

YANDANOOKA BOREFIELD

**ASSESSMENT OF
GROUNDWATER
AVAILABILITY, MINGENEW
SUB-AREA**

**REPORT FOR
KARARA MINING LTD**

MARCH 2017



Rockwater
HYDROGEOLOGICAL AND ENVIRONMENTAL CONSULTANTS

Report No. 319-3/17/01

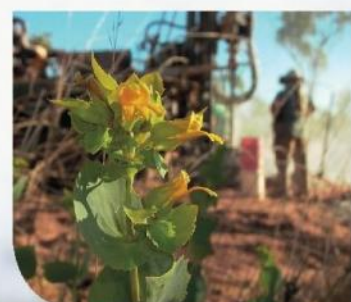


TABLE OF CONTENTS

	PAGE
1. INTRODUCTION	1
1.1 Climate	1
2. HYDROGEOLOGICAL SETTING AND CONCEPTUAL MODEL	1
2.1 AQUIFER EXTENT AND BOUNDARIES	2
2.2 AQUIFER PARAMETERS	3
2.2.1 Horizontal Hydraulic Conductivity	3
2.2.2 Vertical Hydraulic Conductivity	4
2.2.3 Storativity	4
2.2.4 Recharge	4
2.2.5 Discharge	6
2.2.6 Groundwater Levels	8
2.2.7 Groundwater Salinity	8
3. AQUIFER WATER BALANCE	8
4. NUMERICAL GROUNDWATER MODEL	9
4.1 Model Description	9
4.2 Model Parameters, Calibration	10
4.3 Sensitivity Analysis	11
4.4 Model Verification	11
4.5 Modelling to Assess Sustainable Yield of Sub-Area	12
4.5.1 Maintain Current High Groundwater Levels	12
4.5.2 Reduce Groundwater Levels to about 2000 Levels	13
4.6 Impact of Climate Change	13
5. ENVIRONMENTAL IMPACTS	14
5.1 Groundwater Dependent Ecosystems of the Study Area	14
5.2 Change in Water Levels	16
5.3 Response and Susceptibility of GDE to Changing Conditions	18
6. CONCLUSIONS	20
REFERENCES	21

Tables

Table 1: Average Monthly Rainfalls Mingenew, and Dam Evap. Three Springs (mm)	1
Table 2: Summary of Local Stratigraphy and Hydrogeology	2
Table 3: Summary of Model Scenarios	6
Table 4: Springs Included in Groundwater Model	7
Table 5: Model Water Balance for 2016	8
Table 6: Adopted Aquifer Parameters	10



TABLE OF CONTENTS

(cont.)

Table 7: Results of Sensitivity Analysis	11
Table 8: Listed GDEs in the vicinity of the Yandanooka Borefield.	15
Table 9: Modelled Water Level Change (m) after 10 years of pumping at variable rates.	17

Figures

1	Locality Plan
2	Annual Rainfalls Mingenew
3	Water Levels (m AHD) February to June 2012
4	Elevation (m AHD) Base of Parmelia Aquifer
5	Hydrogeological Cross Section
6	Extent of Model Grid
7	Annual Rainfalls at Mingenew, and Flows in Arrowsmith River at Robb Crossing (334439 mE, 6722250 mN)
8	Hydrographs for DoW Arrowsmith River Bores
9	Field Salinities (mg/L TDS) for Yandanooka Bores YB1, YB2 and YB3
10	Hydrographs for Yandanooka Bores M1, M2 and M3, Observed and Model-Calculated
11	Hydrographs for Bores RMB1 to RMB3, Observed and Model-Calculated
12	Hydrographs for Arrowsmith Bores TEC Nested, DL5W and TEC-MS, Observed and Model-Calculated
13	Hydrographs for Arrowsmith Bores AR7, AR22 and AR24, Observed and Model-Calculated
14	Hydrographs for Arrowsmith Bores TEC Nested Deep and AR7, Observed, and Predicted for 10 GL/a
15	Hydrographs for Bores RMB1 to RMB3, Measured, and Predicted for 10 GL/a
16	Hydrographs for Bores RMB1 to RMB3, Measured, and Predicted for 23 GL/a
17	Hydrographs for Arrowsmith Bores TEC Nested Deep and AR7, Observed, and Predicted for 23 GL/a
18	GDEs of the Yandanooka Area (Showing Drawdown Contours)

Appendix

I	Measured and Model-Calculated Groundwater Levels, Rockwater (2010)
---	--

REVISION	AUTHOR	REVIEW	ISSUED
Rev 0	PHW	JRP	internal
Rev 1	PHW & NE	RH (Karara)	16/03/2017
Rev 2	PHW & NE	RH (Karara)	30/03/2017



1. INTRODUCTION

Karara Mining Limited (Karara) is assessing options to increase water supply to meet demand requirements at its processing facility at the Karara mine site. One option that is being assessed is to increase its extraction from the Yandanooka borefield from 5 GL/a to 6 GL/a and possibly 10 GL/a. Currently, only 0.4 GL/a are available for allocation from the Mingenew Sub-Area of the Arrowsmith Groundwater Area in which the borefield is located, according to the Department of Water (DoW) Groundwater Management Plan for the area. The locations of the Sub-Area and the borefield are shown in Figure 1.

Rockwater was engaged to prepare a Groundwater Yield Review for the sub-area, with the intent to determine the sustainable yield of the Parmelia aquifer, and whether there is sufficient groundwater available to support an increase to the available allocation from the aquifer.

1.1 CLIMATE

Yandanooka has a Mediterranean-type climate with hot dry summers and mild to cool winters. Average monthly rainfall for the closest Bureau of Meteorology station (Mingenew, Station No. 8088), are given in Table 1, and annual rainfalls are shown in Figure 2. Most rain falls during the winter months, although there are irregular falls from thunderstorms in the summer. There have generally been below-average rainfalls since 2000 (Fig. 2), as there were from 1976 to 1980. The long-term average annual rainfall is 403.1 mm (1896 – 2015).

Dam evaporation at Three Springs (Luke, Burke and O'Brien, 1988), 53 km south-east of Mingenew, exceeds average rainfall in all months except June and July, and by a factor of five overall (Table 1).

Table 1: Average Monthly Rainfalls Mingenew, and Dam Evap. Three Springs (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rainfall	8.6	12.1	17	22.3	55.6	81.9	76.6	56.5	32.5	19.1	10.5	6.3	403.1
Dam Evap.	298	273	239	154	101	59	73	80	105	167	216	286	2051

2. HYDROGEOLOGICAL SETTING AND CONCEPTUAL MODEL

The Yandanooka Borefield is developed within sandstone of the Parmelia Group (Crostell and Backhouse, 2000). The stratigraphic sequence of the northern Perth Basin in the Yandanooka area is summarised in Table 2. Detailed descriptions of the local geology and

groundwater systems are given by DoW (2016) and Irwin (2007), and are summarised in Rockwater (2007) and below.

Table 2: Summary of Local Stratigraphy and Hydrogeology

<i>Period</i>	<i>Formation/Unit</i>	<i>Main Lithology</i>	<i>Hydrogeology</i>	<i>Max. Thickness</i>
Cretaceous	Parmelia Gp. (undifferentiated)	sand	major aquifer	>249 ¹
	Otorowiri	silt, shale & clay	aquiclude	34 ²
Jurassic	Yarragadee	sand, silt, & shale	major, regional aquifer	>500 ²

Notes: 1 = this report

2 = Irwin (2007)

2.1 AQUIFER EXTENT AND BOUNDARIES

The undifferentiated Parmelia Group which forms the Parmelia aquifer underlies the Dandaragan Plateau and extends from just south of Mingenew (where it pinches out), to near Coomberdale in the south; and from the western edge of the Dandaragan Plateau where the underlying Otorowiri Member crops out, to the Urella Fault in the east. The Parmelia aquifer increases in thickness from west to east: in the Dongara Line boreholes the Parmelia aquifer was 33 m thick in DL4, and 199 m thick in DL5. Those bores are 18 km south of Mingenew, and about 15 km and 2.5 km, respectively, west of the Urella Fault (Irwin, 2007). During drilling of the Yandanooka Borefield the Otorowiri Formation, consisting locally of dark grey clay, was intersected at depths of between 174 m and 211 m. It was not intersected during the drilling of YB2, indicating the Parmelia aquifer is more than 249 m deep at that location.

The Otorowiri Formation forms an almost impermeable base to the Parmelia Aquifer. This can be seen by groundwater levels, which are 131 m higher in the Parmelia aquifer at DL5 than in the underlying Yarragadee aquifer at that site (Irwin, 2007).

The Urella Fault is taken to form an impermeable boundary on the eastern side of the Parmelia aquifer. It abuts crystalline rocks of Archaean age of the Yilgarn Block (Playford, Cockbain and Low, 1976), or minor, local inliers of Permian sediments which are of relatively low permeability or occur above the regional water table. The low permeability of the rocks east of the Urella Fault and the lack of hydraulic connection across the fault are shown by the perching of groundwater east of the fault. At Yandanooka Well the water table is at an elevation of about 250 m AHD (Fig. 3); and in several lakes to the south the water levels are at about 282 to 286 m AHD. These water levels are much higher than levels of about 230 m AHD (in 2012) at the Yandanooka Borefield.

All available data were used to define the base of the Parmelia Aquifer (= top of Otorowiri Formation). These included elevations measured in the Dongara Line bores, Eneabba Line

bores (Commander, 1978), Arrowsmith River bores (Barnett, 1970), four petroleum exploration wells, five other bores in the WIR database, and the Yandanooka Borefield bores. The contours produced by kriging these data are shown in Figure 4, and these were used to define the aquifer base. They show that the aquifer deepens to the east towards the Urella Fault. A cross-section along the Dongara Line bores, at the northern end of the Yandanooka borefield also depicts the layout of the aquifer and its wedge-shaped nature (Fig. 5).

The area of the Parmelia aquifer covered by the numerical model (Layer 1) is shown in Figure 6.

2.2 AQUIFER PARAMETERS

2.2.1 Horizontal Hydraulic Conductivity

The Parmelia Group overlying the Otorowiri Formation in the Dandaragan Trough consists of feldspathic sandstone, with minor siltstone and claystone (Mory and Iasky, 1996). In the Yandanooka borefield, the Parmelia Aquifer comprises fine to very coarse grained sand and gravel up to 8 mm size (predominantly coarse/very coarse grained sand), with minor thin claystone and siltstone beds/lenses. The fine-grained units caused little or no restriction to (vertical) flow within the aquifer during the pumping tests and so are almost certainly localised lenses.

In the Perth region, Davidson and Yu (2008) describe the Parmelia Group as being interbedded sandstone, siltstone and shale, with sandstone beds generally about 5 m thick and consisting of predominantly medium grained sand with weak kaolinitic or siliceous cement. The average hydraulic conductivity is said to be less than 2 m/d. Higher hydraulic conductivity will apply at Yandanooka where the sandstone beds are thicker and coarser-grained, and there is no evidence of interstitial material.

Bore PB2 pumping test results (Rockwater, 2007) indicated an aquifer transmissivity of 1,060 m²/d and an average hydraulic conductivity of 9.7 m/d. The average transmissivity calculated from the pumping tests on Yandanooka bores YB2 and YB3 was 1,870 m²/d, which divided by an aquifer thickness of about 180 m gives an average hydraulic conductivity of 10 m/d.

Further south on the Dandaragan Plateau at Tathra, a pumping test of a bore in the Parmelia indicated a slightly lower hydraulic conductivity of 6.6 m/d (Aquaterra, 2005). At that site the sandstone was medium to coarse or very coarse grained, but the sandstone beds appear to be thinner than at Yandanooka.

The hydraulic conductivity value of 10 m/d was adopted for the modelling.

2.2.2 Vertical Hydraulic Conductivity

The Parmelia aquifer forms a single, quite homogeneous layer at Yandanooka and so it is modelled as such. This would not usually require consideration of vertical hydraulic conductivity. However, there will be leakage through the Otorowiri Formation to the underlying Yarragadee Formation because of the high heads in the Parmelia aquifer and a relatively high hydraulic gradient through the Otorowiri Formation.

Basal vertical leakage of groundwater was represented in the model by low values of vertical hydraulic conductivity in both Layer 1 (Parmelia) and Layer 2 (Yarragadee). Values were varied during model calibration to match observed groundwater levels in both the Parmelia and Yarragadee aquifers. The adopted values range from 0.001 to 0.000001 m/d for Layer 1 and 0.0001 m/d for Layer 2. Taken together, these are equivalent to vertical hydraulic conductivities for the Otorowiri Formation ranging from 3.7×10^{-7} m/d to 1.4×10^{-5} m/d, which are very low and indicate that the Formation has low permeability.

2.2.3 Storativity

The Parmelia Aquifer is unconfined, at least at the water table, and so the specific yield (drainable porosity) controls the magnitude of groundwater level variations resulting from recharge to and discharge from the aquifer. The value of specific yield was varied to calibrate the model to the observed regional rises in groundwater levels. The values adopted were 0.1 over much of the modelled area, and 0.075 in an area between the Yandanooka borefield and the Arrowsmith River.

Values of storage coefficient measured during the YB3 pumping test using data from M1 Deep and M1 Shallow ranged from 2.5×10^{-5} to 3.82×10^{-3} . These represent the release of water from elastic storage in the aquifer that occurs in the early stages of pumping. After an extended period of pumping, drainage of pores in the sandstone at the water table would dominate the release of water from storage and so specific yield would apply.

2.2.4 Recharge

A trend of rising water levels has been recorded in DoW and Water Corporation monitoring bores in the aquifer over the last 40 years. The rising water levels are attributed to higher recharge rates following land-clearing for agriculture (Commander, 1996). Recharge to the Parmelia aquifer occurs following high rainfall events and has been calculated at rates of between 20mm/yr and 50 mm/yr (Bekele, Salama and Commander, 2006). These rates have been calculated for cleared land south of Mingenew, and are two to three times higher than

the recharge rates that are likely to have occurred prior to land clearing (Rockwater 2007). Commander (1996) estimated a pre-clearing recharge rate for the Yarragadee Formation in the Irwin valley of 7 % of 450 mm annual rainfall, and that groundwater levels were rising due to an increase in recharge by a factor of two or three as a result of land clearing.

The model was calibrated to water levels measured in the Arrowsmith Scheme monitoring bores and Dongara Line bore DL5W over the period 1966 to 2010, with a close correspondence between observed and calculated water levels. Recent water level data show that water levels have continued to rise even though rainfalls have generally been below average since 2000.

An attempt was made to calibrate the model by increasing recharge rates in wet years, and reducing them in dry years. It was found that the model then over-estimated groundwater levels in the period of generally above-average rainfalls in the 1960's and early 1970's, and under-estimated groundwater levels since 2000 when rainfalls have been mostly below average. This indicates that recharge rates, as a percentage of annual rainfall, have gradually increased, presumably as more land has been cleared or the land has been more-deeply ploughed for agriculture. Also, there may now be more high-intensity rainfalls – most recharge occurs during rainfall events of at least 25 mm or more: on average there were 1.7 such events per year from 1960 to 1972, and 2.2 events per year from 1998 to 2016.

