA and OTD area) as well as results of additional routine monitoring completed since 2011. Key aspects of the CSM include the following:

- In general, groundwater flow at Rum Jungle is conceptualized to be controlled by local topography (shallow, local flow system) flowing from the local hill sides (recharge areas) to the EBFR and its tributaries along topographic lows (discharge areas).

- The flooded Main and Intermediate Pits are hydraulically connected to the surrounding bedrock aquifer system and control groundwater levels in the central mining area. These pits receive groundwater during the wet season but act as a net source of groundwater recharge during the dry season.
- Groundwater flow occurs primarily in shallow overburden soils (comprised of laterite and saprolite) and in partially weathered and/or fractured bedrock (typically in upper 30-50m below ground).
- The effective hydraulic conductivity of bedrock can vary significantly and is influenced by bedrock lithology. The Coomalie dolostone represents the most permeable bedrock unit while the quartz/ breccia of the Geolsec formation represents the least permeable unit. Shale and schist of the Whites formation and granites of the Rum Jungle Complex are moderately permeable.
- Natural recharge over undisturbed areas was estimated to range from about 20 to 30%. Recharge into waste rock was estimated to range from 25 to 50% depending on the condition of the cover.
- The conceptual groundwater balance suggests that total inflow to the model domain (predominantly via recharge) could range from 70 to 200 L/s. Approximately 50-60% of this inflow is inferred to discharge directly to the EBFR and its tributaries while about 15-25% discharge to the flooded pit. The remainder is inferred to be lost during the dry season via evapotranspiration.
- From 1969 to 1984 (before initial rehabilitation), average loads of 7,220 t/year SO_4 and 56 t/year Cu were observed for the East Branch of the Finniss River. These loads were related to seepage to groundwater from the uncovered WRDs and surface water loads from the flooded pits and the Old Tailings Dam area.
- After initial rehabilitation, SO_4, Cu, and loads of other metals, i.e. Mn, Zn, were reduced by 50 to 80%. Loads to the East Branch of the Finniss River have decreased further over the last three decades, as some residual, AMD-impacted groundwater is flushed from the groundwater system.
- From 2010 to 2015, average SO_4 and Cu loads in the East Branch of the Finniss River were 1,840 t/year SO4 and 2.7 t/year Cu.
    - About 60% of the annual SO_4 load (and 80% of the annual Cu load) enters the groundwater system from the WRDs and other point sources of AMD, such as Dysons (backfilled) Pit and shallow contaminated soils in the former mill area and Copper Extraction Pad area).
    - About 40% reports to the East Branch of the Finniss River 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).

8.1.3 Updated Groundwater Flow Model

The 2012 groundwater flow model for Rum Jungle (RGC, 2012b) was updated using the updated conceptual model. The groundwater flow model was calibrated transiently using the groundwater elevation changes observed from December 2010 to March 2015 at 94 monitoring bores located across the site.

The key findings of this transient calibration of the groundwater flow model can be summarized as follows:

- The calculated NRMS values for the dry and wet season data sets are 3.6% and 3.2%, respectively. The computed NRMS values are well below the target NRMS of 5% suggesting good calibration to head targets. The calibrated model tends to show some bias (overprediction of heads) in the dry season but residuals do not show any systematic bias across the observed head range and lie on average within the acceptable target range of +/-1m.
- Model calibration indicated that a much better fit to the seasonal heads would be obtained by adjusting the soil moisture deficit (SMD) for the different model years. The calibrated SMDs ranged from a low of 102 mm for the 2014/2015 water year to a high of ~275 mm for the water years 2010/2011 and 2011/2012.
- Calibration of dry season water level trends could be improved by applying evapotranspiration to several areas with dense vegetation. Calibrated ET rates typically ranged from 1.5 to 2 mm/day. In selected areas, higher ET rates of 3.5 to 5 mm/day were required to match dry season recession trends.
- The calibrated hydraulic properties for overburden and bedrock units generally fall within the range of hydraulic properties determined during conceptual modelling. In general, the highest hydraulic conductivity in overburden was calibrated for laterite (and waste rock) while saprolite is less permeable. Calibrated hydraulic conductivity in bedrock units varied by 3-4 orders of magnitude, depending on lithology and depth. The highest permeability in bedrock was calibrated for the Coomalie dolostone, followed by bedrock of the Whites Formation and Rum Jungle Complex. Calibrated specific yield values in overburden units range from 1% to 10% and in bedrock units from 0.5 to 0.1%.
- The calibrated groundwater flow model provides a good representations of observed current groundwater flow conditions at the Rum Jungle mine site:
    - o The model reproduces the observed local flow field, i.e. groundwater flows from highlands to lower areas where it discharges to local drainage lines, the East Finniss River, the East Finniss Diversion Channel (EFDC) or the open pits.
    - o The model reproduces the observed seasonal variations in the water table (timing and amplitude).

- Sensitivity analyses indicated that the groundwater flow model is most sensitive to variations in horizontal hydraulic conductivity and recharge, with the specific yield of the overburden being significant to a lesser degree for the dry season.

8.1.4 Solute Transport Modelling

A solute transport model was developed to simulate historic and current groundwater quality for selected contaminants of concern (i.e. sulphate and copper). The overall objective of the solute transport modelling described herein was to develop a better understanding of the sources, geochemical controls and current extent of water quality impacts in groundwater at the Rum Jungle mine site. In addition, the results of this modelling effort provide a suitable benchmark (and initial conditions) for the prediction of future contaminant transport to assess the environmental effects of the preferred rehabilitation strategy.

A detailed, quantitative calibration of the transport model using historic time trends of groundwater quality at specific monitoring bores was not attempted. Instead, simplified historic and current flow and contaminant loading conditions were assumed and used in the numerical model to simulate current contaminant transport with the aim to reproduce a general, qualitative match to observed current groundwater quality conditions.

Two separate flow and transport models were set up covering different simulation periods:

- “Historic” flow & transport model covering 25 years of pre-rehabilitation conditions (1969 to 1984)
- “Current” flow & transport model covering 30 years of post-rehabilitation conditions (1985 to 2015)

The primary objective of the historic model was to develop suitable initial concentrations for the current transport model (immediately prior to rehabilitation).

The key findings of the sulphate transport modelling can be summarized as follows:

- The total historic sulphate load discharging to the receiving surface water is predicted to be about 4,062 t/yr. The simulated historic sulphate load explains about 93% of the historic sulphate load in groundwater estimated using conceptual modelling (4,349 t/yr).
- The total current sulphate load in groundwater discharging to the receiving surface water is predicted to be about 1,439 t/yr. This load represents only about 35% of the historic sulphate load in groundwater, i.e. a threefold decrease.
- The highest proportion of current sulphate load in groundwater is predicted to discharge in the reach of Fitch Creek, EFDC and Wandering Creek impacted by the Main WRD (32%), followed by the reach of EFDC and Wandering Creek near Intermediate WRD (28%).

- Although the current sulphate load to the Upper EBFR (Dysons area) has decreased (relative to pre-rehabilitation), the relative proportion of the total current load has increased to about 14%.
- Similarly, the relative proportion of current sulphate load to the Intermediate Pit (from CEPA and Intermediate WRD) has also increased to about 15%. Sulphate loading to the Main Pit has remained a minor component to total sulphate load (about 5 % of total).
- Sulphate loading to the lower EBFR (including Old Tailings Creek) has significantly declined (from 429 t/yr to 64 t/yr) due to the removal of the historic tailings. The current sulphate load to this reach of the model domain is predicted to be about 5 % of the total sulphate load.

For copper transport, three different attenuation scenarios were simulated:

- No Attenuation (conservative transport)
- Moderate Attenuation (sorption in overburden and bedrock and chemical precipitation in dolostone)
- High Attenuation (sorption in overburden and shallow bedrock beneath WRDs and chemical precipitation in all bedrock lithologies).

The key findings of the copper transport modelling can be summarized as follows.

- The total historic copper load discharging to the receiving surface water is predicted to range from a low of 15 t/yr (high attenuation) to a high of 38 t/yr (no attenuation). The difference in the copper mass reporting to the receiving surface water indicates the extent of removal of copper from the aqueous phase by sorption and precipitation:
  - 20 t/yr for moderate attenuation
  - 23 t/yr for high attenuation

  Note that a high retardation factor in bedrock (Rf=100 assumed for the moderate attenuation scenario) is almost as effective as a fully irreversible reaction in bedrock (assumed in the high attenuation scenario).
- Transient transport modelling for the period 1985 to 2015 indicates that the following has occurred as a result of the rehabilitation carried out in the 1980s:
  - While a substantial reduction in copper loading for all WRDs (due to cover placement in 1984/85) does not significantly change the spatial extent of the associated copper plumes in groundwater, the copper concentrations in both overburden and bedrock have decreased significantly as a result of reduced loading.
  - The removal of the ore stockpiles in the former mill site have reduced the copper load and hence copper concentrations in groundwater in that area (north-east of the Main Pit).
  - Removal of the historic tailings from the OTD area has resulted in significant clean-up of the historic copper plume in this area.

- A comparison of the copper plume predicted for conservative behaviour (i.e. no chemical attenuation) with the copper plumes simulated for the scenarios of moderate and high attenuation illustrate the influence of geochemical controls on current copper transport. The key observations can be summarized as follows:
  - Moderate sorption assumed in the shallow soils (R=3.5 in layers 1 and 2) does not significantly influence copper concentrations in those layers, except near the margin of the plume. Travel times in the shallow soils tend to be short (< 2-5 years) and a threefold increase in travel time (retardation) does not significantly delay the plume advance over a 30-year modelling period.
  - Strong sorption assumed in bedrock (R=100 in all lithologies except dolostone) significantly delays copper transport in bedrock. In areas where current copper source concentrations have declined, higher residual copper concentrations remain present ("trapped") in deeper bedrock due to slow travel velocities and retardation.
  - Chemical precipitation assumed for dolostone (moderate and high attenuation scenarios) and for all other bedrock lithologies (high attenuation scenario) completely removes copper from the aqueous phase, thus effectively eliminating any copper plume in those bedrock units. In the moderate attenuation scenario, this affects primarily the copper plume in the OTD area. In the high attenuation scenario, copper is precipitated out in all bedrock units (except in shallow bedrock (layer 3) beneath mine waste units where historic leaching is assumed to have depleted any buffering capacity).
- The total current copper load discharging to the receiving surface water is predicted to range from a low of 1.1 t/yr (high attenuation) to a high of 3.1 t/yr (no attenuation). This represents a 14 to 12-fold reduction in copper load from groundwater to surface water since rehabilitation in the mid-1980s.
- The moderate attenuation scenario predicts only a slightly lower copper load (2.7 t/yr) than the conservative scenario (3.1 t/yr), indicating the relatively small effect of attenuation of copper in bedrock under current conditions.
- Seepage from the Intermediate WRD represents the highest source of current copper load, followed by seepage from the Main WRD, CEPA (to Intermediate Pit) and Dysons WRD/backfilled Pit.
- Residual copper loading from the former mill site and the OTD are not predicted to be a major source of copper loading for current conditions (for all attenuation scenarios).

Based on a comparison of simulated and observed spatial distribution of copper concentrations in groundwater and load estimates of copper in the EBFR today, the "moderate attenuation" scenario is considered to be the scenario that most closely represents current copper transport at Rum Jungle and should be used for predictive modelling.

However, there is significant uncertainty in reactive transport modelling and the high attenuation scenario (featuring irreversible reaction in bedrock) cannot be ruled out at this time. Furthermore, the “no attenuation“ scenario provides a useful, albeit likely unrealistic, reference scenario representing conservative transport. Consequently, these two attenuation scenarios for copper should also be included in predictive modelling to evaluate the sensitivity of predicted post-rehabilitation performance to uncertainty in geochemical controls.

8.2 PATH FORWARD

The calibrated groundwater flow and solute transport model described here is a suitable tool for predictive modelling to inform planning of active rehabilitation strategies (e.g. CEPA clean-up, pit dewatering, water management and treatment) and environmental assessment of the rehabilitation plan:

- Designing the remediation strategy for groundwater in the Copper Extraction Pad area.
- Modelling groundwater inflows to the Main and Intermediate Pits when they are partially de-watered during the construction phase of rehabilitation.
- Modelling future contaminant transport in groundwater as residual plumes are flushed and new loads from backfilled Main Pit and the new WSF report to groundwater.

Groundwater modelling in support of groundwater remediation design (pump-and-treat) for the impacted groundwater in the CEPA area is summarized in RGC Report No. 183006/5 entitled “*Groundwater Remediation Strategy for the former Copper Extraction Pad area*” (RGC, 2016e).

Groundwater inflow estimates during Main Pit dewatering are discussed in RGC Report No. 183006/3 entitled “*Options Assessment for Pit Backfilling*” (RGC, 2016c) and RGC Report No. 183006/4.entitled “*Conceptual Water Management and Treatment Plan for Construction Phase of Rehabilitation (Progress Report)*” (RGC, 2016d).

The 2016 flow and transport model has also been modified to assess post-closure conditions and inform the environmental performance of the preferred rehabilitation strategy (see RGC, 2016g). Modifications to the model required for assessment of post-rehabilitation conditions included:

- Adjustment of surface topography to reflect post-closure conditions (e.g. removal of WRDs, realignment of EBFR channel in CMA, backfilled Main Pit, new WSF)
- New source terms for sulphate and copper to reflect removal of current contaminant sources (e.g. WRDs, Copper Extraction Pad area, contaminated soils) and introduction of new contaminant sources (backfilled waste rock in Main Pit, new WSF)

The simulated sulphate and copper concentrations for current conditions will be used as initial concentrations for prediction of post-closure groundwater quality and contaminant loading to surface water. The methods and results of transport modelling of selected contaminants of concern for post-rehabilitation conditions (using MT3DMS) are described in RGC Report No. 183006/7 entitled "*Environmental Performance Assessment for the Preferred Rehabilitation Strategy*" (RGC, 2016g).

9 CLOSURE

Robertson GeoConsultants Inc. is pleased to submit this report entitled 'Groundwater Flow and Transport Model for Current Conditions, Rum Jungle'.

This report was prepared by Robertson GeoConsultants Inc. for the use of the NT Department of Mines and Energy and prior consent by the Department is required before the contents of this report are considered by any third party.

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,

ROBERTSON GEOCONSULTANTS INC.

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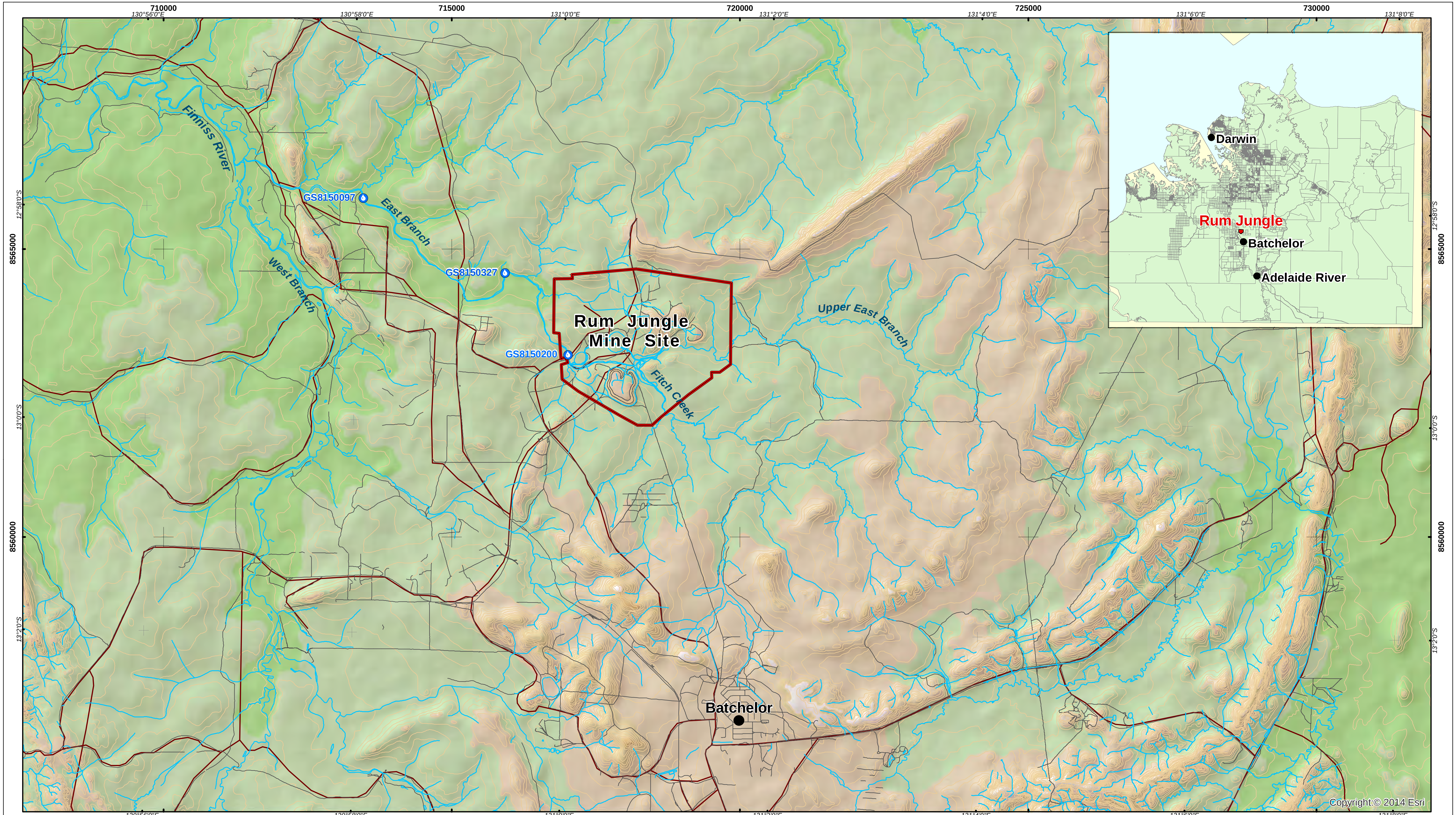
END

FIGURES



Location, Regional Topography and Drainage

near Rum Jungle Mine Site

N W E S

Scale 1:60,000

0 0.5 1 2 3 4 5 Km

Projection: GDA 1994 MGA Zone 52 (m)

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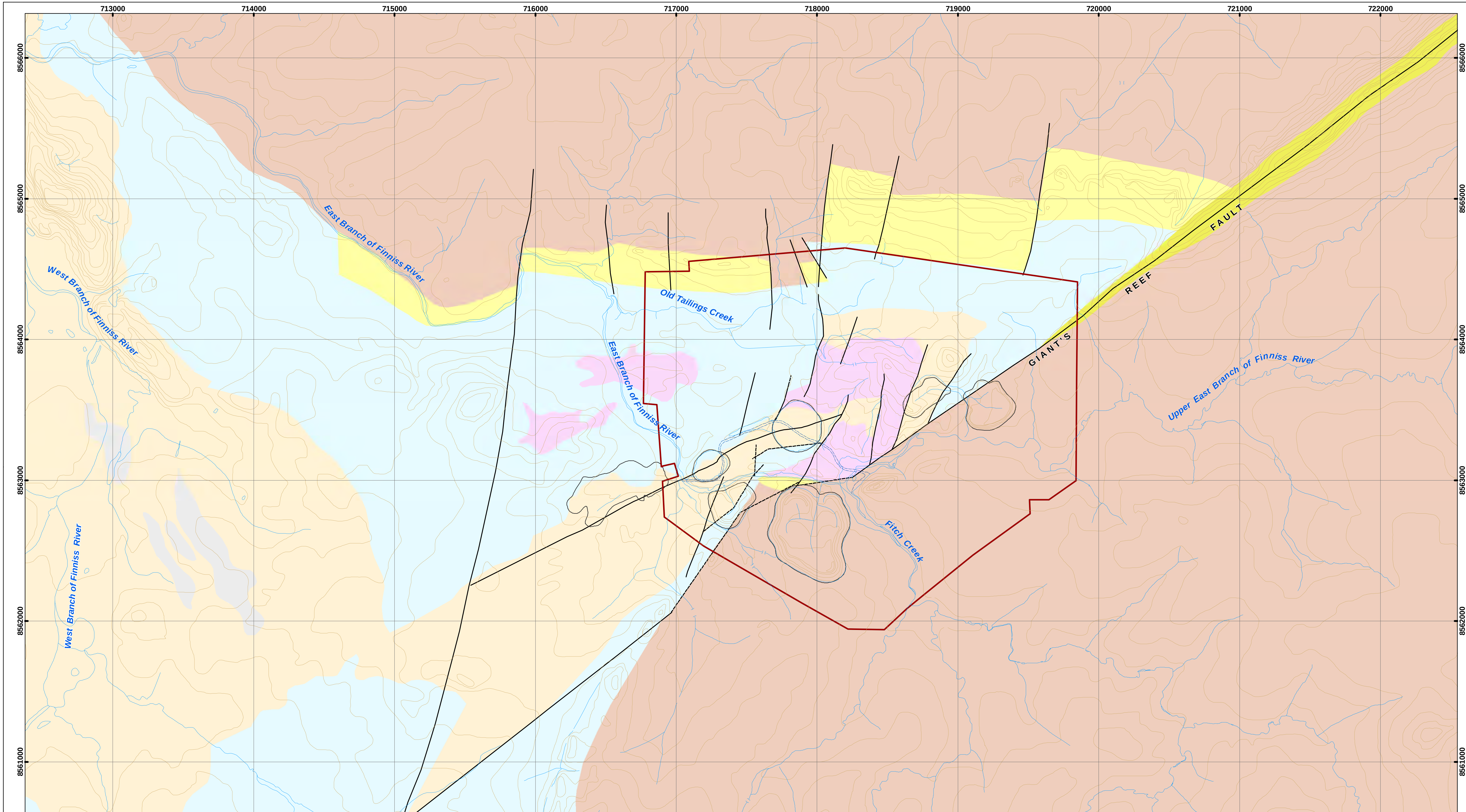
Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 2-1
Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 08, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure2-1_RJ_MineSite_60K.mxd	



Lithology

- Whites Formation
- Geolsec Formation
- Coomalie Dolostone
- Crater Formation
- Quartz Vein
- Rum Jungle Complex
- Historical Mining Footprint
- Drainage
- Fault
- Mine Site Boundary

Regional Geology near the Rum Jungle Mine Site

Rum Jungle Mine Site

Scale 1:25,000

0 500 1,000 2,000 Metres

Projection: GDA 1994 MGA Zone 52 (m)

N E S W

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Client: Northern Territory Government Department of Resources - Minerals and Energy	Figure: 2-2
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: May 31, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure2-2_RJ_Litho_May2016.mxd	

Graphic	Formation	Lithology	Depositional Environment	Age	Geological Province
	Geolsec Formation	Hematitic paraquartzite breccia, milky quartz & chert breccia; hematitic mudstone, siltstone and sandstone; minor phosphatic siltstone and breccia	Shallow marine	Paleoproterozoic	
	Whites Formation	Calcareous & carbonaceous pyritic argillite, dololutite & dolarenite, rare quartzite	Marine, euxinic	Proterozoic	Mount Partridge Group
	Coomalie Dolostone	Stromatolitic magnesite, dolostone, some silicified, para-amphibolite, metapelite	Subtidal, evaporitic		
	Crater Formation	Quartz-pebble arkose, poorly sorted BIF-quartz pebble-boulder conglomerate, sandstone, siltstone, shale	Fluvial		
	Rum Jungle Granite	Coarse, medium, and porphyritic adamellite, biotite-muscovite granite, migmatite, gneiss, schist, pegmatite, metadiorite, banded iron formation		Archean	Rum Jungle Complex

Stratigraphic Sequence and Lithologies at the Rum Jungle Mine Site

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 2-3
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 31 May, 2016
Original File: Figure2-3.pptx	

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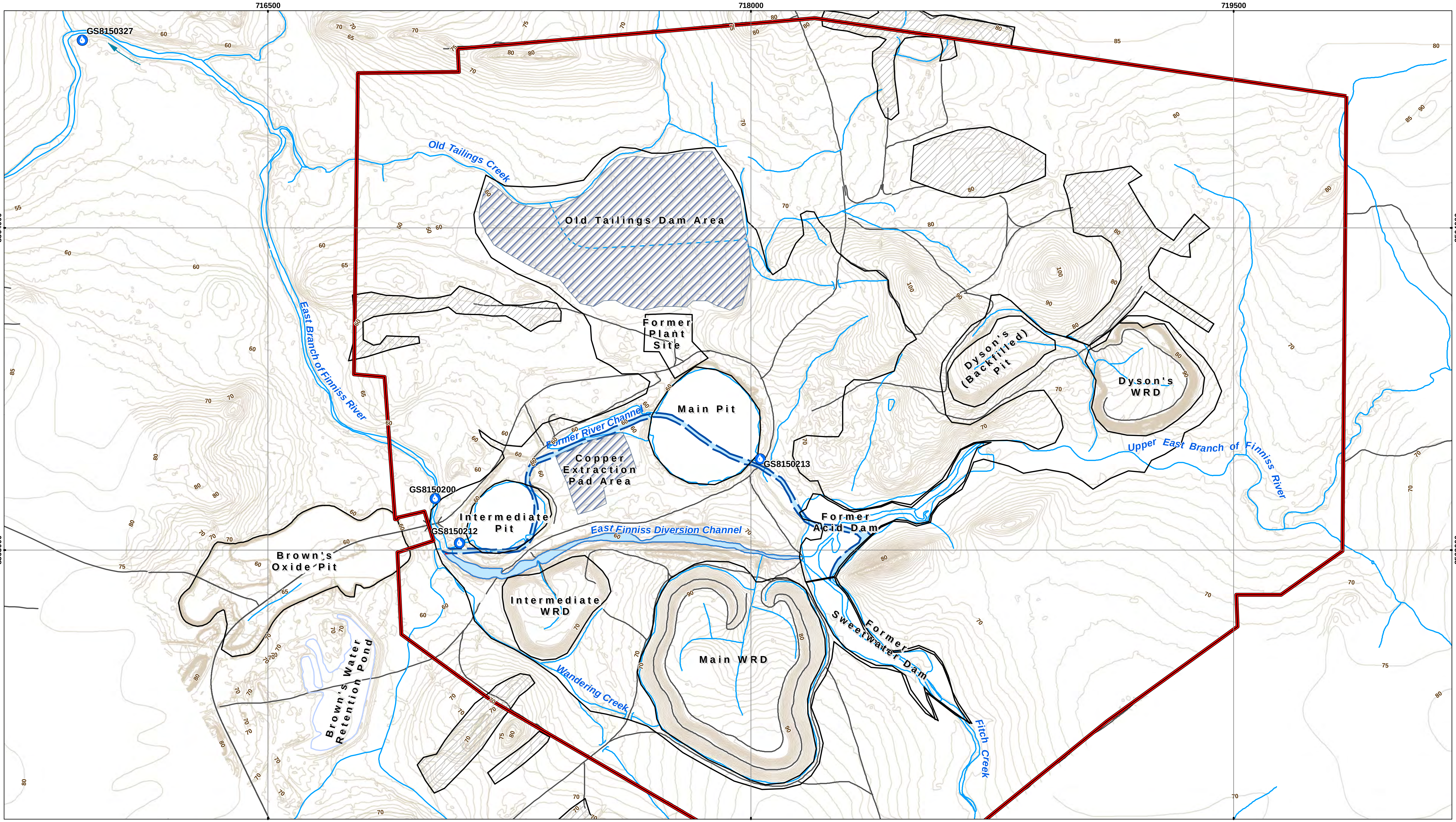

LEGEND

- Stream Gauge
- Drainage
- Road
- Property Boundary
- Borrow Pit

Site Layout Plan

Rum Jungle Mine Site

Scale 1:11,000

0 50 100 200 300 400 500 600 700 800 Metres

Projection: GDA 1994 MGA Zone 52 (m)

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Client: Northern Territory Government	Figure: 2-4
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 07, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure2-4_RJ_MineSiteLayout_May2016.mxd	

Air Photo of Rum Jungle Mine Site

Prior to Rehabilitation (early 1980s)

NT, Australia

Scale 1:10,000

0 50 100 200 300 400 500 600 700 800 900 1,000 Metres

Projection: GDA 1994 MGA Zone 52 (m)

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Client: Northern Territory Government	Figure: 2-5
Project: Specifications-2014 Hydrogeological Drilling Program	Project No: 183006
Report: RGC 183006/6	Last Update: Dec 09, 2015
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure2-5_RJ_mine_ortho1980_2011.mxd	

Air Photo of Rum Jungle & Browns Oxide

Current Conditions (2010)

NT, Australia

Scale 1:9,000

0 50 100 200 300 400 500 600 700 800 900 Metres

Projection: GDA 1994 MGA Zone 52 (m)

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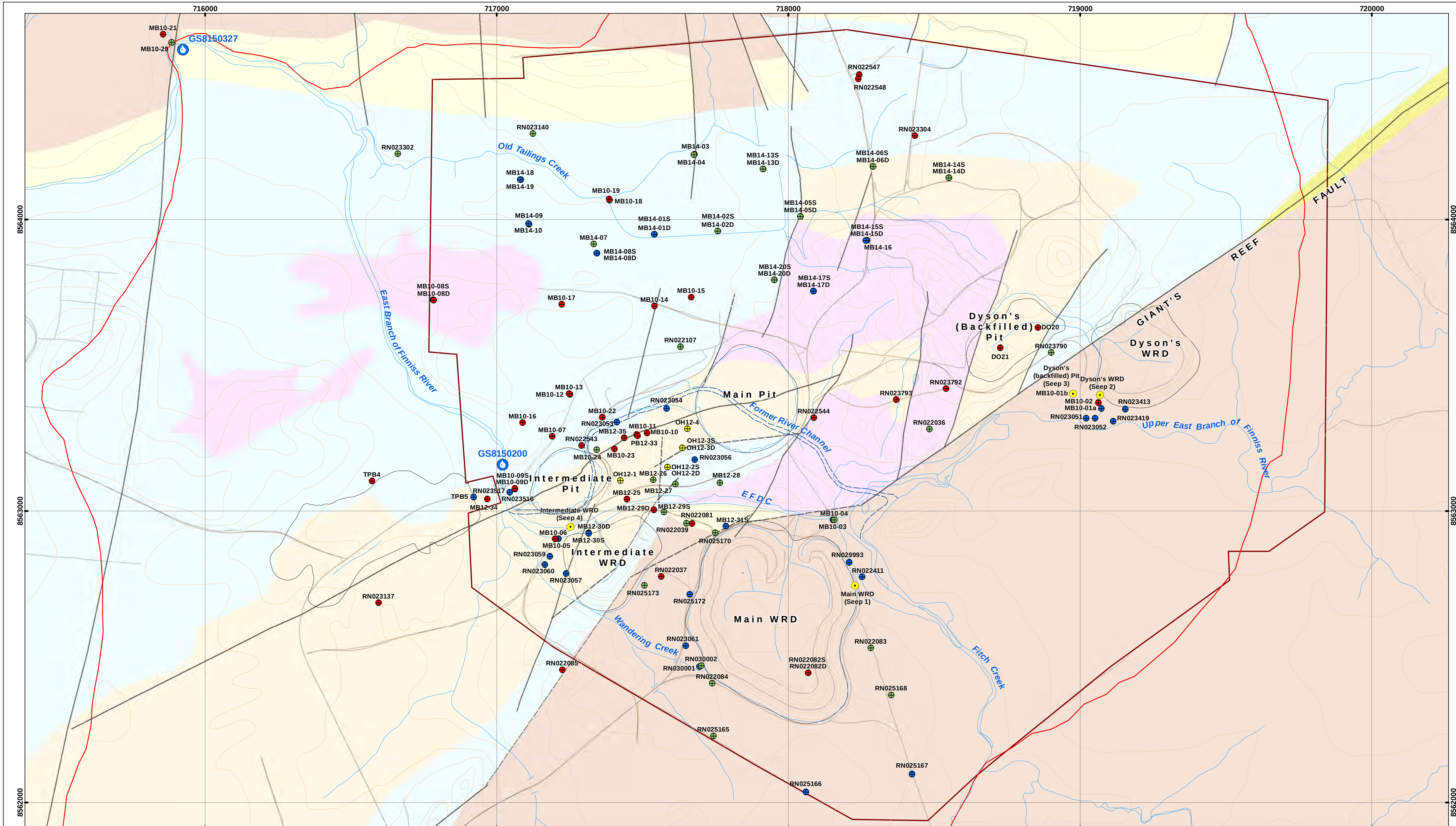
Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 2-6**
Project: Specifications-2014 Hydrogeological Drilling Program	Project No: 183006
Report: RGC 183006/6	Last Update: Dec 09, 2015
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure2-6_RJ_mine_ortho2010_2011.mxd	



LEGEND

- Groundwater Bore (Depth <5m)
- Groundwater Bore (Depth from 5 to 15m)
- Groundwater Bore (Depth >15m)
- Groundwater Bore (Open Hole)
- Seep
- Drainage
- Road
- Fault
- Mine Site Boundary
- Model Domain
- Stream Gauge

Lithology

- Whites Formation
- Geolsec Formation
- Coomalie Dolostone
- Crater Formation
- Quartz Vein
- Rum Jungle Complex

Groundwater Monitoring Bore Network

Rum Jungle Mine Site

Scale 1:12,000

0 50 100 200 300 400 500 600 700 800 900 1,000 Metres

Projection: GDA 1994 MGA Zone 52 (m)

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Client: Northern Territory Government	**Figure: 2-7**
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 08, 2016
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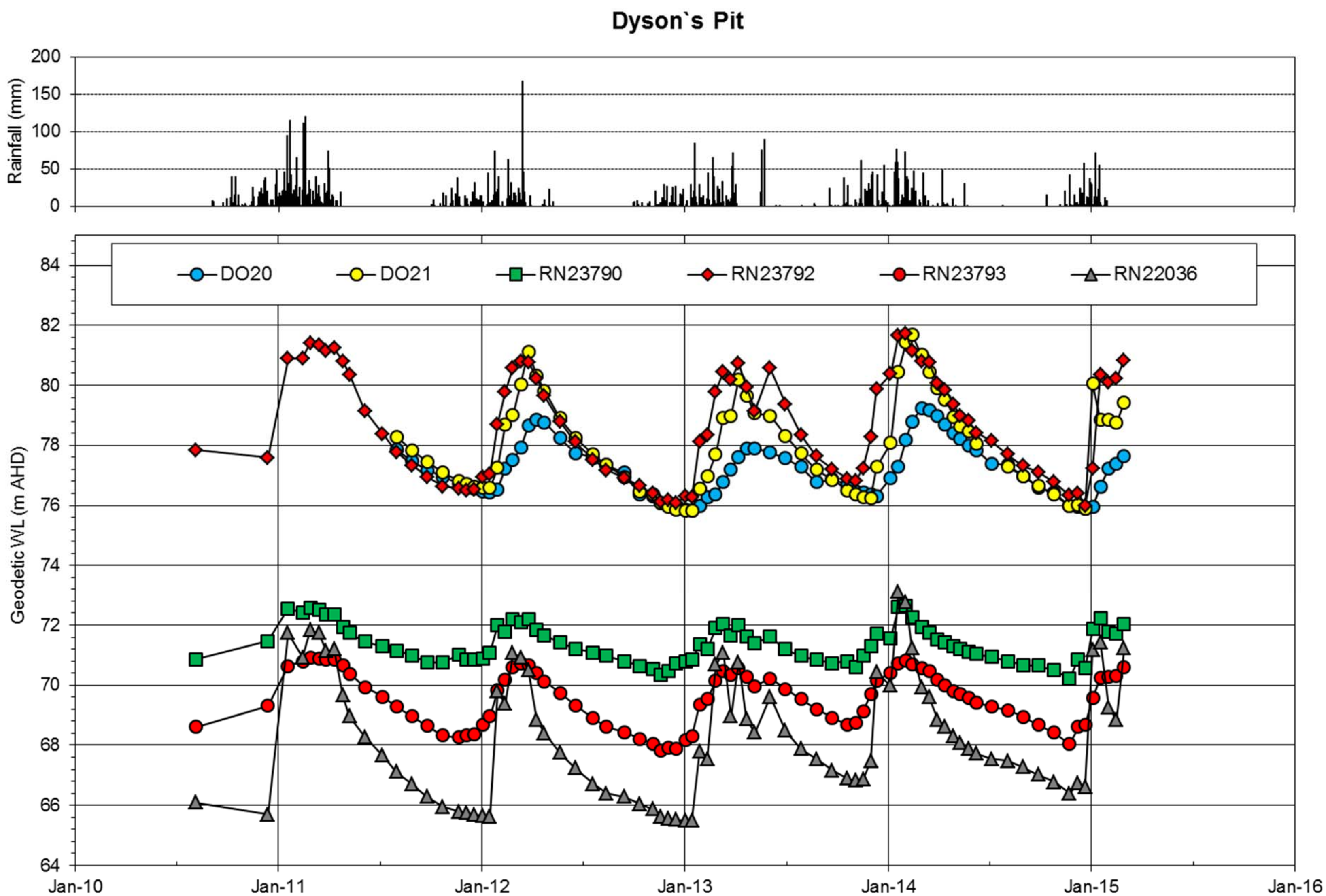

