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Groundwater Remediation Strategy for the Copper Extraction Pad Area

1 Introduction

Groundwater near the former Copper Extraction Pad between the Main and Intermediate Pits contains up to 1,000 mg/L of dissolved copper (Cu). Groundwater quality in this area was impacted primarily by seepage losses during the so-called 'Copper Heap Leach Experiment' of the late 1960s (Anderson and Allman, 1968[1]). The experiment involved heap leaching sulphide and oxide ore from the Intermediate ore body on a low-permeable pad between the Main and Intermediate Pits. It was largely unsuccessful and seepage losses to groundwater were substantial (Davey, 1975[2]).

RGC proposes a pump-and-treat system to remediate impacted groundwater in this area as part of the implementation of the preferred rehabilitation strategy. The system would likely be operated during the first two years of the construction phase of rehabilitation in order to reduce contaminant concentrations in groundwater before the Main Pit is de-watered. This timing would prevent inflows of highly-impacted groundwater to the pit while it is being backfilled.

The purpose of this report is to describe the pump-and-treat system and how it would be operated during rehabilitation. Of particular interest for 'construction phase' rehabilitation planning is the duration (and rate) of pumping, as well as the total volume of groundwater that would require treatment. Of further interest is the expected condition of groundwater in the Copper Extraction Pad area after remediation is complete.

Further description of the system and post-remediation groundwater conditions will be provided in RGC's report on groundwater flow and transport modeling (RGC Report 183006/6) includes the following supporting information:

[1] Andersen, J.E. and Allman, M.B., (1968), Some operational aspects of heap leaching at Rum Jungle, Proc. Aust. Inst. Min. Metal., 225: 27-31.

[2] Davy, D.R. (1975), Rum Jungle Environmental Studies, Australian Atomic Energy Commission report. September 1975.

- Overview of the ‘Copper Heap Leach Experiment’ and contaminant sources to groundwater.
- Overview of current groundwater quality conditions in the Copper Extraction Pad area.
- Delineation of residual ‘copper plumes’ near the pits.
- Estimation of the volume of highly-impacted groundwater that may require treatment.
- Numerical modeling of the proposed ‘pump-and-treat’ strategy.

Also provided are preliminary recommendations for additional investigative work that could improve the delineation of ‘copper plumes’ and thereby reduce uncertainties that pertain to groundwater volume estimates and contaminant recovery rates.

2 Historical Operation of Copper Heap Leach Pad

Figure 1 shows the Copper Extraction Pad area in an aerial photograph from 1977. The heap leach pad was operated for six years from 1965 to 1971 (Davey 1975). The heap leaching process initially involved piling low-grade sulphide ore (0.7 to 2.0 % Cu) onto a low-permeable pad and then spraying the top of the pile with pH 2 acid. The acidic mixture used to leach copper from the sulphide ore consisted of mill process water, barren liquor, and pit water from the Main Pit. Liquor drained from the sulphide pile (nominally pH 1.5) was then pumped onto a pile of oxide ore (2 % Cu) to leach additional copper before the pregnant liquor was pumped to launders for copper recovery (by cementation) (Davey, 1975).

The ‘Copper Heap Leach Experiment’ was not particularly efficient, and substantial losses of pregnant liquor occurred by seepage and evaporation. Davey (1975), for instance, estimates that ~2 L/s was lost to evaporation and infiltration to groundwater during the wet season, while ~4 L/s was lost during the dry season. Pregnant liquor typically contained 1,000 mg/L Cu and concentrations of up to 9,000 mg/L Cu were observed. Losses appear to have occurred from the heap leach pad itself, and from the various ditches and storage ponds that were used for the heap leaching process. Moreover, overflow from the system and excess barren liquors (with pH < 2) were discharged to Copper Creek (which flowed north of the Copper Extraction Pad area to the East Branch of the Finniss River).

Seepage losses from the Main Pit (which is up-gradient of the Copper Extraction Pad area) may have been a secondary source of contaminants to groundwater during the heap leach operation. However, Cu concentrations in pit water were much lower than in seepage lost during the heap leach operation (i.e. 50 to 60 mg/L Cu in the 1970s), so loads from pit water can only explain some moderately-impacted groundwater in the vicinity of that pit. The Intermediate Pit (which was mined until 1965) was likely de-watered during the initial stages of the heap leaching operation and could have been flooded with groundwater and rainfall during the later stages of the operation. The Intermediate Pit was therefore a sink (or discharge zone) for highly-impacted groundwater from the heap leach area during this period.