The adopted recharge rates after model calibration range from 29 to 73 mm/yr and averaging 50.6 mm/yr over the model area. The average value is at the upper end of the range calculated by Bekele, Salama and Commander, 2006. The Yandanooka borefield area has deep sandy soil which provides ideal conditions for groundwater recharge, and it is unlikely that there is any surface runoff after rainfall events.

To evaluate the potential impacts of climate change, recharge variation resulting from declining rainfall for four climatic scenarios were modelled, ranging from continuation at current recharge rates to a high level of climate change (and reduction in recharge) based on the IPCC and CSIRO climate modelling (CSIRO, 2007).

The recharge rates were calculated as a percentage of historical rainfall for the period 1966 to 2015, and as similar percentages of the predicted rainfall for the years to 2020, 2025 and 2030. Rainfall predictions are based on varying degrees of temperature rise that are assumed to be caused by increased CO₂ emissions (CSIRO, 2007). The 'low' change to recharge represents a drop in rainfall ranging from 13% in 2020 to 17% in 2030 compared to the long-term average for Mingenew; and the 'high' change to recharge represents a drop in rainfall ranging from 19% in 2020 to 28% in 2030. Adopted recharge rates and the respective climate scenarios are summarised in Table 3. Future recharge rates for the three climate change scenarios (Numbers 2 to 4) range from 21 mm/a to 62 mm/a, and are 14% to 28% below those adopted for the no-change scenario.

Table 3: Summary of Model Scenarios

Scenario	Description	Basis of Rainfall Prediction*	Adopted Recharge Rate (mm/a)	
			1966 - 2009	2009 - 2030
No. 1	No change to recharge	No change to the recharge used in 2008 Yandanooka model	29 to 73	29 to 73
No. 2	Low level of change to recharge	Based on IPCC climate model B1 which assumes a low rate of global warming (1.7 degrees for a doubling of CO2 from 280 ppm to 560 ppm).	29 to 73	24 to 62
No. 3	Moderate level of change to recharge	Based on IPCC climate model A1B which assumes a medium rate of global warming (2.6 degrees for a doubling of CO2 from 280 ppm to 560 ppm).	29 to 73	22 to 59
No. 4	High level of change to recharge	Based on IPCC climate model A1F1 which assumes a high rate of global warming (4.2 degrees for a doubling of CO2 from 280 ppm to 560 ppm).	29 to 73	21 to 58

*CSIRO 2007

Note that despite the period to 2016 being within a drying climate for perhaps 46 years, there is no evidence yet from monitoring data of any decrease in groundwater recharge.

2.2.5 Discharge

Groundwater discharges from the aquifer by the following mechanisms:

1. Discharge to the Arrowsmith River;
2. Discharge to springs (including undefined springs along the Arrowsmith River);
3. Evapotranspiration in areas of shallow water table;
4. Seepage down through the Otorowiri Formation; and
5. Extraction from bores.

The Arrowsmith River is an ephemeral stream, but as a result of rising groundwater levels there have probably been some reaches of the river with permanent flow. Aquaterra (2005) reported a flow of 4,700 m³/d in April 2005 immediately west of the Dandaragan Scarp at a time of seasonally low groundwater levels (and hence, river base-flow). There is only one gauging station on the river near Yandanooka: station 701005 at Rob Crossing, downstream of the Dandaragan Plateau. Measurements there ceased in 2001. There was typically no flow at that station from November to between April and June (Fig. 7); but the periods of no flow appeared to have been getting shorter and the base flows higher, taking into account variations in rainfall. In 1999/2000, there were still some flows early in November 1999; and from late April 2000. There were very high rainfalls in March and May 1999, but in subsequent months they were around average.

There is little throughflow in, or natural discharge from, the formation because of the effective bounding seal formed by the Otorowiri Formation. Aquaterra (2005) reports there is a palaeochannel near the Arrowsmith River. There could be some sub-surface groundwater discharge via the palaeochannel.

Modflow's Drain package was used to simulate groundwater discharge to the Arrowsmith River, and evapotranspiration losses along it. Drain conductance, which controls discharge to the Arrowsmith River, was varied in the calibration process. Model-calculated base-flow in the Arrowsmith River was greater than, but in the order of, the observed flow of 4,700 m³/d. A higher rate was accepted to allow for evapotranspiration losses, and any flow in the palaeochannel aquifer.

Groundwater also discharges to a number of springs on the western edge of the Dandaragan Plateau where the Parmelia aquifer wedges-out against outcropping Otorowiri Member. Springs shown on topographic maps and listed in Rutherford et. al., 2005 (Table 4) were also simulated in the model using Modflow's Drain package with drain elevations set at the elevations of the springs. As for flows in the Arrowsmith River, spring flows (and evapotranspiration from vegetation) will have increased as groundwater levels have risen. Eventually, increases in discharge via these mechanisms will curtail the rate of groundwater rise, and this may already be evident in monitoring data for RMB3, which is near a drainage line that has likely become a locus for groundwater discharge.

Seepage through the Otorowiri Member has been described under Vertical Hydraulic Conductivity, above.

Table 4: Springs Included in Groundwater Model

Spring	mE	mN	Elevation (m AHD)
Moordongawa	352400	6737230	188
Woonaroo	350700	6739400	198
Eramba Waterhole	347500	6736950	177
Yuwarana	340700	6754600	185
Otorowiri	355410	6740840	207
Nebroo	348140	6724460	196

Groundwater allocation data and bore locations were obtained in 2010 from the DoW. Licensed allocations from the Parmelia Formation were assumed to be actual extraction rates in the model, and were simulated at recorded locations using Modflow's Well package. They have not been updated in subsequent modelling.

2.2.6 Groundwater Levels

Groundwater levels measured in 2006/07 (Fig. 3) show that the water table in the Parmelia Formation is relatively flat as would be expected in a closed basin, although there are lower levels along the Arrowsmith River as a result of discharge to the river and springs, and pumping from bores including those of the Arrowsmith Scheme. There are steeper gradients in the west where the Arrowsmith River cuts through the Dandaragan Scarp.

Groundwater levels in the DoW Arrowsmith River monitoring bores have risen by 6 m to 20 m (10 m to 15 m in general) since monitoring commenced in 1965 (e.g. Fig 8), as a result of increased recharge following land-clearing (discussed in Section 2.2.4, above).

2.2.7 Groundwater Salinity

Salinity is derived regularly, typically monthly, from electrical conductivity and temperature measurements when production bores are operating. The monitoring results are shown in Figure 9.

The results show that salinities have fluctuated but remained in a constant range, or decreased slightly, in bores YB2 and YB3. Those in YB1 have increased from low levels initially, to be in a similar level to the other two bores – about 400 mg/L TDS.

3. AQUIFER WATER BALANCE

While not part of the conceptual model, the water balance is given in Table 5 for the numerical groundwater model in simulating 2016, so that the significance of various model components can be judged.

Table 5: Model Water Balance for 2016

Inputs:	
Average Recharge	85,630 m ³ /d
Outputs:	
Bores	11,100 m ³ /d
Springs	2,215 m ³ /d
Arrowsmith River	7,500 m ³ /d
Leakage to Yarragadee	19,230 m ³ /d
Increase in Storage	45,600 m ³ /d

This shows that:

- 52 % of the recharge is increasing the volume of groundwater stored in the aquifer, i.e. resulting in groundwater-level rises;
- 22 % of the recharge is leaking through the Otorowiri Formation into the underlying Yarragadee; and
- 11 % is discharging to the Arrowsmith River, springs, and by evapotranspiration.

A large part of the first component could be utilised as additional groundwater extraction without compromising environmental water requirements (the third component).

4. NUMERICAL GROUNDWATER MODEL

The numerical groundwater model constructed for the Yandanooka borefield (Rockwater, 2008) was updated with data obtained from the 2010 drilling and test-pumping programme (Rockwater, 2010). The model was re-calibrated and then run to simulate the impacts of pumping 5.3 GL/annum from the borefield, and variations in recharge based on historical data and climate-change predictions. Sections 4.1 to 4.3 below are largely repeated from Rockwater (2010).

4.1 MODEL DESCRIPTION

The groundwater model utilises Processing Modflow Pro, which incorporates Modflow, the industry-standard finite-difference groundwater model designed by the U.S. Geological Survey (McDonald and Harbaugh 1988). The model domain is described in Rockwater (2008) and is summarised below. The base elevation of the upper model layer (representing the Parmelia aquifer) was amended to the levels determined from the drilling results.

The model consists of two layers; layer one represents the Parmelia aquifer and layer two the Yarragadee Formation. Low values of vertical hydraulic conductivity have been used to simulate the effect of the Otorowiri Formation which lies between the Parmelia and Yarragadee.

The model grid consists of 80 rows and 57 columns and extends 28.5 km east–west and 40 km north–south. All boundaries in layer 1 are set as no-flow boundaries – the eastern boundary approximates the Urella Fault and the western boundary follows the western edge of the Parmelia aquifer where the Otorowiri Formation outcrops. Constant-head boundaries are set in the north, west and south in layer 2 to enable water in the Yarragadee aquifer to flow out of the modelled area. Discharge from the model occurs via drains that are set to represent the Arrowsmith River and local springs, and via bore abstraction. There is also some vertical leakage from layer one to layer two.

4.2 MODEL PARAMETERS, CALIBRATION

Hydraulic conductivity of the Parmelia aquifer was taken to be the average value of 10 m/d determined from the test-pumping results.

Extraction from the Arrowsmith Scheme bores, other known licensed allocations in 2010, and the Yandanooka production bores were simulated using Modflow's Well package. Pumping rates assume full use of allocations and any unlicensed users were not included.

The model was calibrated to water levels measured in the Arrowsmith Scheme monitoring bores and Dongara Line bore DL5W over the period 1966 to 2010 (Appendix I). There is a close correspondence between the observed and calculated water levels.

Horizontal conductivity (KH) was fixed across the model domain. Recharge zones, specific yield, drain conductance and vertical hydraulic conductivity (KV) were varied to achieve calibration (Table 6). The Yarragadee Formation was included in the model, but was not considered in the model calibration except to ensure that leakage from the Parmelia did not cause groundwater levels in the Yarragadee to rise above measured levels. The combined values of vertical hydraulic conductivity for the Parmelia and the Yarragadee aquifers account for the presence of the almost-impermeable Otorowiri Member, although that formation is not specifically included in the model.

Drain conductance, which controls discharge to the Arrowsmith River, was varied in the calibration process. The conductance $C_d = K \cdot L$, where:

K = the equivalent hydraulic conductivity, and

L = length of the drain within the model cell.

Specific yield controls the rate of groundwater-level rise that results from recharge to the aquifer.

Aquifer parameters that were adopted to achieve calibration are given in Table 6.

Table 6: Adopted Aquifer Parameters

Parameter	Units	Layer 1	Layer 2
		(Parmelia)	(Yarragadee)
KH	m/d	10	10
KV	m/d	0.0000012–0.017	0.0001
SY		0.075-0.1	N/A
Sc		N/A	0.0001
Drain Conductance	m ² /d	5 to 20	N/A
Recharge	mm/a	21 - 73	N/A

Observed and model-calculated groundwater levels in the monitoring bores can be compared in Appendix I (Figs. APPI-i to APPI-iii). A maximum error about five metres is observed from actual water levels versus calculated groundwater levels, and the Scaled Root Mean Square error for all the measurements is about 8 % which means that a predicted water-level drawdown of 1 m could actually be in the range of 0.92 to 1.08 m.

Much of the error can be accounted for in differences in two bores, Bores 14 and 6ART, and there is likely to be unrecorded pumping near these bores. Bore 14 shows a marked reduction in the rate of the observed water level rise from about 1986, indicating that pumping may have commenced near the bore, or alternatively, slots in the bore may have become blocked, making it unrepresentative.

4.3 SENSITIVITY ANALYSIS

Model parameters were varied in turn to determine the effect on calculated groundwater levels in two key model cells: one within the borefield, and one alongside the Arrowsmith River. The results are given in Table 7, giving changes in modelled water levels in 2030.

Table 7: Results of Sensitivity Analysis

<i>Parameter, and Variation</i>	<i>Change In Modelled Water Levels (m)</i>	
	<i>Cell 29,39 (Yandanooka Borefield)</i>	<i>Cell 49,34 (Near River)</i>
Horizontal conductivity +20%	0.09	0.07
Vertical conductivity +20%	-0.24	-0.22
Specific yield +20%	-1.13	-1.04
Drain conductance +20%	-0.24	-0.74
Recharge +20%	3.34	2.85

The results indicate that the model is most sensitive to recharge followed by specific yield (SY), and is insensitive to drain conductance (river-bed and spring), horizontal hydraulic conductivity (KH1) of the Parmelia aquifer, and vertical hydraulic conductivity (KV1).

4.4 MODEL VERIFICATION

The model was run to simulate pumpage from the Yandanooka borefield, plus Water Corporation and private extraction, from 2010 to 2016 to verify the efficacy of the model. Model parameters including recharge were left unchanged.

Measured and model-calculated water levels for key bores, including M1 to M3 near the production bores; regional Karara Mining monitoring bores RMB1 to RMB3 and TEC

Nested Deep; and DoW Arrowsmith and Dongara Line monitoring bores AR7, AR22, AR24 and DL5W, are shown in Figs 10 to 13. They show there continues to be a very close correspondence between observed and model-calculated groundwater levels; and where there is a difference in levels such as at RMB2 and 3, the trends in water-level rise are the same. TEC-MS is an exception – that bore monitors shallow, perched water.

Scaled Root Mean Square (SRMS) errors for model-calculated groundwater levels, compared with measured levels, range from 1.3% (M3D) to 27.3% (RMB3), and 8.9% overall. The two largest errors are for RMB2 and RMB3, regional monitoring bores located west and south-west of the borefield. The water levels in those bores are two to four metres higher than the nearest monitoring bores to the east – RMB1 and AR22, whereas they would be expected to be lower, towards areas of groundwater discharge in the west and south. It is likely that the reduced levels for the bore-heads of RMB2 and RMB3 are too high. Without those two bores, the overall SRMS error is 4.4%, below the limit of 5% recommended in the groundwater modelling guidelines (Middlemis, 2000), and 5% or 10% (if achievable) given in the more-recent guidelines (Barnett *et al.*, 2012).

The SRMS have improved slightly since 2010, for all three monitoring bores that have been used both before and after that year (DL5W, AR22 and AR24). This, together with the other low SRMS values, shows that continued monitoring since 2010 has verified that the model is suitable for predicting the future impacts of extraction from the borefield.

4.5 MODELLING TO ASSESS SUSTAINABLE YIELD OF SUB-AREA

The model was run to assess the sustainable yield of the Parmelia aquifer in the Mingenew sub-area for two scenarios, by increasing the rate of extraction from the Yandanooka borefield until:

1. The rise in groundwater levels in regional monitoring bores is stopped; and
2. Groundwater levels in regional bores are lowered back to levels that are about half of rise that has occurred.

The potential environmental impacts of these two cases are covered in Section 5 below.

4.5.1 Maintain Current High Groundwater Levels

The rates of extraction from the Yandanooka bores were progressively increased in the model until groundwater levels in the monitoring bores were indicated to remain stable over the next 10 years. The final rate was 10 GL/a, plus 0.5 GL/a from the Water Corporation Arrowsmith bores, and 0.29 GL/a from private bores in the Tathra Sub-Area to the south.