Groundwater Levels in Dyson's Area
2010 - 2015

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 3-1a
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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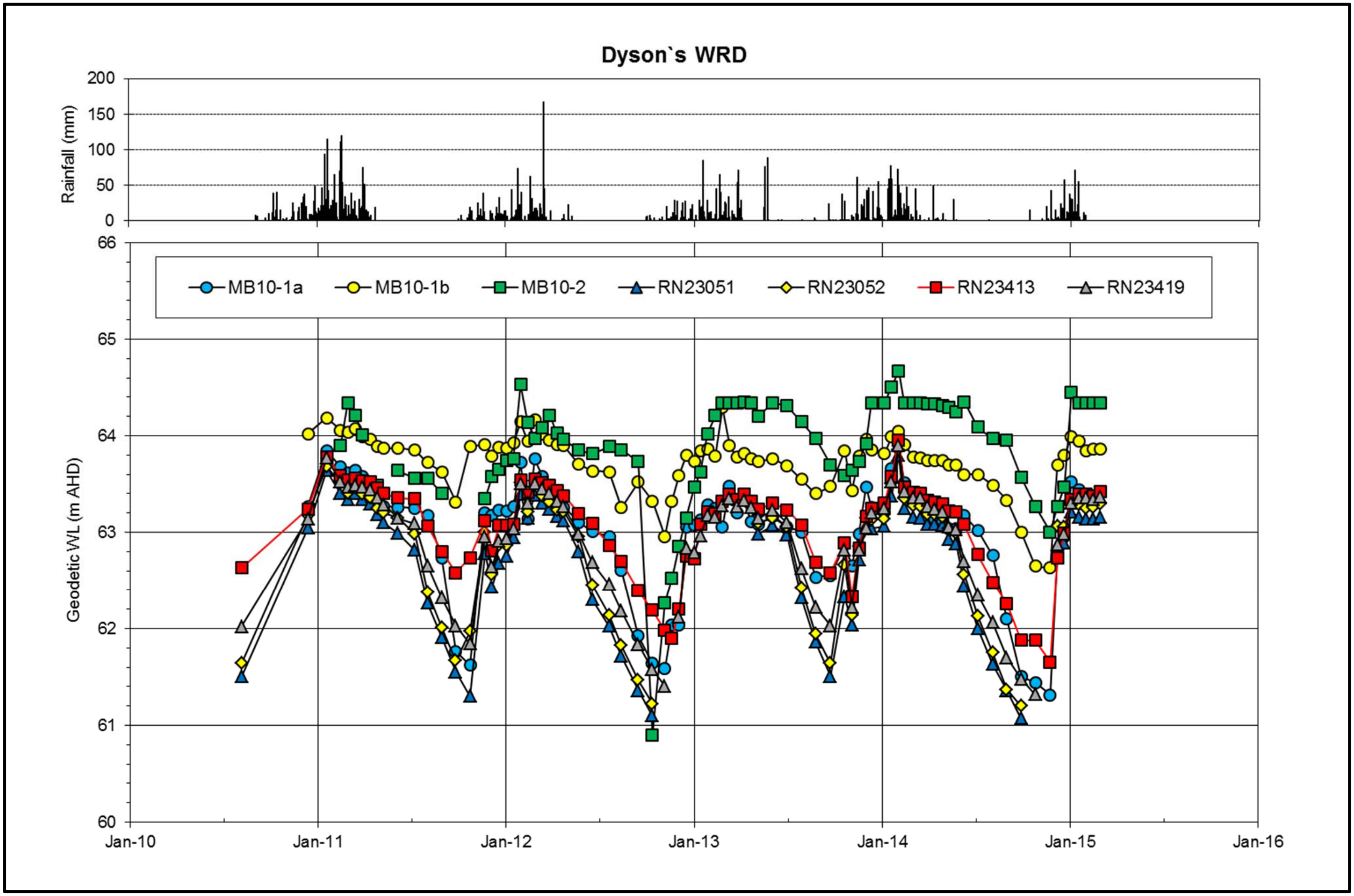
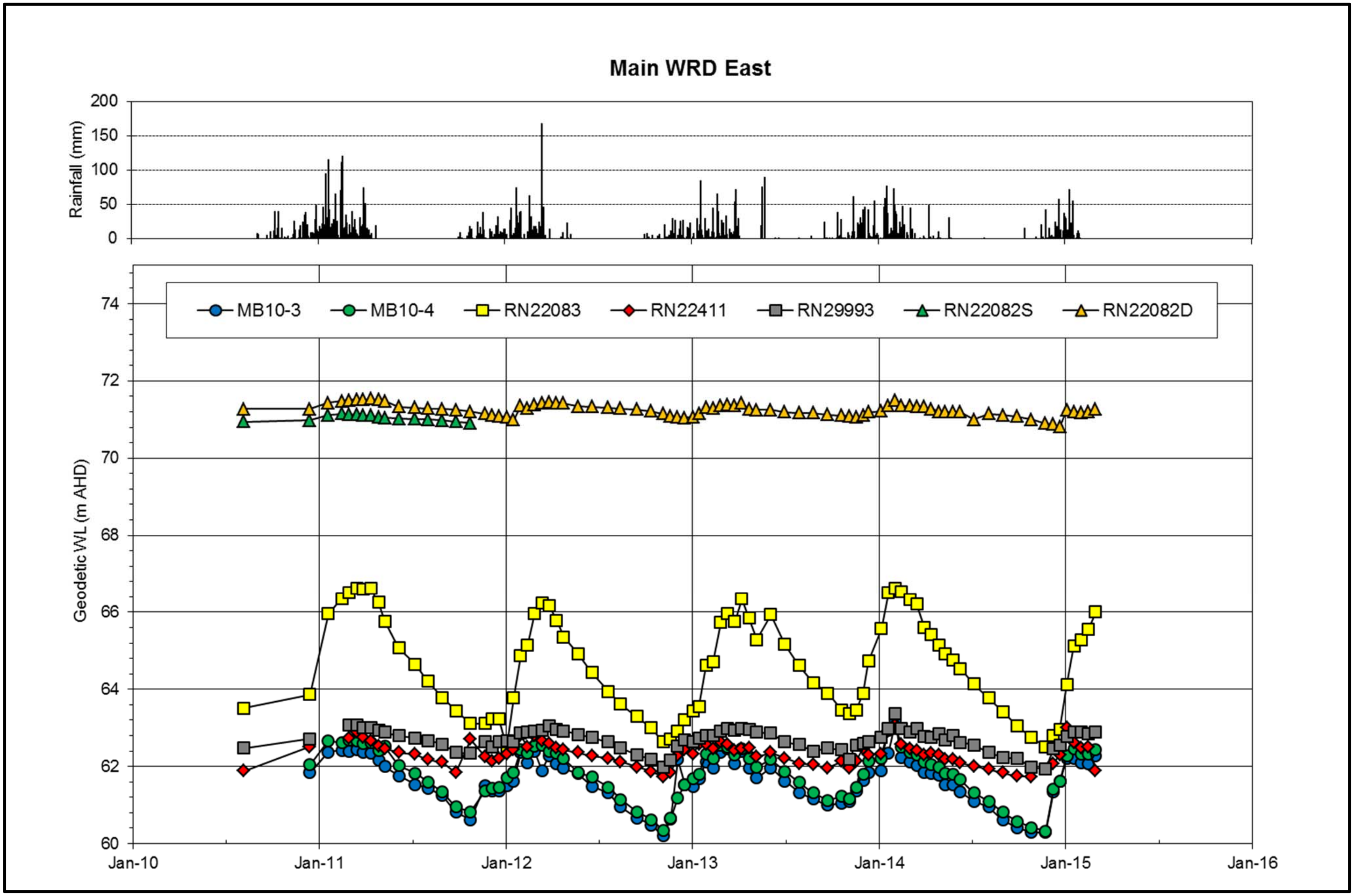


Groundwater Levels in Dyson's Area
2010 - 2015

Robertson GeoConsultants Inc.

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 3-1b
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	



Groundwater Levels Near the Main and Intermediate WRDs 2010 - 2015

Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 3-2a**
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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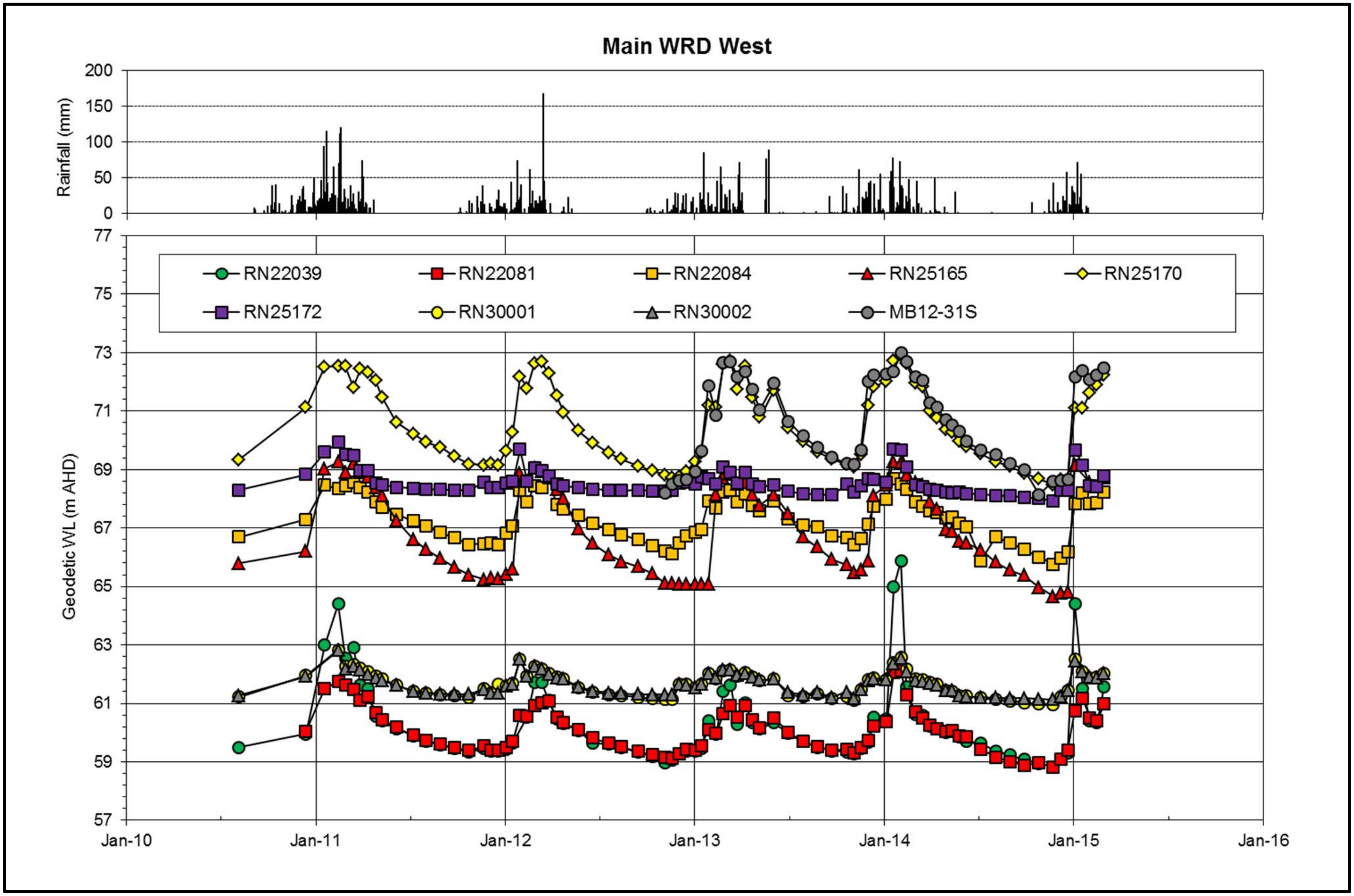

Groundwater Levels Near the Main and Intermediate WRDs 2010 - 2015

Client: Northern Territory Government Department of Resources - Minerals and Energy	Figure: 3-2b
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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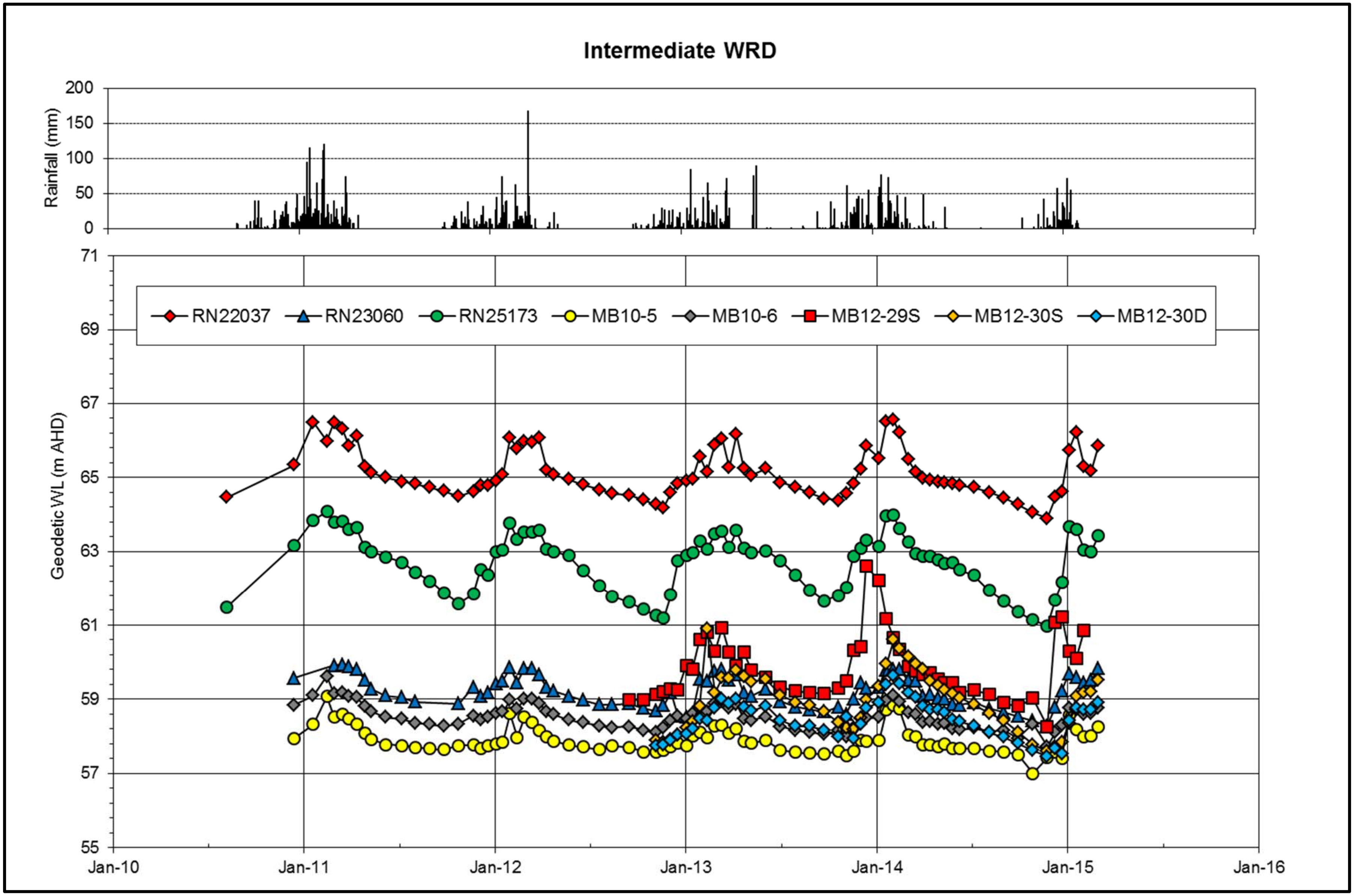

Groundwater Levels Near the Main and Intermediate WRDs 2010 - 2015

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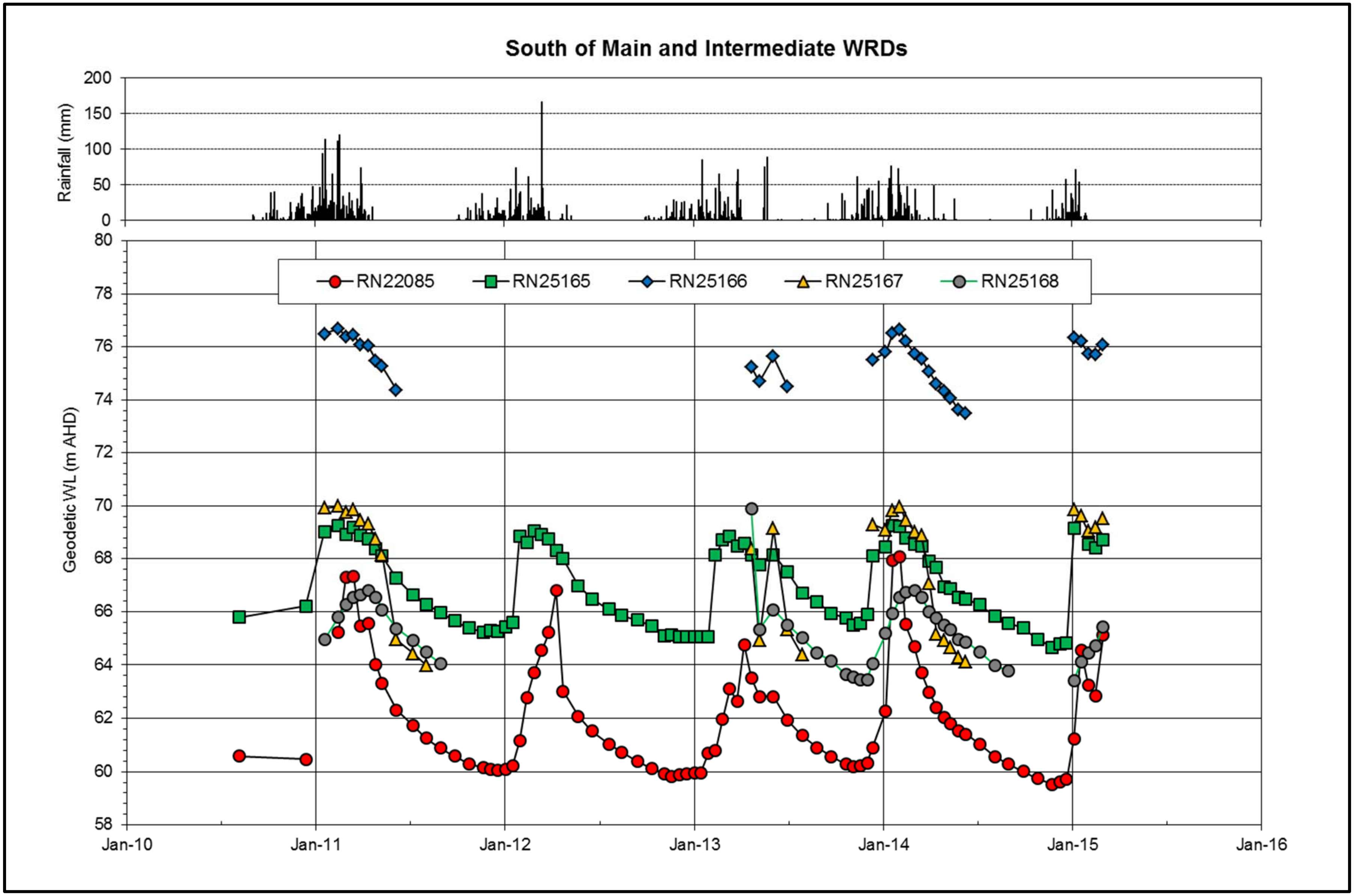
Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 3-2c**
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	



Groundwater Levels Near the Main and Intermediate WRDs 2010 - 2015

Client: Northern Territory Government Department of Resources - Minerals and Energy	Figure: 3-2d
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
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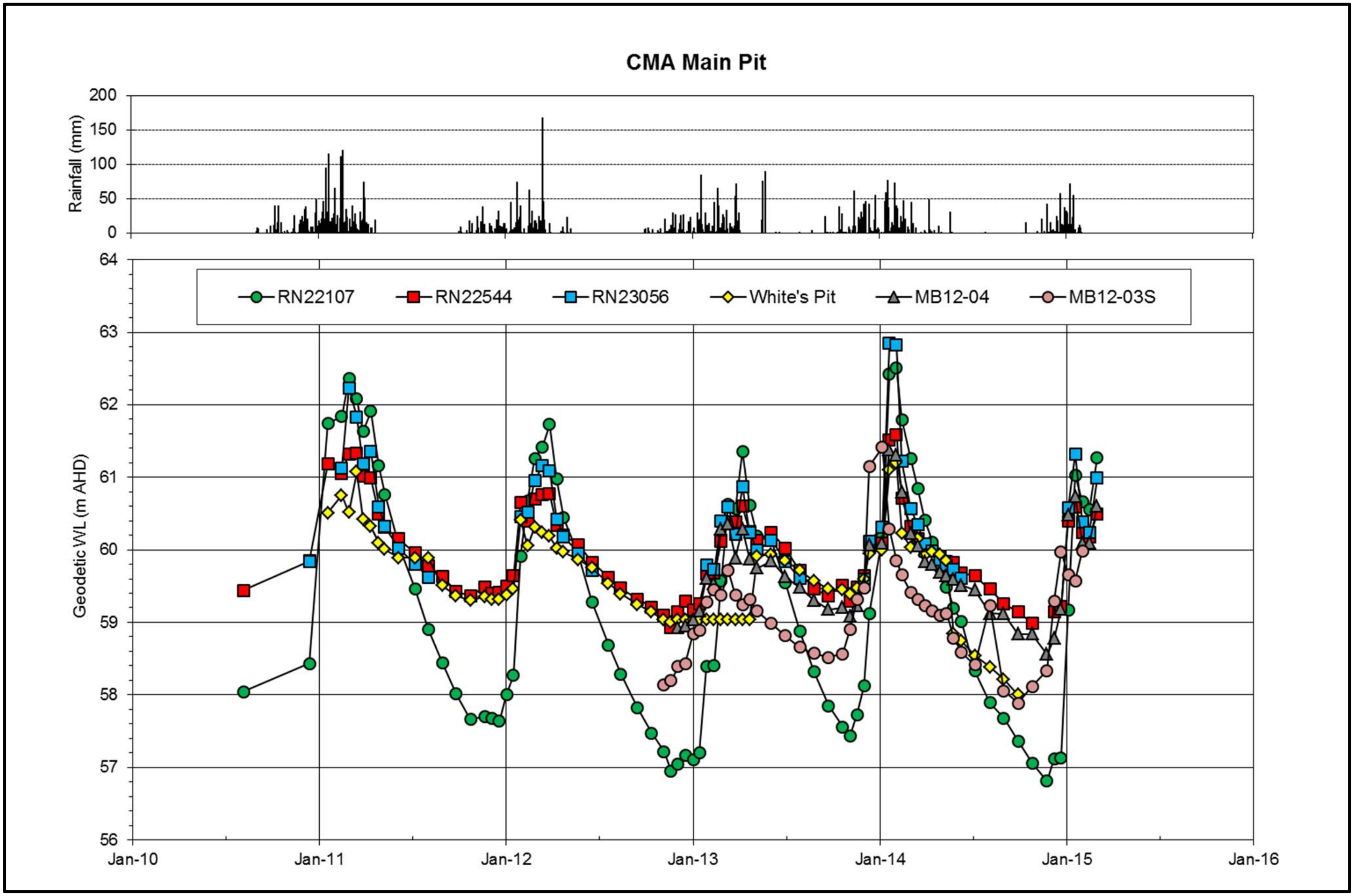

Groundwater Levels in the Central Mining Area 2010 - 2015

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 3-3a
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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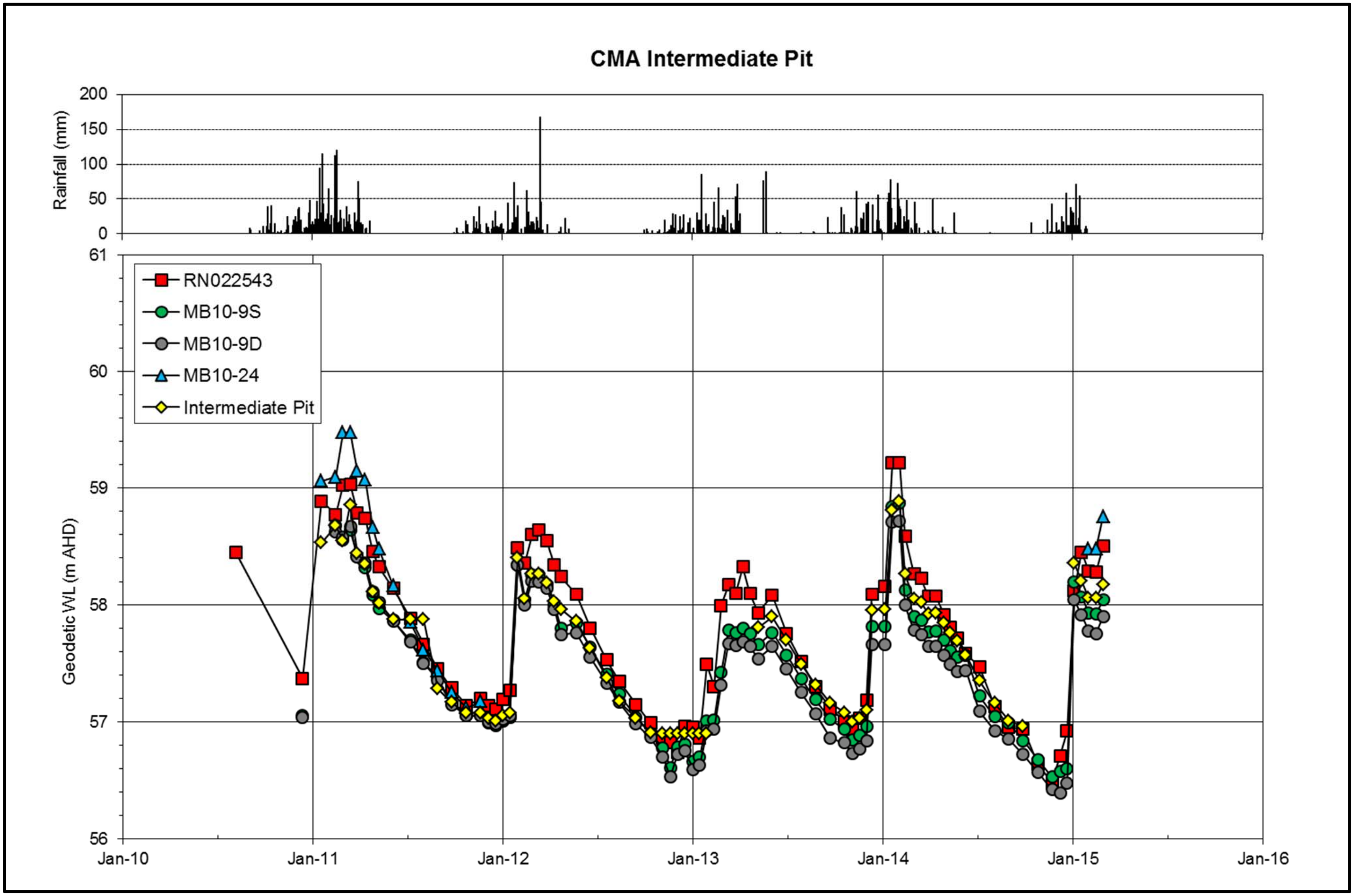

Groundwater Levels in the Central Mining Area 2010 - 2015

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 3-3b
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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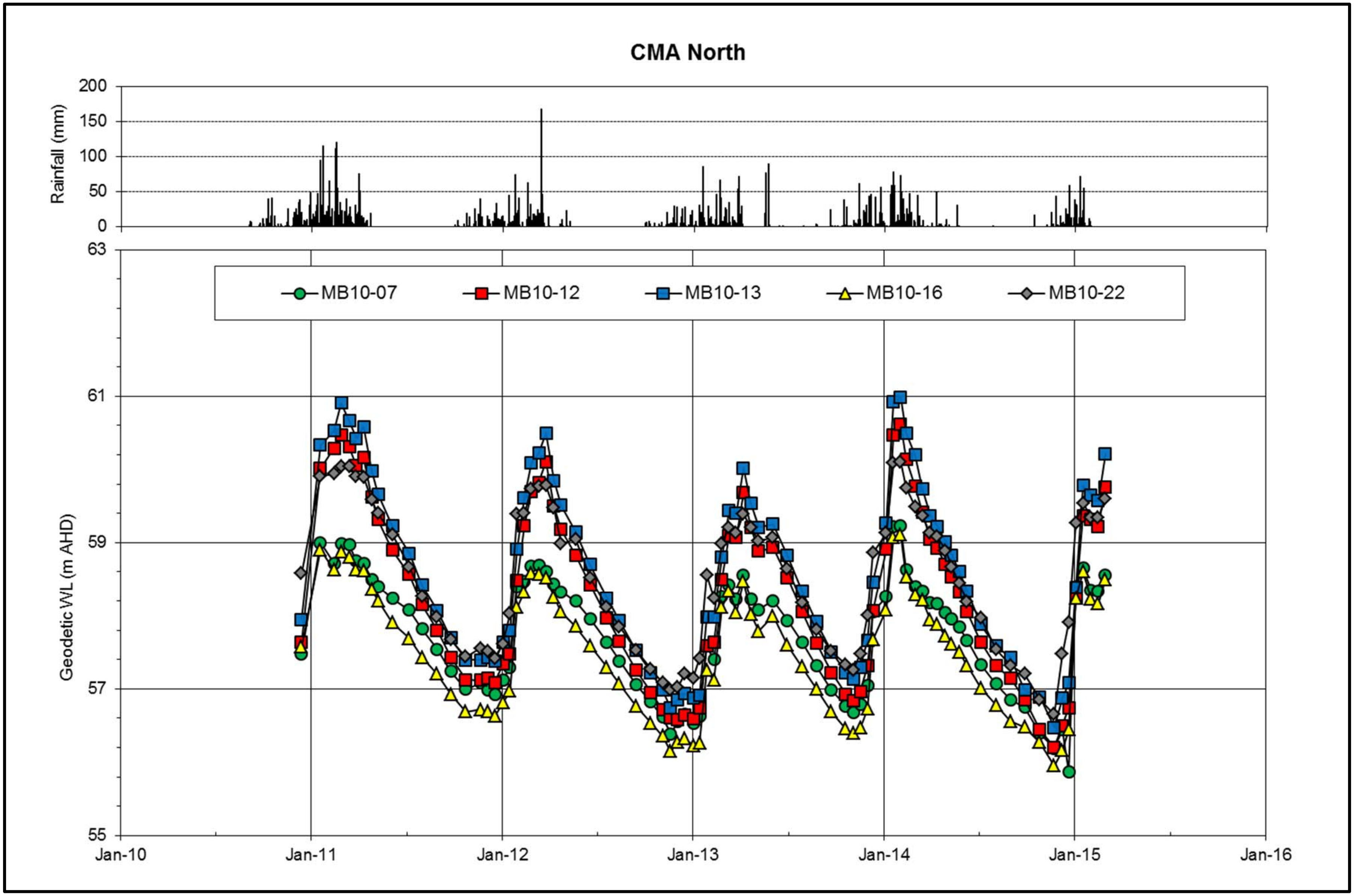

Groundwater Levels in the Central Mining Area 2010 - 2015

Client: Northern Territory Government Department of Resources - Minerals and Energy	**Figure: 3-3c**
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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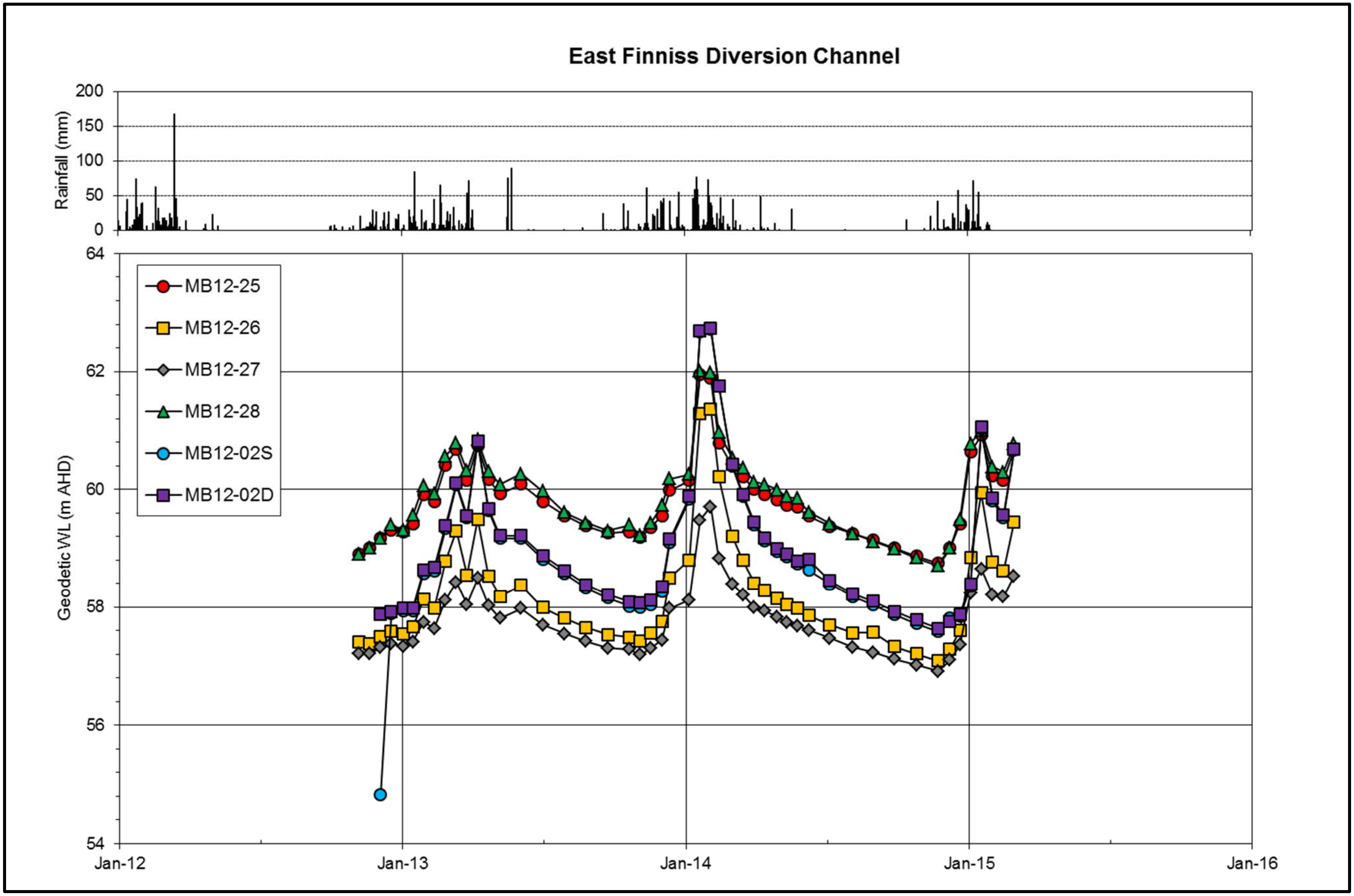