3 Current Groundwater Quality Conditions

Figure 1 shows the locations of monitoring bores in the Copper Extraction Pad area. Also shown is the screened interval (in metres below ground surface, bgs), the pH of groundwater, and the concentrations of dissolved Cu and sulphate (SO_4) in groundwater in October 2014 (i.e. the 'dry season'). These same concentrations are shown in Figure 2, wherein surficial geology and the inferred, 'wet season' groundwater flow field in the Copper Extraction Pad area are shown for reference. This groundwater flow field is likely representative of the ~40 years since the Main Pit and the Intermediate Pit were both flooded (in the 1970s).

Four monitoring bores (MB10-10, MB10-11, MB12-33 and MB12-35) are located beneath the former copper extraction pad (Figure 1). Monitoring bores MB12-25, MB12-26, MB12-27 and MB12-28 are located to the south near the East Finniss Diversion Channel (EFDC). These bores are up-gradient/cross-gradient of the wells near the former extraction pad. Monitoring bores MB10-23, MB10-24 and RN022543 are located down-gradient of the Copper Extraction Pad area, whereas monitoring bore MB10-22 is positioned cross-gradient near the flood channel of the East Branch of the Finniss River.

The highest copper concentrations in the Copper Extraction Pad area are observed in monitoring bores MB10-23 (561 mg/L Cu) and MB12-35 (551 mg/L Cu). Groundwater from both of these monitoring bores is acidic ($pH < 4.5$) and characterized by 3,500 to 8,500 mg/L SO4. MB10-23 is screened from 13 to 25 m bgs and MB12-35 is screened from 22 to 34 m. Both of the bores are located near a major fault that runs across the Copper Extraction Pad area in a south-westerly direction (from the Main Pit to the Intermediate Pit). Regional mineralization is associated with this fault and it extends west to the Browns Oxide Pit. No definitive information on the hydraulic properties of the fault is available to determine whether it is an area of preferential groundwater flow or impedance to groundwater flow.

At monitoring bore MB10-11, up to 80 mg/L Cu is observed during the dry season. This monitoring bore is screened relatively deep (from 31.5 to 34.5 m) in fractured bedrock of the White’s Formation immediately below the Copper Extraction Pad area. Like MB10-23 and MB12-35, this monitoring bore is located along the fault that runs across the Copper Extraction Pad area, so low concentrations may reflect aquifer heterogeneity (or less seepage losses to groundwater immediately below the Copper Extraction Pad area).

Near the EFDC, Cu concentrations are less than 0.1 mg/L Cu (and the pH of groundwater is either neutral or only slightly acidic, i.e. pH 6.5).

Monitoring bores located north of the Copper Extraction Pad area (at bore MB10-22) and near the Intermediate Pit (at bore RN022543) show a circum-neutral pH and very low copper concentrations (< 0.01 mg/L). However, sulfate concentrations are moderately elevated suggesting that this area is impacted by seepage from the Copper Extraction Pad area. Note that these wells are screened in the Coomalie Dolostone (Figure 2). The very low copper concentrations in the Coomalie Dolostone are likely due to buffering of the acidic groundwater from the Copper Extraction Pad area by dissolution of calcite in the Dolostone.

4 Delineation of Copper Plume and Estimation of Volume to be Pumped and Treated

Groundwater quality data were used to delineate several possible copper plumes in the Copper Extraction Pad area (Figure 2). Three potential plumes were delineated to emphasize the current uncertainty regarding the extent of contamination in this area (particularly to the west towards the Main Pit and south towards the EFDC) (Figure 2). The ‘best estimate’ represents the most likely volume of groundwater to be treated based on the available data, whereas the upper and lower bound estimates are provided to bracket the ‘best estimate’. Estimated surface areas for these different inferred plumes are in Table 4-1.