The results indicate that with these rates of extraction, water levels would stabilise or continue to rise slightly in bores AR7 and TEC Nested Deep near the Arrowsmith River (Fig. 14); and in regional monitoring bores RMB1 to 3 north-west, west and south-west of the borefield (Fig. 15).

As a reality check, potential recharge rates were multiplied by the area of the Mingenew sub-area ($4.5 \times 10^8 \text{ m}^2$). Annual recharge is calculated to be 22.8 GL (modelled rate) or ranging from 9 to 22.5 GL (Bekele, Salama and Commander, 2006). Subtracting modelled losses to springs, Arrowsmith River (including evapotranspiration), and leakage to the Yarragadee, of 10.6 GL, the availability is 12.6 GL/a (using modelled recharge rate) or between 0 and 11.98 GL/a (Bekele, Salama and Commander, 2006) recharge rates. The modelled and upper end of the (Bekele, Salama and Commander, 2006) rates are similar to the 10 GL/a indicated above.

4.5.2 Reduce Groundwater Levels to about 2000 Levels

The modelled rates of extraction from the Yandanooka bores were increased further, until groundwater levels were reduced back to about 1998 to 2000 levels near the Arrowsmith River (by about one quarter of the observed rise in groundwater levels), over a period of 100 years from 2016. At a rate of 23 GL/a from the borefield, groundwater levels are indicated to stabilise at about 228 m to 231 m AHD in bores RMB1 and RMB2; and to continue to decline slightly at levels of 222 m to 228 m AHD in bores RMB3, AR7, and TEC Nested Deep (Figs 16 and 17).

This would result in some of the new springs that have appeared in recent years drying up, and flows in the Arrowsmith River returning to the rates and duration each year of 10 to 20 years ago. The potential environmental impacts of this are discussed in Section 5 below.

4.6 IMPACT OF CLIMATE CHANGE

The potential impacts of climate change based on CSIRO climate modelling as discussed in Section 2.2.4, have been modelled previously (Rockwater, 2010). The results showed that under a moderate climate model, where rainfall is predicted to decline by more than 10% below the baseline climate (1990), water-levels may be lowered by at least one metre within 4.5 km of the borefield, decreasing to about 0.25 m at seven kilometres from the borefield after 10 years of pumping at 5 GL/a.

Rainfall since 1990 at Mingenew has averaged 355 mm, 12% below the long-term average, but as discussed in Section 2.2.4, climate change has also resulted in more high-rainfall events that enhance groundwater recharge. Consequently, there has been no need to decrease recharge rates in calibrating and validating the model to measured groundwater levels, and so

actual recharge rates (since land clearing) appear to have remained constant and are likely to remain so in the future.

5. ENVIRONMENTAL IMPACTS

As part of the environmental assessment for Karara's proposed 10 GL/a groundwater licence amendment, Rockwater was engaged to determine whether the aquifer response to the increase in extraction would affect groundwater dependent ecosystems (GDE) in the vicinity of the borefield. This work follows a 2010 GDE investigation commissioned by Karara (Soil Water Consultants 2010), which characterised the type and extent of known potential GDE in the vicinity of the Yandanooka Borefield, and the potential changes to their groundwater regime as a result of the initial proposed extraction of 5 GL/a. This investigation addresses the potential impacts on GDE of increasing the volume extracted from the Yandanooka borefield to between 10 GL/a and 23 GL/a.

5.1 GROUNDWATER DEPENDENT ECOSYSTEMS OF THE STUDY AREA

The study area consists largely of cleared agricultural land with small pockets of remnant vegetation. Remnant vegetation occurs mainly in road reserves and along the Arrowsmith River although there are some isolated remnants of native vegetation on freehold land and in Nature Reserves in the region. Much of the area shown along the Arrowsmith River occurs where the water table is at or near to the ground surface. Potentially groundwater dependent vegetation in the study area is shown in Figure 18.

A vegetation survey of the area was undertaken by Woodman Environmental Consultants (WEC, 2010) as part of the environmental approval process for the Yandanooka borefield. WEC (2010) provided an assessment of potential groundwater dependence of 50 surveyed plant communities based on landscape position and species composition. Thirteen plant communities were identified as 'highly likely to be groundwater dependent' and a further 30 as 'potentially groundwater dependent'. However, the assessment did not consider depth to groundwater or the groundwater regime at each site.

The hydrogeology of GDE in the Northern Perth Basin has been described by Rutherford, Roy and Johnson (2005). That work identified six GDE sites in the vicinity of the Yandanooka borefield (Table 8); however, site number 24 (Eramba Waterhole) is listed within the literature as not being dependant on groundwater. The Eramba Waterhole is positioned in the weathering profile of the Yarragadee Formation and the presence of water at the site is dependent on rainfall and runoff (Rutherford et al. 2005). Five of the six GDE sites (excluding Eramba Waterhole) represent overflow from, and water levels that are maintained by, the Parmelia Aquifer. Consequently, any drawdown impacts associated with

proposed increases in extraction from the Parmelia Aquifer need to be considered to ensure adequate allocation is made for ecological water requirements.

Table 8: Listed GDEs in the vicinity of the Yandanooka Borefield.

Site Number	Name	Location		Aquifer
		Easting	Northing	
18	Yuwarana Spring	340900	6754510	Parmelia
20	Otorowiri Spring	355480	6742040	Parmelia
21	Danthatarra Spring	356651	6739689	Parmelia
22	Woonara Spring	350654	6739500	Parmelia
23	Moordongawa Spring	352378	6737315	Parmelia
24*	Eramba Waterhole	347531	6737170	Yarragadee

*Listed as 'not dependent on groundwater' (Rutherford et al. 2005)

Potentially sensitive GDE in the study area have been defined by several previous investigations. A study of GDE in the vicinity of the borefield was undertaken by Soil Water Consultants (2010). That study only considered terrestrial vegetation mapped by WEC (2010) and some wetland GDE associated with springs in the borefield area previously reported by Rutherford et al. (2005). The 2010 GDE study concluded that there was no phreatophytic vegetation in the vicinity of the borefield that could be impacted by extraction from the Parmelia Aquifer at a rate of 5 GL/a.

Additional studies of GDE in the Mingenew – Arrino area by Borger (2005) and Borger and Jeffery (2010) have identified sites containing potentially groundwater dependent remnant vegetation. The nearest of those GDE sites to the Yandanooka borefield is an area of modified remnant vegetation associated with a mound spring, approximately 4 km east of the borefield (Borger and Jeffery 2010); however, the site is on the eastern side of the Urella Fault and therefore not associated with the Parmelia Aquifer. Several other nearby sites are known to have been completely cleared and converted to farm dams (Rees and Broun 2005, Borger and Jeffery 2010), or are beyond the influence of the 10 GL/a modelled cone of depression in water levels.

Data provided by Karara Mining Limited indicate that the nearest Listed Threatened Ecological Communities (TEC) occur to the south of the borefield, along the Arrowsmith River (Fig. 18). There are two listed TEC in the vicinity of the borefield. These are the 'Assemblages of organic mound springs of the Three Springs area' (TEC 97, listed as Endangered) and the Ferricrete Floristic Community (TEC72, listed as Vulnerable) (DPAW 2016). Occurrences of known GDE sites are shown in Figure 18. From an EIA perspective, the nearest TEC that is relevant to the assessment of groundwater availability is the 'Assemblages of organic mound springs of the Three Springs area'. Four occurrences of the mound springs TEC (MSTS16–20) are located within 10 km of the borefield. These sites occur in a single cluster, approximately 8.5–9.0 km south of the borefield (Fig 18.). Slightly further to the south/southwest are MSTS20 and MSTS21–23, which are 11.5 km and 13 km

south of the borefield, respectively. The critical habitat for this TEC includes the mound springs and surrounding vegetation buffer (Rees and Broun 2005).

The 2010 flora survey of the borefield area (WEC 2010) discusses five of the TEC sites in further detail. Vegetation communities mapped by WEC (2010) that contain the five occurrences of the mound springs TEC include:

- T98 (MSTS 16) - Dense thicket of *Melaleuca viminea* subsp. *viminea* over Open Tall Sedges of *Juncus kraussii* subsp. *australiensis* on grey silty sand or cracking clays on midslope, flats and drainage lines.
- H11 (MSTS 17 and 18) - Heath to Dense Thicket of *Kunzea micrantha* subsp. *petiolata* with emergent *Actinostrobilus pyramidalis* over sedges on grey or black clay-loam in valley floors and drainage lines.
- H15 (MSTS19) - Dense Heath of *Melaleuca ?ryeae* on grey sandy clay on valley floor to midslope.
- W65 (MSTS20) - Low Woodland of *Eucalyptus camaldulensis* subsp. *obtusata* and *Melaleuca preissiana* over Dwarf Scrub of mixed species on grey or dark brown sand or sandy loam on creekline.

The dominant emergent species (*Melaleuca preissiana* and *Eucalyptus camaldulensis*) recorded for occurrences of the TEC Mound Springs by Borger (2005) were not recorded within plant communities H11, H15 and T98 by WEC (2010), due to the scale of mapping.

Additional Biological studies of TEC in the area have been undertaken by Pinder and Penniford (2001) and Pinder and Stratford (2006). Rees and Broun (2005) compiled an Interim Recovery Plan for the 'Assemblages of organic mound springs of the Three Springs area' TEC. The recovery plan outlines various actions that are required to address threatening processes affecting the ongoing survival of the listed community.

The nearest occurrences of the Ferricrete Floristic Community (Rocky Springs Type) TEC are approximately 17 km south of the borefield.

5.2 CHANGE IN WATER LEVELS

Phreatophytic vegetation has been shown to access groundwater up to about 10 m below ground level; however, it is assumed that under favourable conditions, phreatophytic tree species may access groundwater up to about 20 m depth. At depths greater than about 10 m, it is thought that the importance of groundwater to terrestrial vegetation (in terms of total plant water use) is negligible (Froend and Zencich 2001, Loomes, *et al.* 2006). Altered water levels demonstrate the importance of the water regime to groundwater dependent vegetation. For the identified GDE south of the Yandanooka borefield the most significant change in the

water regime is the trend of rising groundwater levels in the Parmelia Aquifer that has resulted from extensive vegetation clearing for agricultural development in the area. Regional groundwater levels in the Parmelia Aquifer have shown a rising since trend over the last 40 years (see Section 2.2.4). This rising trend has been documented previously and is noted in the Arrowsmith Groundwater Allocation Plan (DoW 2010).

Potential changes to the water regime that may affect GDE in the vicinity of the Arrowsmith River have been identified for the two scenarios outlined in section 4 of this report. For the 23 GL/a scenario, under which groundwater levels would be reduced back to levels of around 2000, the discharge to the springs associated with TEC along the river would decline over the next 40–50 years, at which point some of the monitoring bores along the Arrowsmith River in the vicinity of the Water Corporation’s Arrowsmith Borefield would stop flowing. However, groundwater levels in monitoring bores near the river and discharge to the River would still remain higher than they were up to the mid- 1990s.

Under the 10 GL/a extraction scenario, the cone of depression of water levels is expected to extend for up to 4 km from the borefield after 10 years of continuous pumping. There are no potential GDE within this area on the western side of the Urella Fault that could be impacted by drawdown of water levels in the Parmelia Aquifer. Water levels in the Parmelia aquifer beyond the localised influence of the borefield would continue to rise in line with the regional trend outlined in section 2.

The water level in bores to the south of the borefield near the river (e.g. AR7 and TEC Nested Deep) are predicted to continue to rise slightly. Water levels in other regional monitoring bores to the north-west, west and south-west of the borefield show a similar trend of rising slightly or stabilising over the next decade at the proposed maximum rate of extraction.

Even with total extraction of 10 GL/a from the Yandanooka Borefield, water levels in the vicinity of all listed GDEs are indicated to continue to rise, albeit at a reduced rate. Modelled groundwater level changes at each site and selected monitoring bores under the two modelled scenarios are listed in Table 9.

Table 9: Modelled Water Level Change (m) after 10 years of pumping

Site Number	Name	Water Level Change (m)	
		6 GL/a	10 GL/a
18	Yuwarana Spring	+5.40	+5.35
20	Otorowiri Spring	+2.88	+2.05
21	Danthatarra Spring	+3.22	+2.60
22	Woonara Spring	+3.90	+3.65
23	Moordongawa Spring	+3.83	+3.60
-	Bore TEC nest deep	+2.8	+1.90
-	Bore AR7	+2.95	+2.15

MSTS19	Mound Springs TEC	+3.2	+2.5
MSTS23	Mound Springs TEC	+3.8	+3.6

[#]Bore TEC nest deep is located approximately 7 km south of the Yandanooka borefield and 2.2 km north of the nearest TEC site (MSTS19)

5.3 RESPONSE AND SUSCEPTIBILITY OF GDE TO CHANGING CONDITIONS

Given the long-term rising trend of water levels in the area and predicted future water level rises, the ecosystems associated with mound springs and shallow groundwater near the Arrowsmith River are not at risk from impacts caused by current or proposed extraction (up to 10 GL/a) from the Yandanooka borefield. Assessing the response of GDE beyond the area of influence of the borefield to rising water levels in the Parmelia Aquifer is beyond the scope of the current study. However, some general comments regarding potential impacts of rising water levels can be made.

The response of vegetation to altered water levels is complex as each species has adapted to a specific water regime and any prolonged or permanent change in water levels can affect the health and distribution of that vegetation. Previous studies of GDE have provided only limited assessment of the impact of rising water levels.

Results of numerical modelling indicate that, under the current level of allocation, several occurrences of the mound springs TEC will remain vulnerable to rising water levels (see section 5.2). In addition, rising water levels represent a potential risk to both riparian and terrestrial buffer vegetation surrounding the TEC occurrences. The impact of the altered water regime is unclear; however, it is likely that additional extraction from the Yandanooka borefield would reduce the impact of rising water levels on GDE to the south near the Arrowsmith River.

The Interim Recovery Plan for the ‘Assemblages of organic mound springs of the Three Springs area’ TEC acknowledges that rising (rather than declining) water levels represent a significant risk to the biota of the mound springs. The characteristic flora and fauna of the mound springs are adapted to the permanently moist environment and many species are unlikely to be able to survive in the longer term under conditions of permanent inundation, which may result from rising water levels in the Parmelia Aquifer.

The Department of Water has issued specific guidance for consideration of GDE as part of the groundwater allocation planning process for the Northern Perth Basin (DoW 2009). In addition the Groundwater Allocation Plan for the Arrowsmith area outlines the Department’s water resource objective to “manage the needs of the groundwater-dependent ecosystems by maintaining adequate groundwater levels in unconfined and semi-confined aquifers”.

In the absence of specific ecological water requirements for GDE of high conservation value, a preliminary risk assessment for GDE outlined by DoW (2009) uses the generic framework of Froend and Loomes (2004) to assess risk of impact of groundwater abstraction. Under this risk framework, predicted drawdown and depth to groundwater information is used to assess potential risks to GDE. Using the rate and magnitude of drawdown for several depth to groundwater categories, the risk of impact to GDE and phreatophytic vegetation can be determined. A concern with the framework is that the magnitude and rate of water level rise is not considered in the same way as water level drawdown. Therefore, the risk of water level rise to GDE is considered as a similarly low impact as if there were no change in water level. In the instance of a significant rise in water level, potential impacts to sensitive ecological communities may be underestimated. For example, the dominant species in the upper stratum such as *Melaleuca preissiana* and *Eucalyptus camaldulensis* subsp. *obtus*a may show a decline in health after consecutive years of permanent inundation if water levels continue to rise, and prolonged inundation may eventually cause death of these species.