Groundwater Levels in the Central Mining Area 2010 - 2015

Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 3-3d**
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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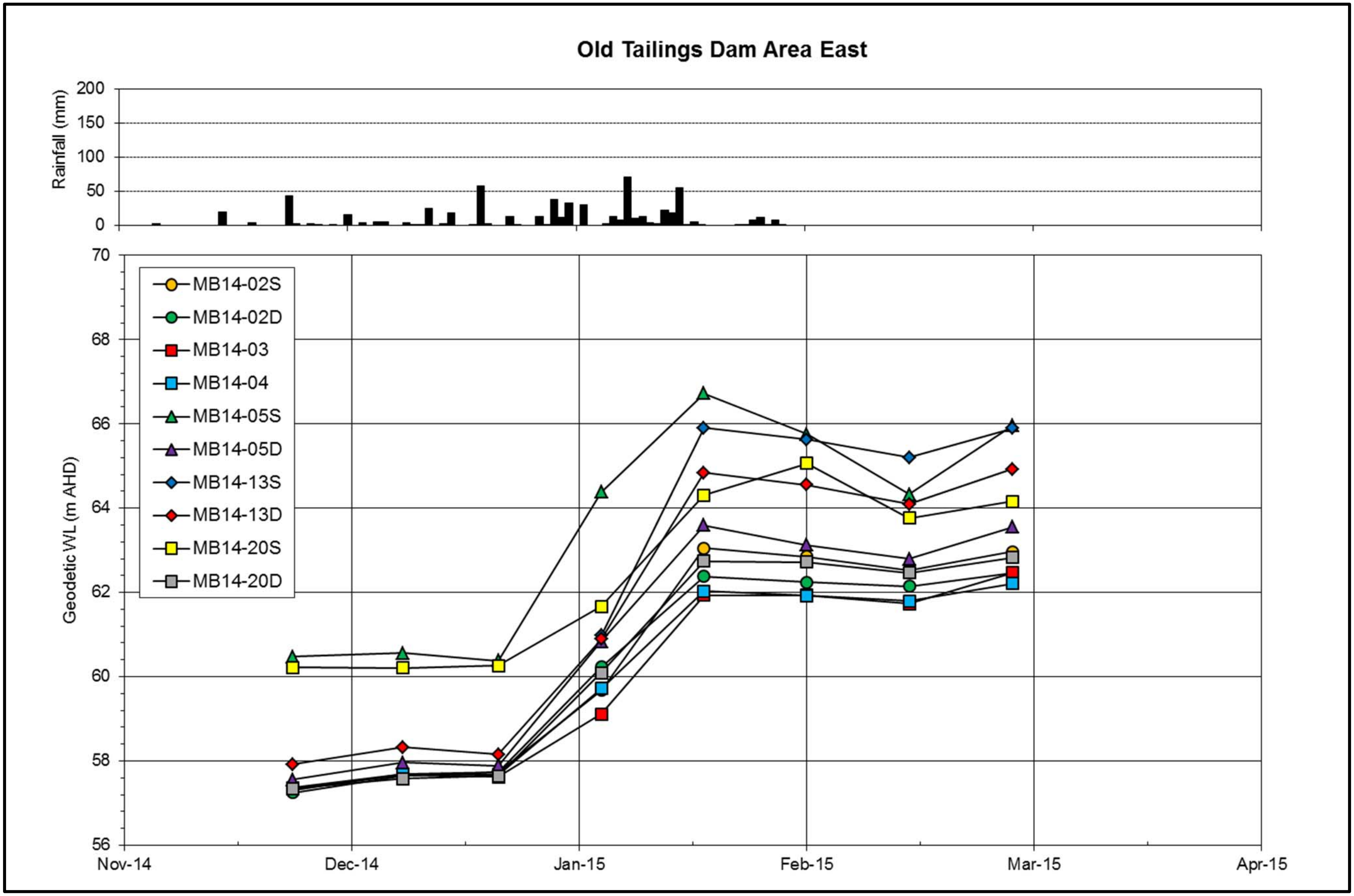

Groundwater Levels in the Old Tailings Dam Area 2010 - 2015

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 3-4a
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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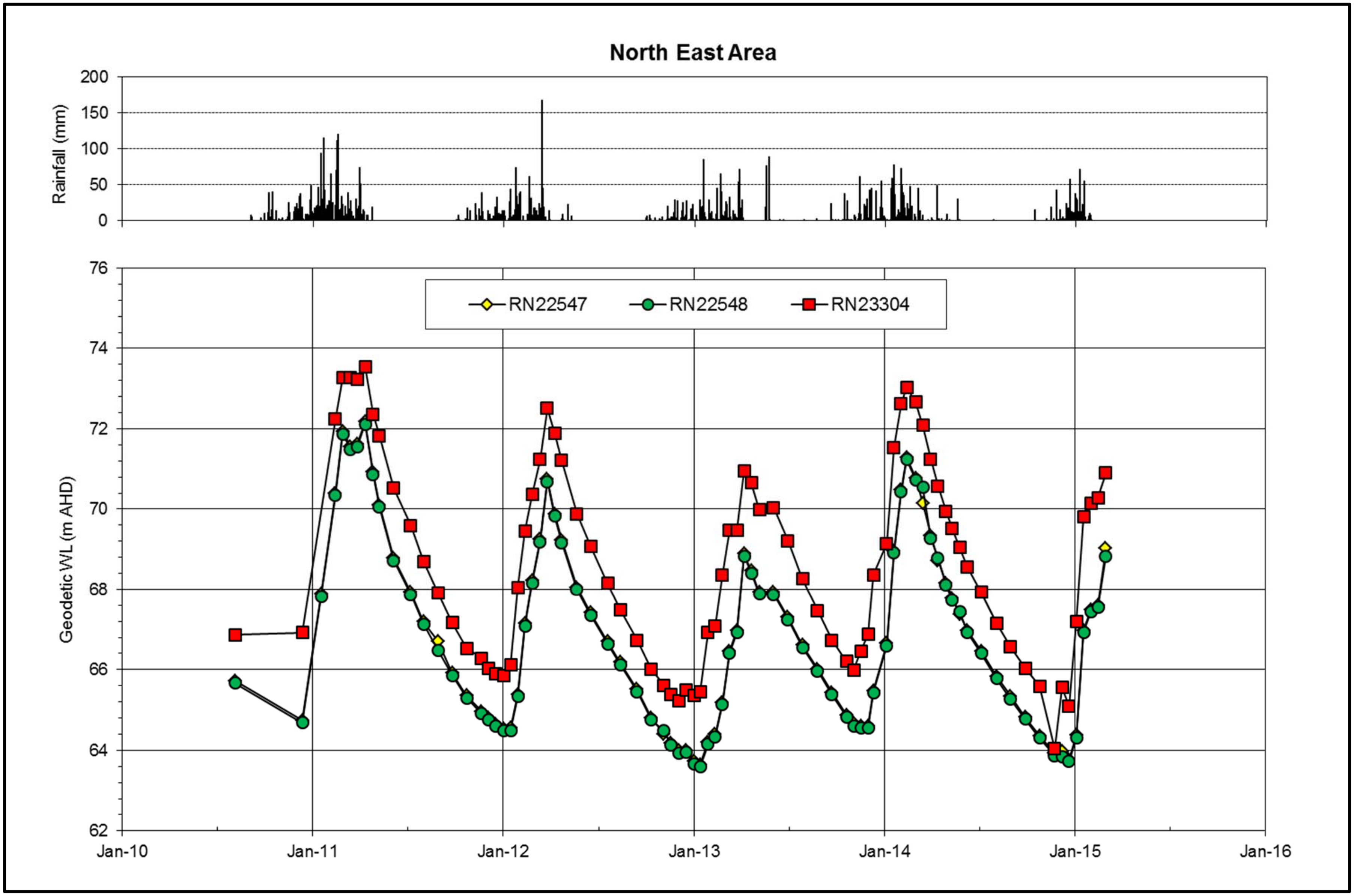

Groundwater Levels in the Old Tailings Dam Area 2010 - 2015

Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 3-4b**
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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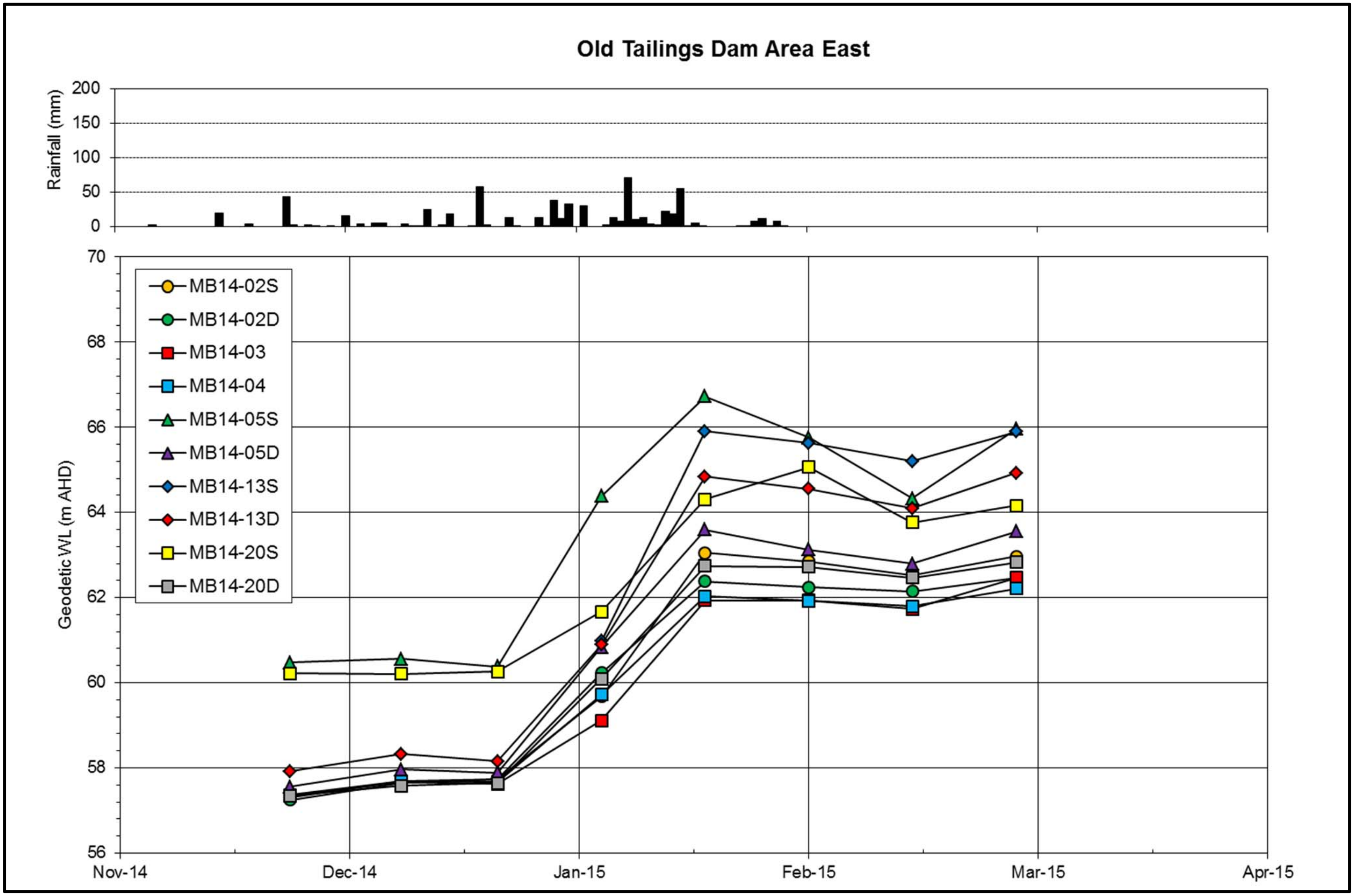

Groundwater Levels in the Old Tailings Dam Area 2010 - 2015

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 3-4c
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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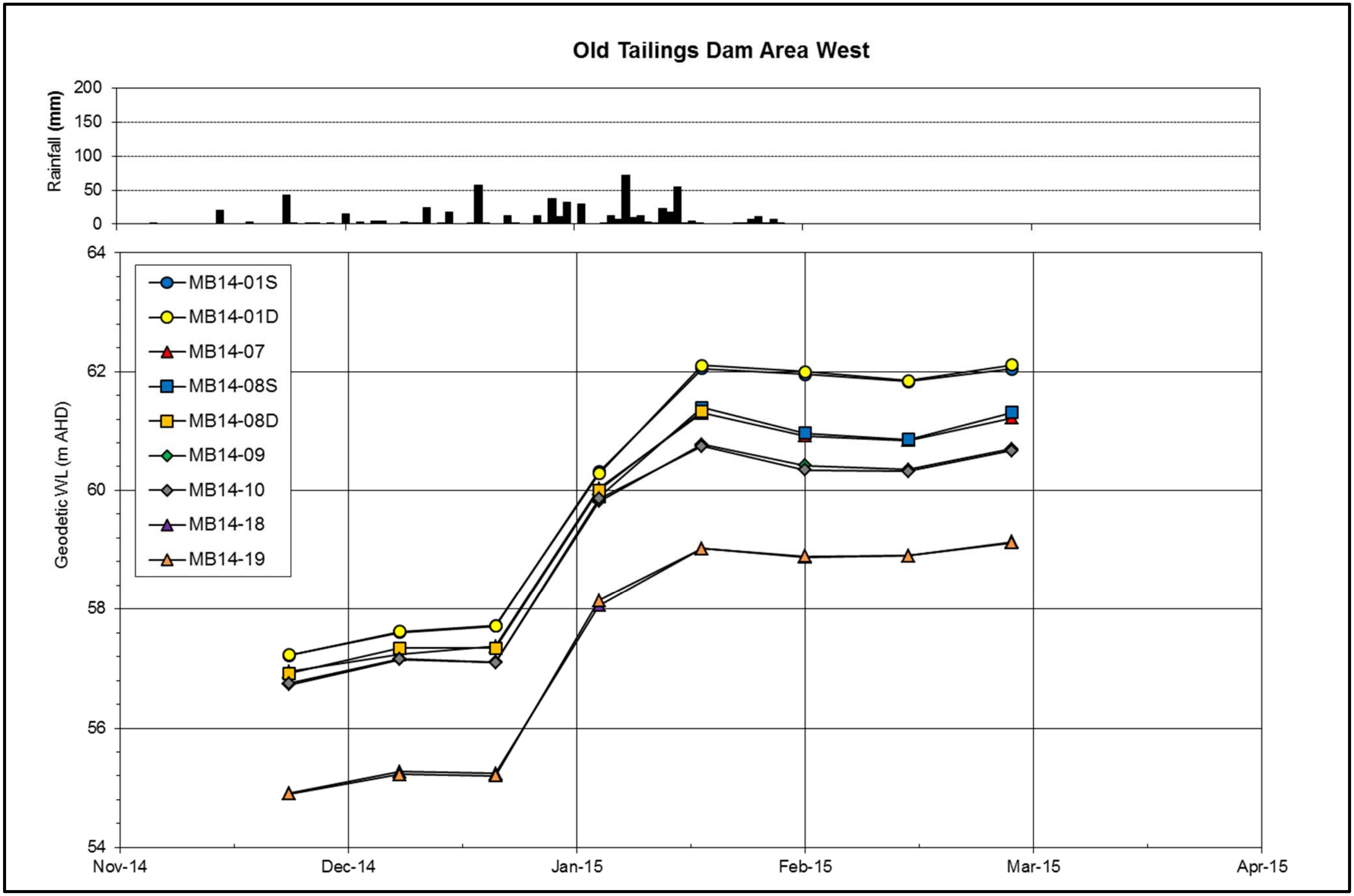

Groundwater Levels in the Old Tailings Dam Area 2010 - 2015

Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 3-4d**
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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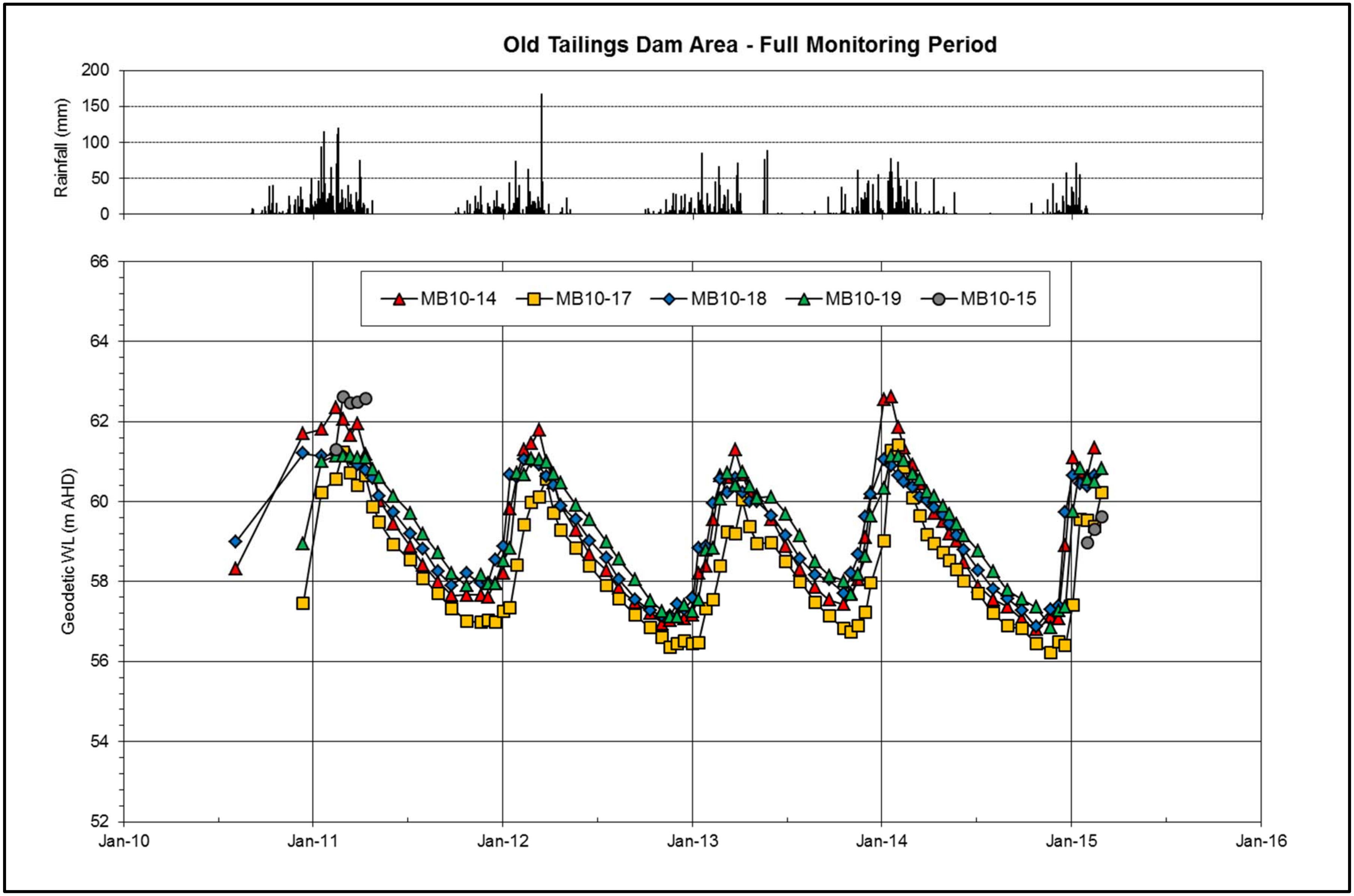

Groundwater Levels in the Old Tailings Dam Area 2010 - 2015

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 3-4e
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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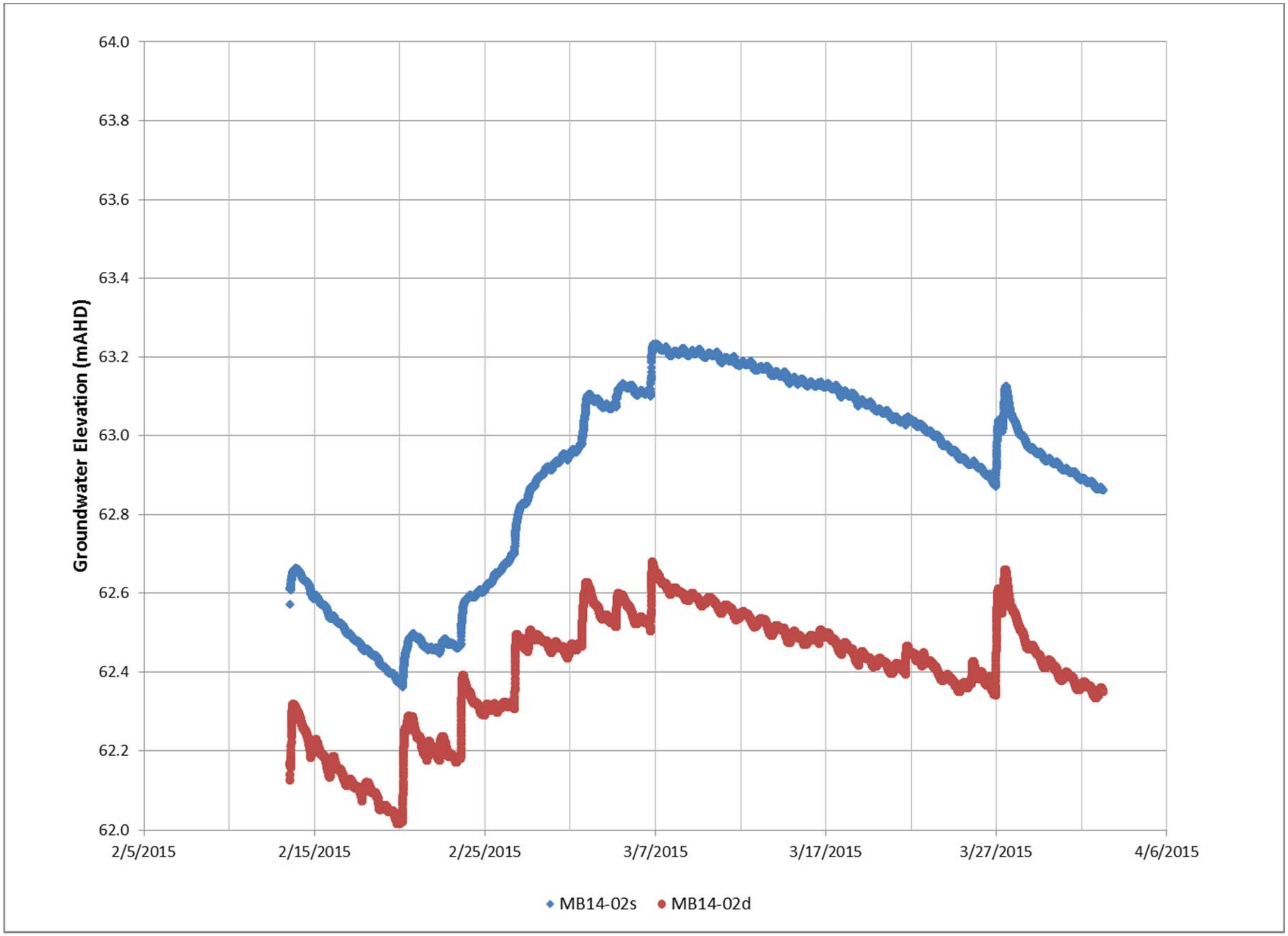

Datalogger Elevations for MB14-02S/D for February to April 2015

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 3-5a
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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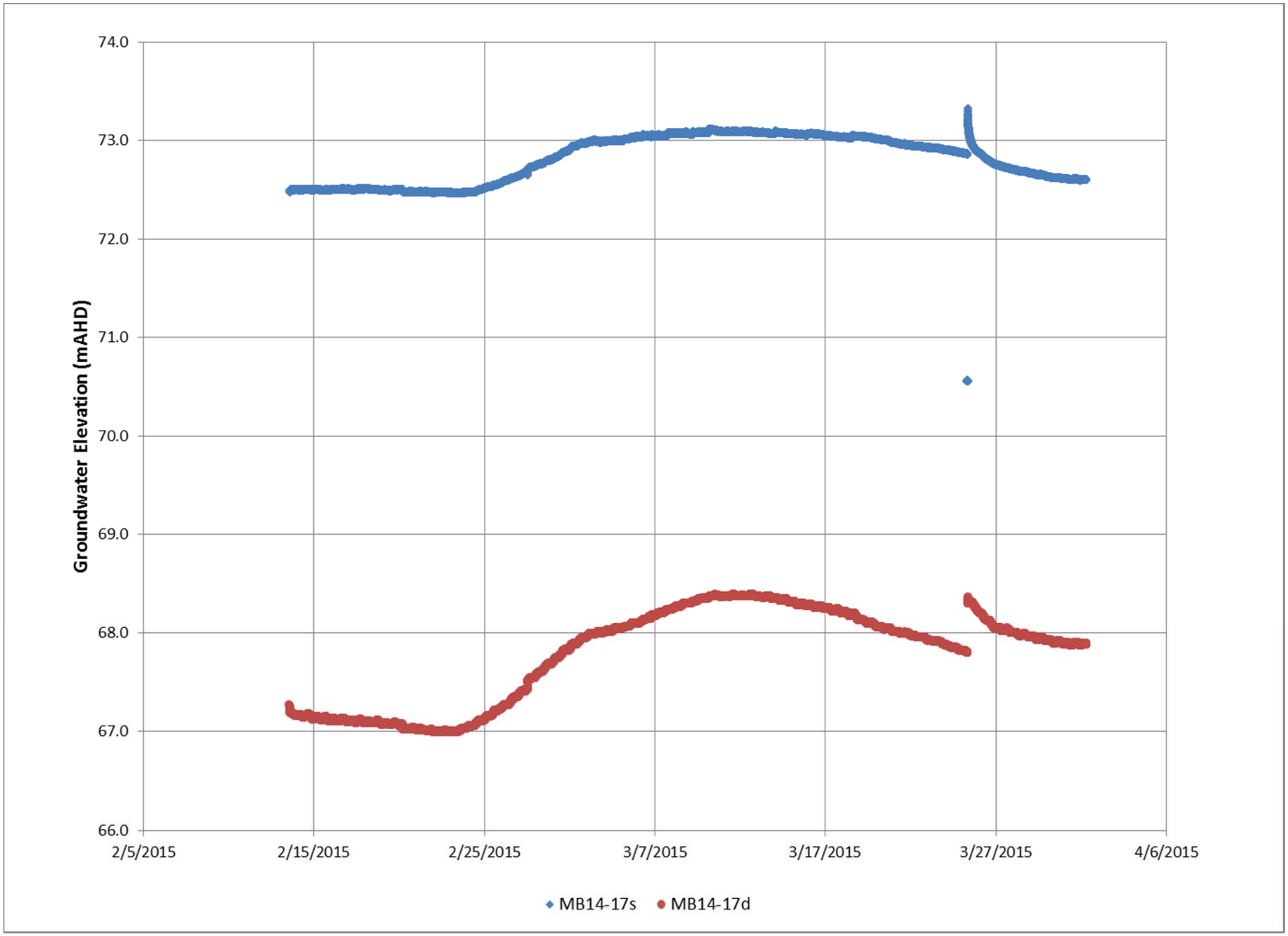

Datalogger Elevations for MB14-17S/D for February to April 2015

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 3-5b
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

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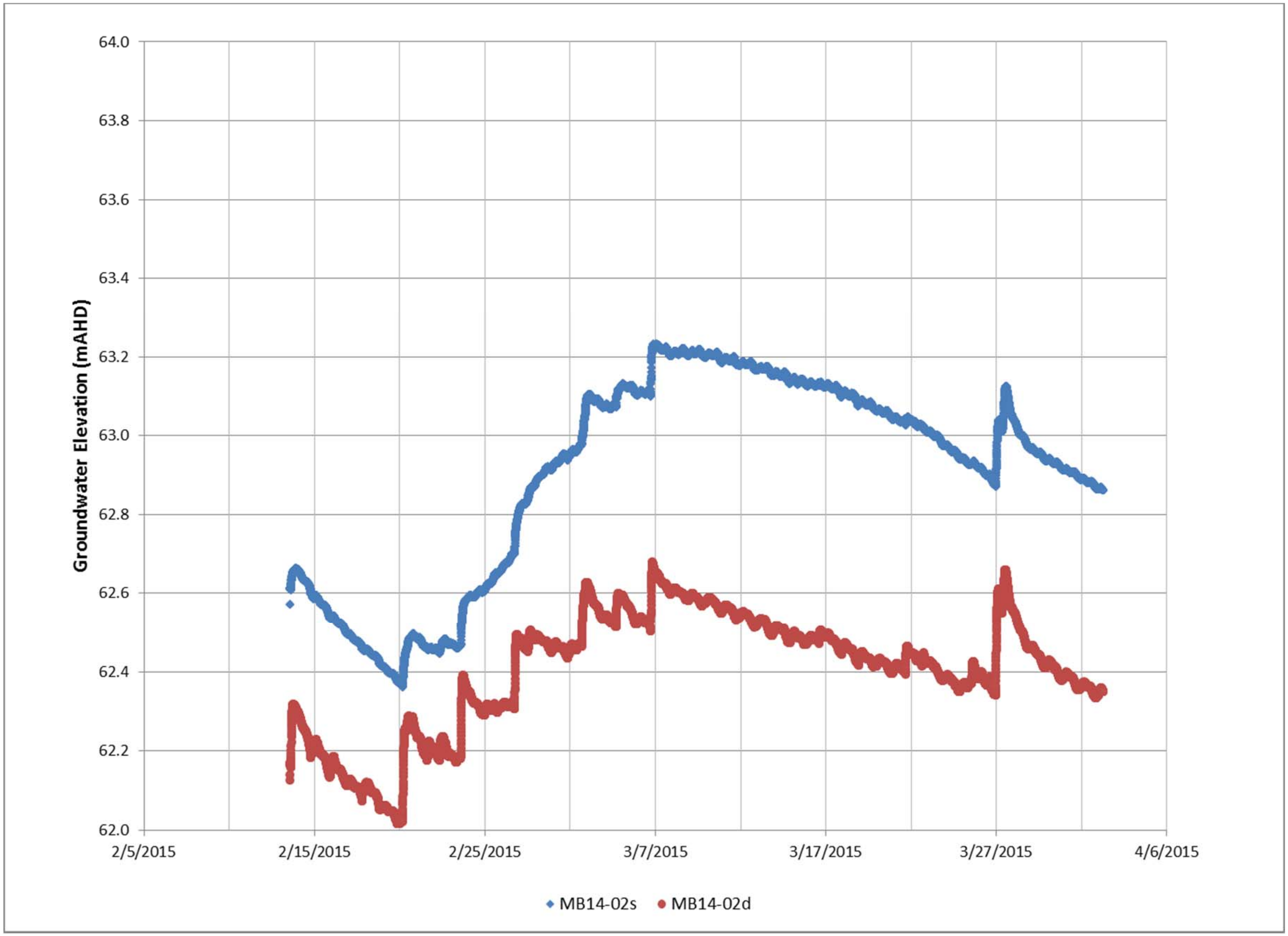

Datalogger Elevations for MB14-20S/D for February to April 2015

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 3-5c
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

Robertson GeoConsultants Inc.
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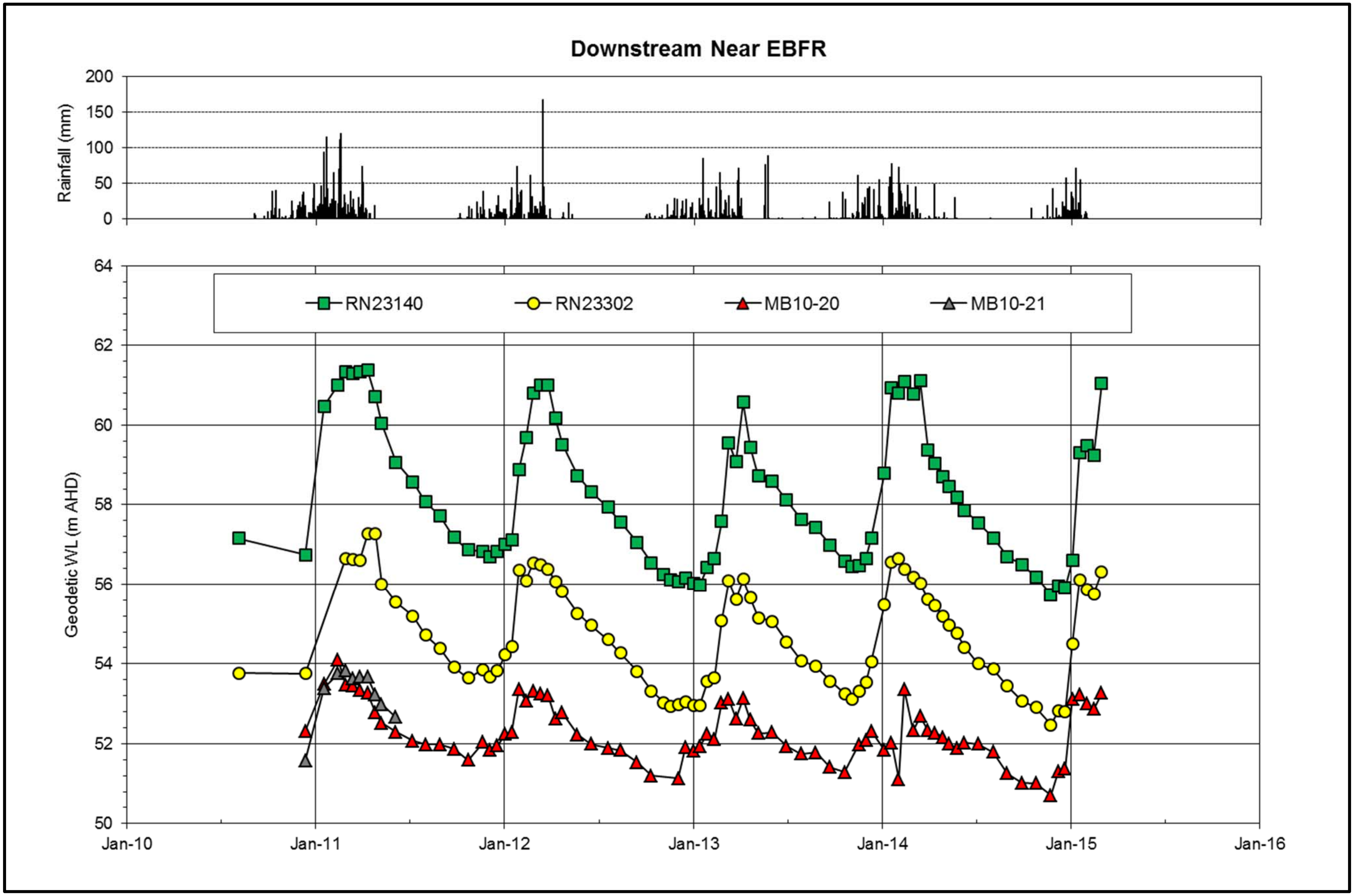