Table 4-1 - Estimated volumes of impacted groundwater in the Copper Extraction Pad area

Plume Extent	Area (m^2)	Aquifer Thickness (m)	Effective Porosity (%)	Pore Volume (m^3)
Best Estimate:				
Area between MB10-10, MB12-26 and Intermediate Pit	30,000	40	2	24,000
Lower Bound:				
50 m wide corridor (from MB10-10 to Intermediate Pit)	10,000	40	3	12,000
Upper Bound:				
All of Copper Extraction Pad area	58,000	40	3	69,600
Plus high porosity fault (20 m wide)	3,500	40	5	7,000

Importantly, the copper plumes are assumed to be restricted to groundwater in the White's Formation (i.e. the plume does not extend into the Coomalie Dolostone, either vertically or horizontally). This is consistent with groundwater quality data in the area, but further drilling would be needed to verify this assumption. Also assumed here is that highly elevated copper concentrations are only present in the upper 40 m of the bedrock aquifer. This corresponds to the estimated thickness of the White's Formation in the Copper Extraction Pad area (and is defined by a dipping contact between the White's Formation and the underlying Coomalie Dolostone). To estimate the volume of groundwater to be pumped and treated, the areal extent of the plumes was multiplied by 40 m (the estimated depth of contamination) and the effective porosity of bedrock (in %) (Table 4-1).

Some key observations regarding the estimates from Table 4-1 are summarized here (see also Figure 2):

- Best Estimate; for this estimate, the layout of the former Copper Extraction Pad area was used to define the southern and south-eastern extents of the copper plume, whereas the eastern extent of the copper plume was inferred to be west of monitoring bore MB10-10. The western (down-gradient) extent of the copper plume is inferred to extend to the Intermediate Pit. Of the three plumes, the 'best estimate' plume is the most consistent with observed Cu concentrations in groundwater. However, there are no monitoring bores east of monitoring bore MB10-10 (towards the Main Pit), so it should be viewed with some caution until additional information is available. Also, the effective porosity for the best estimate was assumed to be 2 % (or four times the 0.5 % specific yield for bedrock in the Copper Extraction Pad area from the calibrated groundwater flow model). This is a reasonable porosity estimate for fractured bedrock, but additional drilling/hydraulic testing would be needed to refine this estimate.

- Upper Bound; for this estimate (which is the largest, and therefore most conservative), RGC assumes that the copper plume encompasses the entire disturbed area from the 1977 aerial photograph. More conservative still is the assumption that the fractured bedrock in this disturbed area has a higher effective porosity (3 %) and that a 20 m wide fault zone with a very high effective porosity of 5 % is also present. This porosity implies a series of open fractures and/or dissolution channels along the fault (and therefore increases the volume of groundwater present).
- Lower Bound; here it was assumed that the areal extent of the residual copper plume is limited to an approximately 50 m wide corridor that includes all of the bores that contain more than 50 mg/L Cu in the dry season. This corridor is roughly aligned with the major fault through the area (and it extends from monitoring bore MB10-11 to the Intermediate Pit). A higher effective porosity of 5 % was assumed for this area owing to the likely presence of sand-filled cavities in this area.

5 Design of Pump and Treat System

In November 2012, a 7 day pumping test was conducted by pumping from the production bore PB12-33. At a constant pumping rate of ~ 0.7 L/s, 450 m^3 of groundwater was extracted and 4.95 m of drawdown was observed in the pumping well. A drawdown of 0.88 m was observed at bore MB10-10 (about 42 m east of the pumping well) and only slightly less drawdown (0.64 m) was observed at bore MB12-35 (about 44 m west of the pumping well).

Drawdown induced during the pumping test suggests a reasonable degree of hydraulic connectivity in the area and that a reasonable radius of capture can be achieved in White's Formation using pumping rates in the order of 0.5 to 1 L/s.

The calibrated flow model for Rum Jungle was used to design a pump-and-treat system taking into account the findings of the pumping test described above. The hydraulic conductivity for the bedrock in this area (White's Formation) used in the model was based on the interpretation of the pumping test at PB12-33 (i.e. $K = 2 \times 10^{-6}$ m/s). The pumping rate for each extraction well was assumed to be 0.5 L/s, i.e. slightly lower than the observed sustainable pumping rate at PB12-33. For more details on numerical methods the reader is referred to RGC Report 183006/6.

The model was used to design a pump-and-treat system for two different scenarios of groundwater contamination in the Copper Extraction Pad Area: (i) our 'best estimate' of current extent of the copper plume and (ii) our 'upper bound' estimate of copper contamination in groundwater.

Figure 3 shows the proposed locations of the pumping bores and the flow field at the end of nine months of pumping for the 'best estimate' case. For this scenario a total of six pumping wells would be required with a total pumping rate of 3 L/s (0.5 L/s each). The pathlines of particles placed throughout the area of the 'best estimate' plume illustrate capture of impacted groundwater within the inferred copper plume by the pumping well system.