Under a scenario of 10 GL/a extraction, water levels in the vicinity of mound springs TEC will continue to rise, albeit at a lower rate than under the existing pumping regime. A rising water table has the potential to increase groundwater discharge and cause a shift in the composition and structure of wetland and riparian vegetation communities, as species less tolerant of inundation are either lost or migrate upslope to a more suitable water regime and landscape position. This could affect the mound springs and their associated communities and also surrounding buffer vegetation. Therefore, there should be a positive effect from increasing extraction from the borefield on the GDE of the Yandanooka area, by slowing the rate of water level rise and reducing discharge to the mound springs that support several occurrences of the ‘Assemblages of organic mound springs of the Three Springs area’ threatened ecological community.

The Statewide Policy for environmental water provisions (WRC 2000) outlines that the ecological water requirements of high conservation value groundwater dependent ecosystems should be met in order to meet the objective of low level risk to such GDE. Of relevance to the Yandanooka Borefield study is that a higher level of risk than ‘low risk’ to GDE of high conservation value (such as threatened ecological communities) may be considered acceptable when allocating water use rights where “*the groundwater levels in the area have risen due to land use changes (so there may be ecosystems that are being maintained by the higher groundwater levels that would not otherwise be) and the ecological management objective is to reduce groundwater levels to a more ‘normal’ level*” (WRC 2000). In the case of the mound springs TEC and other GDE associated with the Arrowsmith River, groundwater extraction will play an important part in curbing the rising water table and maintaining a more suitable water regime.

6. CONCLUSIONS

With current extraction from the Yandanooka borefield of about 4.8 GL/a, groundwater levels have been lowered by about 0.5 to 1.0 m in monitoring bores close to the production bores, but have continued a gradual rise in regional monitoring bores (except in bore AR7 which now flows).

The groundwater flow model continues to closely represent changes in groundwater levels arising from recharge, extraction, and discharge to springs and via evapotranspiration. There is no evidence of any decrease in recharge rates despite a 12% reduction in average rainfall since 1990. Increases in rainfall events of greater than 25 mm seem to have compensated for the rainfall decline.

Modelling results indicate that 10 GL/a can be extracted from the Yandanooka borefield without causing any groundwater-level decline at groundwater-dependent ecosystems near the Arrowsmith River. Under this increased extraction scenario, there are unlikely to be any impacts to GDE as a result of the borefield operating because regional groundwater levels in the vicinity of all known springs are indicated to continue to rise. Extraction of a substantially larger quantity of 23 GL/a from the borefield would result in regional groundwater levels returning to those measured in about 2000. This rate of extraction would eventually cause a reduction in discharge from the aquifer, and would reduce flows in the Arrowsmith River to those observed in around year 2000, and could have the benefits of reducing waterlogging and tree deaths at high conservation value ecological communities and surrounding buffer vegetation.

Dated: 30 March 2017

Rockwater Pty Ltd

N Evelegh
Principal Environmental Scientist

PH Wharton
Principal

REFERENCES

- Aquaterra, 2005, Tathra sub-area groundwater investigations. Unpub. rept. to Mount Gibson Iron Ltd.
- Barnett, J. C., 1970, Hydrogeology of the Arrowsmith area, Western Australia: Western Australia Geological Survey, Record 1969/15.
- Barnett et al, 2012, Australian groundwater modelling guidelines. Waterlines report series No.82, National Water Commission, Canberra.
- Bekele, E. B., Salama, R. B., and Commander, D. P., 2006, Impact of change in vegetation cover on groundwater recharge to a phreatic aquifer in Western Australia: assessment of several recharge estimation techniques. Australian Journal of Earth Sciences 53, (905–917).
- Borger, J. 2005 Vegetation survey of remnants on the property of Cliff and Tony Harding, Arrowsmith River Catchment. Organic mound springs, Siltstone springs assemblages, Lateritic breakaways, Sandplain systems. Unpublished report to the Department of Conservation and Land Management, WA.
- Borger, J. and Jeffery, S., 2010, Surveys of Groundwater Dependent Remnant Vegetation within the Arrino – Mingenew area.
- Commander, D. P., 1978, Geology and hydrogeology of the Eneabba borehole line: Western Australia Geological Survey, Record 1978/7.
- Commander, D. P., 1996, Groundwater prospects for irrigation in the Irwin River valley. Water and Rivers Commission Hydrogeology Report 10.
- CSIRO, 2007. Oxclim: Climate Change Scenario Generator.
<http://www.csiro.au/ozclim/home.do>. CSIRO Australia
- Crostella, A., and Backhouse, J., 2000, Geology and petroleum exploration of the central and southern Perth Basin, Western Australia. Geological Survey of Western Australia Report 57.
- Davidson W.A., & Yu, X, 2008, Perth regional aquifer modelling system (PRAMS) model development: Hydrogeology and groundwater modelling, Western Australia Department of Water, Hydrogeological record series HG 20.

- Department of Parks and Wildlife (DPAW), 2016, List of Threatened Ecological Communities (TECs) endorsed by the Western Australian Minister for Environment Species & Communities Branch (Correct as at 6 October 2016)
- Department of Water (DoW), 2009, Environmental considerations for groundwater management in the Northern Perth Basin. Environmental Water Report Series, Report 8, May 2009
- Department of Water (DoW), 2010, Arrowsmith groundwater allocation plan. Water resource allocation planning series Report 28. August 2010.
- DoW, 2016, Hydrogeology of the Northern Perth Basin. Bulletin No.1 (in prep.)
- Froend, R.H. and Zencich, S.J. (2001). Phreatophytic Vegetation and Groundwater Study: Phase 1. Report to the Water and Rivers Commission and the Water Corporation of Western Australia. Centre for Ecosystem Management, Joondalup.
- Froend, R and Loomes, R 2004, Approach to determination of ecological water requirements for groundwater-dependent ecosystems in Western Australia – a report to the Department of Environment, Edith Cowan University, Perth.
- Irwin, R., 2007, Hydrogeology of the Dongara Borehole Line, Department of Water, Hydrogeological Series, HG4.
- Loomes, Froend and Bertuch (2006) Determination of Ecological Water Requirements for Groundwater Dependent Ecosystems – Southern Blackwood and Eastern Scott Coastal Plain: Baseline Monitoring Results and Monitoring Protocol. A report to the Department of Environment. Report by Centre for Environmental Management (No. 2005-07) Edith Cowan University, Joondalup
- Luke, G.J., Burke, K.L., and O'Brien, T.M., 1988, Evaporation data for Western Australia. Tech. Report No. 65 (2nd Ed), W.A. Dept. of Agriculture.
- McDonald, M.G., and A.W. Harbaugh, 1988, A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. Book 6, Chapter A1, Techniques of Water Resources Investigations. U.S. Geol. Surv., Washington, DC. (A:3980).
- Middlemis, H., 2000, Groundwater Flow Modelling Guideline. Report to Murray-Darling Basin Commission.
- Mory, A. J. and Iasky, R. P., 1996, Stratigraphy and Structure of the Onshore Perth Basin, Western Australia. Western Australia Geological Survey Report 46.

- Pinder, A., Clarke, V. and Harding, C. (2009). Monitoring of the Invertebrate Assemblages of Mound Springs of the Three Springs Area Threatened Ecological Community. Version 1.0 (August 2009). Prepared for Significant Native Species and Ecological Communities – Resource Condition Monitoring Project.
- Pinder, A.M. and Penniford, M.G. 2001 A survey of the aquatic invertebrates of some organic mound springs in the Shire of Three Springs, W.A. Report to the W.A. Threatened Species and Communities Unit, Department of Conservation and Land Management, Woodvale, WA.
- Pinder, A.M. and Stratford, L. 2006 Report on August 2001 sampling of invertebrate assemblages at mound springs of the Three Springs area. Produced for the Western Australian Threatened Species and Communities Unit, Department of Conservation and Land Management, Woodvale, WA.
- Playford, P. E., Cockbain, A. E., and Low, G. H., 1976, Geology of the Perth Basin, Western Australia: Western Australia Geological Survey, Bulletin 124, 311p.
- Rees, R. and Broun, G. 2005 Interim Recovery Plan 196. Assemblages of organic mound springs of the Three Springs area. Interim Recovery Plan 2005-2010. Department of Conservation and Land Management, Woodvale, WA.
- Rockwater, 2007, Karara Project: Planned Yandanooka Borefield, Report on bore construction, testing and numerical modelling, unpublished report No. 319/07/07 for Gindalbie Metals Limited
- Rockwater, 2008, Karara Iron Ore Project: Groundwater impact assessment, Yandanooka Borefield, unpublished report No. 319/08/03b for Karara Management Services.
- Rockwater, 2010, Karara Iron Ore Project, Yandanooka Borefield completion report and hydrogeological assessment. Report for Karara Mining Ltd.
- Rutherford, J., Roy, V. and Johnson, S.L., 2005, The hydrogeology of groundwater dependent ecosystems in the Northern Perth Basin. Dept. of Environment Hydrogeological Record Series, HG11.
- Soil Water Consultants, 2010, Yandanooka Borefield Groundwater Dependent Ecosystem (GDE) Investigation. Report for Karara Mining Ltd.
- Woodman Environmental Consulting (WEC) (2010). Flora and vegetation survey of the Yandanooka Borefield. Unpublished report to Karara Mining Limited.

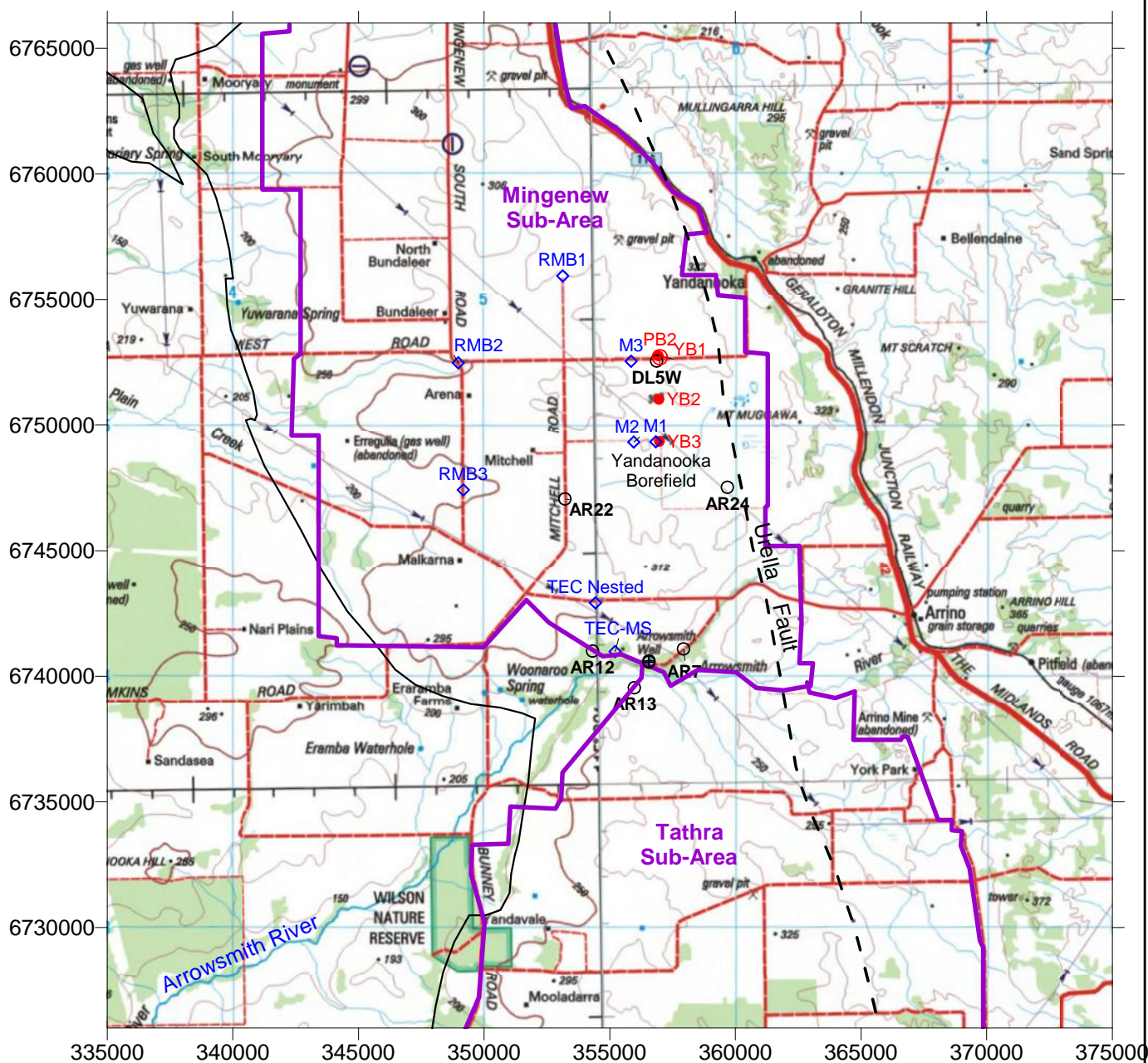
Water and Rivers Commission (WRC), 2000, Statewide policy no. 5 – Environmental water provisions policy for Western Australia, Water and Rivers Commission, Perth.