Groundwater Levels near East Finniss River
Downstream of Mine Site
2010 - 2015

Robertson GeoConsultants Inc.
Consulting Engineers and Scientists for the Mining Industry
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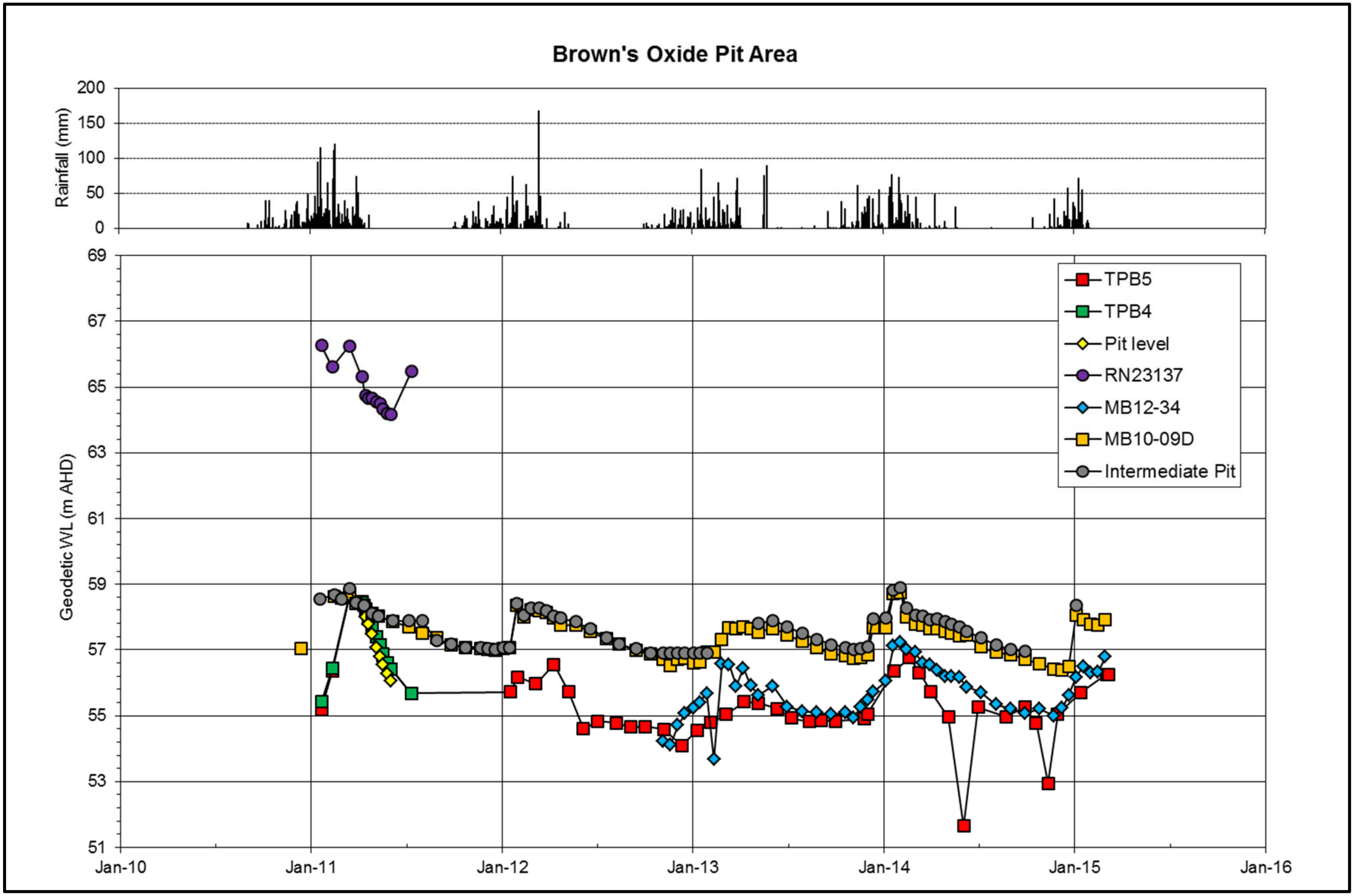
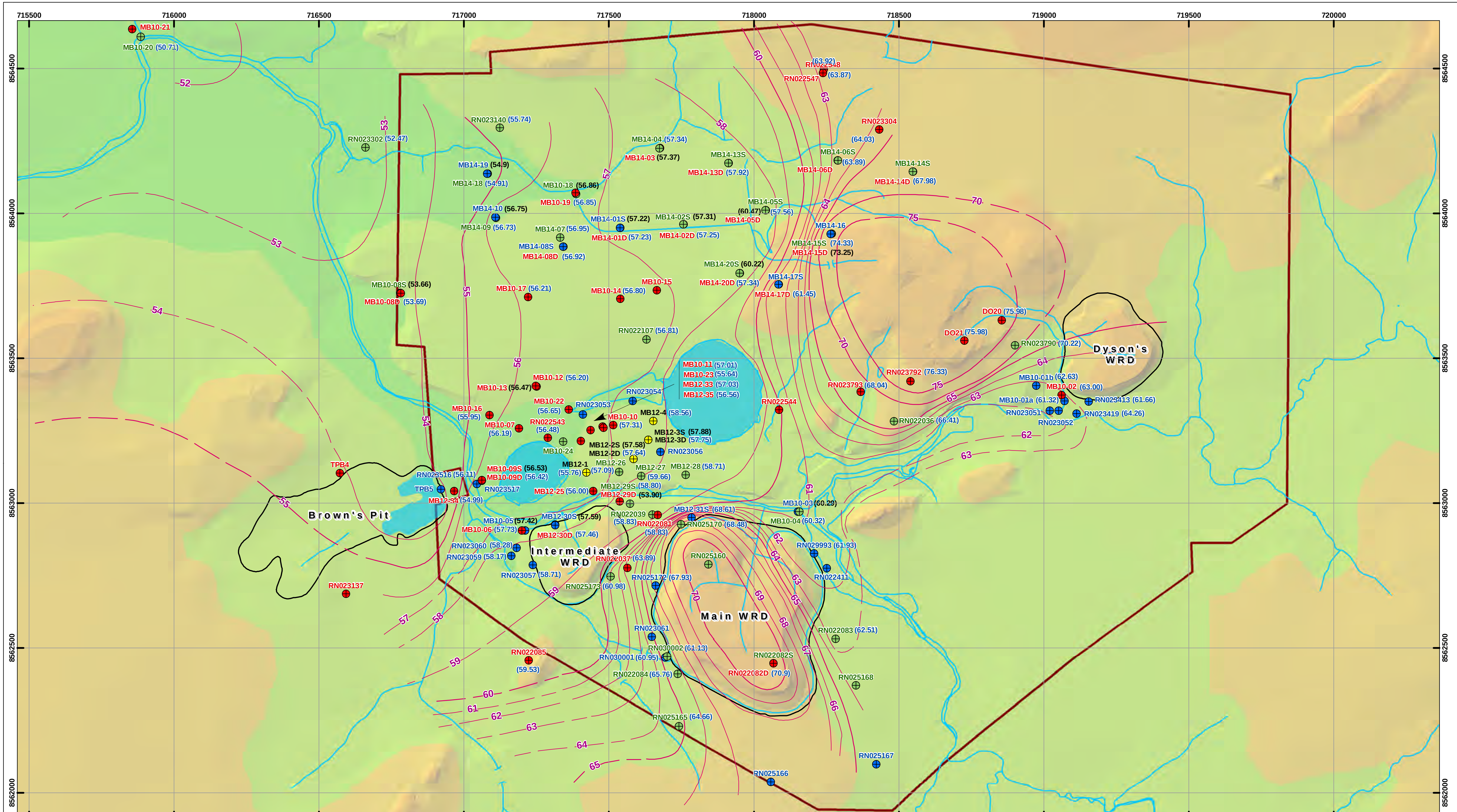
Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 3-6**
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	



Groundwater Levels
near the Brown's Oxide Pit
2011 - 2015

Robertson GeoConsultants Inc.
Consulting Engineers and Scientists for the Mining Industry
www.robertsongeoconsultants.com

Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 3-7**
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 9 Dec 2015
Original File: Section 6 Figures.pptx	



Groundwater Levels & Inferred Flow Field for Dry Season (Nov. 2014)

Rum Jungle Mine Site

Scale 1:12,000

0 50 100 200 300 400 500 600 700 800 900 1,000 Metres

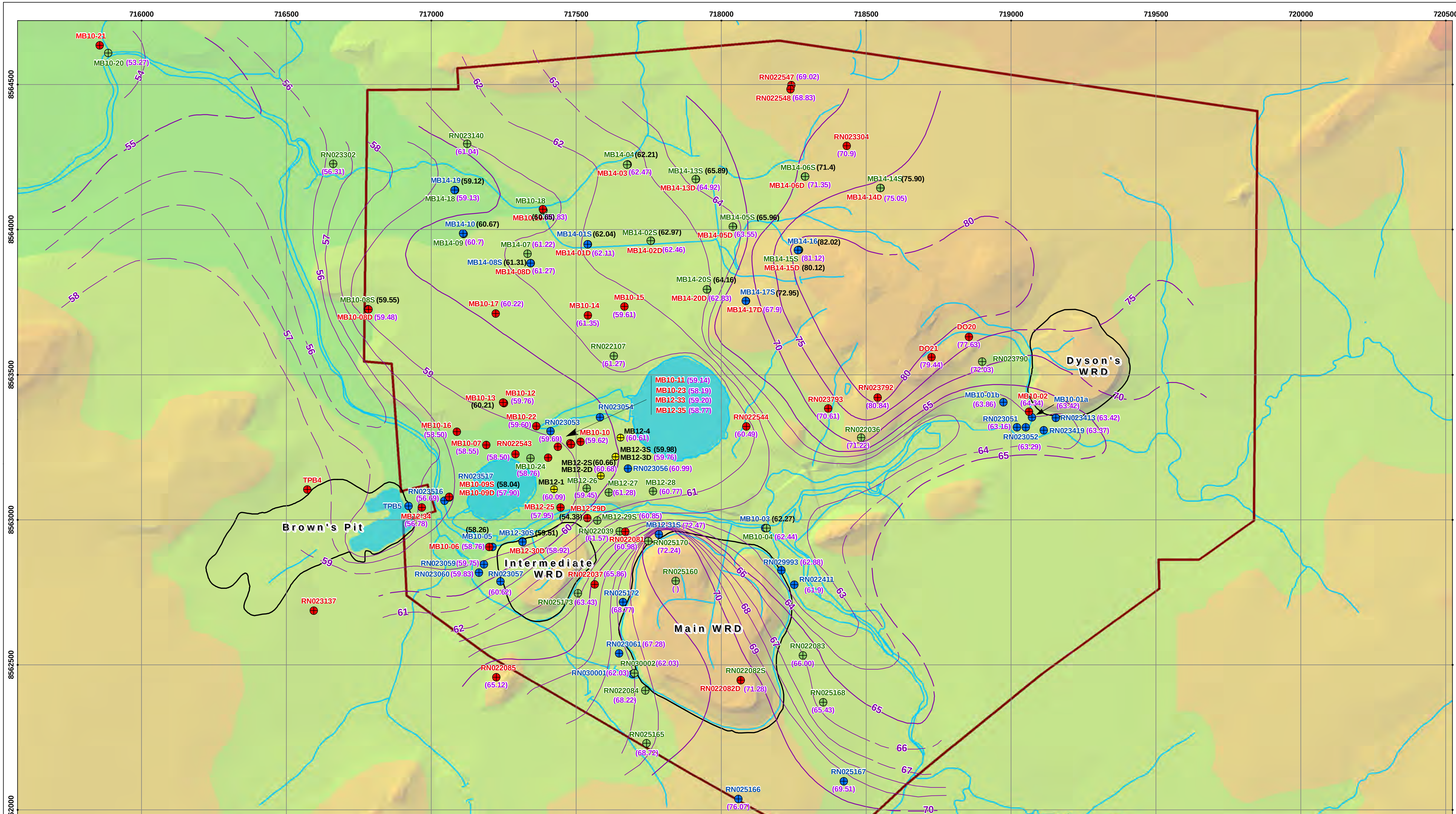
Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

LEGEND

- Groundwater Bore (Depth <5m)
- Groundwater Bore (Depth from 5 to 15m)
- Groundwater Bore (Depth >15m)
- Groundwater Bore (Unclassified)
- (54.99) (55.23) GWL used for contouring
- Pit/WRD outline
- Groundwater Levels
- Dry Season
- Property Boundary

Client: Northern Territory Government	Figure: 3-8a
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 07, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure3-8a_RJ_GWL_DrySeason_May2016.mxd	



Groundwater Levels & Inferred Flow Field for Wet Season (Mar. 2015)

Rum Jungle Mine Site

Scale 1:12,000

0 50 100 200 300 400 500 600 700 800 900 1,000 Metres

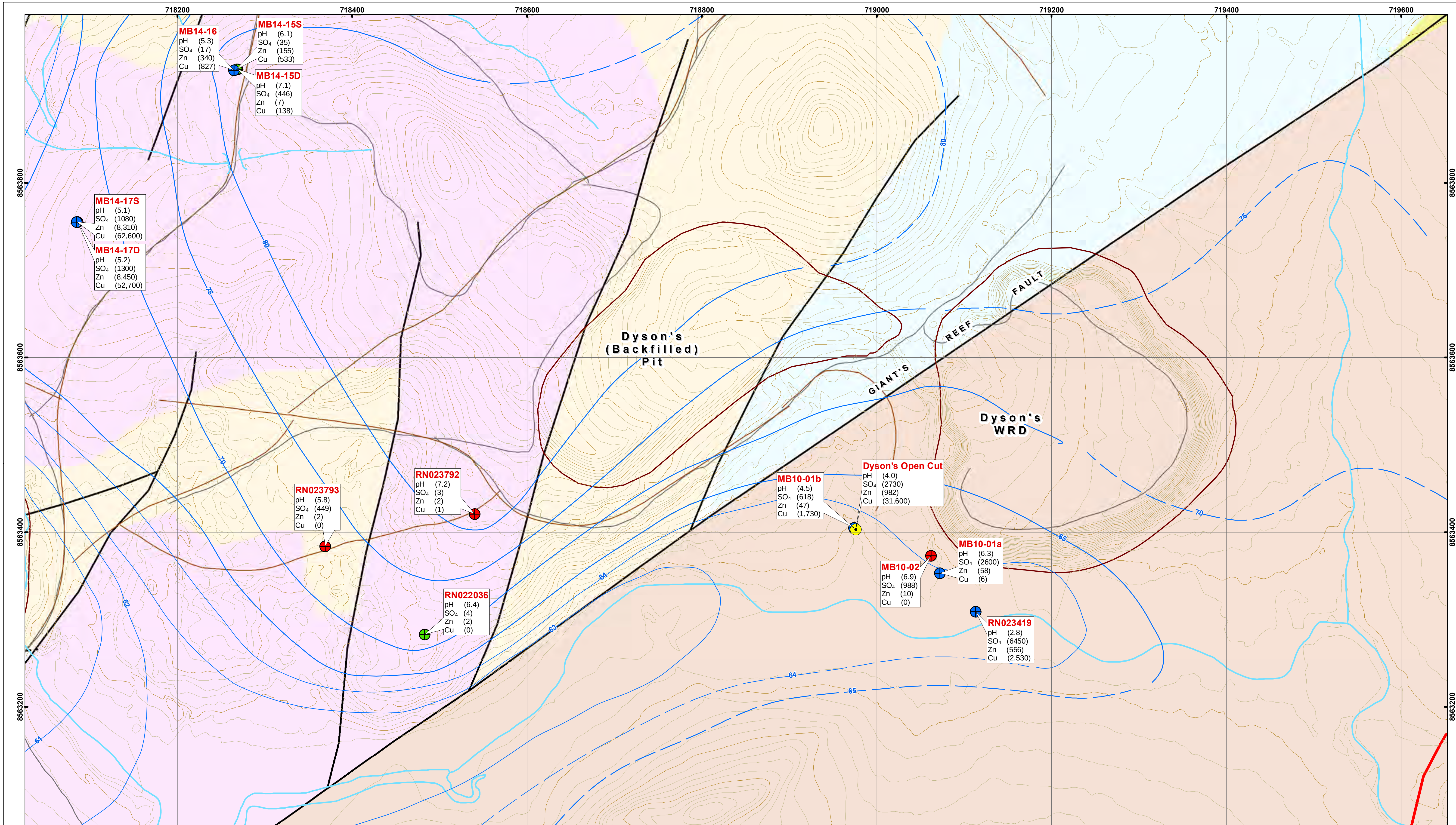
Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

LEGEND

- Groundwater Bore (Depth <5m)
- Groundwater Bore (Depth from 5 to 15m)
- Groundwater Bore (Depth >15m)
- Groundwater Bore (Unclassified)
- (54.99) (55.23) GWL used for contouring
- Pit/WRD outline
- Groundwater Levels Wet Season
- Property Boundary

Client: Northern Territory Government, Department of Resources – Minerals and Energy	Figure: 3-8b
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 07, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure3-8b_RJ_GWL_WetSeason_May2016.mxd	



LEGEND

- Groundwater Bore (Depth <5m)
- Groundwater Bore (Depth from 5 to 15m)
- Groundwater Bore (Depth >15m)
- Groundwater Bore (Open Hole)
- Drainage
- Road
- Fault
- Mine Site Boundary
- Model Domain
- Groundwater Levels Wet Season

Lithology

- Whites Formation
- Geolsec Formation
- Coomalie Dolostone
- Crater Formation
- Quartz Vein
- Rum Jungle Complex

Labels

MB12-25
pH - pH units
SO₄ - mg/L
Cu - µg/L
Zn - µg/L

N E S W

Groundwater Quality for Dyson's Area

Wet Season

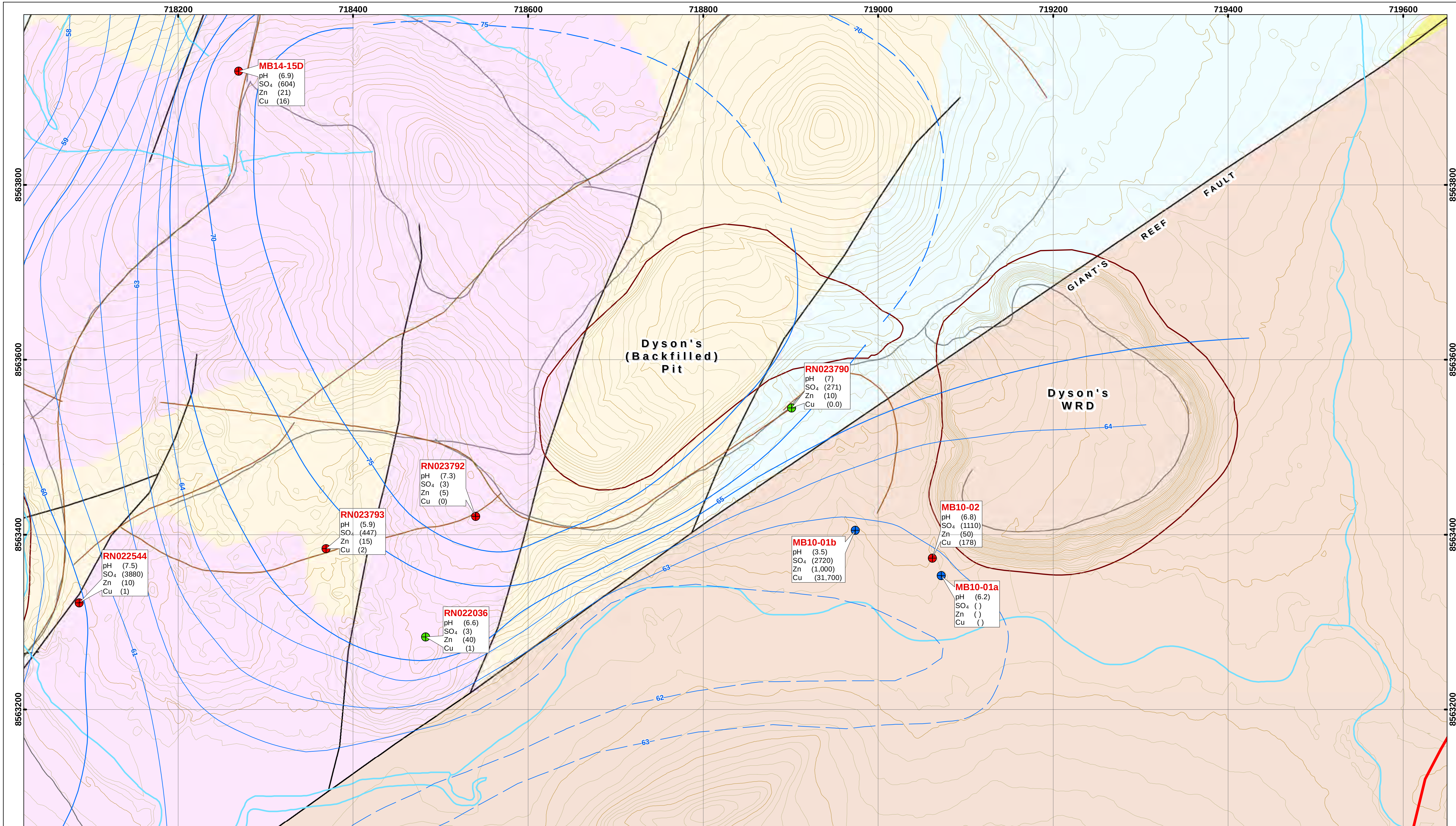
Scale 1:4,000

0 50 100 200 300 Metres

Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 3-9a**
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 02, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure3-9a_RJ_GWQ_Wet_DysonsArea.mxd	



LEGEND

- Groundwater Bore (Depth <5m)
- Groundwater Bore (Depth from 5 to 15m)
- Groundwater Bore (Depth >15m)
- Groundwater Bore (Open Hole)
- Drainage
- Road
- Fault
- Mine Site Boundary
- Model Domain
- Groundwater Levels Dry Season

Lithology

- Whites Formation
- Geolsec Formation
- Coomalie Dolostone
- Crater Formation
- Quartz Vein
- Rum Jungle Complex

Labels

MB12-25
pH - pH units
SO₄ - mg/L
Cu - µg/L
Zn - µg/L

N W E S

Groundwater Quality for Dyson's Area

Dry Season

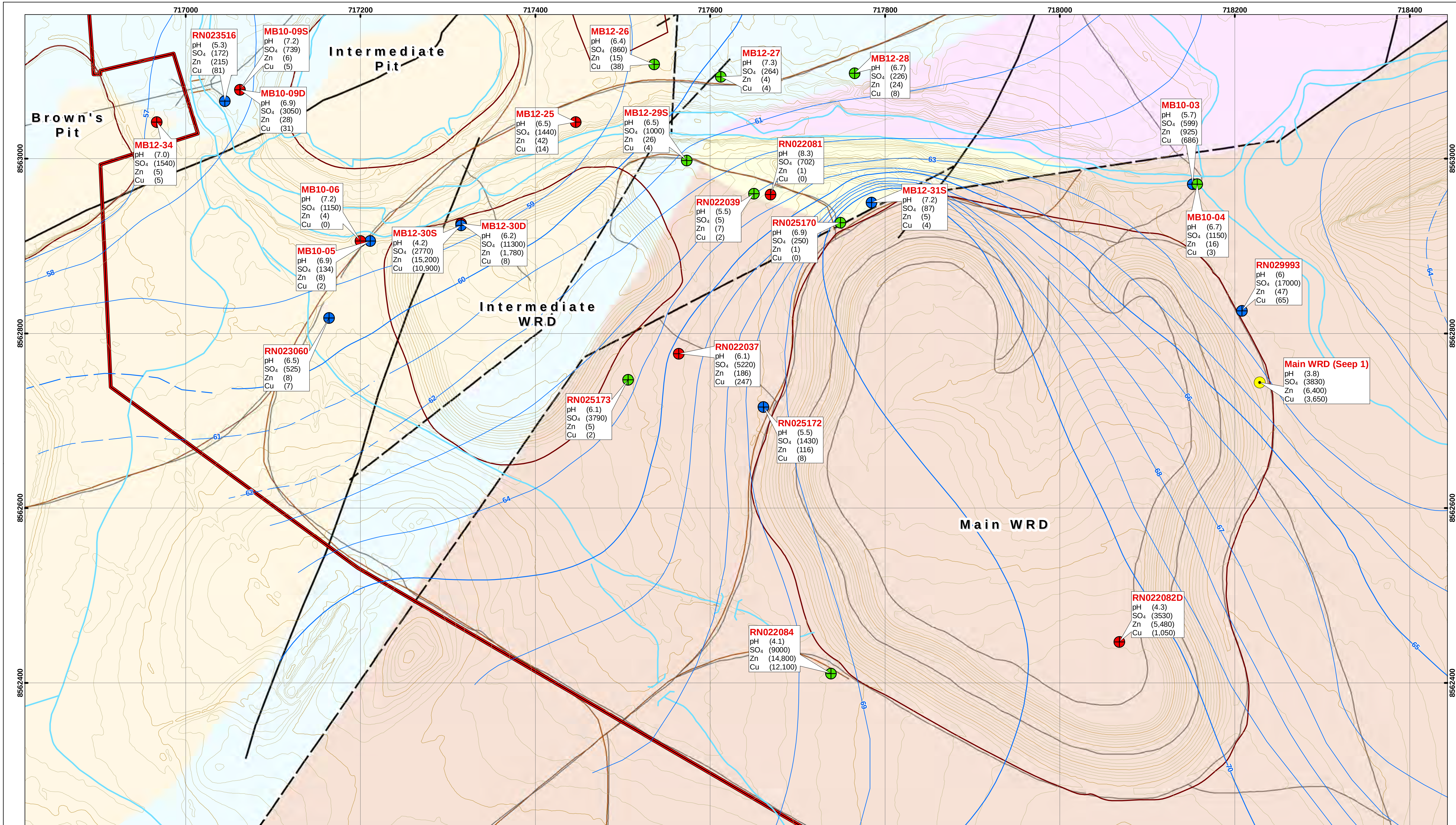
Scale 1:4,000

0 50 100 200 300 Metres

Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 3-9b
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 02, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure3-9b_RJ_GWQ_Dry_DysonsArea.mxd	



LEGEND

- Groundwater Bore (Depth <5m)
- Groundwater Bore (Depth from 5 to 15m)
- Groundwater Bore (Depth >15m)
- Groundwater Bore (Open Hole)

- Drainage
- Road
- Fault
- Mine Site Boundary
- Model Domain
- Groundwater Levels Wet Season

Lithology

- Whites Formation
- Geolsec Formation
- Coomalie Dolostone
- Crater Formation
- Quartz Vein
- Rum Jungle Complex

Labels

MB12-25

pH	- pH units
SO_4	- mg/L
Cu	- µg/L
Zn	- µg/L

Groundwater Quality for Main and Intermediate WRDs Area

Wet Season

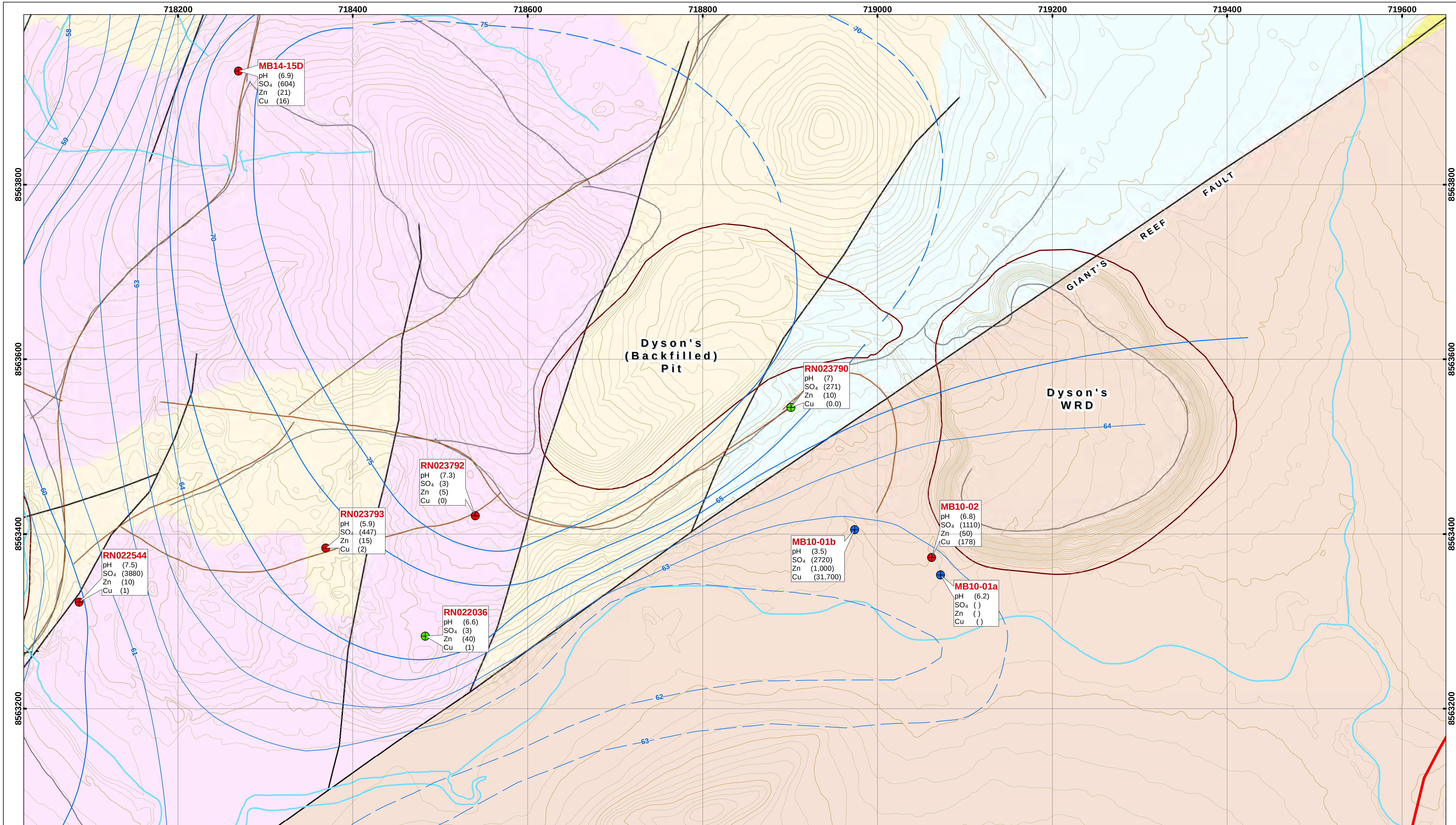
Scale 1:4,000

0 50 100 200 300 Metres

Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 3-10a**
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 02, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure3-10a_RJ_GWQ_Wet_IntermediateWRD-Area.mxd	



LEGEND

- Groundwater Bore (Depth <5m)
- Groundwater Bore (Depth from 5 to 15m)
- Groundwater Bore (Depth >15m)
- Groundwater Bore (Open Hole)
- Drainage
- Road
- Fault
- Mine Site Boundary
- Model Domain
- Groundwater Levels Dry Season

Lithology

- Whites Formation
- Geolsec Formation
- Coomalie Dolostone
- Crater Formation
- Quartz Vein
- Rum Jungle Complex