Figure 4 shows the modeling results for the upper bound estimate of copper contamination. For this scenario, eight pumping wells are used with a combined pumping rate of 4 L/s for (0.5 L/s per well). Again, the simulated flow field and pathlines for particles placed throughout the area of the inferred plume, after 22 months of pumping are shown. The results indicate that adequate capture for the upper bound plume could be achieved with an eight pumping well system.

Due to aquifer heterogeneity and potential release of contaminants from the solid phase, pump-and-treat scenarios typically require extraction of multiple pore volumes to remediate the aquifer. For this design, we assumed that the removal of three pore volumes would be required in order to recover most of the highly-impacted groundwater from the Copper Extraction Pad area (and thereby reduce Cu concentrations to acceptable levels, i.e. less than 1 mg/L Cu).

Table 5-1 summarizes the estimated volume of groundwater to be pumped and the duration of pumping for the three different scenarios evaluated here. For the 'best estimate' scenario, pumping would be completed in about nine months. Longer pumping may be needed if monitoring results indicate that groundwater quality is not improving due to more extensive contamination (Table 5-1) or if the contaminant removal process is less efficient than expected. Alternatively, the pumping duration may be closer to the lower bound estimate if the plume is smaller than estimated here or if the removal of fewer pore volumes is required. For planning purposes, we suggest that DME adopt the more conservative scenario, i.e. pumping for 22 months (at 4 L/s).

Table 5-1 - Estimated volume and duration of pump-and-treat in the Copper Extraction Pad area

Plume Extent	**Impacted Pore Volume (m^3)**	**No. of Pore Volumes Pumped**	**Total Volume to be Pumped & Treated (m^3)**	**Total Pumping Rate (L/s)**	**Estimated Duration of Pumping (months)**
Best Estimate:					
Area between MB10-10, MB12-26 and Intermediate Pit	24,000	3	72,000	3	9.2
Lower Bound:					
50 m wide corridor (from MB10-10 to Intermediate Pit)	12,000	2	24,000	1.5	6.1
Upper Bound:					
All of Copper Extraction Pad area plus high porosity fault (20 m wide)	76,600	3	229,800	4	22.0

In practice, water quality monitoring during rehabilitation would be performed to determine when pumping should stop. Moreover, only those pumping wells that provide a sustainable yield of more than 0.2 L/s (and which recover groundwater with at least 1 mg/L Cu would be operated as extraction wells). Similarly, pumping would be stopped once the Cu concentration in pumped groundwater fell below a trigger concentration.

6 Recommendations

RGC recommends that the highly-impacted groundwater ('copper plume') in the Copper Extraction Pad area be remediated using a temporary pump-and-treat system that consists of eight pumping bores with a total pumping capacity of 4 L/s. This system would be operated for up to 22 months in order to improve groundwater quality conditions in the Copper Extraction Pad area. RGC recommends that the majority of pumping be done before the Main Pit is backfilled in order to avoid inflows of highly-impacted groundwater to the pit while it is de-watered. Up to 230,000 m^3 could be pumped to the water treatment system during the 22 months of pumping.

Note that the current copper plume and associated volume of impacted groundwater to be extracted and treated is not very well defined. RGC recommends that the implications of this remaining uncertainty on closure planning be assessed using the range of pumping scenarios described herein. If the duration of pumping and volume to be treated has important implications for cost and scheduling of the rehabilitation works, additional investigative work should be considered to better constrain these parameters.

If required, RGC would recommend the following scope:

(i) Drilling pilot holes at the five proposed pumping well locations not yet characterized.

(ii) Air lift testing and sampling at these five test holes.

(iii) Installation of pumping wells and completion of 24 hour pumping tests at those locations where adequate yield (> 0.2 L/s) and highly impacted groundwater is intersected.

7 Closure

We trust that the information provided 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.