FIGURES



FIGURE 1



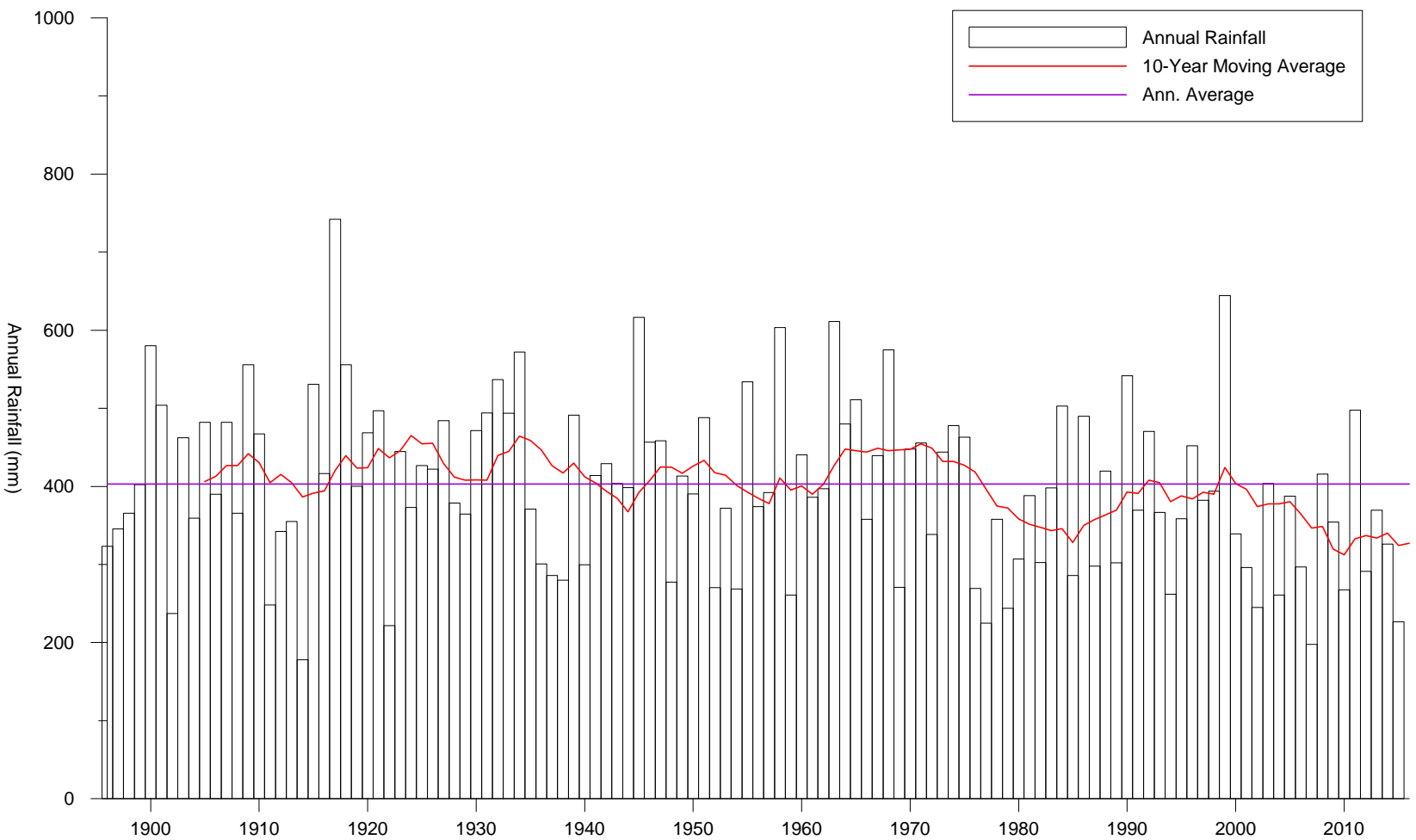
- Arrowsmith River Mon. Bore
- Yandanooka Production Bore
- ◇ Yandanooka Monitoring Bore
- ⊕ Arrowsmith Production Bore

locations.srf

Client: Karara Mining Ltd
 Project : Yandanooka Borefield
 Date : March 2017
 Dwg. No: 319.3/17/1-1

LOCALITY PLAN

FIGURE 2



annual_rainfalls.grf

Client: Karara Mining

Project: Yandanooka Borefield

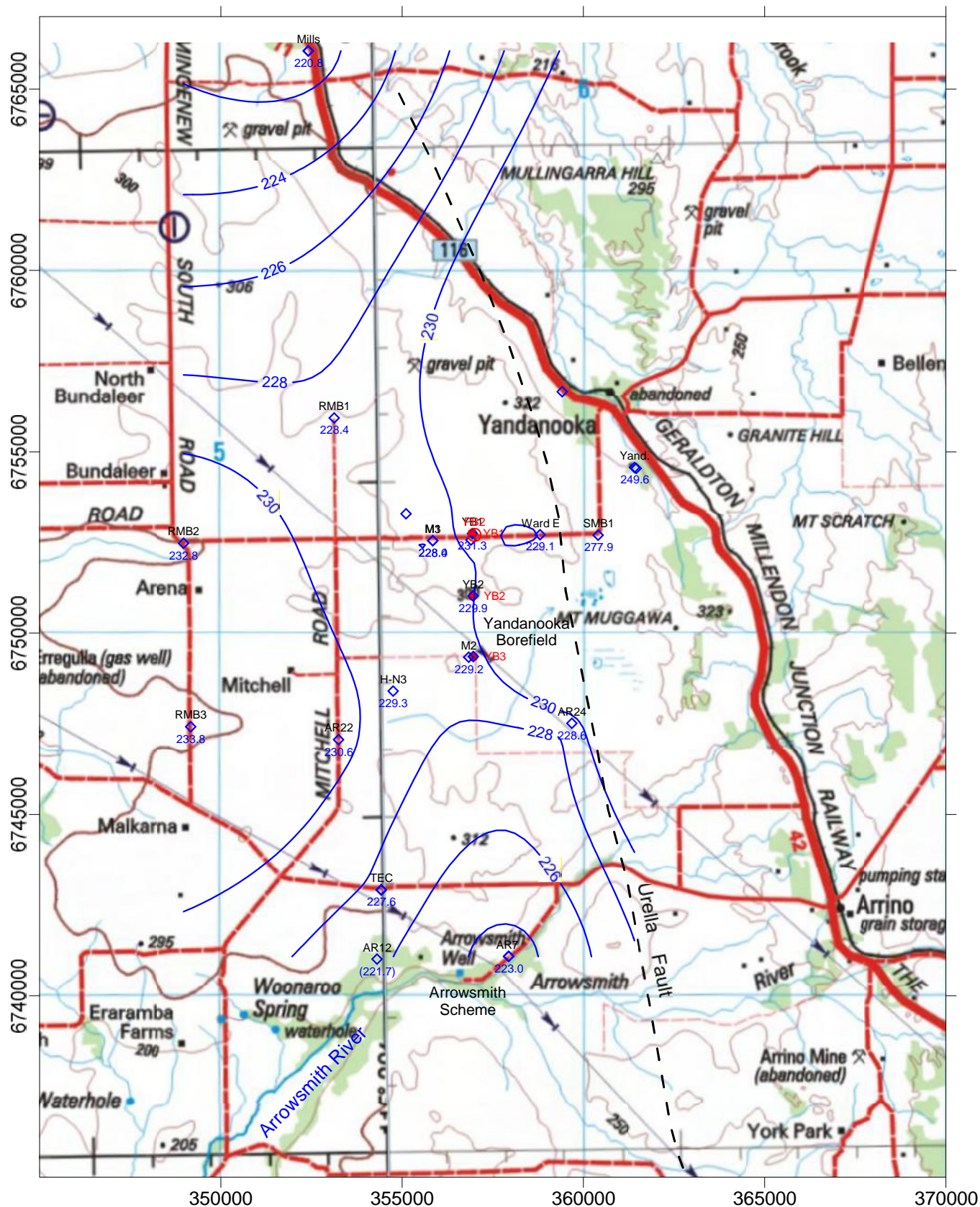
Date: March 2017

Dwg. No: 319.3/17/1-2

ANNUAL RAINFALLS

MINGENEW

FIGURE 3

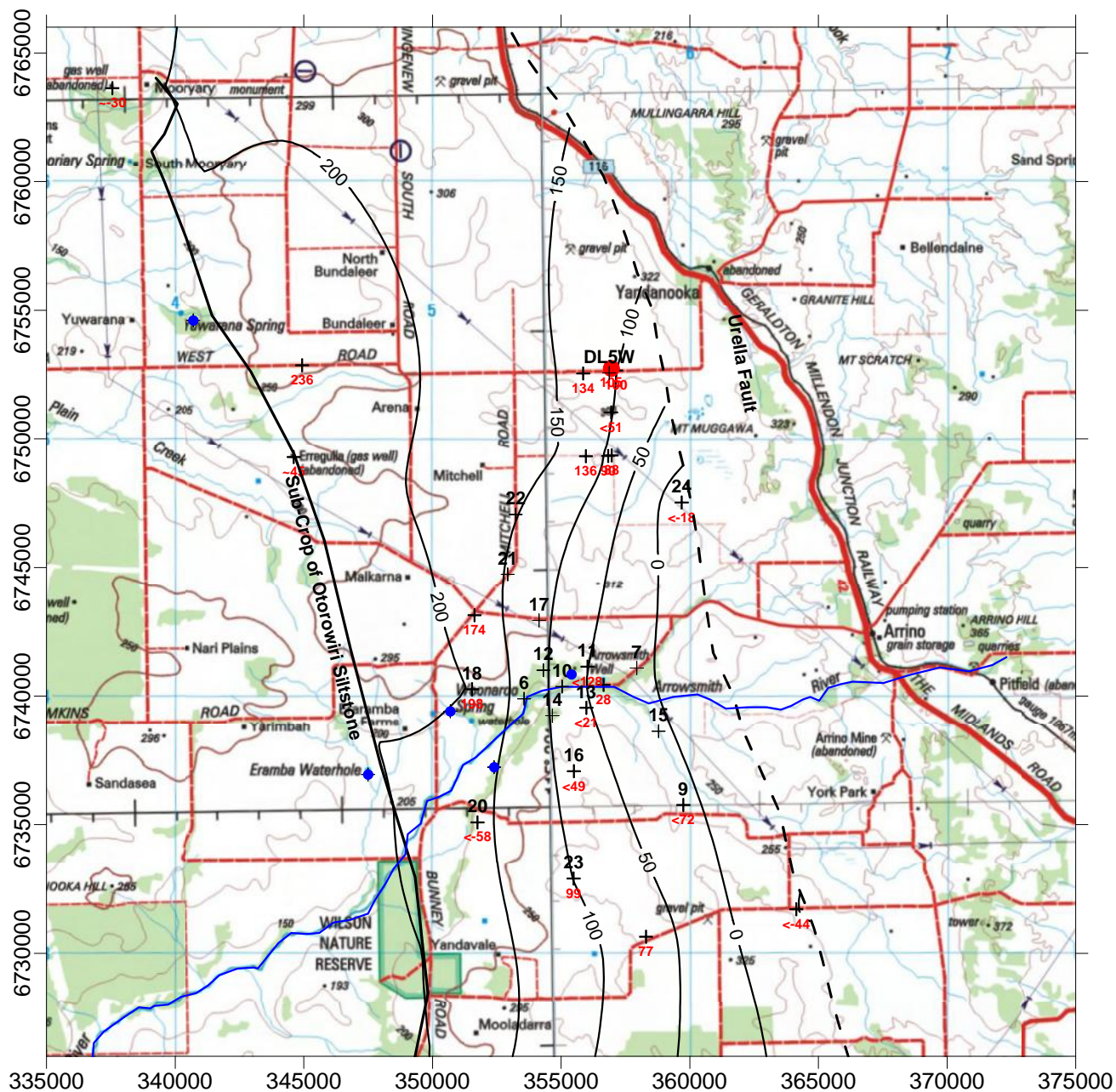


new 2012 wls.srf

Client: Karara Mining Ltd
 Project: Yandanooka Borefield
 Date: March 2017
 Dwg. No: 319.3/17/1-3

WATER LEVELS (m AHD)
 FEBRUARY TO JUNE 2012

FIGURE 4



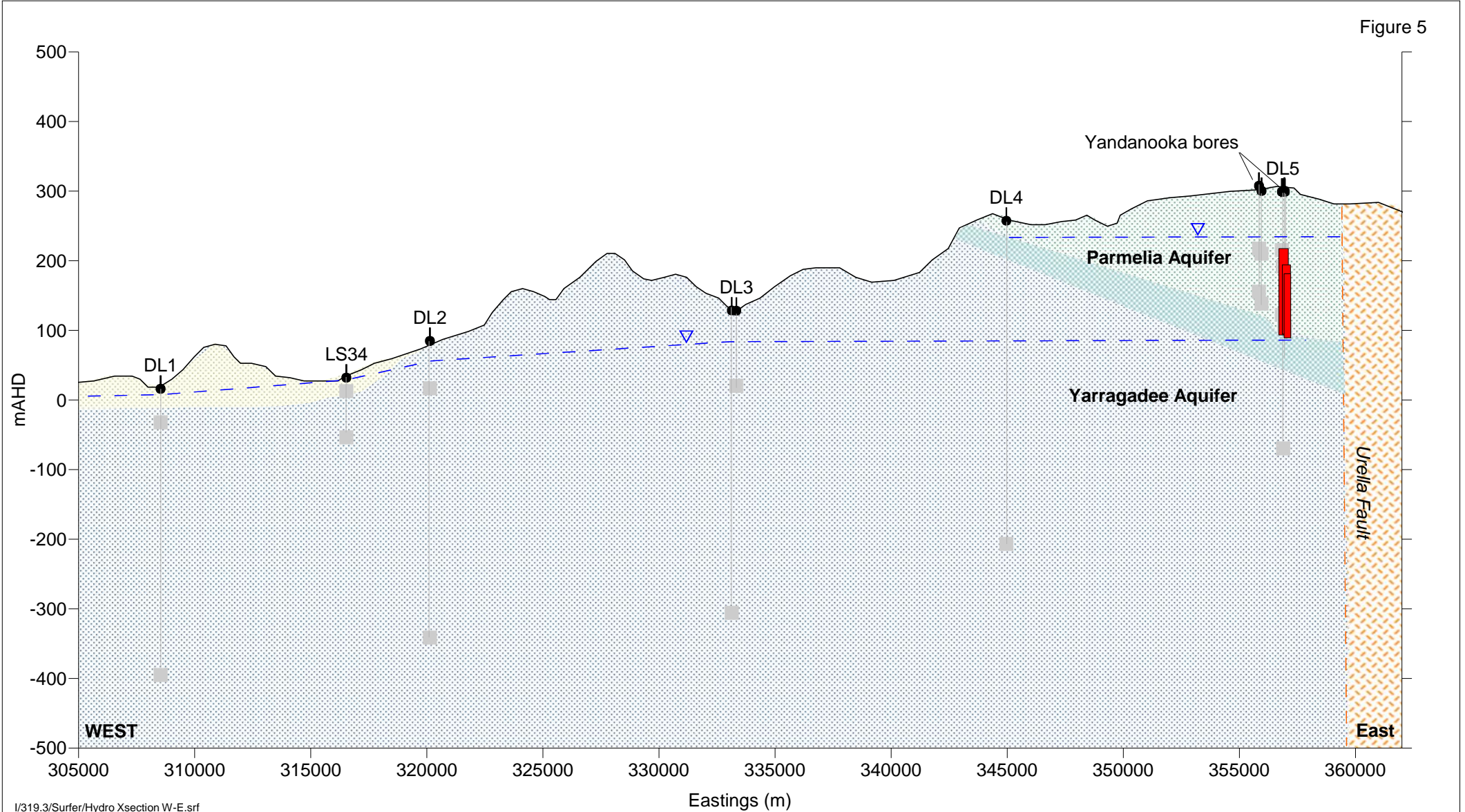
- Spring
- 16 DoW Bore Number
- 77 Elevation, Top of Otorowiri (m AHD)
- Yandanooka PB2

base of parmelia.srt

CLIENT: Karara Mining Ltd
 PROJECT: Yandanooka Borefield
 DATE: March 2017
 Dwg No: 319.3/17/1-4

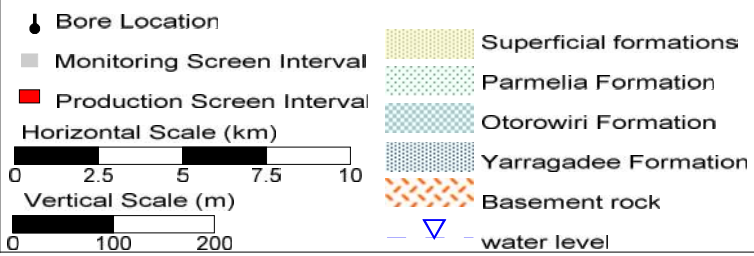
ELEVATION (m AHD) BASE OF
 PARMELIA AQUIFER