Labels

MB12-25
pH - pH units
SO₄ - mg/L
Cu - µg/L
Zn - µg/L

N
W E
S

Groundwater Quality for Dyson's Area

Dry Season

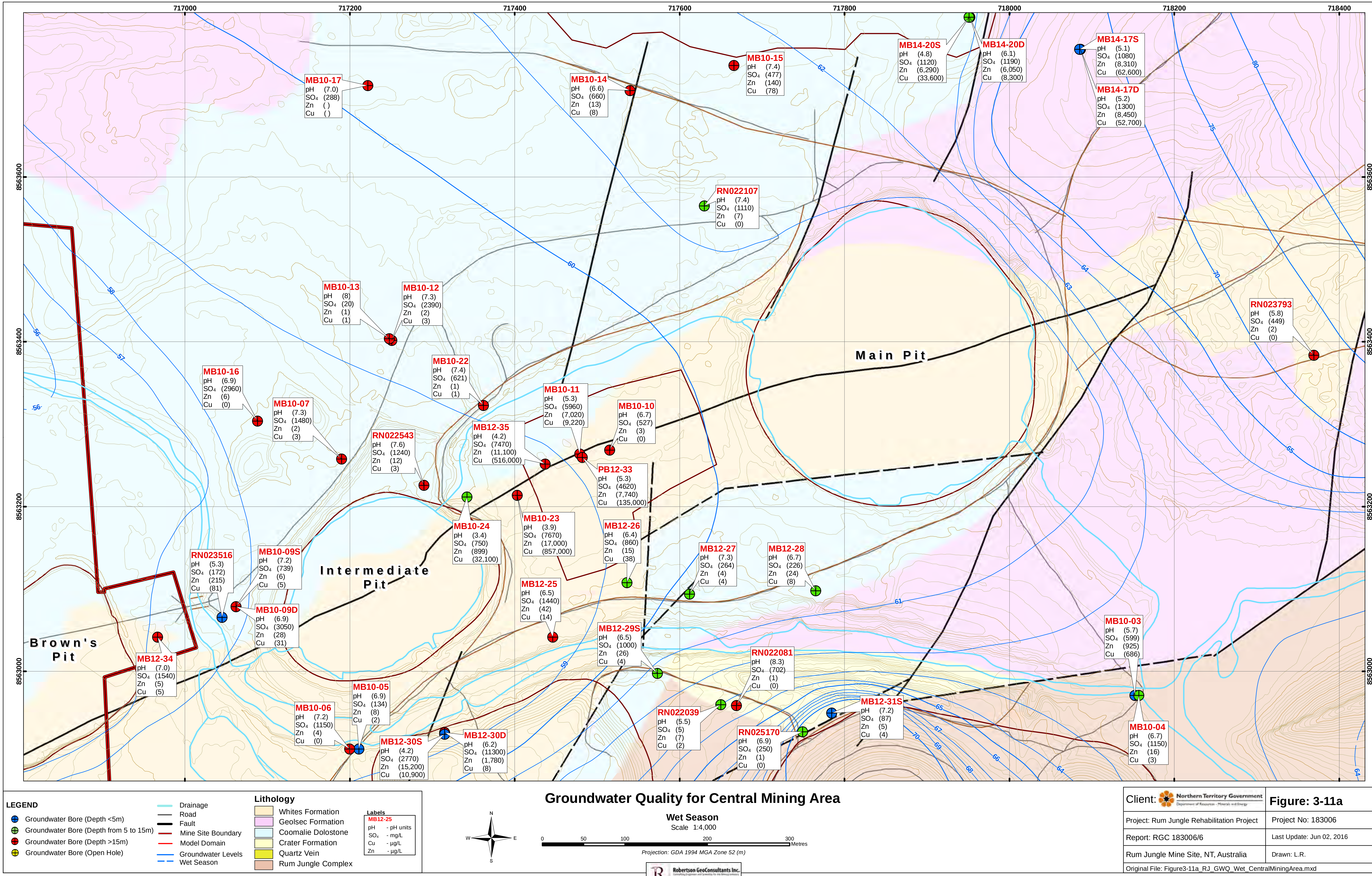
Scale 1:4,000

0 50 100 200 300 Metres

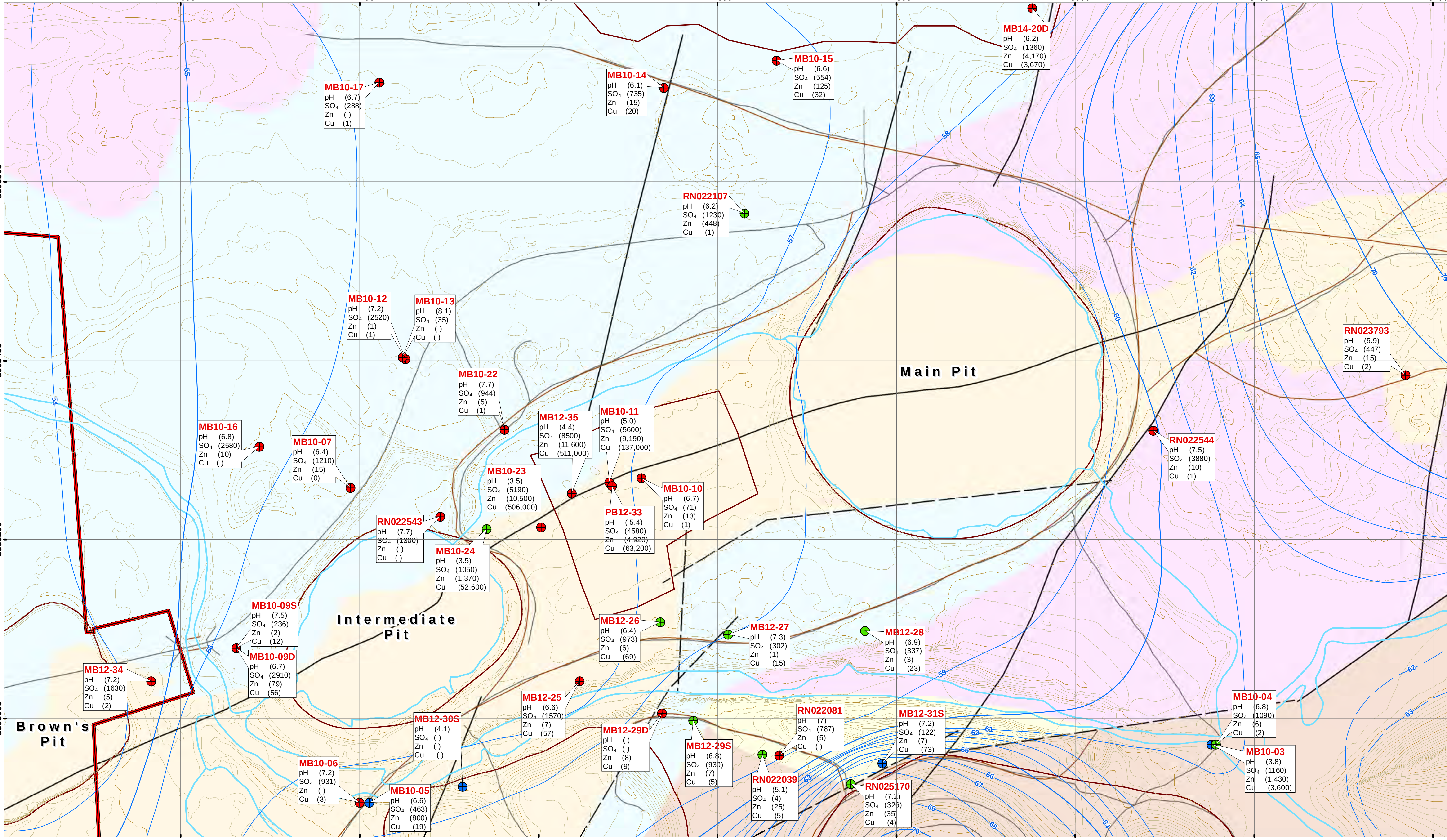
Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

Client: Northern Territory Government	**Figure: 3-10b**
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 02, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure3-10bb_RJ_GWQ_Dry_DysonsArea.mxd	



717000
717200
717400
717600
717800
718000
718200
718400
8563600
8563400
8563200
8563000
MB10-17 pH (7.0) SO₄ (288) Zn ( ) Cu ( )
MB10-14 pH (6.6) SO₄ (660) Zn (13) Cu (8)
MB10-15 pH (7.4) SO₄ (477) Zn (140) Cu (78)
MB14-20S pH (4.8) SO₄ (1120) Zn (6,290) Cu (33,600)
MB14-20D pH (6.1) SO₄ (1190) Zn (6,050) Cu (8,300)
MB14-17S pH (5.1) SO₄ (1080) Zn (8,310) Cu (62,600)
MB14-17D pH (5.2) SO₄ (1300) Zn (8,450) Cu (52,700)
RN022107 pH (7.4) SO₄ (1110) Zn (7) Cu (0)
MB10-13 pH (8) SO₄ (20) Zn (1) Cu (1)
MB10-12 pH (7.3) SO₄ (2390) Zn (2) Cu (3)
RN023793 pH (5.8) SO₄ (449) Zn (2) Cu (0)
Main Pit
MB10-22 pH (7.4) SO₄ (621) Zn (1) Cu (1)
MB10-16 pH (6.9) SO₄ (2960) Zn (6) Cu (0)
MB10-07 pH (7.3) SO₄ (1480) Zn (2) Cu (3)
MB10-11 pH (5.3) SO₄ (5960) Zn (7,020) Cu (9,220)
MB10-10 pH (6.7) SO₄ (527) Zn (3) Cu (0)
RN022543 pH (7.6) SO₄ (1240) Zn (12) Cu (3)
MB12-35 pH (4.2) SO₄ (7470) Zn (11,100) Cu (516,000)
PB12-33 pH (5.3) SO₄ (4620) Zn (7,740) Cu (135,000)
MB10-24 pH (3.4) SO₄ (750) Zn (899) Cu (32,100)
MB10-23 pH (3.9) SO₄ (7670) Zn (17,000) Cu (857,000)
MB12-26 pH (6.4) SO₄ (860) Zn (15) Cu (38)
MB12-27 pH (7.3) SO₄ (264) Zn (4) Cu (4)
MB12-28 pH (6.7) SO₄ (226) Zn (24) Cu (8)
RN023516 pH (5.3) SO₄ (172) Zn (215) Cu (81)
MB10-09S pH (7.2) SO₄ (739) Zn (6) Cu (5)
Intermediate Pit
MB12-25 pH (6.5) SO₄ (1440) Zn (42) Cu (14)
MB10-09D pH (6.9) SO₄ (3050) Zn (28) Cu (31)
Brown's Pit
MB12-34 pH (7.0) SO₄ (1540) Zn (5) Cu (5)
MB12-29S pH (6.5) SO₄ (1000) Zn (26) Cu (4)
MB10-03 pH (5.7) SO₄ (599) Zn (925) Cu (686)
RN022081 pH (8.3) SO₄ (702) Zn (1) Cu (0)
MB10-05 pH (6.9) SO₄ (134) Zn (8) Cu (2)
MB10-06 pH (7.2) SO₄ (1150) Zn (4) Cu (0)
RN022039 pH (5.5) SO₄ (5) Zn (7) Cu (2)
MB12-31S pH (7.2) SO₄ (87) Zn (5) Cu (4)
MB12-30S pH (4.2) SO₄ (2770) Zn (15,200) Cu (10,900)
MB12-30D pH (6.2) SO₄ (11300) Zn (1,780) Cu (8)
RN025170 pH (6.9) SO₄ (250) Zn (1) Cu (0)
MB10-04 pH (6.7) SO₄ (1150) Zn (16) Cu (3)
LEGEND
Groundwater Bore (Depth <5m)
Groundwater Bore (Depth from 5 to 15m)
Groundwater Bore (Depth >15m)
Groundwater Bore (Open Hole)
Drainage
Road
Fault
Mine Site Boundary
Model Domain
Groundwater Levels
Wet Season
Lithology
Whites Formation
Geolsec Formation
Coomalie Dolostone
Crater Formation
Quartz Vein
Rum Jungle Complex
Labels
MB12-25
pH - pH units
SO₄ - mg/L
Cu - µg/L
Zn - µg/L
Groundwater Quality for Central Mining Area
Wet Season
Scale 1:4,000
0 50 100 200 300 Metres
Projection: GDA 1994 MGA Zone 52 (m)
Robertson GeoConsultants Inc.
Client: Northern Territory Government
Figure: 3-11a
Project: Rum Jungle Rehabilitation Project
Project No: 183006
Report: RGC 183006/6
Last Update: Jun 02, 2016
Rum Jungle Mine Site, NT, Australia
Drawn: L.R.
Original File: Figure3-11a_RJ_GWQ_Wet_CentralMiningArea.mxd



LEGEND

- Groundwater Bore (Depth <5m)
- Groundwater Bore (Depth from 5 to 15m)
- Groundwater Bore (Depth >15m)
- Groundwater Bore (Open Hole)
- Drainage
- Road
- Fault
- Mine Site Boundary
- Model Domain
- Groundwater Levels Dry Season

Lithology

- Whites Formation
- Geolsec Formation
- Coomalie Dolostone
- Crater Formation
- Quartz Vein
- Rum Jungle Complex

Labels

MB12-25
pH - pH units
SO₄ - mg/L
Cu - µg/L
Zn - µg/L

Groundwater Quality for Central Mining Area

Dry Season

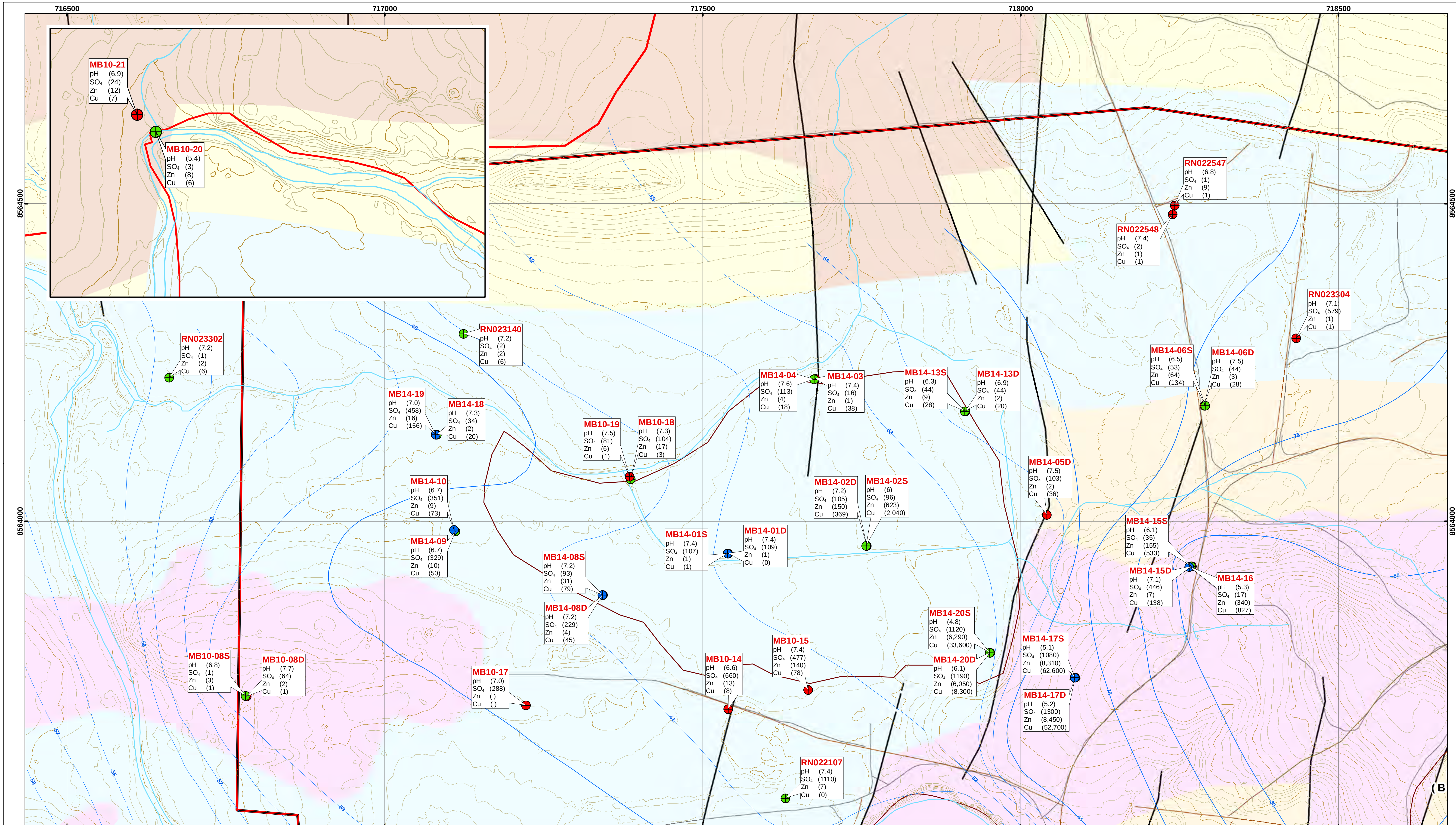
Scale 1:4,000

0 50 100 200 300 Metres

Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

Client: Northern Territory Government	**Figure: 3-11b**
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 02, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure3-11b_RJ_GWQ_Dry_CentralMiningArea.mxd	



LEGEND

- Groundwater Bore (Depth <5m)
- Groundwater Bore (Depth from 5 to 15m)
- Groundwater Bore (Depth >15m)
- Groundwater Bore (Open Hole)
- Drainage
- Road
- Mine Site Boundary
- Fault
- Model Domain
- Groundwater Levels Wet Season

Lithology

- Whites Formation
- Geolsec Formation
- Coomalie Dolostone
- Crater Formation
- Quartz Vein
- Rum Jungle Complex

Labels

MB12-25
pH - pH units
SO₄ - mg/L
Cu - µg/L
Zn - µg/L

Groundwater Quality for Old Tailings Dam Area

Wet Season

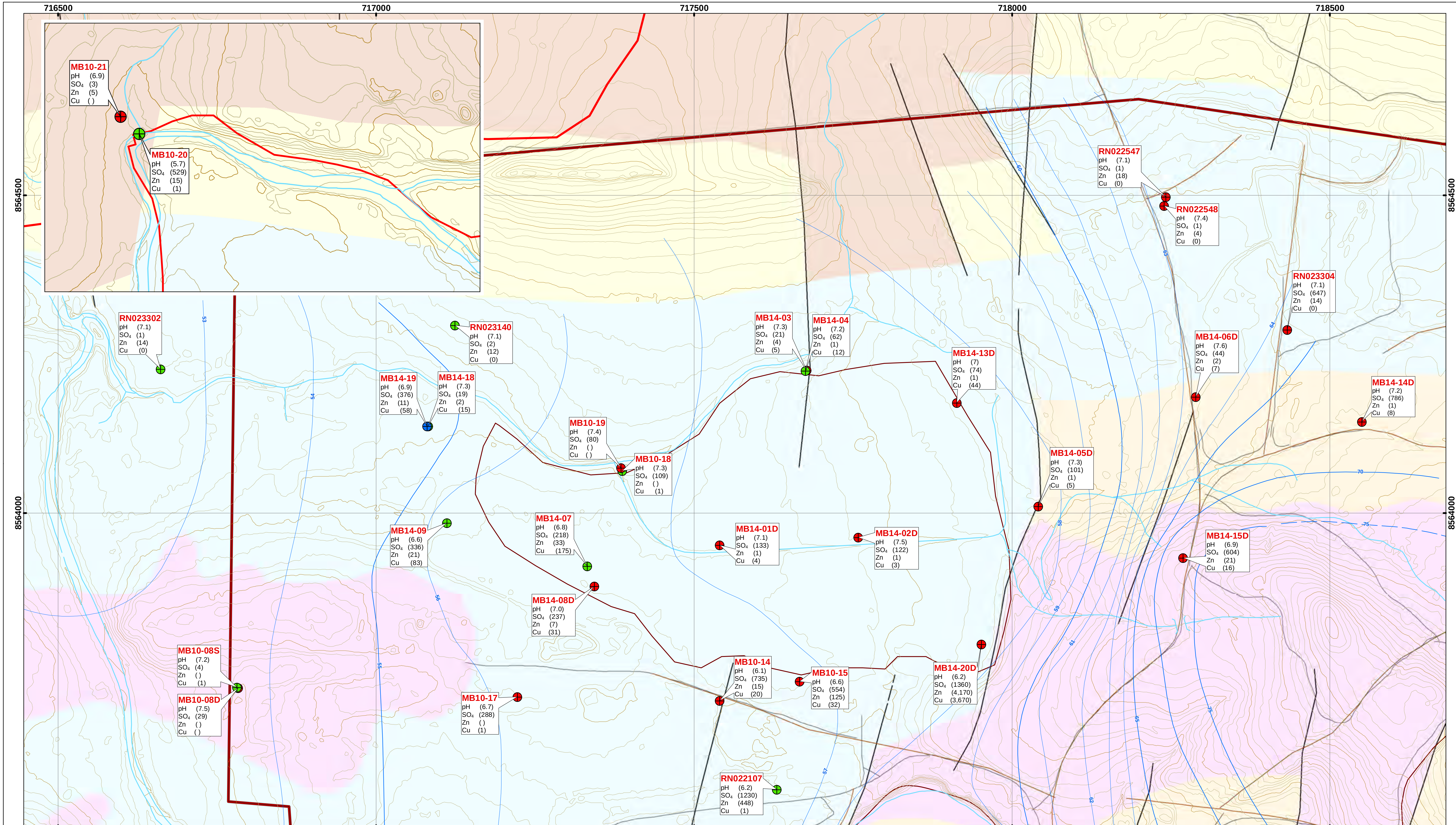
Scale 1:5,500

0 50 100 200 300 400 Metres

Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 3-12a**
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 02, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure3-12a_RJ_GWQ_Wet_NorthernReachArea.mxd	



LEGEND
- Groundwater Bore (Depth <5m)
- Groundwater Bore (Depth from 5 to 15m)
- Groundwater Bore (Depth >15m)
- Groundwater Bore (Open Hole)
- Drainage
- Road
- Fault
- Mine Site Boundary
- Model Domain
- Groundwater Levels Dry Season

Lithology
- Whites Formation
- Geolsec Formation
- Coomalie Dolostone
- Crater Formation
- Quartz Vein
- Rum Jungle Complex

Labels
MB12-25
pH - pH units
SO_4 - mg/L
Cu - µg/L
Zn - µg/L

Groundwater Quality for Old Tailings Dam Area

Dry Season

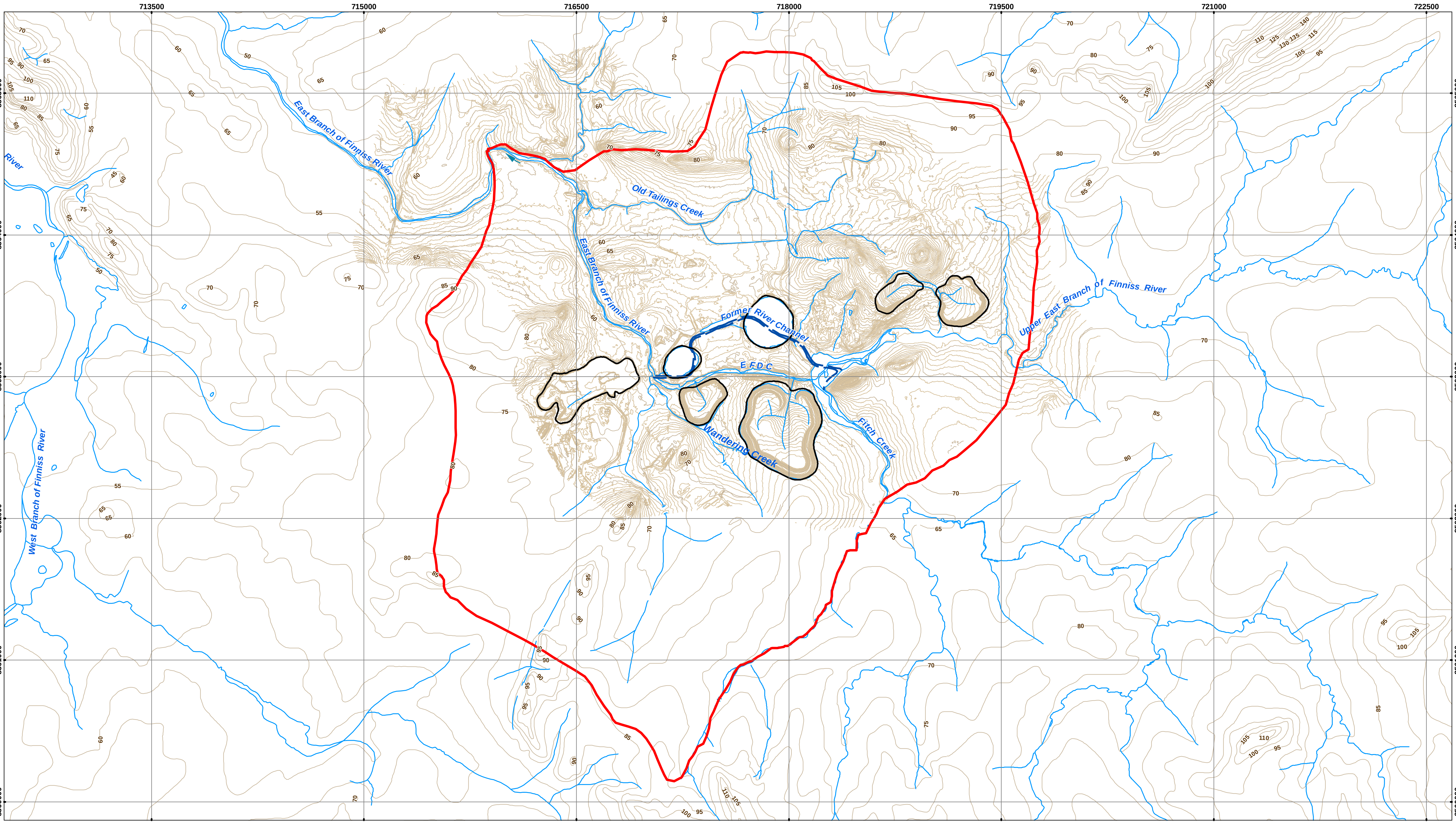
Scale 1:5,500

0 50 100 200 300 400 500 Metres

Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 3-12b
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 02, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure3-12b_RJ_GWQ_Dry_NorthernReachArea.mxd	



Conceptual Model Domain

Rum Jungle Mine Site

Scale 1:25,000

0 0.5 1 2 Km

Projection: GDA 1994 MGA Zone 52 (m)

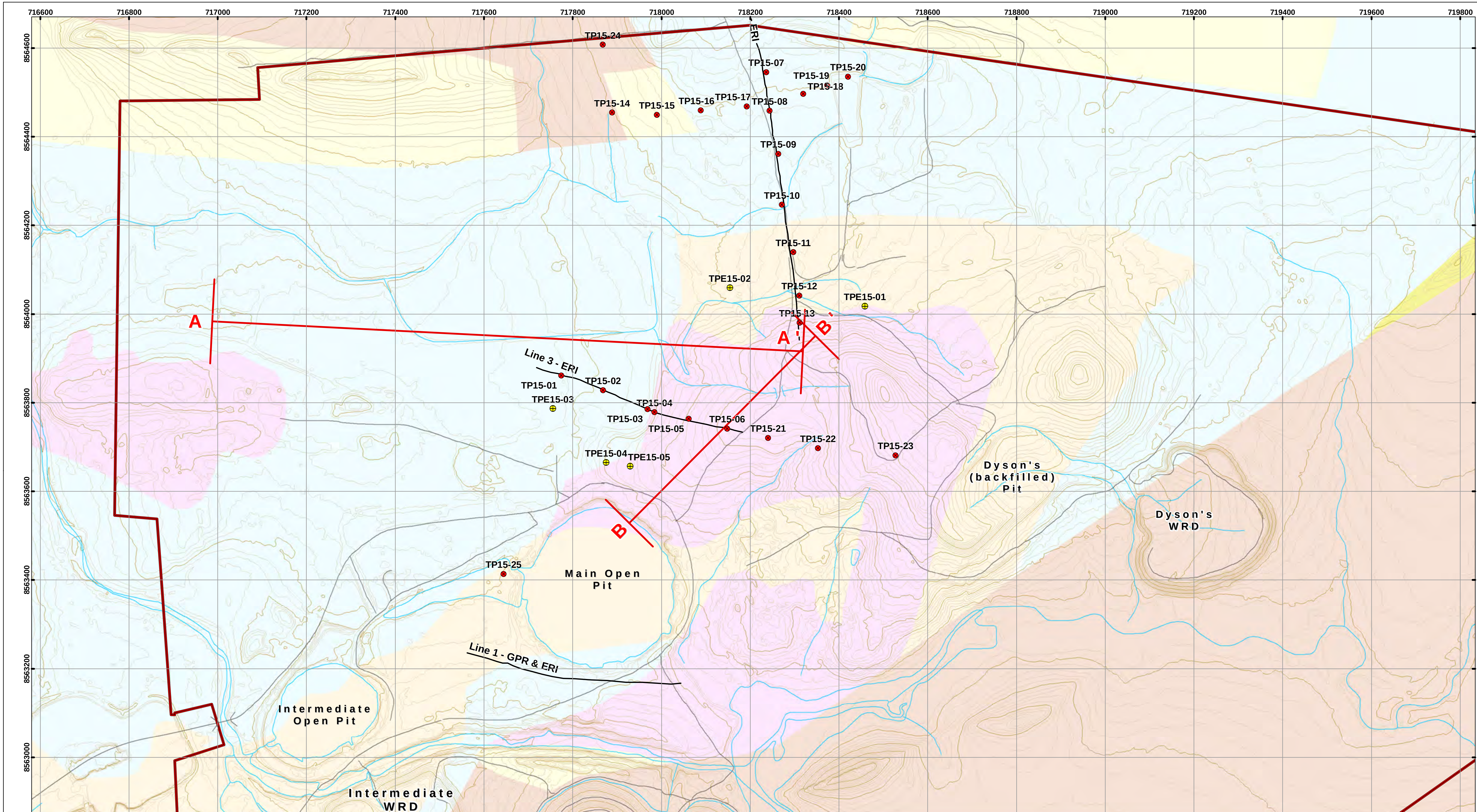
Robertson GeoConsultants Inc.

N W E S

LEGEND

- Drainage
- Model Domain Boundary

Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 4-1**
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jan 05, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure4-1_RJ_ModelDomainBoundary.mxd	



Legend

- 2015 Test Pit
- 2015 Test Pit Enviro
- 2015 GPR and ERI Geophysics Line
- Geological Section

Lithology

- Whites Formation
- Geolsec Formation
- Coomalie Dolostone
- Crater Formation
- Quartz Vein
- Rum Jungle Complex

Surficial Geology

Rum Jungle Mine Site

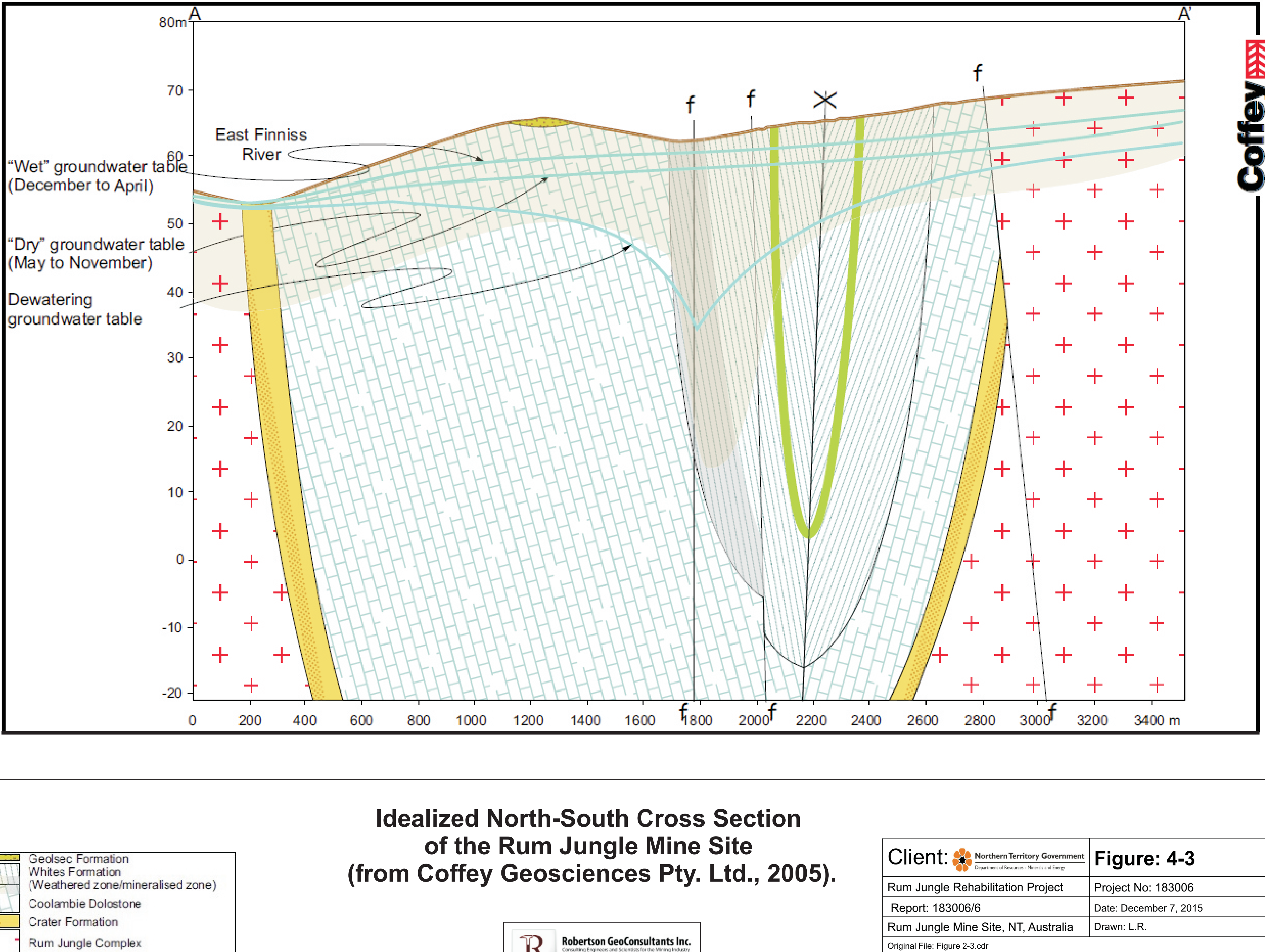
Scale 1:8,000

0 50 100 200 300 400 500 Metres

Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 4-2
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 07, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure4-2_RJ_SurficialGeology_May2016.mxd	



Idealized North-South Cross Section of the Rum Jungle Mine Site (from Coffey Geosciences Pty. Ltd., 2005).