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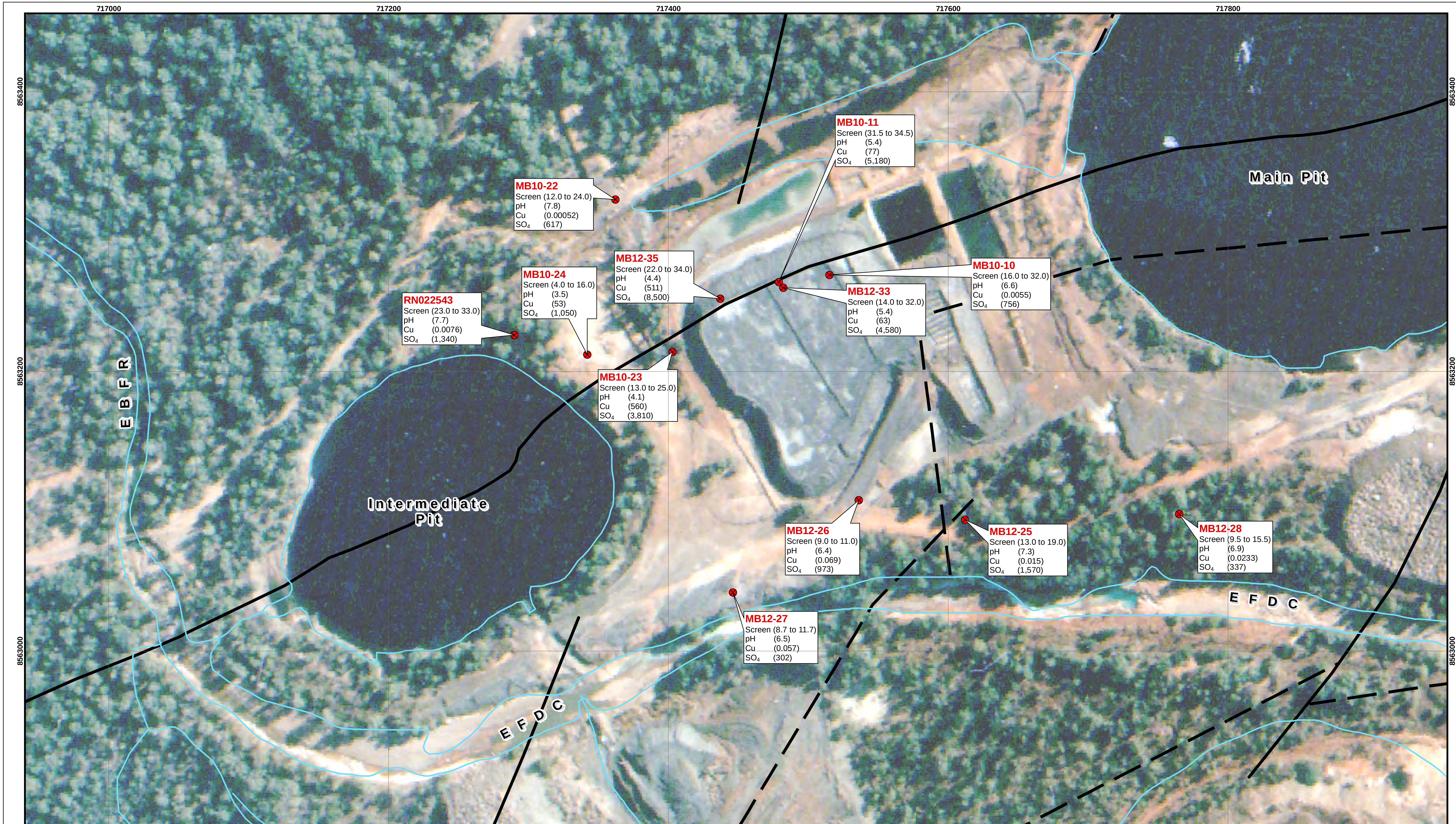

Legend

- Borehole
- Drainage
- Fault
- Fault - Indefinite

Lithology

- Coomalie Dolostone
- Crater Formation
- Geolsec Formation
- Quartz Vein
- Rum Jungle Complex
- White's Formation

Labels

MB12-25
Screen Interval - m bgs
pH - pH units
Cu - mg/L
SO_4 - mg/L

Location Plan & Groundwater Quality

Copper Extraction Pad Area, Rum Jungle Mine Site

Scale 1:2,500

0 50 100 200 Metres

Projection: GDA 1994 MGA Zone 52 (m)