Figure 5



I/319.3/Surfer/Hydro Xsection W-E.srf

CLIENT: Karara Mining Limited
PROJECT: Yandanooka Borefield
DATE: March 2017
DWG No.: 319.3/17/1-5



Based on Irwin 2007
MGA, Zn 50

HYDROGEOLOGICAL CROSS SECTION

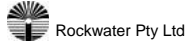
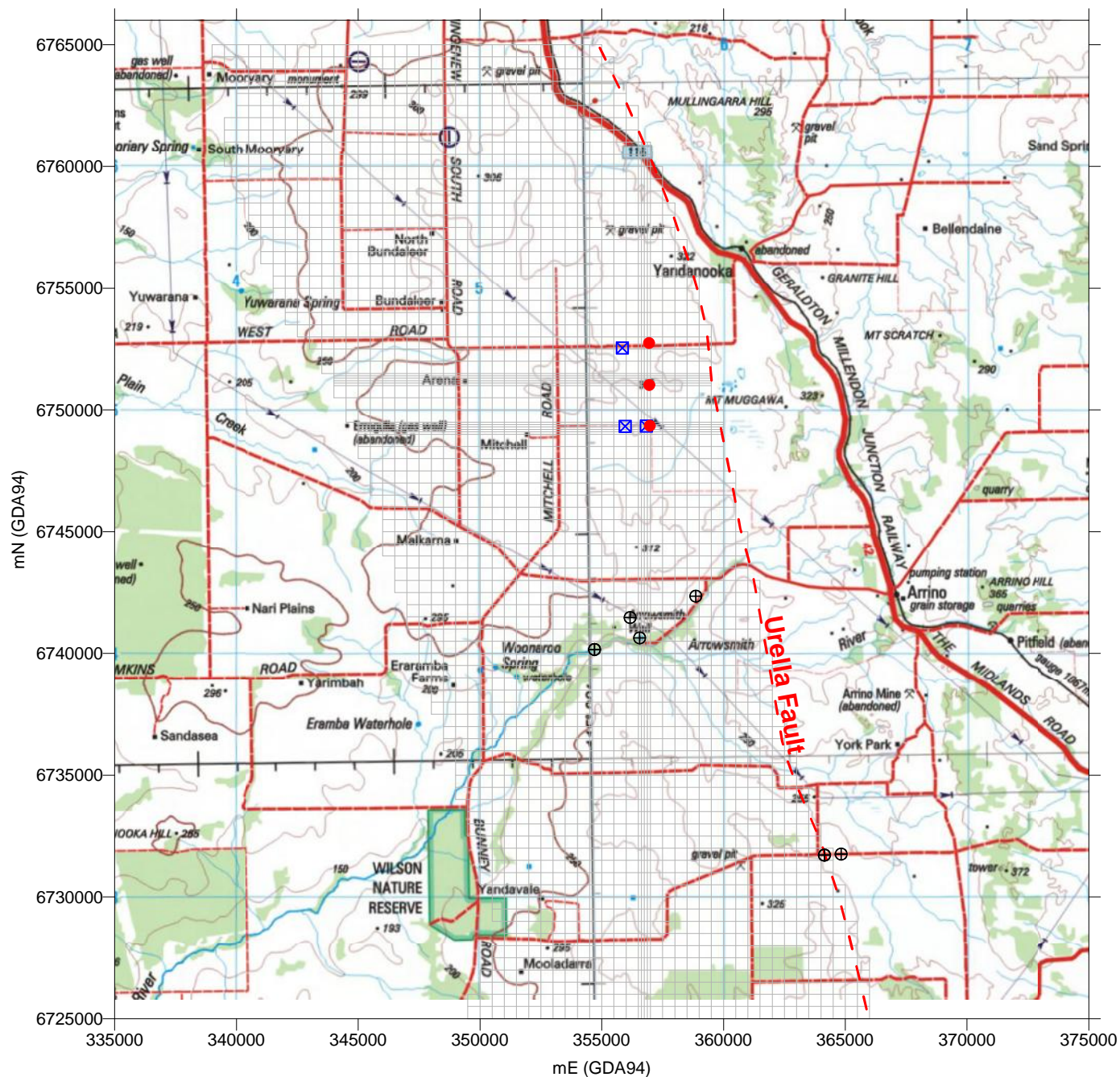


FIGURE 6



- Yandanooka Production Bore
- Yandanooka Monitoring Bore
- ⊕ Water Corporation Production Bore

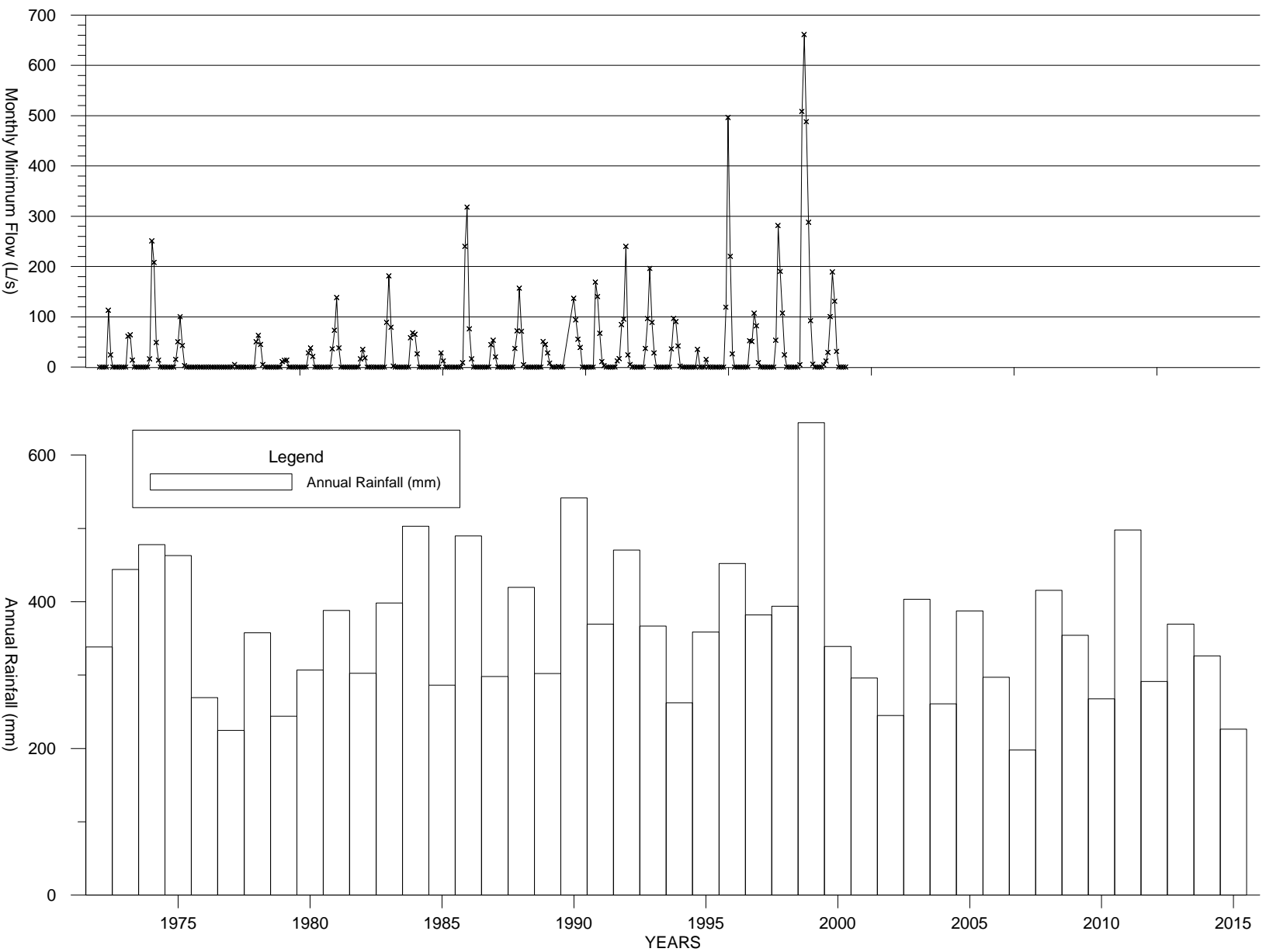
Model Grid.srf

Base Map: Yandanooka 1:100,000 Topographic

CLIENT: Karara Mining Ltd
 PROJECT: Yandanooka Borefield
 DATE: March 2017
 Dwg No: 319.3/17/1-6

EXTENT OF MODEL GRID

FIGURE 7



701005 flows.grf

Client: Karara Mining Ltd

Project: Yandanooka Borefield

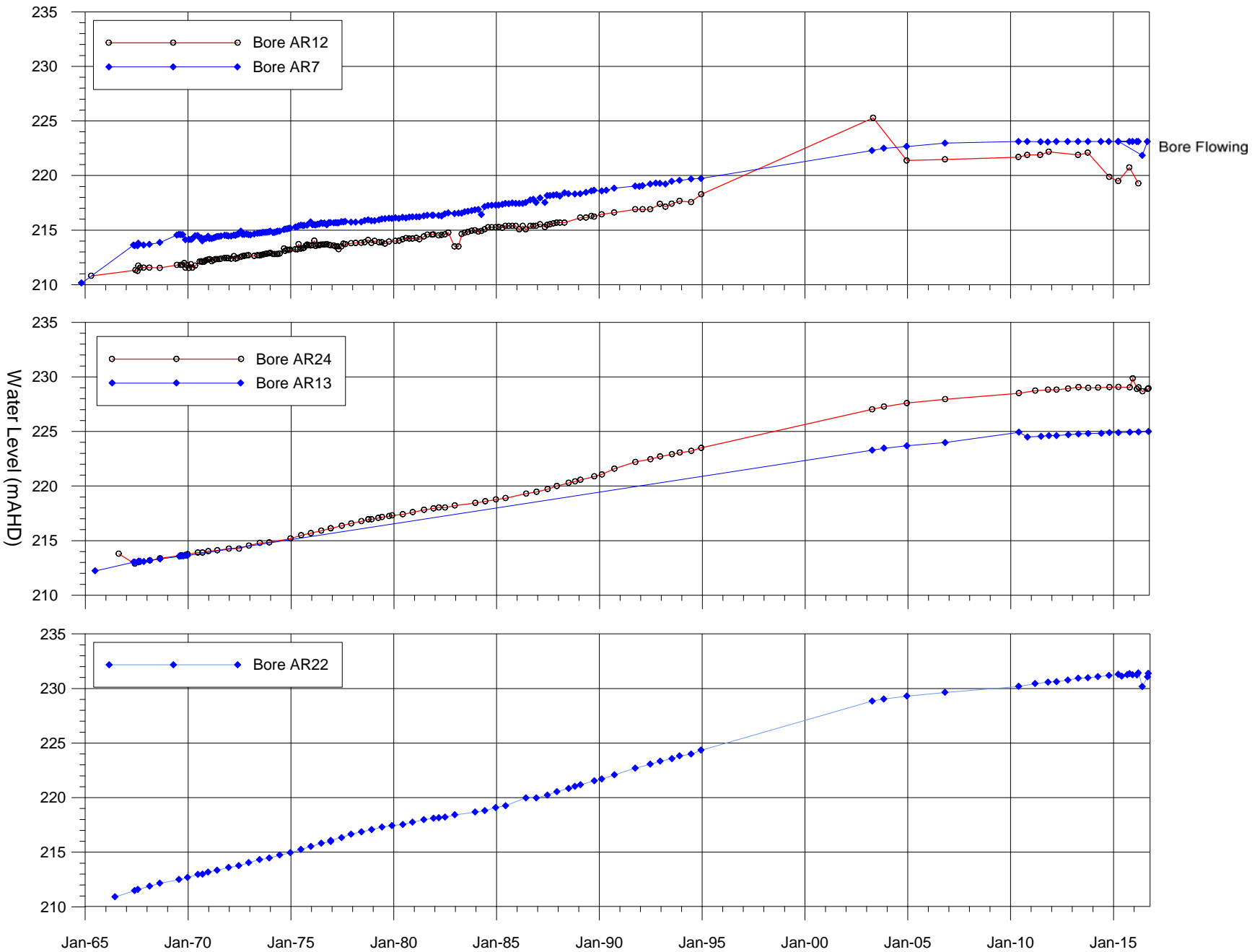
Date: March 2017

Dwg. No: 319.3/17/1-7

ANNUAL RAINFALLS AT MINGENEW,
AND FLOWS IN ARROWSMITH RIVER AT
ROBB CROSSING (334439 mE, 6722250 mN)