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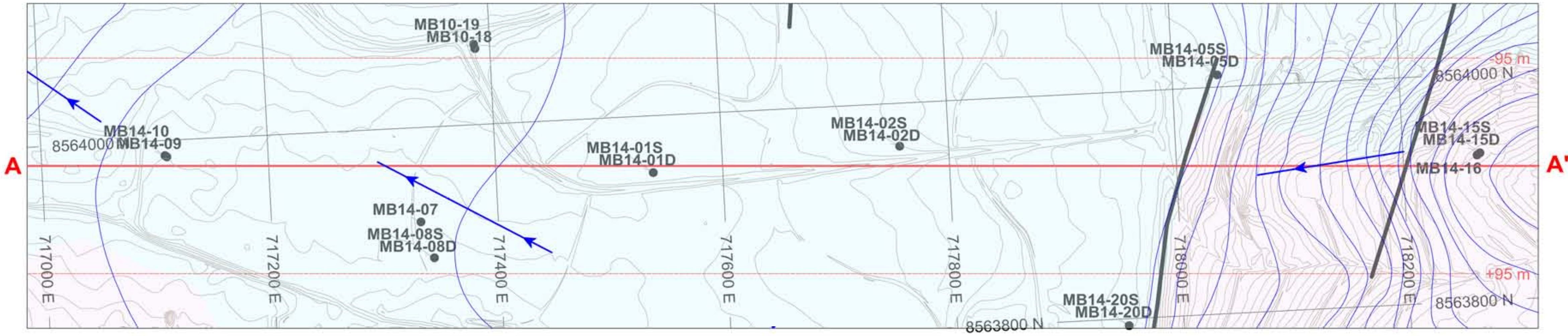
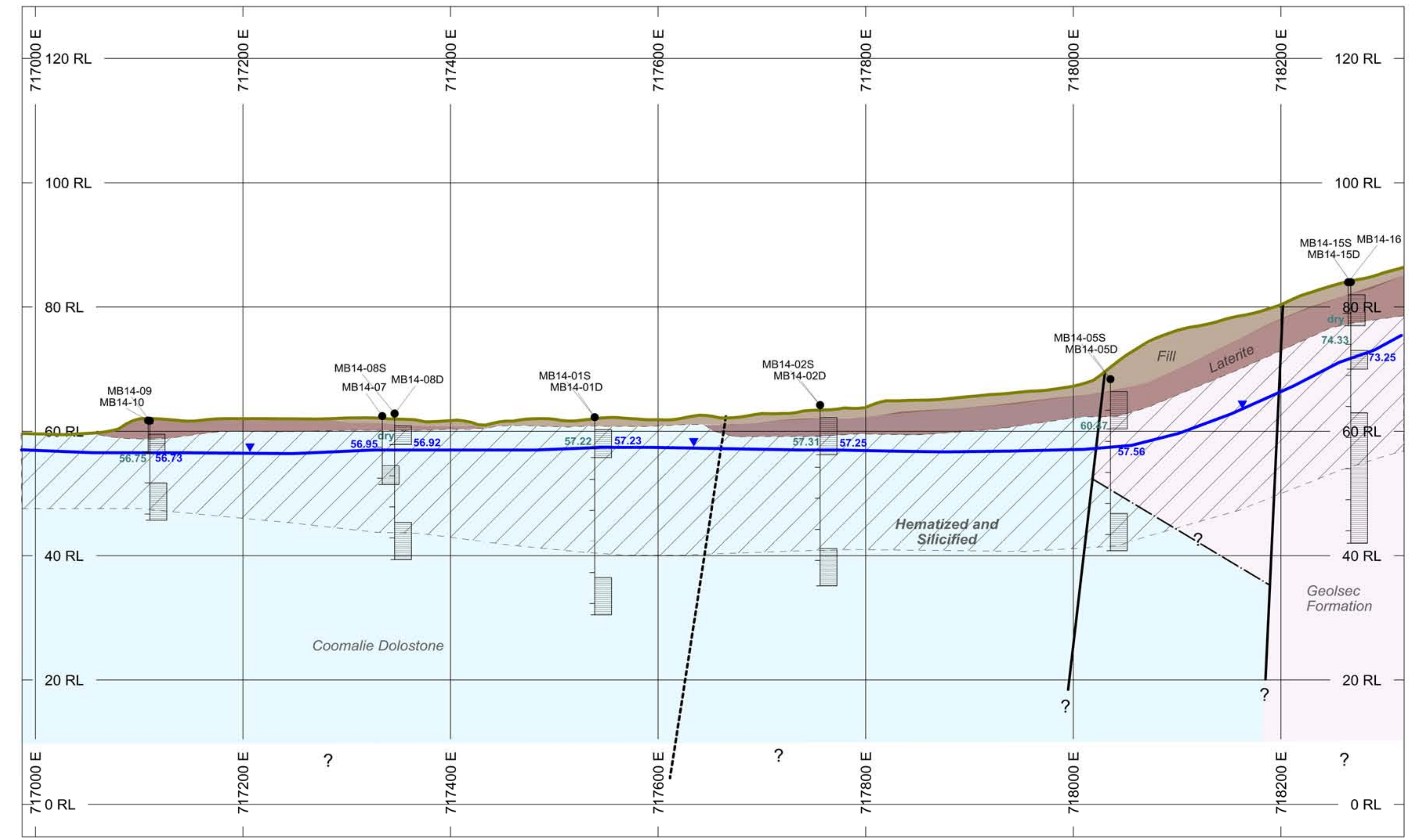
Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 4-3
Rum Jungle Rehabilitation Project	Project No: 183006
Report: 183006/6	Date: December 7, 2015
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure 2-3.cdr	





Legend

- Topography
- SWL m AHD, 24-Nov-2014
- Fault
- Possible Fault
- Contact
- Screen

ROCK CODES	PAT	LABEL	DESCRIPTION
UNIT		F	Fill
		L	Laterite
		GF	Geolsec Formation
		WF	White's Formation
		CD	Coomalie Dolostone
		TZ	Transition Zone

Weathering Profile

- Saprolite to highly weathered bedrock (more clay)
- Weathered to fresh bedrock (less clay)

57.23 m AHD (Deep)

57.22 m AHD (Shallow)

SECTION SPECS:

REF. PT. E, N	717653 m	8563950 m
EXTENTS	1333 m	133.6 m
SECTION TOP, BOT	128.4 m	-5.225 m
TOLERANCE +/-	95 m	
VERTICAL EXAG.	6	

(m)

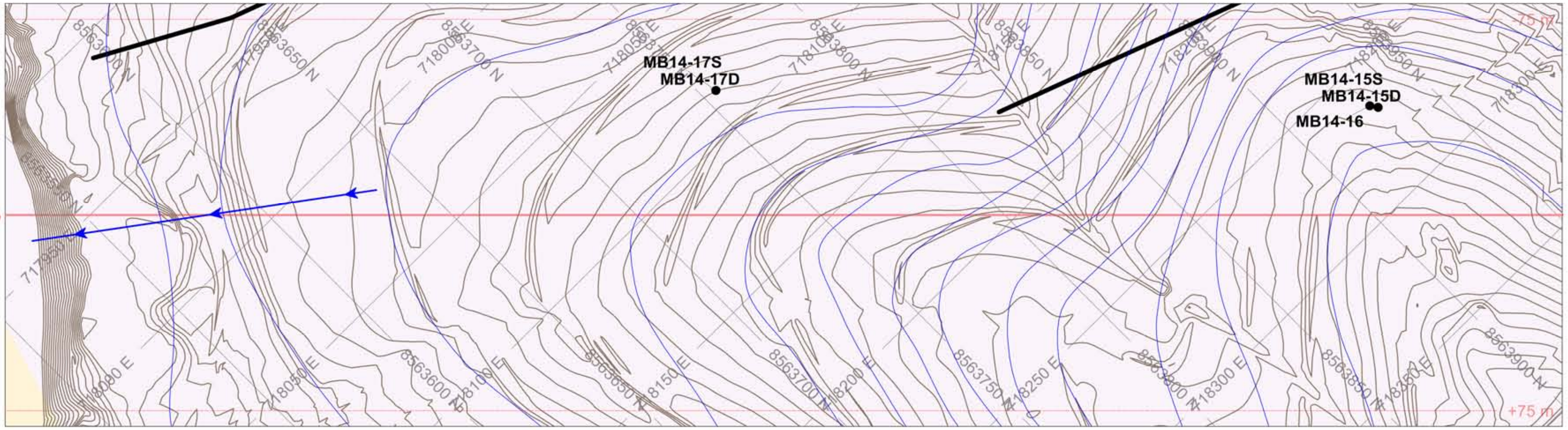
-50 0 50 100 150 200

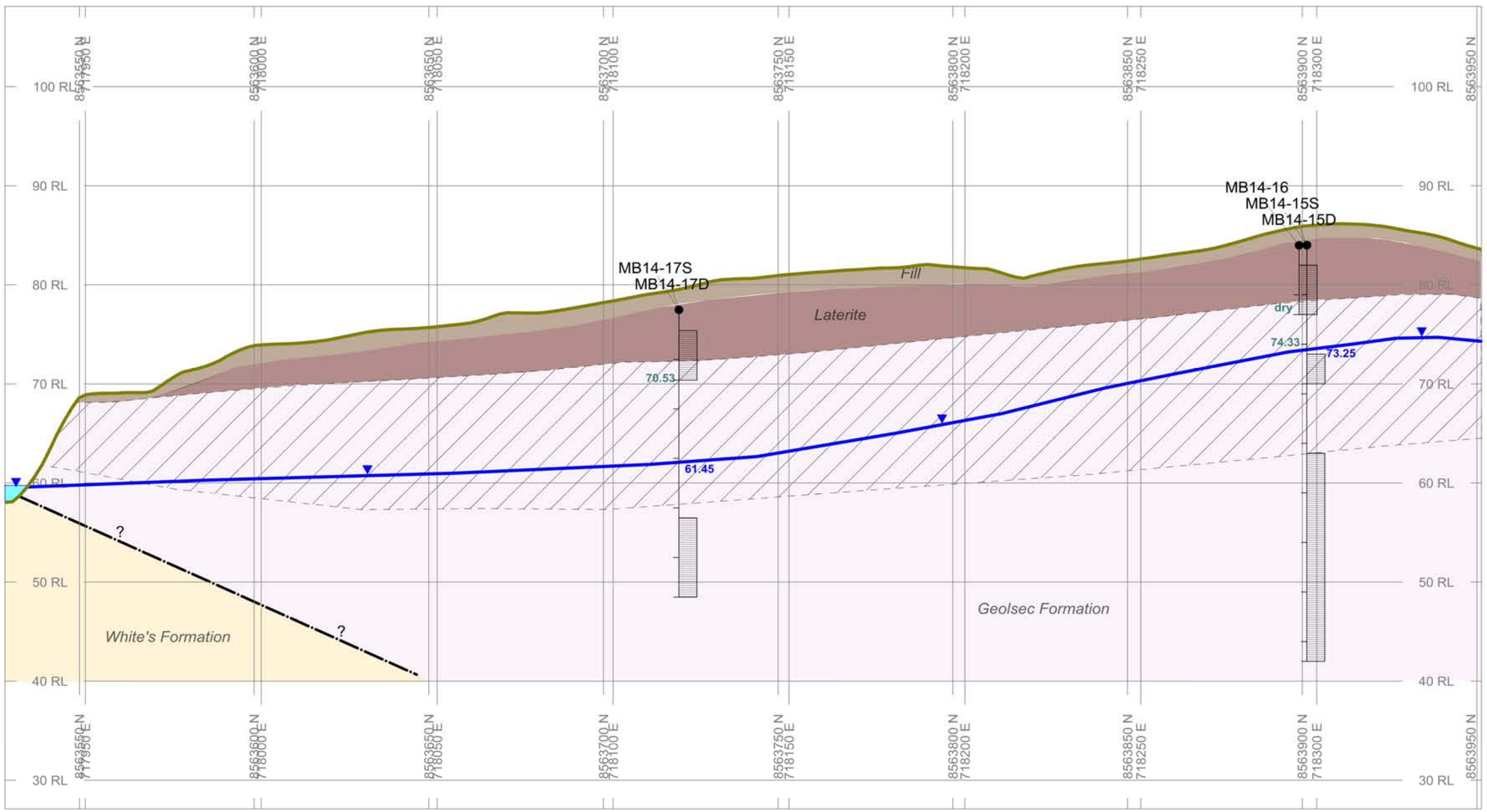
GDA94 / MGA zone 52

AZIMUTH = 92.9°

N W E S

Section A-A'	Figure: 4-4
Client: Northern Territory Government, Department of Resources - Minerals and Energy	Robertson GeoConsultants Inc.
Project: Specifications-2014 Hydrogeological Drilling Program	Rum Jungle Mine Site, NT, Australia
Report: RGC 183006/6	Project No: 183006
Last Update: Dec 9, 2014	Drawn: L.R.
Original File: Section_A-A'_Jan2016.map	





Legend

- Topography
- SWL m AHD, 24-Nov-2014
- Fault
- Possible Fault
- Contact
- Screen

ROCK CODES UNIT	PAT	LABEL	DESCRIPTION
		F	Fill
		L	Laterite
		GF	Geolsec Formation
		WF	White's Formation
		CD	Coomalie Dolostone
		TZ	Transition Zone

Weathering Profile
- Saprolite to highly weathered bedrock (more clay)
- Weathered to fresh bedrock (less clay)

57.23 m AHD (Deep)
57.22 m AHD (Shallow)

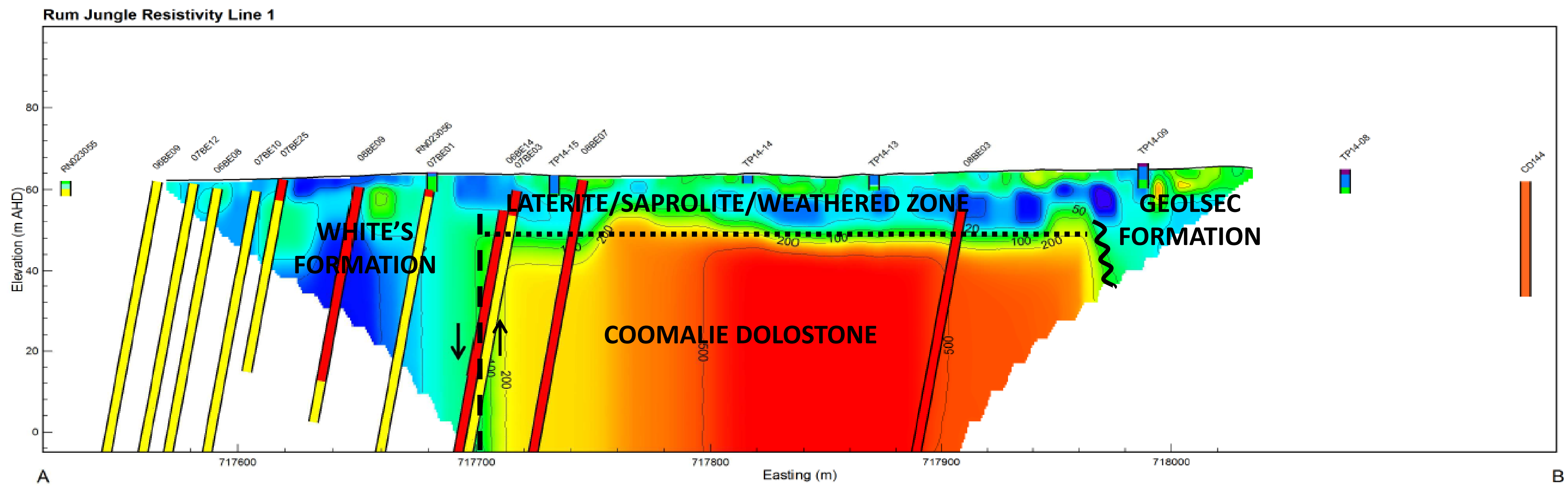
SECTION SPECS:

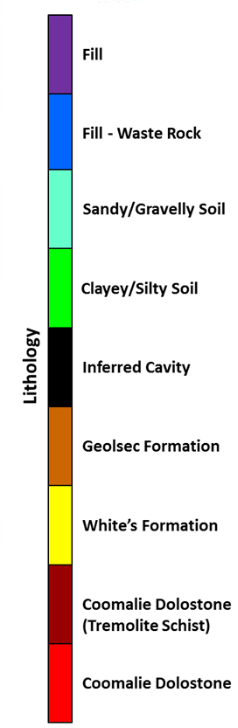
REF. PT. E, N	718137 m	8563740 m
EXTENTS	595.6 m	80.99 m
SECTION TOP, BOT	108.1 m	27.11 m
TOLERANCE +/-	75 m	
VERTICAL EXAG.	4	

(m)
-20 0 20 40 60 80 100
GDA94 / MGA zone 52

AZIMUTH = 44.8°
N
W E
S

Section B-B'	Figure: 4-5
Client: Northern Territory Government, Department of Resources - Minerals and Energy	Robertson GeoConsultants Inc.
Project: Specifications-2014 Hydrogeological Drilling Program	Rum Jungle Mine Site, NT, Australia
Report: RGC 183006/6	Project No: 183006
Last Update: Dec 9, 2014	Drawn: L.R.
Original File: Section B-B'_Jan2016.map	





Notes:

- Coordinate system is GDA94, MGA zone 52
- Horizontal scale is 1:2000 (for A3 plot)
- Vertical scale is 2:1
- Line traverse is denoted by A - B
- Current line is highlighted in red on overview map
- Logarithmic contours overlain on resistivity plot

Project:	Rum Jungle Geophysics, 2015
Figure:	A1
Caption:	Electrical Resistivity Line 1
Northern Territory Government	ASST EXPERIENCE. QUALITY. RELIABILITY.

Legend:

- Boundary
- Fault
- Unconformity
- Possible Antiform

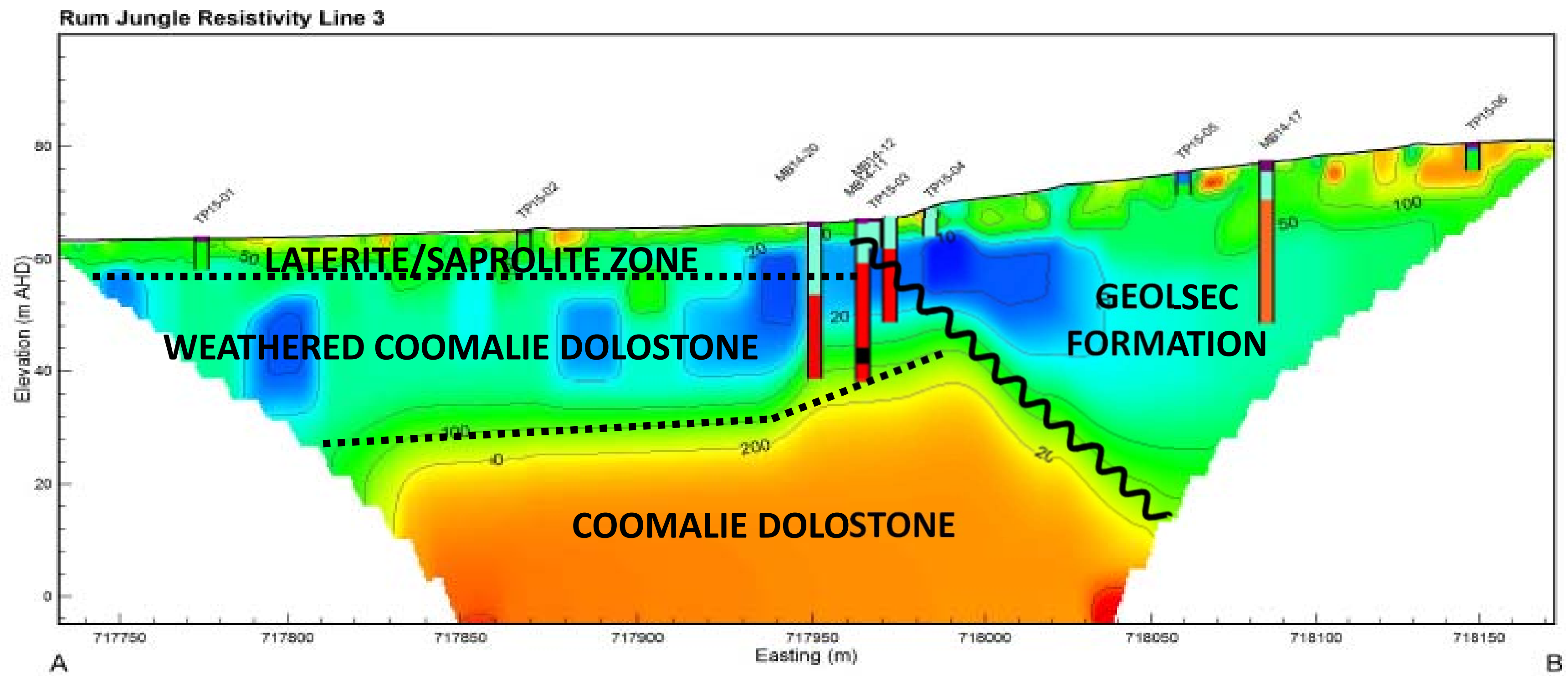
ERI Line 1 – Geological Interpretation

Robertson GeoConsultants Inc.

Client: Northern Territory Government	Figure: 4-6
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report No: 183006/6	Last Update: 31 May 2016

Original File: S:\Files\Projects\183000 RumJungle\183005 Phase 5\Stage 5\Report May 2016\Figures\Section 4

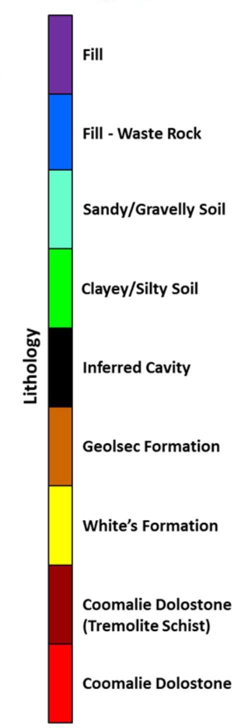
Rum Jungle Resistivity Line 3



Overview Map

Scale 1 : 2000

0m 40m 80m 120m 160m 200m 220m



Notes:

- Coordinate system is GDA94, MGA zone 52
- Horizontal scale is 1:2000 (for A3 plot)
- Vertical scale is 2:1
- Line traverse is denoted by A - B
- Current line is highlighted in red on overview map
- Logarithmic contours overlain on resistivity plot

Project:	Rum Jungle Geophysics, 2015
Figure:	A3
Caption:	Electrical Resistivity Line 3
Northern Territory Government	ASST EXPERIENCE. QUALITY. RELIABILITY.

Legend:

- Boundary
- Fault
- Unconformity
- Possible Antiform

ERI Line 3 – Geological Interpretation

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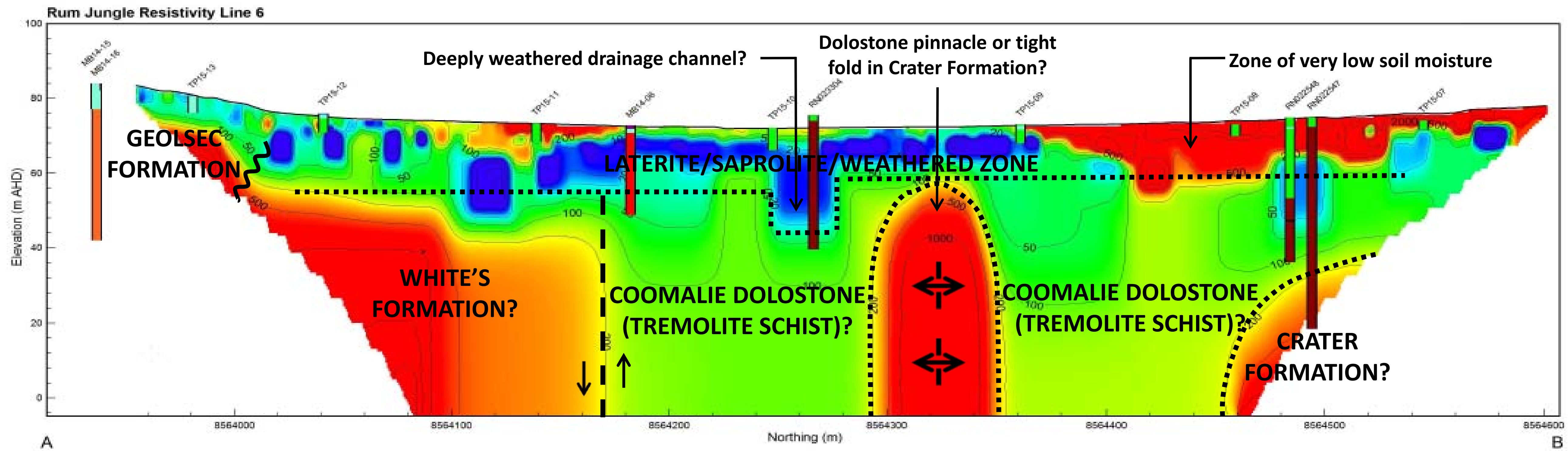
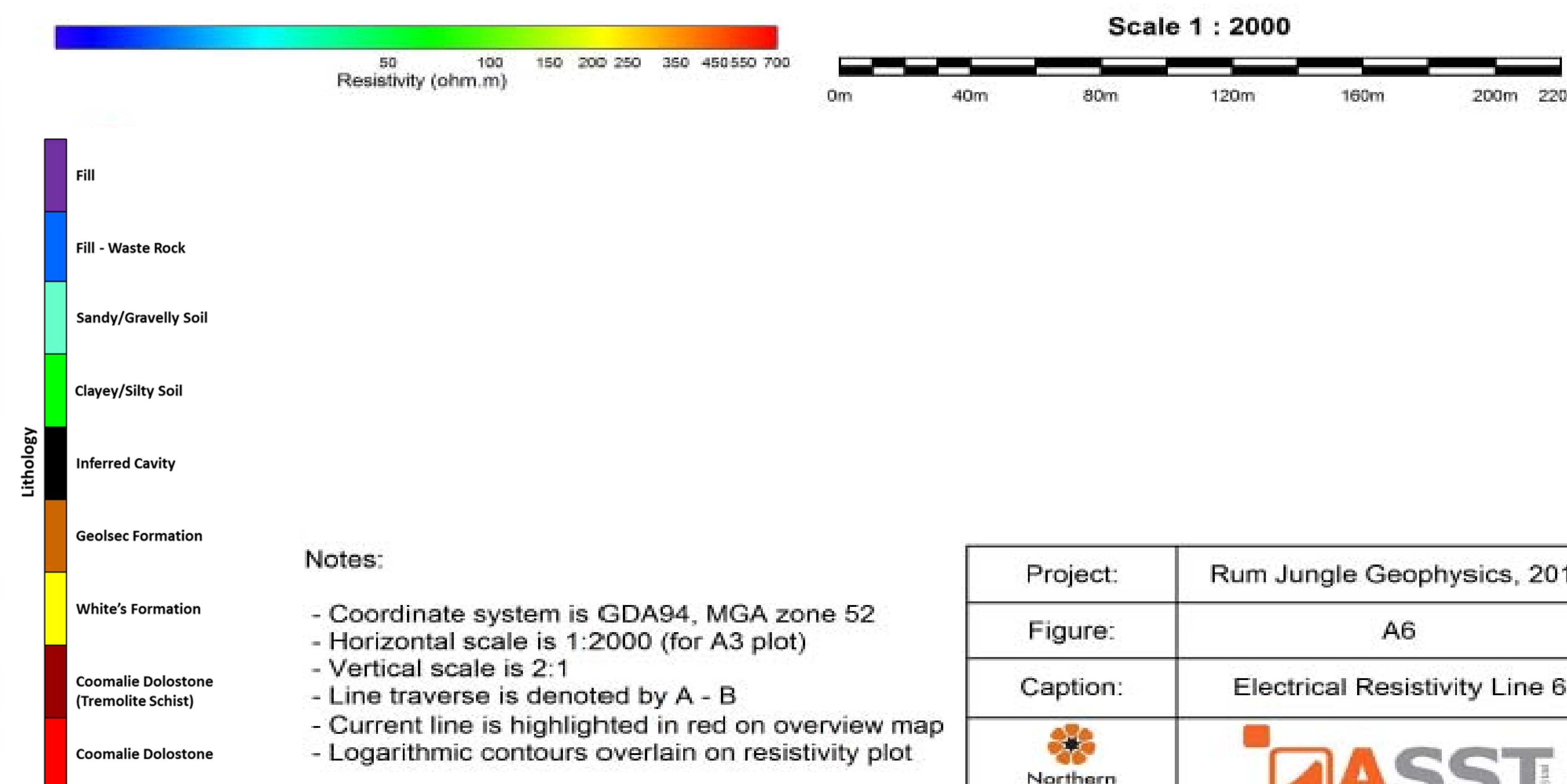
Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 4-7**
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report No: 183006/6	Last Update: 31 May 2016

Original File: S:\Files\Projects\183000 RumJungle\183005 Phase 5\Stage 5\Report May 2016\Figures\Section 4





Notes:

- Coordinate system is GDA94, MGA zone 52
- Horizontal scale is 1:2000 (for A3 plot)
- Vertical scale is 2:1
- Line traverse is denoted by A - B
- Current line is highlighted in red on overview map
- Logarithmic contours overlain on resistivity plot

Project:	Rum Jungle Geophysics, 2015
Figure:	A6
Caption:	Electrical Resistivity Line 6
Northern Territory Government	ASST EXPERIENCE. QUALITY. RELIABILITY.

Legend:

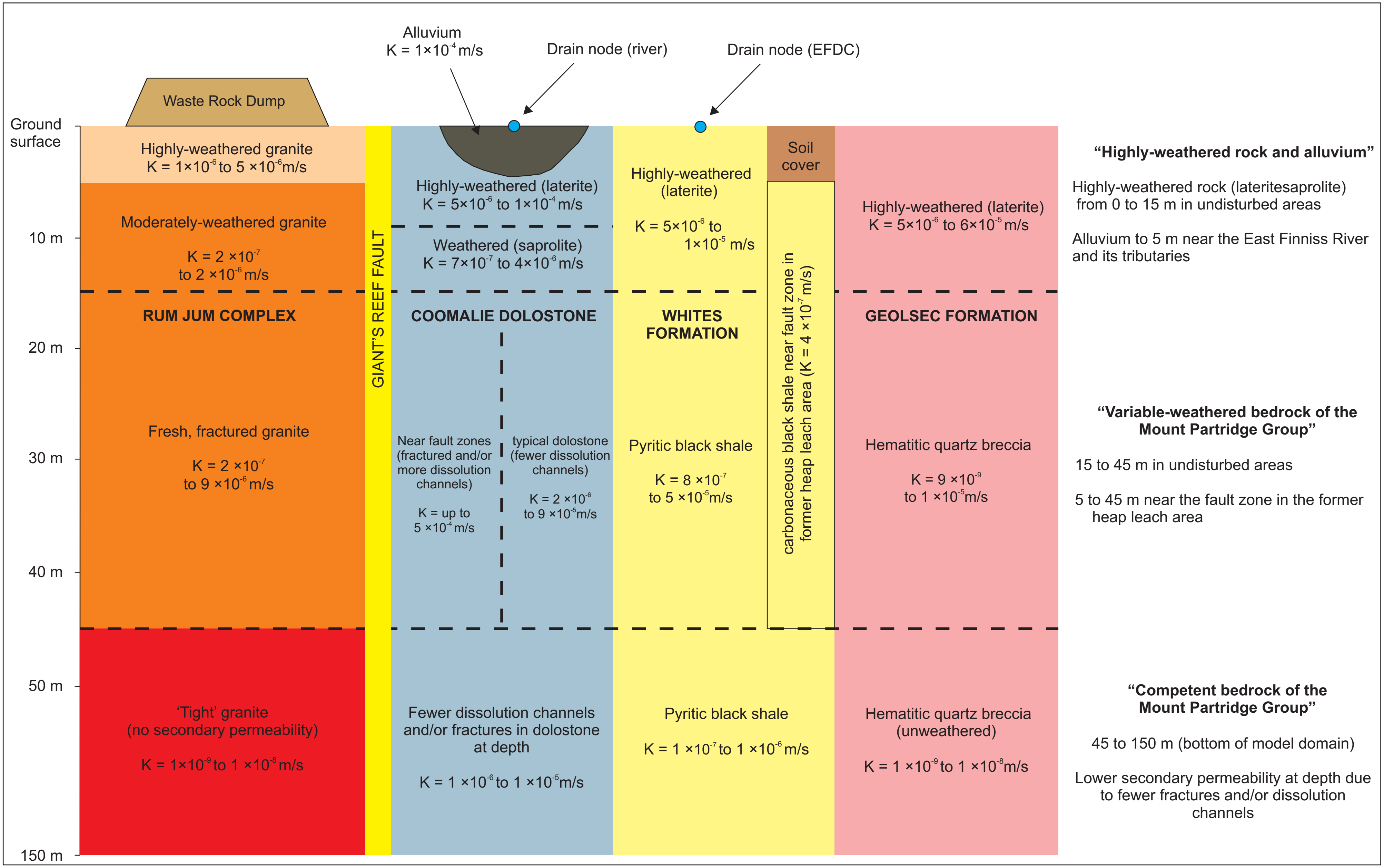
- Boundary
- Fault
- Unconformity
- Possible Antiform

ERI Line 6 – Geological Interpretation

Robertson GeoConsultants Inc.