N E S W

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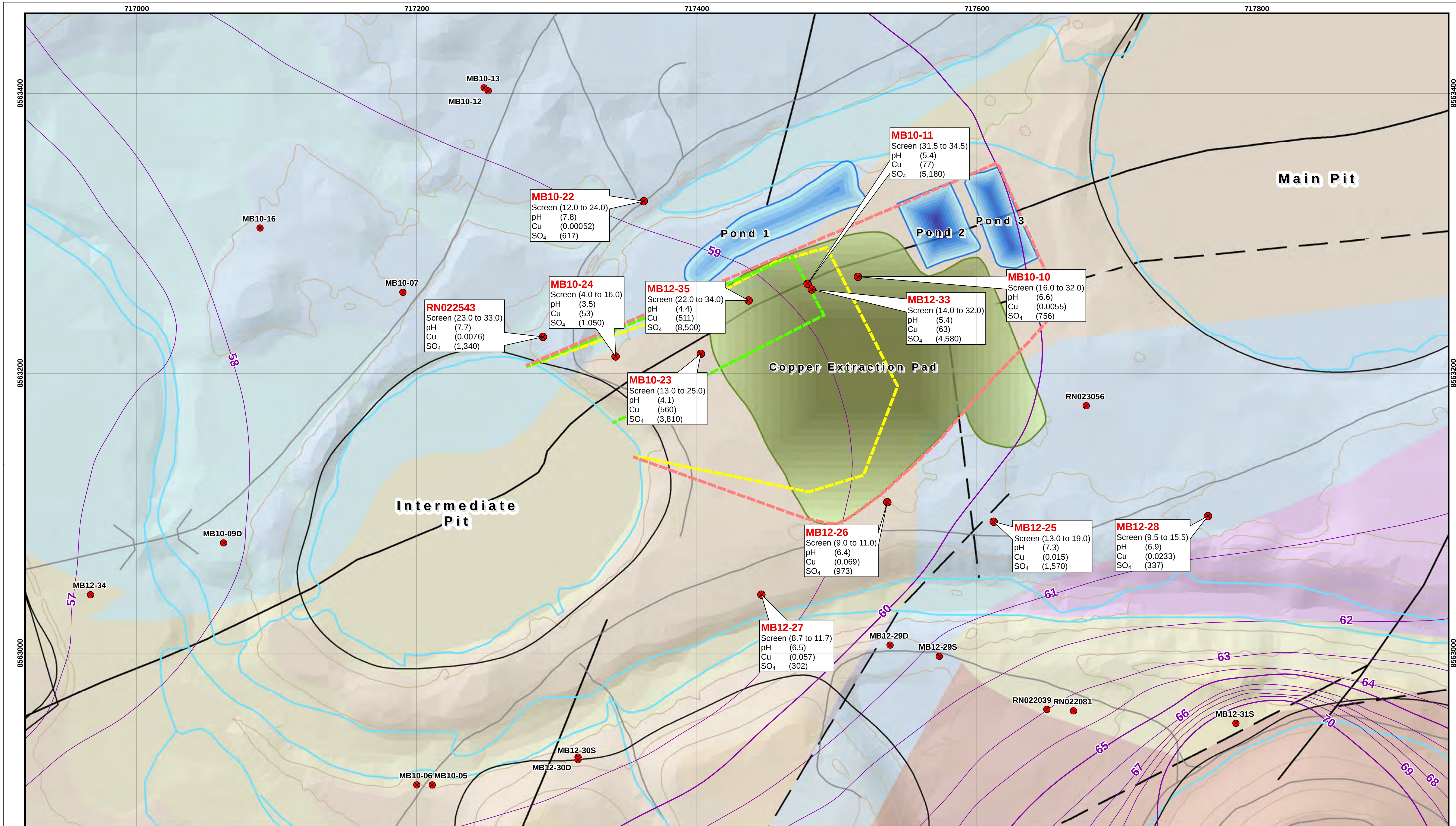
Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 1**
Project: Copper Extraction Pad Area Rehabilitation Plan	Project No: 183006
Report: RGC 183006/5	Last Update: Mar 02, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure1_GWQ_CopperExtractionPad_Feb2016.mxd	



Legend

Borehole	
Drainage	
Road	
Fault	
Fault - Indefinite	
Groundwater Levels for Wet Season (March 2015)	

Lithology

- Coomalie Dolostone
- Crater Formation
- Geolsec Formation
- Quartz Vein
- Rum Jungle Complex
- White's Formation

Labels

MB12-25
Screen Interval - m bgs
pH - pH units
Cu - mg/L
SO_4 - mg/L

- Inferred Best Estimate of Cu Contamination
- Inferred Lower Bound of Cu Contamination
- Inferred Upper Bound of Cu Contamination

Groundwater Flow Field & Surficial Geology

Copper Extraction Pad Area, Rum Jungle Mine Site

Scale 1:2,500

N E S W

0 50 100 200 Metres

Projection: GDA 1994 MGA Zone 52 (m)