ROCKWATER PTY LTD

Figure 8



Arrowsmith R WLS.grf

Client: Karara Mining Ltd

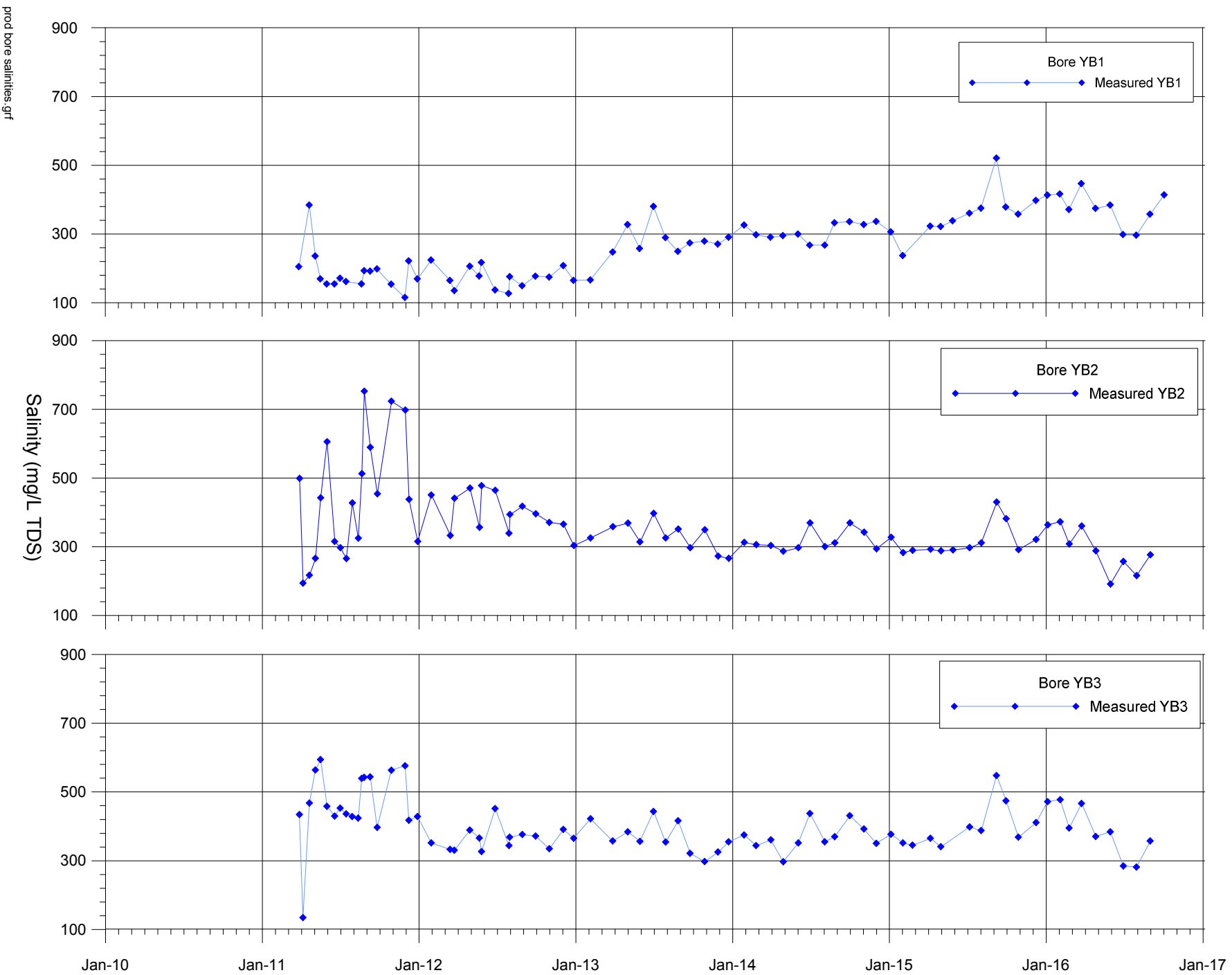
Project: Yandanooka Borefield

Date: March 2017

Dwg. No: 319-3/17/1-8

HYDROGRAPHS for DOW
ARROWSMITH RIVER BORES

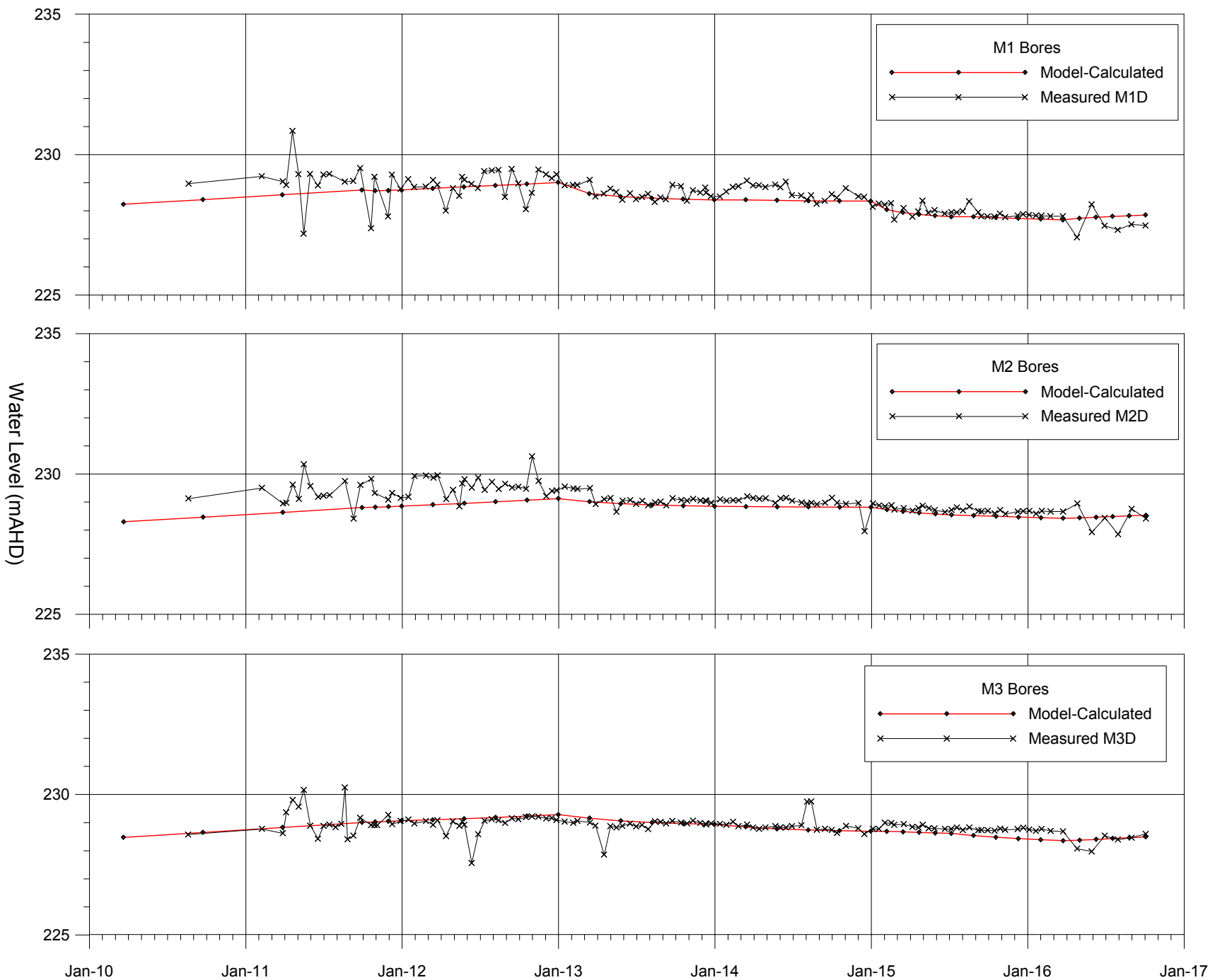
Figure 9



Client: Karara Mining Ltd
 Project: Yandanooka Borefield
 Date: March 2017
 Dwg. No: 319-3/17/1-9

FIELD SALINITIES (mg/L TDS) for YANDANOOKA BORES
 YB1, YB2 and YB3

Figure 10



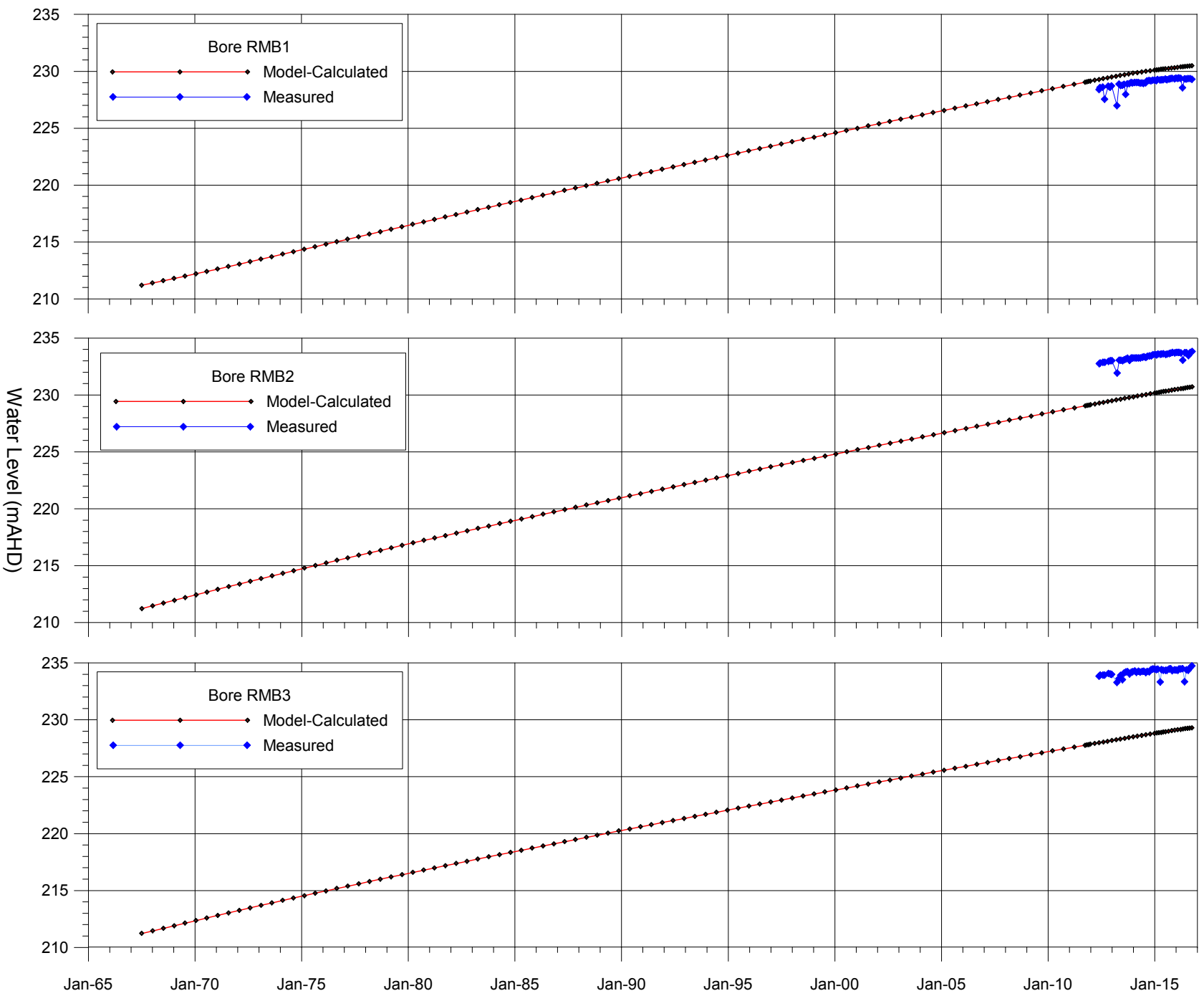
Meas and Modelled WLS - M1,M2,M3 new.grf

Water Level (mAHd)

Client: Karara Mining Ltd
 Project: Yandanooka Borefield
 Date: March 2017
 Dwg. No: 319-3/17/1-10

HYDROGRAPHS for YANDANOOKA BORES
 M1, M2 and M3
 Observed and Model-Calculated

Figure 11

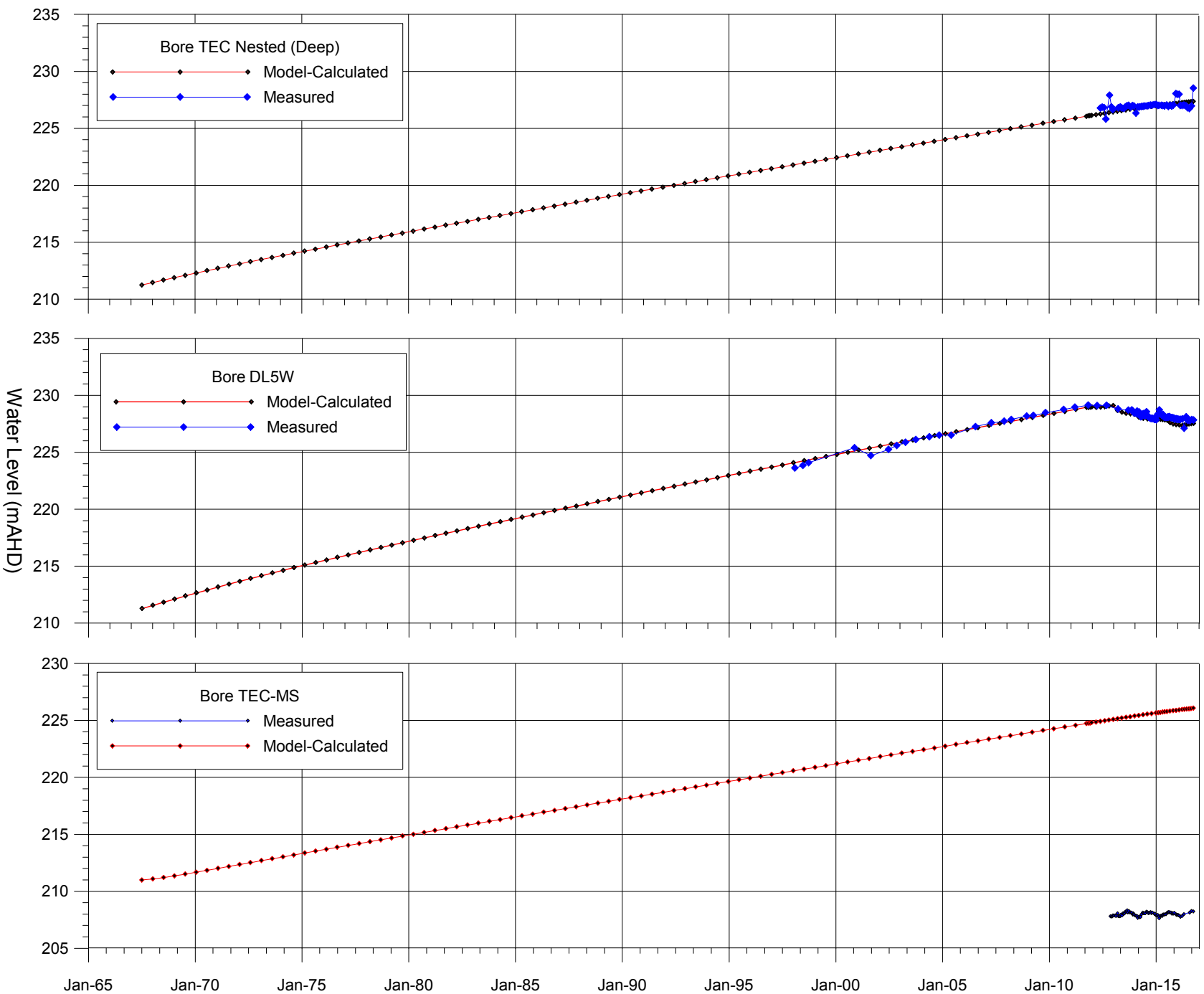


meas and modelled WLS - rmb1-3.grf

Client: Karara Mining Ltd
 Project: Yandanooka Borefield
 Date: March 2017
 Dwg. No: 319-3/17/1-11