Client: Northern Territory Government	Figure: 4-8
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report No: 183006/6	Last Update: 31 May 2016

Original File: S:\Files\Projects\183000 RumJungle\183005 Phase 5\Stage 5\Report May 2016\Figures\Section 4



Conceptual Hydrostratigraphic Model for the Rum Jungle Mine Site

Robertson GeoConsultants Inc.
Consulting Engineers and Scientists for the Mining Industry
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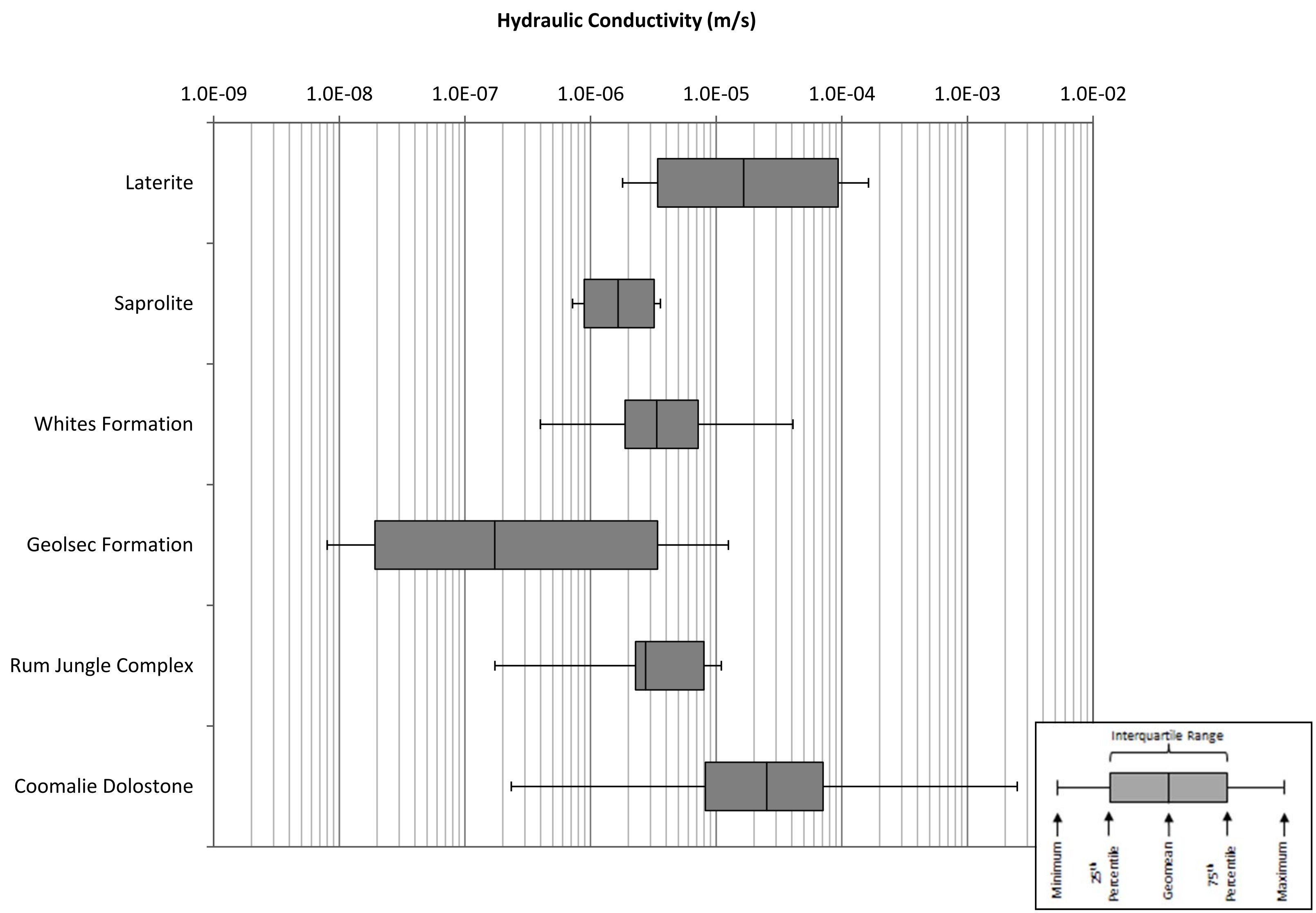
Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 4-9
Rum Jungle Rehabilitation Project	Project No: 183006
Report: 183006/6	Date: May 31, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure 4-4.cdr	



Hydraulic Conductivity Statistics by Lithology

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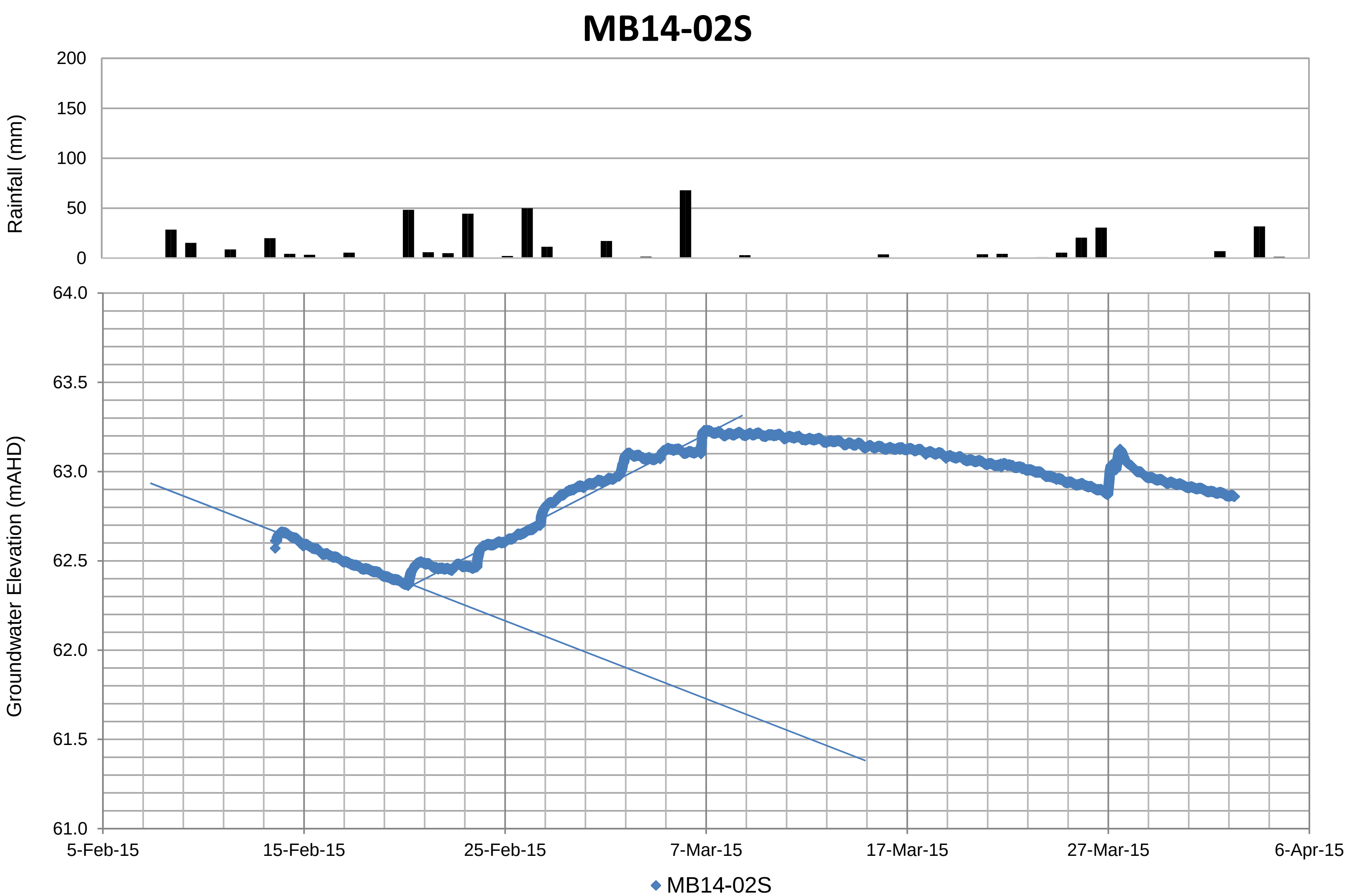
Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 4-10
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 26 Jan 2016
Original File: Section 6 Figures.pptx	



Response to Precipitation at Monitoring Bore MB14-02S

Robertson GeoConsultants Inc.
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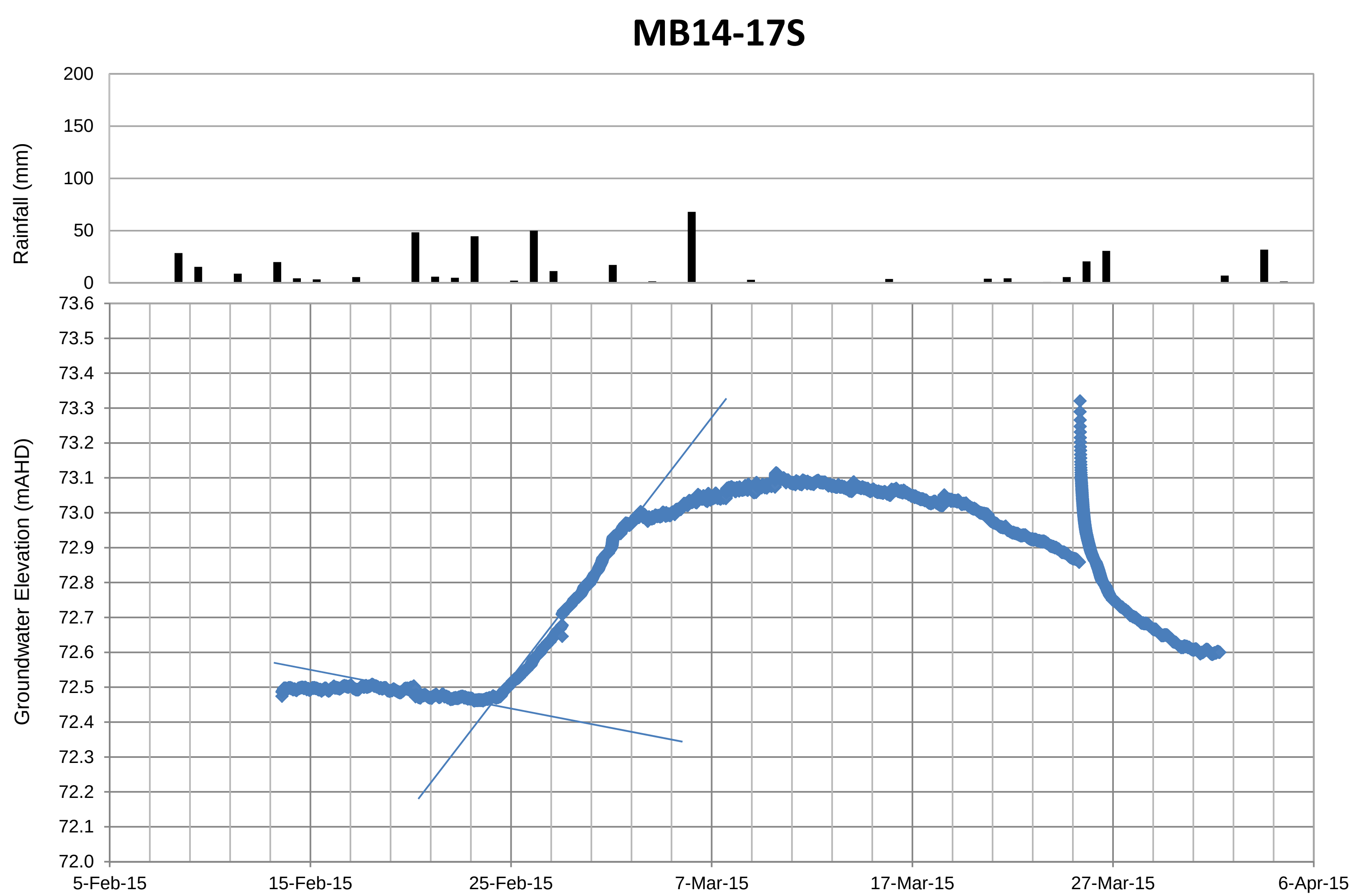
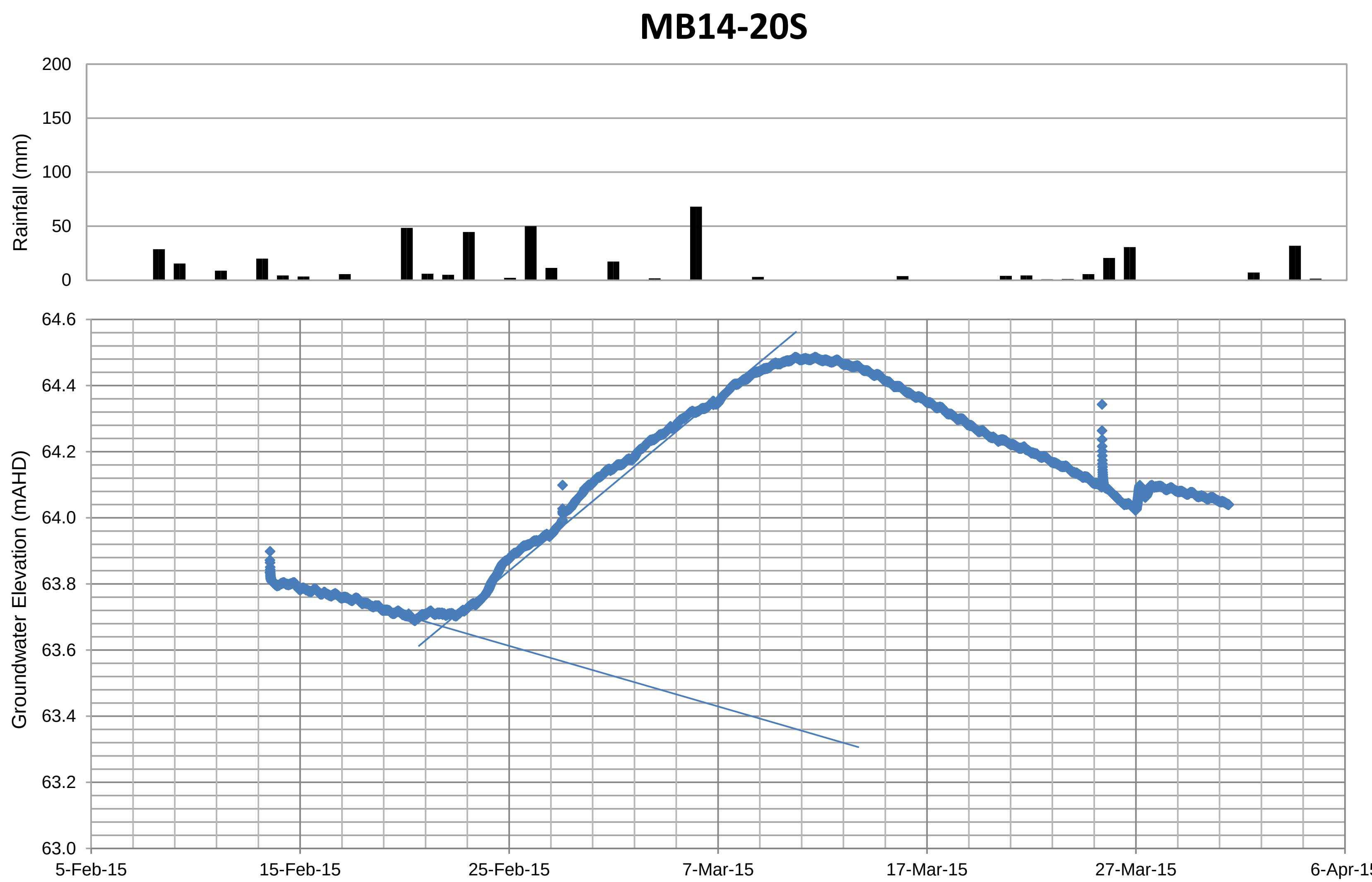
Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 4-11
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 31 May 2016
Original File: Section 6 Figures.pptx	



Response to Precipitation at Monitoring Bore MB14-17S

Robertson GeoConsultants Inc.

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 4-12
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 31 May 2016
Original File: Section 6 Figures.pptx	



Response to Precipitation at Monitoring Bore MB14-20S

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 4-13
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 31 May 2016
Original File: Section 6 Figures.pptx	

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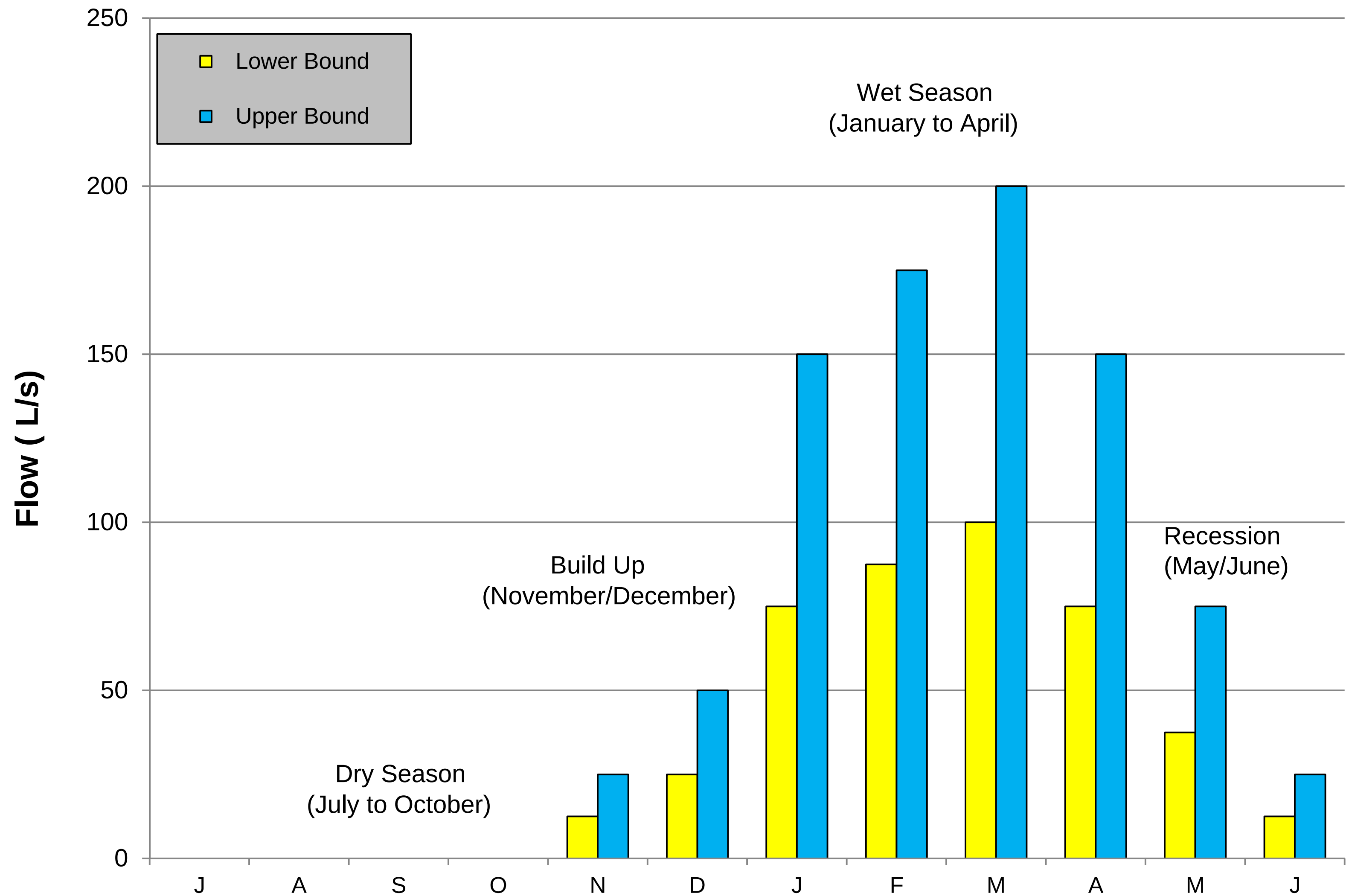
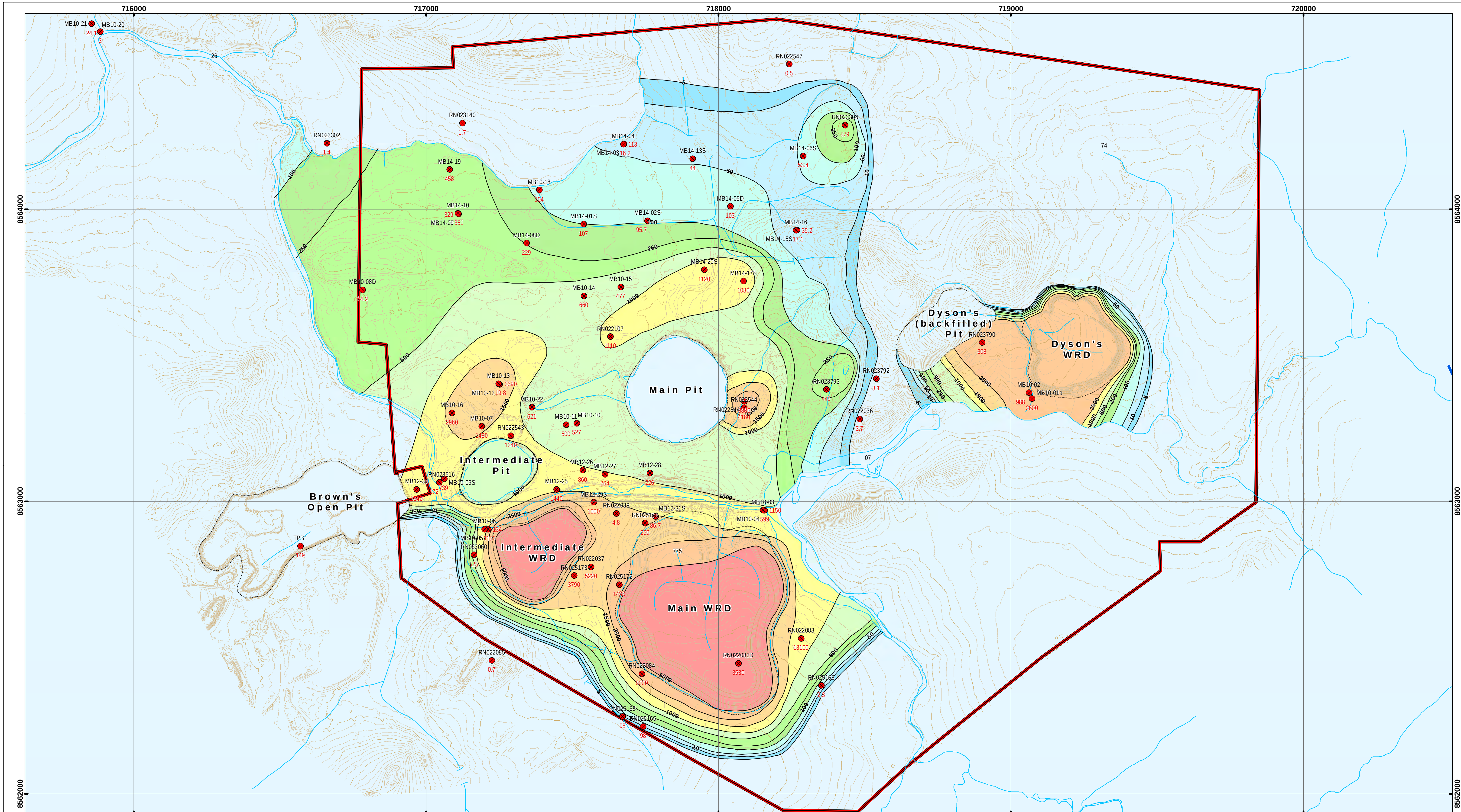


Potential Groundwater Flows to EBFR
Downstream of Gauge GS8150200

Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 4-14**
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 19 Jan 2016
Original File: Section 6 Figures.pptx	

Robertson GeoConsultants Inc.



SO₄ Zones (in mg/L)

- > 5,000
- 2,500 - 5,000
- 1,500 - 2,500
- 1,000 - 1,500
- 500 - 1,000
- 250 - 500
- 100 - 250
- 50 - 100
- 10 - 50
- 5 - 10
- < 5

Legend

- MB10-03 / 1150 — Well Location, Number & SO_4 Value (mg/L)
- SO_4 Contour
- Drainage
- Pit/WRD Outline
- Mine Site Boundary

Conceptual SO_4 Plume in Groundwater (Current Conditions)

Rum Jungle Mine Site

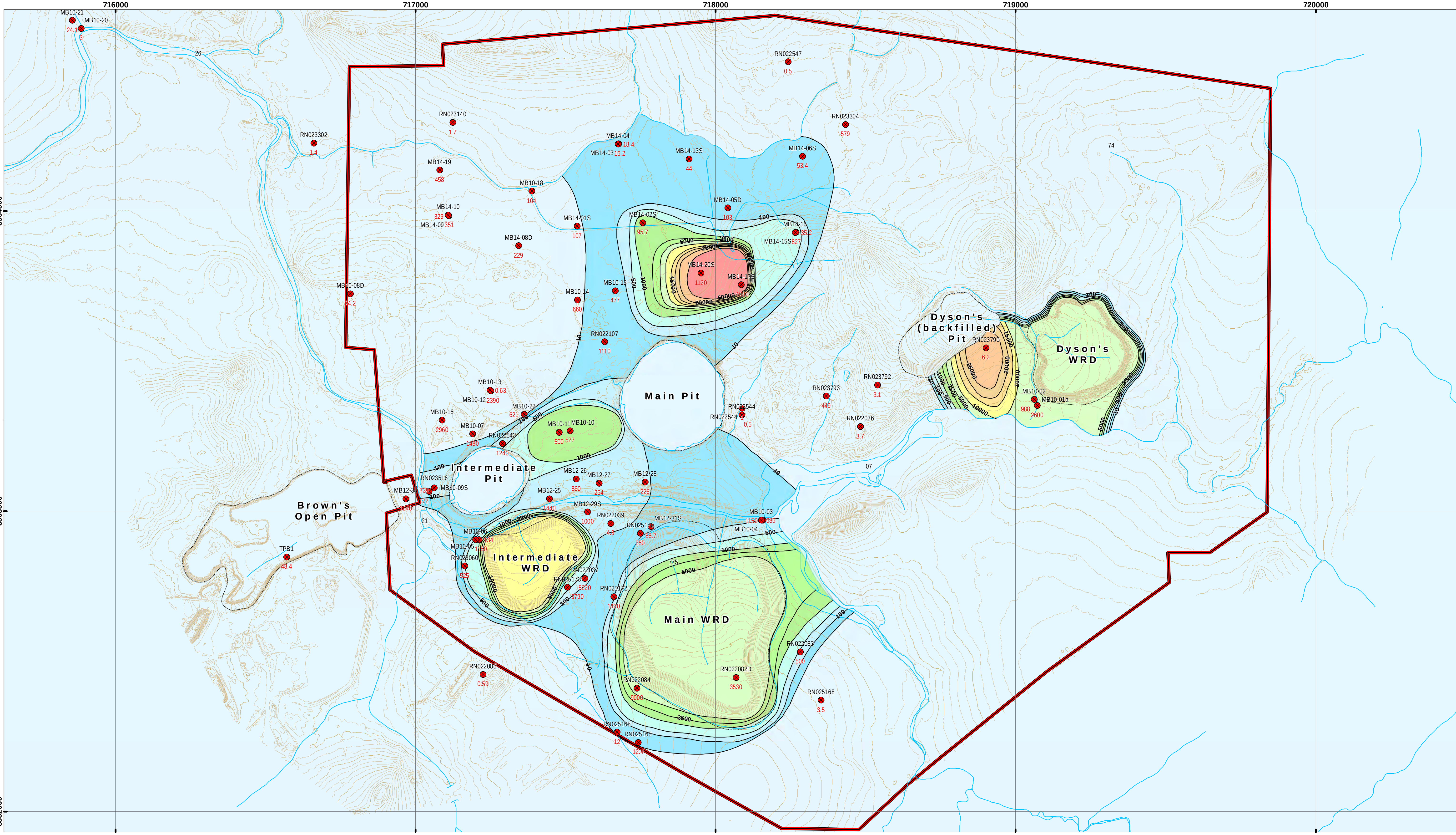
Scale 1:12,000

0 500 1,000 Metres

Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 4-15a**
Project: New Waste Storage Facility Investigation	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 09, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure4-15a_RJ_GWQ_SO4Plume.mxd	



Cu Zones (in µg/L)

> 50,000	2,500 - 5,000
25,000 - 50,000	1,000 - 2,500
20,000 - 25,000	500 - 1,000
15,000 - 20,000	100 - 500
10,000 - 15,000	10 - 100
5,000 - 10,000	< 10

Legend

MB10-03 1150 Well Location, Number & Cu Value (µg/L)

Cu Contour

Drainage

Pit/WRD Outline

Mine Site Boundary

Conceptual Copper Plume in Groundwater (Current Conditions)

Rum Jungle Mine Site

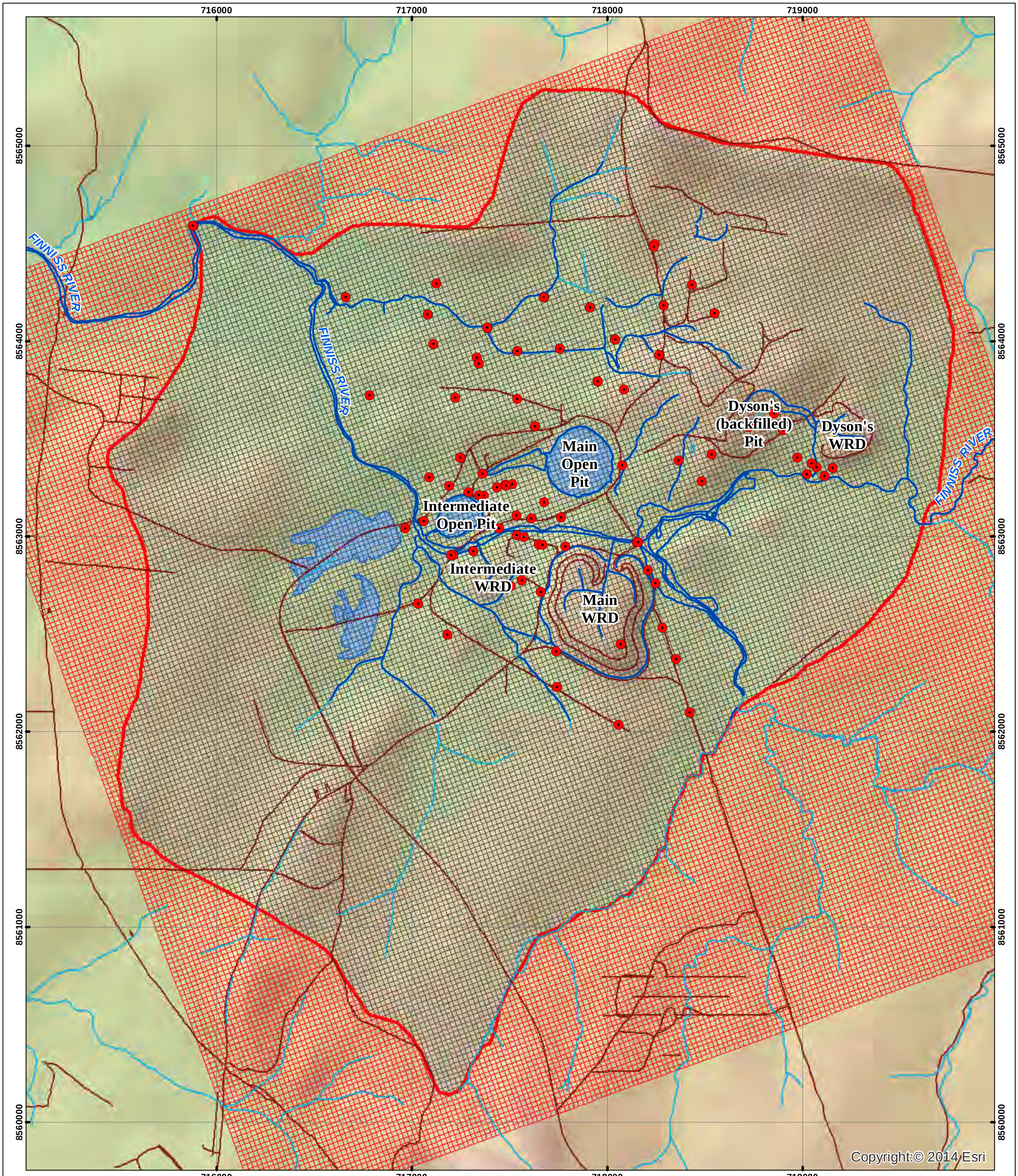
Scale 1:12,000

0 500 1,000 Metres

Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

Client: Northern Territory Government	Figure: 4-15b
Project: New Waste Storage Facility Investigation	Project No: 183006
Report: RGC 183006/6	Last Update: Jun 10, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure4-15b_RJ_GWQ_CuPlume.mxd	



LEGEND

- Monitoring Bore
- Active Cell
- Inactive Cell
- Model Domain Boundary

Model Domain and Finite Difference Grid

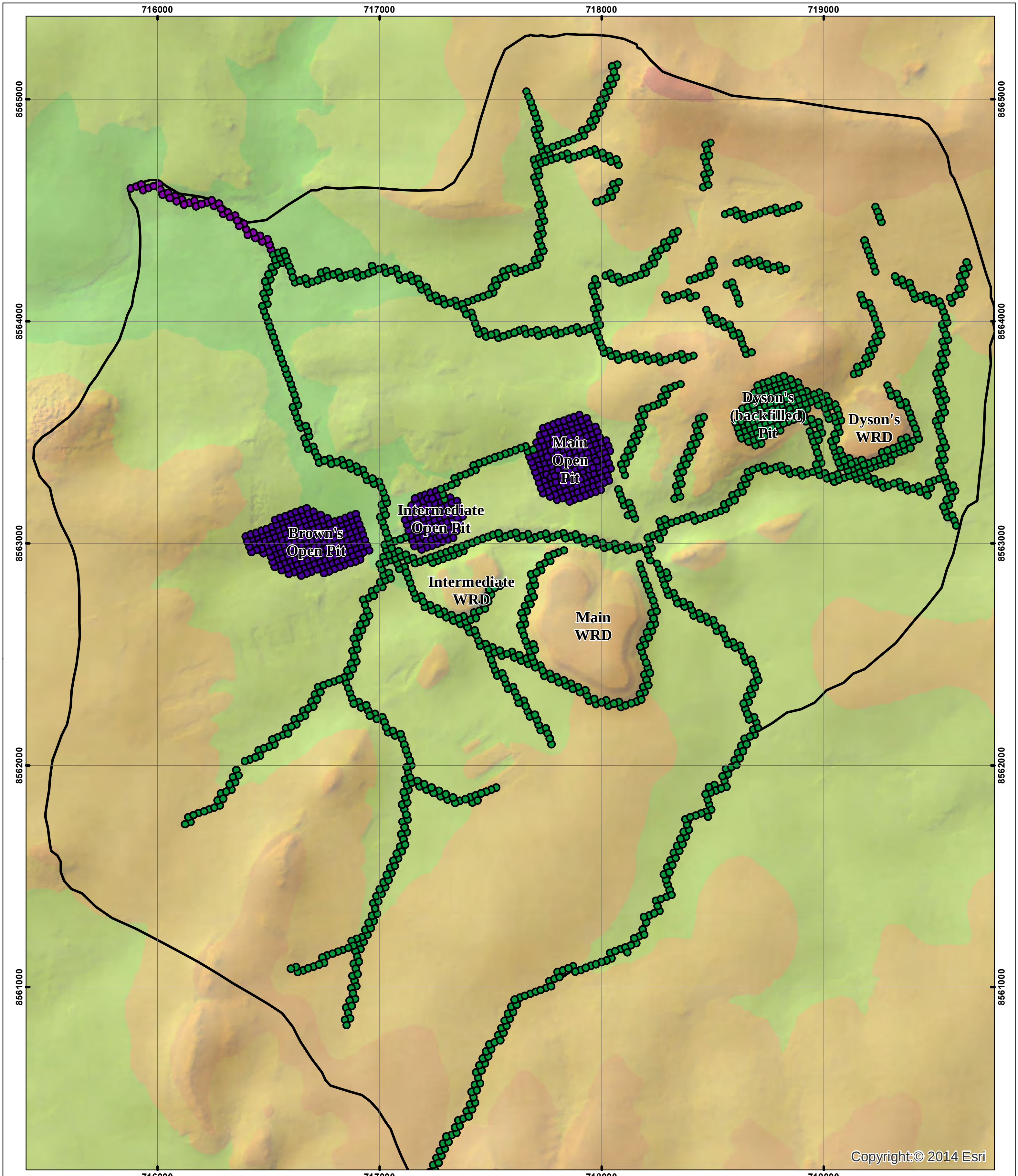
Scale: 1:25,000

0 100 200 400 600 800 1,000 Meters

Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

Client: Northern Territory Government	Figure: 5-1
Rum Jungle Rehabilitation Project	Project No:183006
Repor Not: 183006/6	Last Update: Dec 07, 2015
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure5-1_RJ_ModelDomain.mxd	



LEGEND

- Drain Node
- Drain Arc
- Drain Polygon
- Time Variant Constant Head Polygon
- Time Variant Constant Head Arc
- Model Domain Boundary

Boundary Conditions

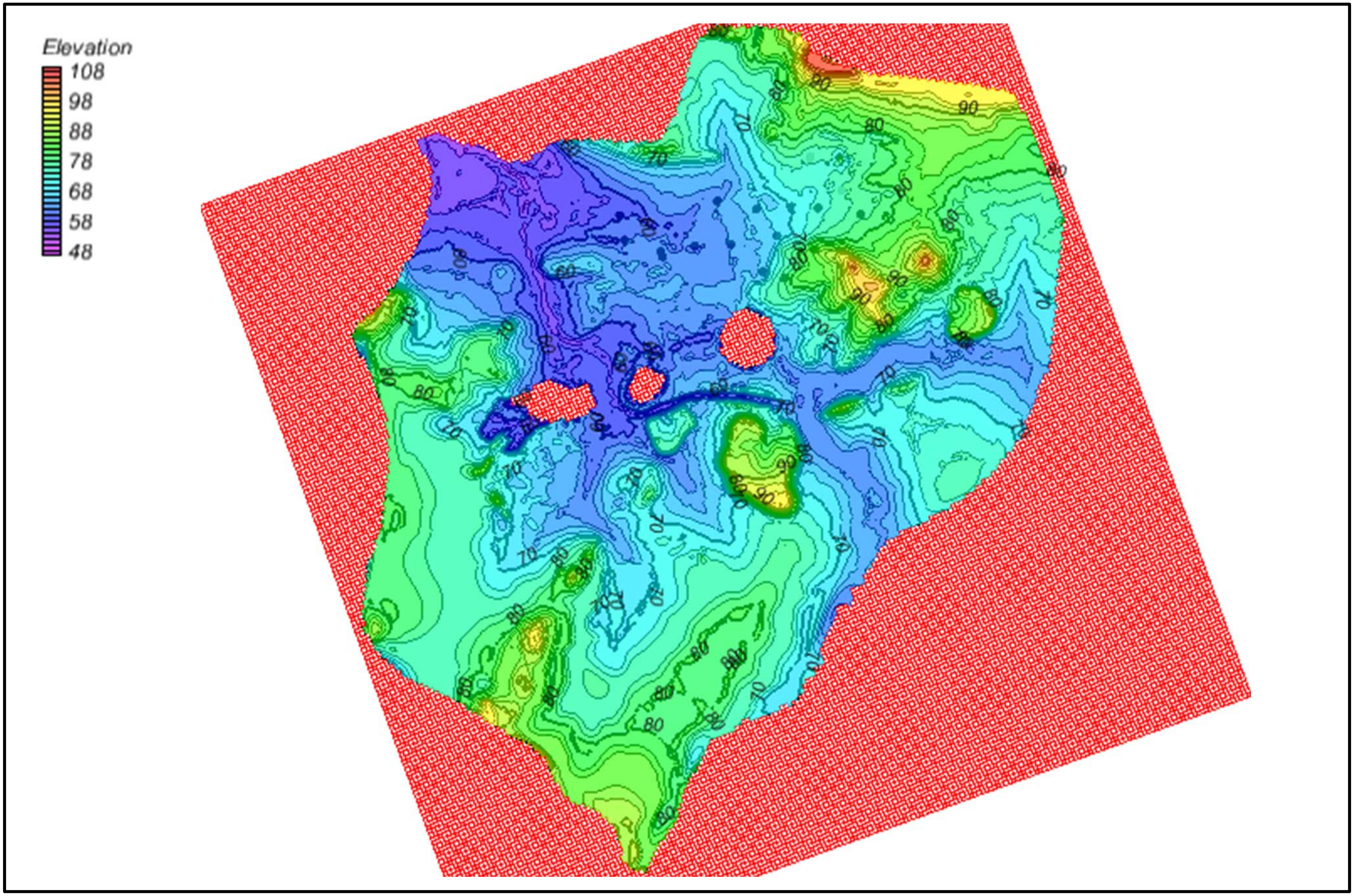
Scale: 1:22,000

0 90 180 360 540 720 900 Meters

Projection: GDA 1994 MGA Zone 52 (m)

Robertson GeoConsultants Inc.