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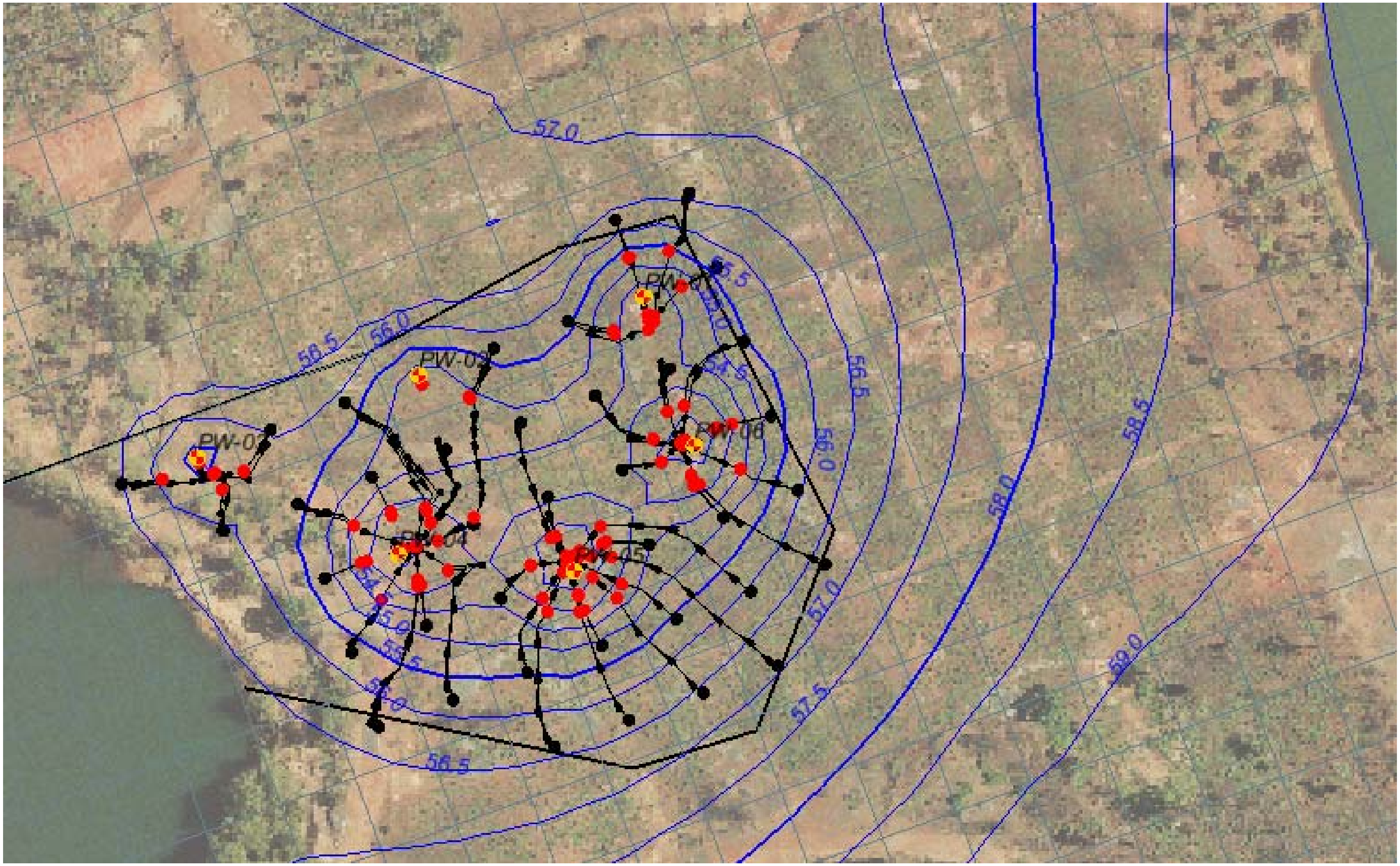
Client: Northern Territory Government, Department of Resources - Minerals and Energy	**Figure: 2**
Project: Copper Extraction Pad Area Rehabilitation Plan	Project No: 183006
Report: RGC 183006/5	Last Update: Mar 02, 2016
Rum Jungle Mine Site, NT, Australia	Drawn: L.R.
Original File: Figure2_GWQ_CopperExtractionPad_Feb2016.mxd	



Predicted Flow Field and Particle Paths for Copper Extraction Pad Area (End of Pumping Period, Best Estimate)