Client: Northern Territory Government	**Figure: 5-2**
Rum Jungle Rehabilitation Project	Project No:183006
Repor Not: 183006/6	Last Update: Dec 07, 2015
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure5-3_RJ_BoundaryConditions.mxd	



Current Model Topography
(Top of Model Layer 1)

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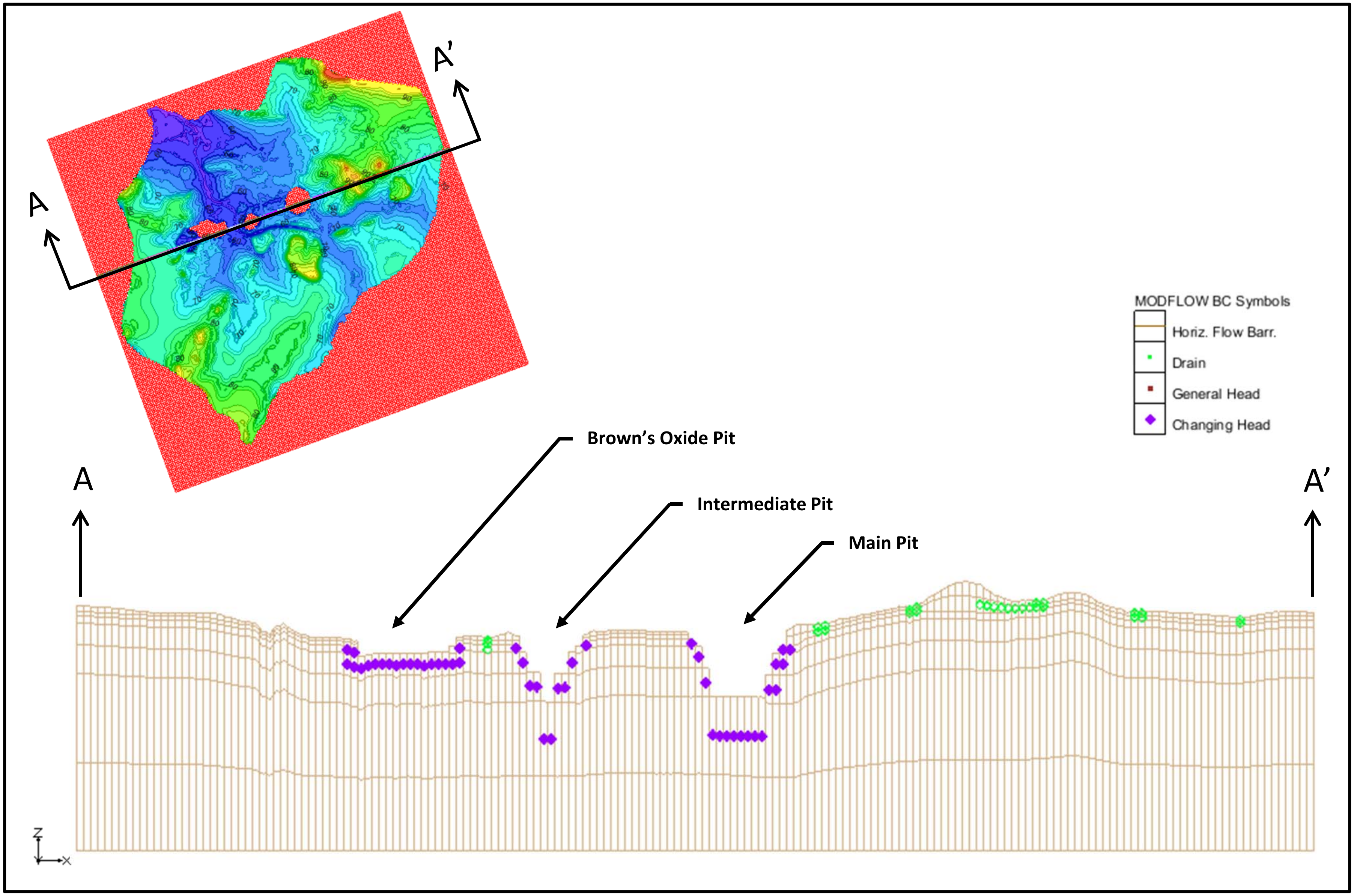
Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 5-3
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

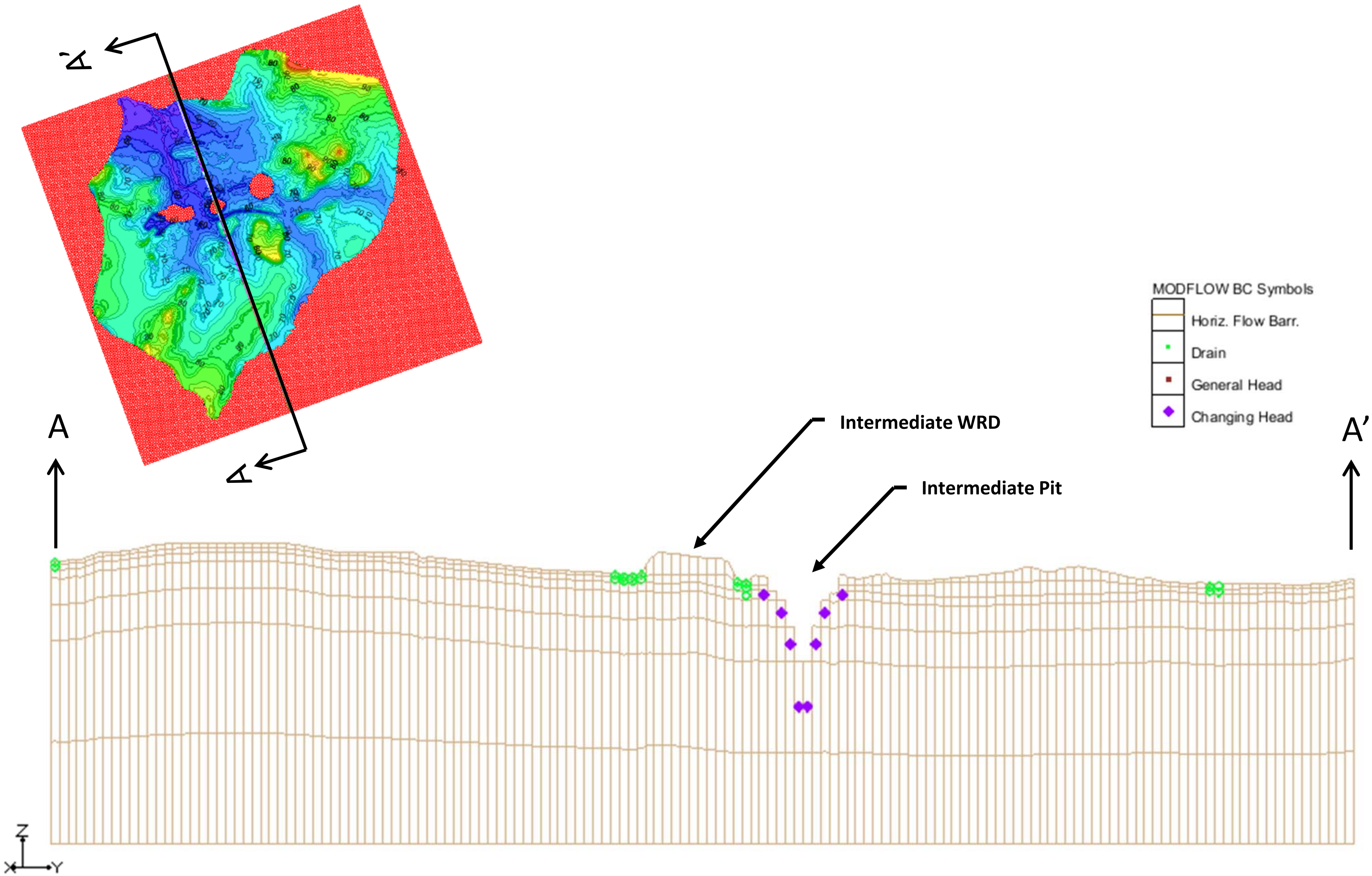


Model E-W Cross-Section Through Central Mining Area (Row 78)

5x Vertical Exaggeration

Robertson GeoConsultants Inc.

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 5-4a
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	

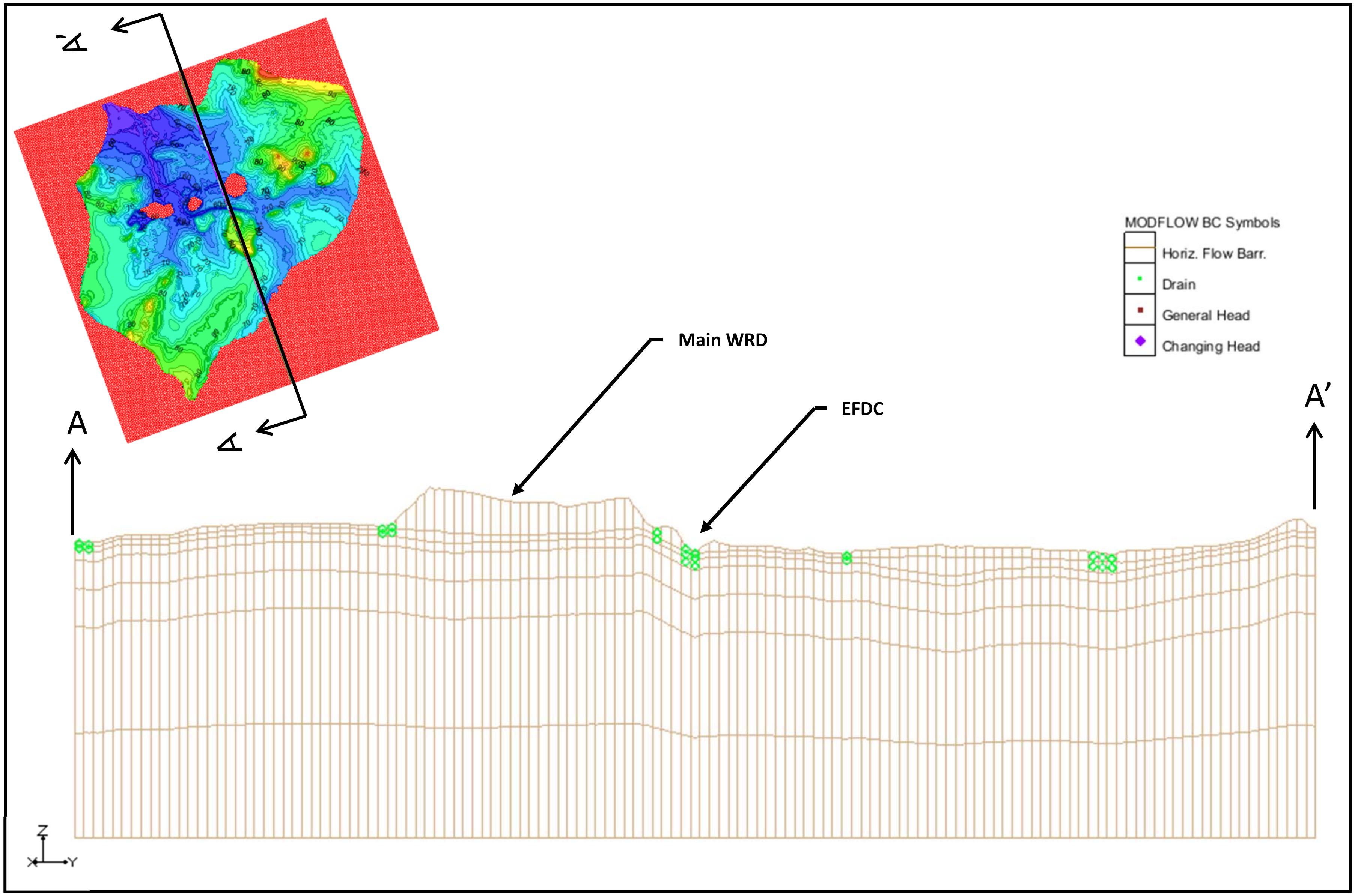


Model Cross-Section S-N Through Intermediate Pit and WRD (Column 87)

5x Vertical Exaggeration

Robertson GeoConsultants Inc.

Client: Northern Territory Government	Figure: 5-4b
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015
Original File: Section 6 Figures.pptx	



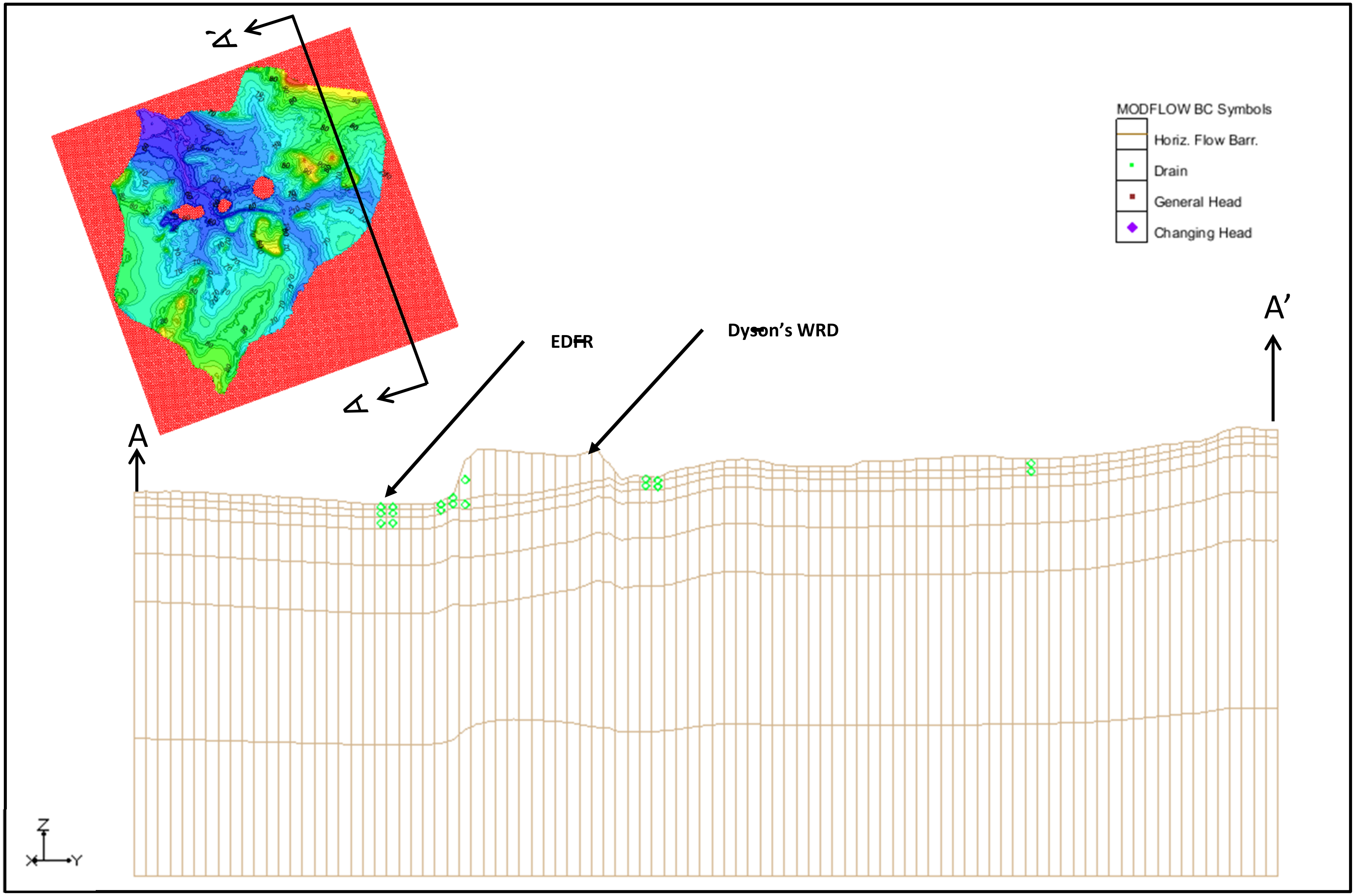
Model Cross-Section N-S Through Main WRD (Column 106)

5x Vertical Exaggeration

Robertson GeoConsultants Inc.

Client: Northern Territory Government	**Figure: 5-4c**
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015

Original File: Section 6 Figures.pptx



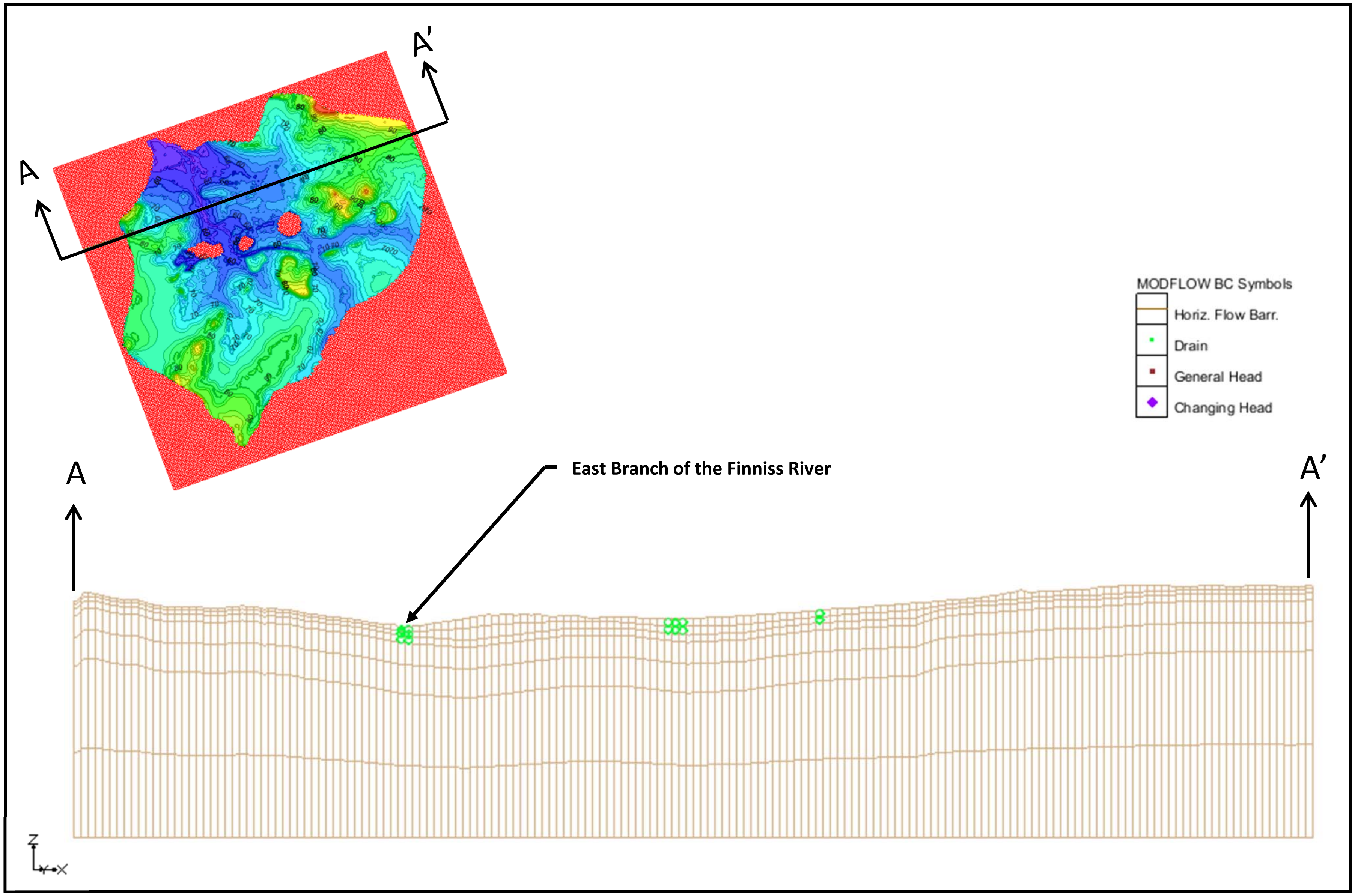
Model Cross-Section N-S Through Dyson's WRD (Column 169)

5x Vertical Exaggeration

Robertson GeoConsultants Inc.

Client: Northern Territory Government Department of Resources - Minerals and Energy	Figure: 5-4d
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015

Original File: Section 6 Figures.pptx



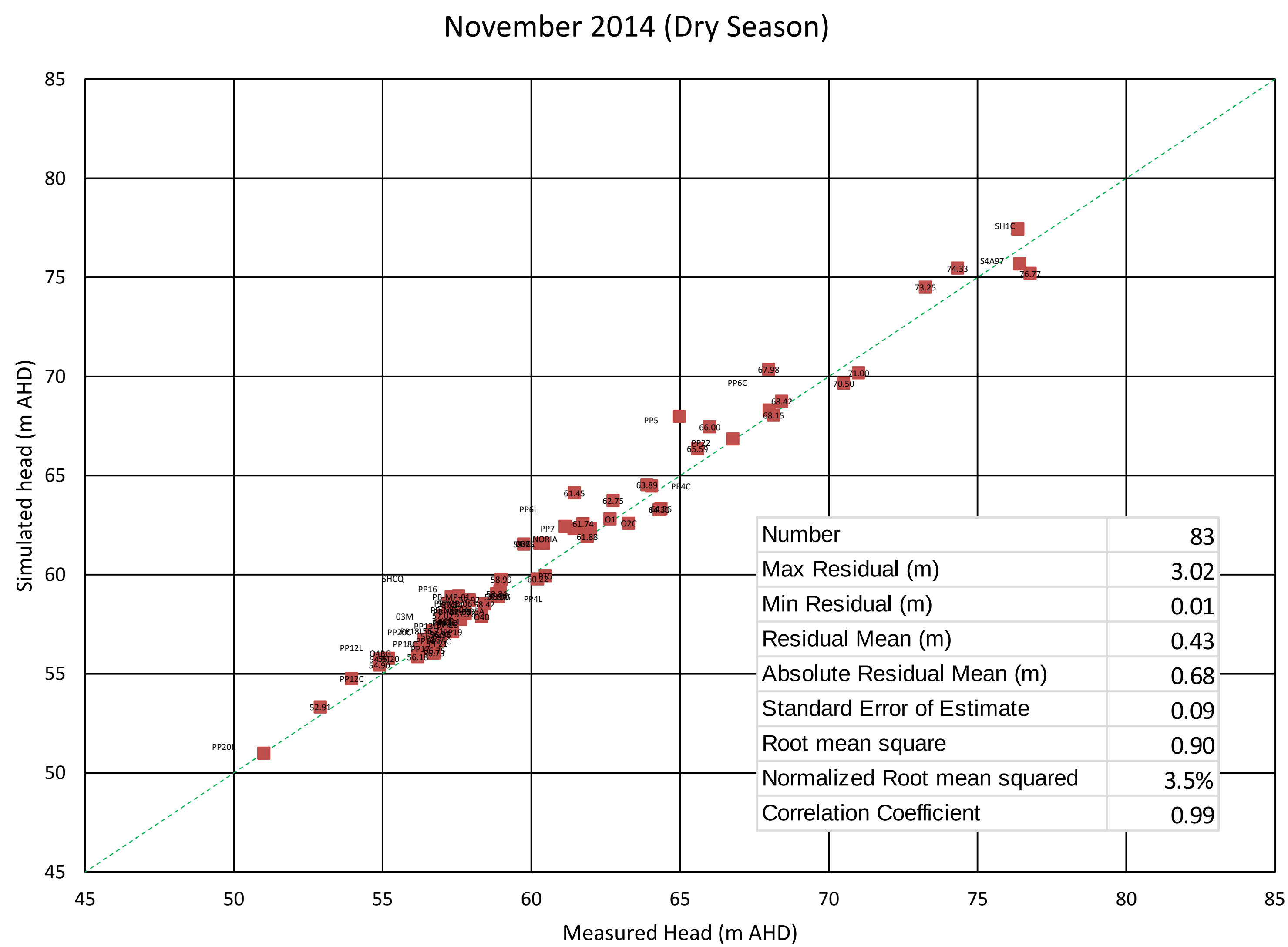
Model Cross-Section W-E Through Old Tailings Dam Area (Row 51)

5x Vertical Exaggeration

Robertson GeoConsultants Inc.

Client: Northern Territory Government	Figure: 5-4e
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update: 7 Dec 2015

Original File: Section 6 Figures.pptx



Number	83
Max Residual (m)	3.02
Min Residual (m)	0.01
Residual Mean (m)	0.43
Absolute Residual Mean (m)	0.68
Standard Error of Estimate	0.09
Root mean square	0.90
Normalized Root mean squared	3.5%
Correlation Coefficient	0.99

Goodness-of-Fit and Calibration Statistics for Dry Season

Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 6-1a**
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update : 27 May 2016
Original File: Section 6 Figures.pptx	

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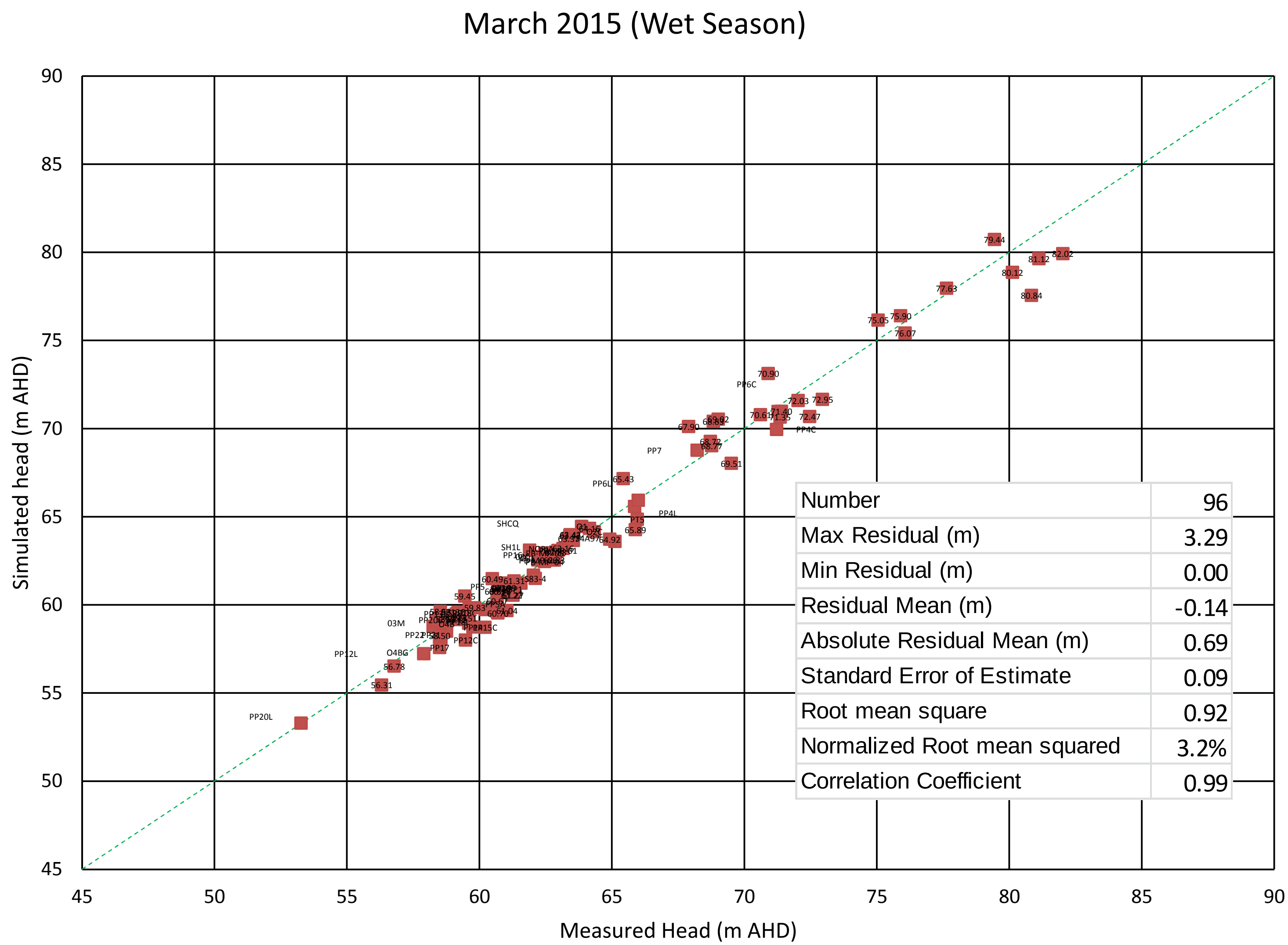

Goodness-of-Fit and Calibration Statistics for Wet Season

Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 6-1b**
Rum Jungle Rehabilitation Planning	Project No: 183006
Report No: 183006/6	Last Update : 27 May 2016
Original File: Section 6 Figures.pptx	

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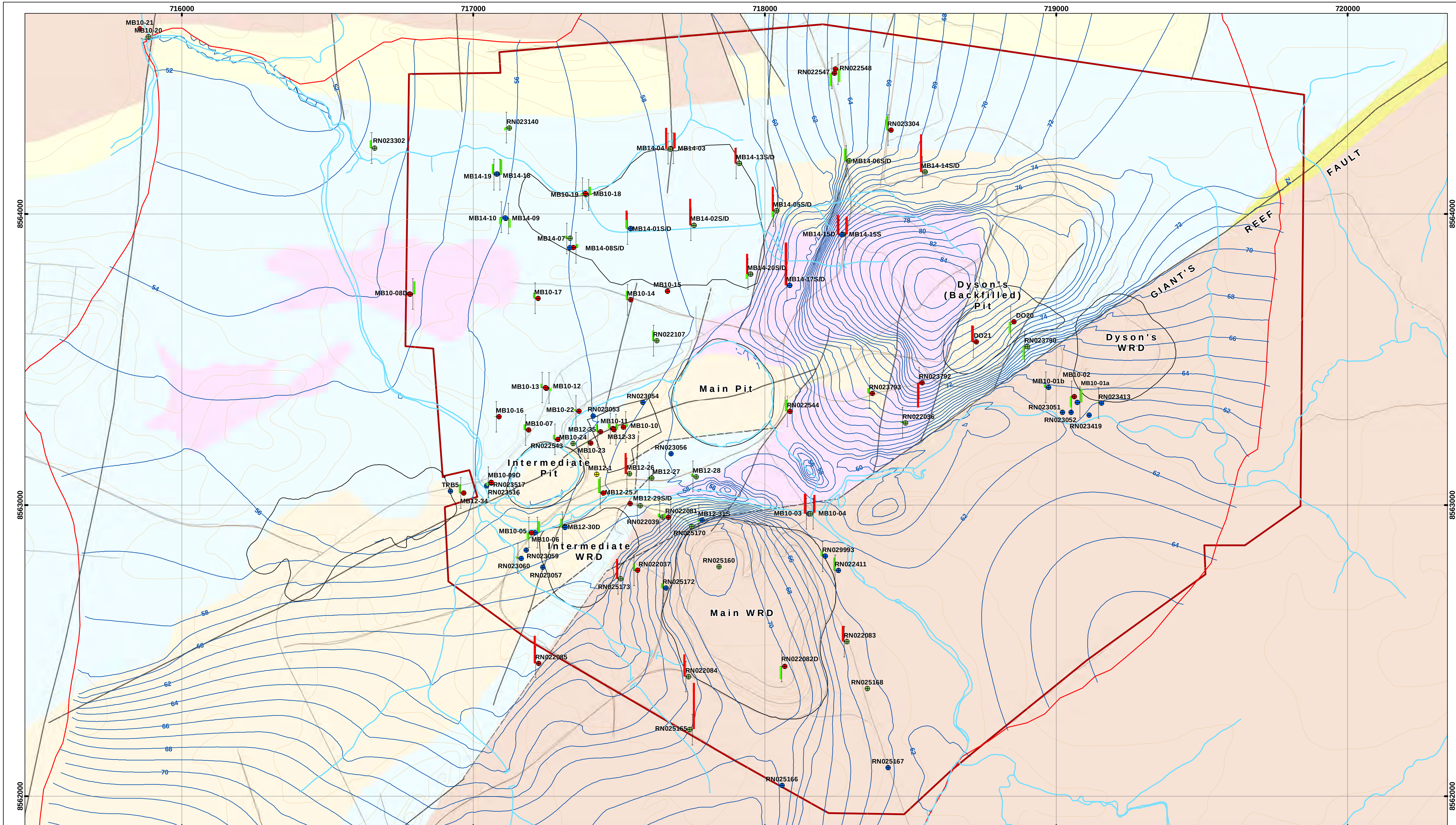

LEGEND

- Groundwater Bore (Depth <5m)
- Groundwater Bore (Depth from 5 to 15m)
- Groundwater Bore (Depth >15m)
- Groundwater Bore (Unclassified)
- Drainage
- Road
- Fault
- Mine Site Boundary
- Model Domain
- GWL Contour

Lithology

- Whites Formation
- Geolsec Formation
- Coomalie Dolostone
- Crater Formation
- Quartz Vein
- Rum Jungle Complex

Simulated vs Observed (< ± 1)

Simulated vs Observed (> ± 1)

Simulated Head Contours and Computed Residuals for Dry Season (Nov.2014)

Rum Jungle Mine Site

Scale 1:12,000

0 50 100 200 300 400 500 600 700 800 900 1,000 1,100 Metres

Projection: GDA 1994 MGA Zone 52 (m)

N E S W

Robertson GeoConsultants Inc.

Client: Northern Territory Government	Figure: 6-2a
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report: RGC 183006/6	Last Update: May 31, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure6-2a_RJ_CalibrationStats_Dry_Jan2016.mxd	