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 3
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report No: 183006/5	Last Update: 4 Mar 2016
Original File: Figures.pptx	

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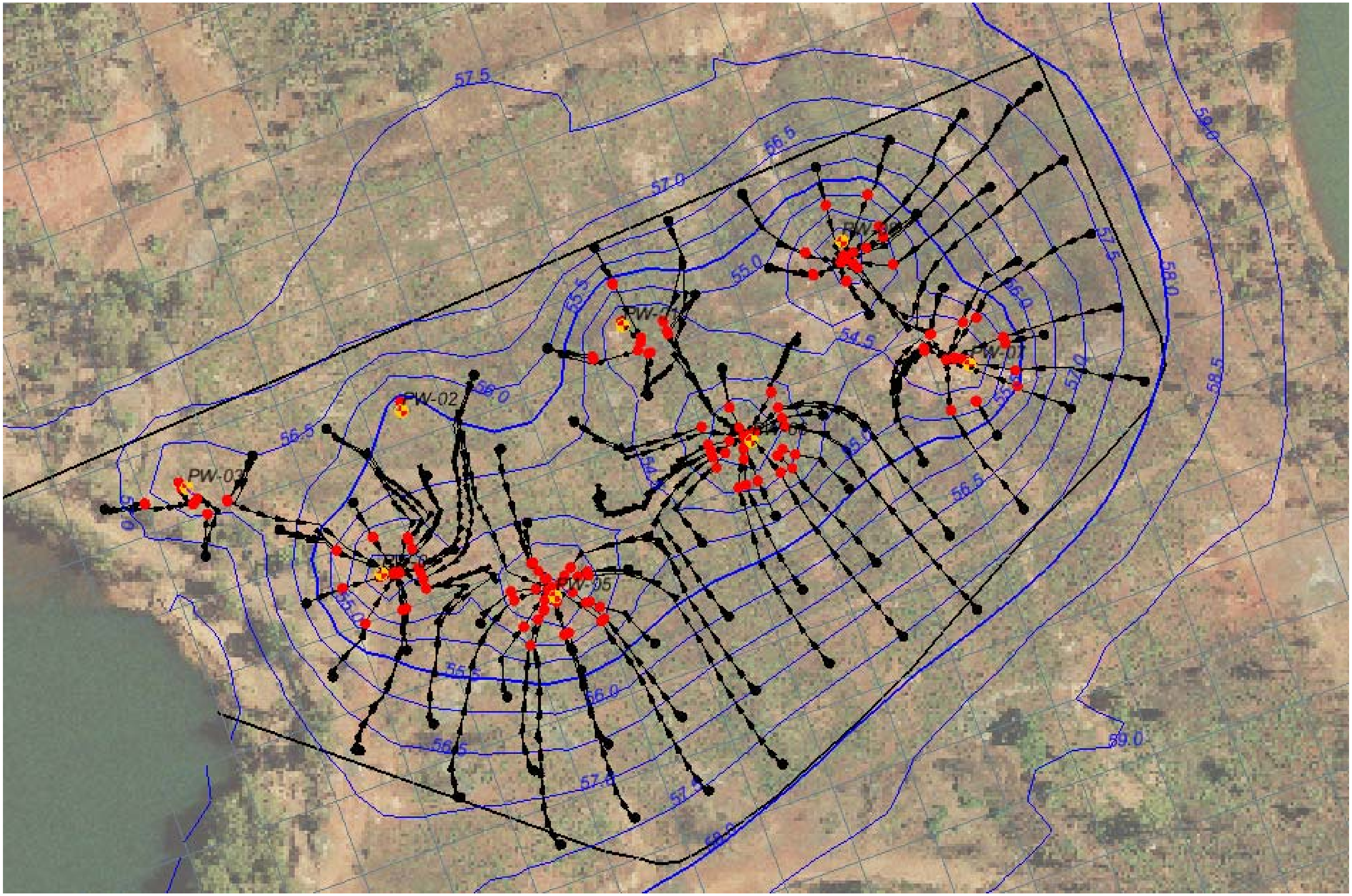

Predicted Flow Field and Particle Paths for Copper Extraction Pad Area (End of Pumping Period, Upper Bound)

Client: Northern Territory Government, Department of Resources - Minerals and Energy	Figure: 4
Project: Rum Jungle Rehabilitation Project	Project No: 183006
Report No: 183006/5	Last Update: 4 Mar 2016
Original File: Figures.pptx	

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