HYDROGRAPHS for BORES RMB1 to RMB3
 Measured and Model-Calculated

Figure 12

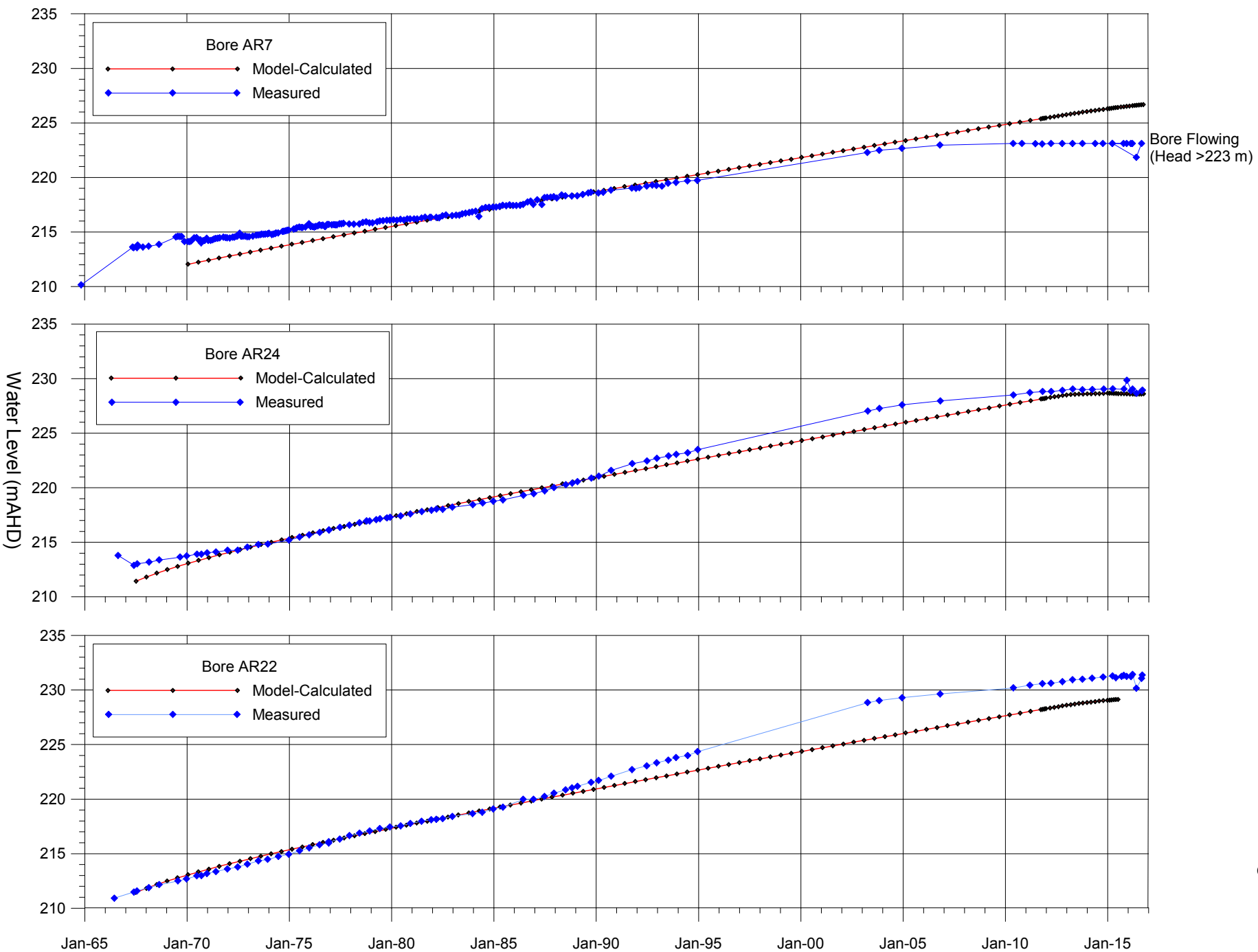


Obs and Modelled WLS - TEC Nested, DL5W, TEC-MS new.grf

Client: Karara Mining Ltd
 Project: Yandanooka Borefield
 Date: March 2017
 Dwg. No: 319-3/17/1-12

HYDROGRAPHS for ARROWSMITH BORES
 TEC NESTED, DL5W and TEC-MS
 Observed and Model-Calculated

Figure 13

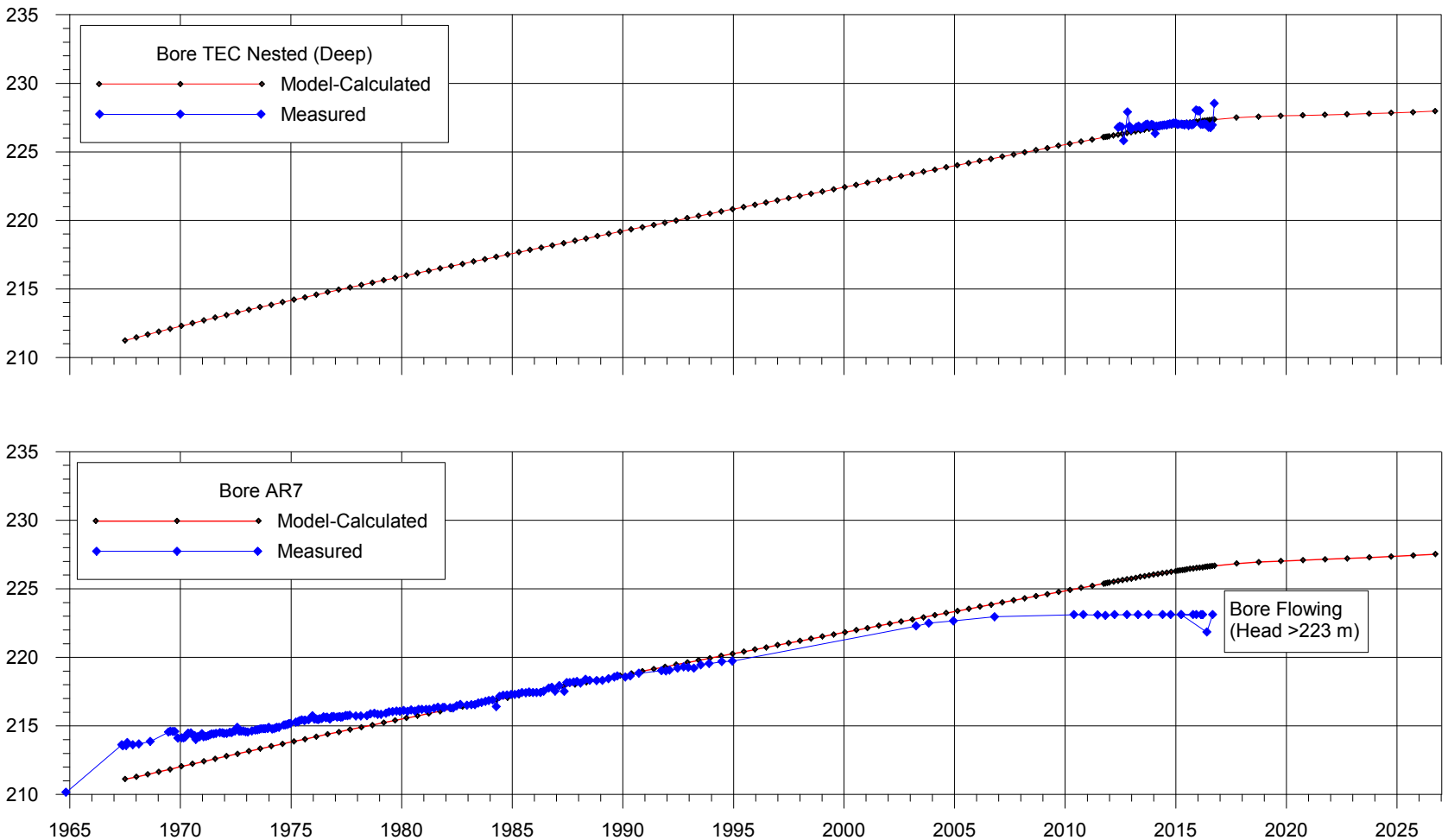


Obs and Modelled WLS - AR7,24, 22 new.grf

Client: Karara Mining Ltd
 Project: Yandanooka Borefield
 Date: March 2017
 Dwg. No: 319-3/17/1-13

HYDROGRAPHS for ARROWSMITH BORES
 AR7, AR22 and AR24
 Observed and Model-Calculated

Figure 14

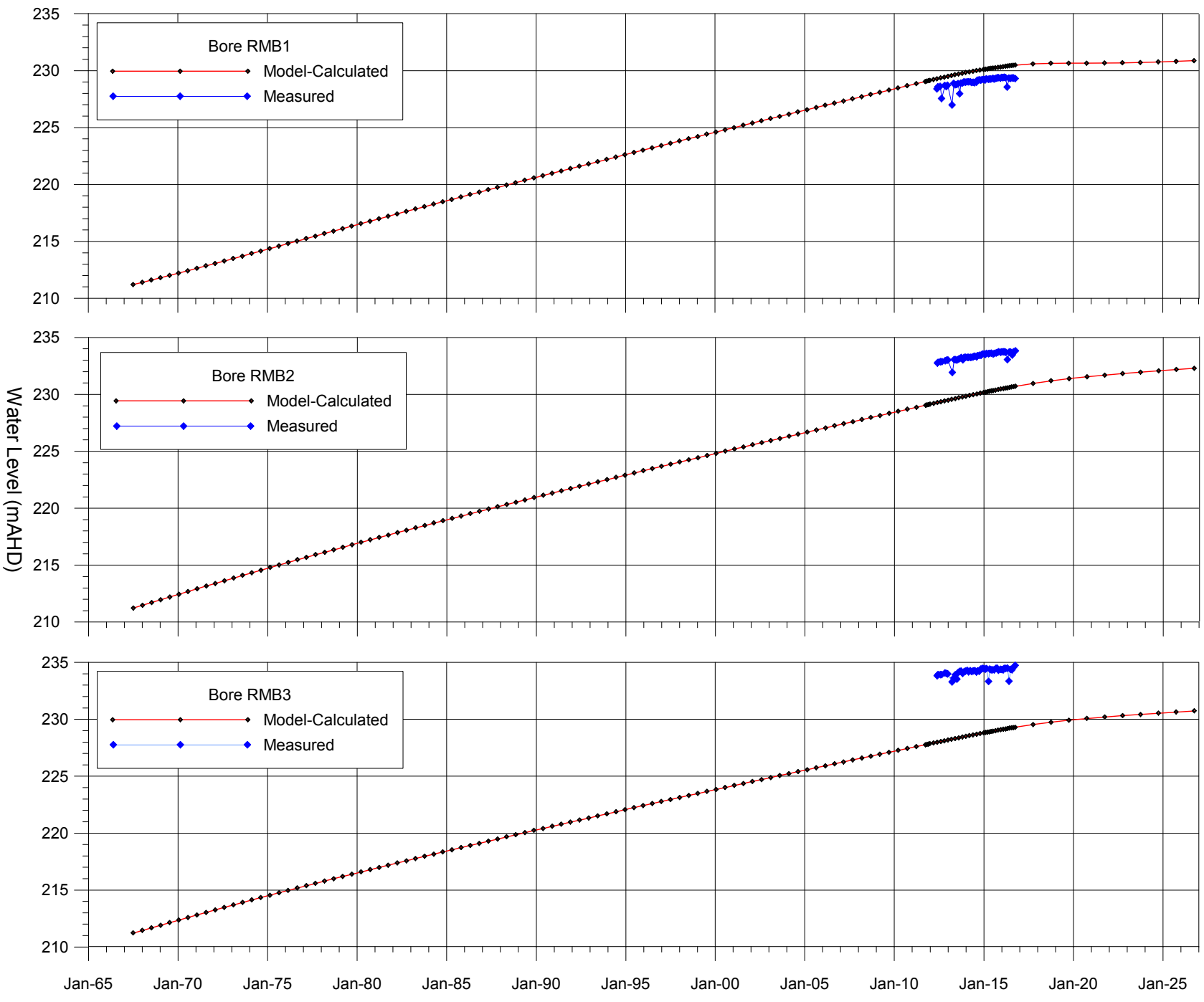


predicted WLS 10 GL - TEC Nested Deep, AR7 gft

Client: Karara Mining Ltd
Project: Yandanooka Borefield
Date: March 2017
Dwg. No: 319-3/17/1-14

HYDROGRAPHS for ARROWSMITH BORES
TEC NESTED Deep and AR7
Observed, and Predicted for 10 GL/a

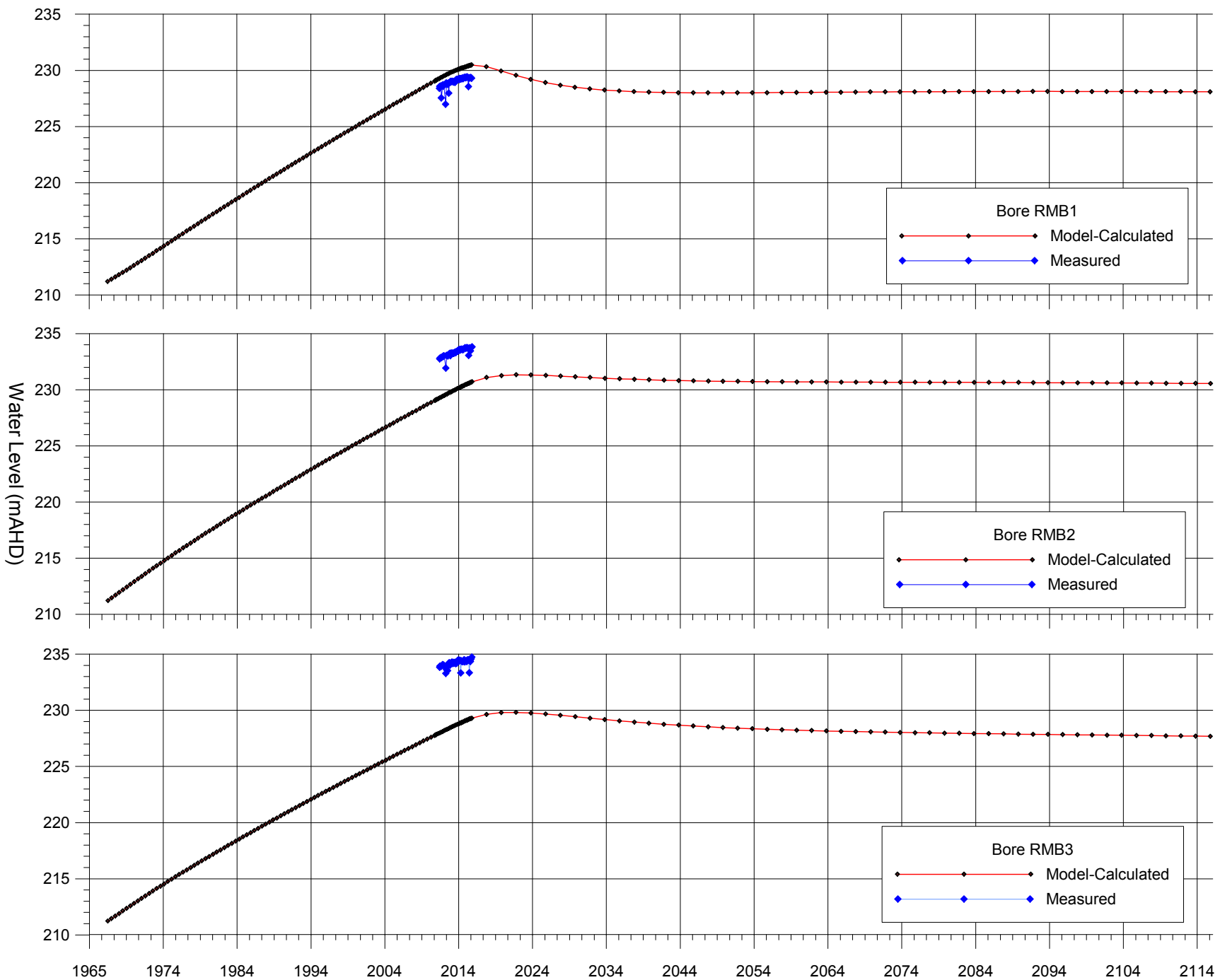
Figure 15



Client: Karara Mining Ltd
 Project: Yandanooka Borefield
 Date: March 2017
 Dwg. No: 319-3/17/1-15

HYDROGRAPHS for BORES RMB1 to RMB3
 Measured, and Predicted for 10 GL/a

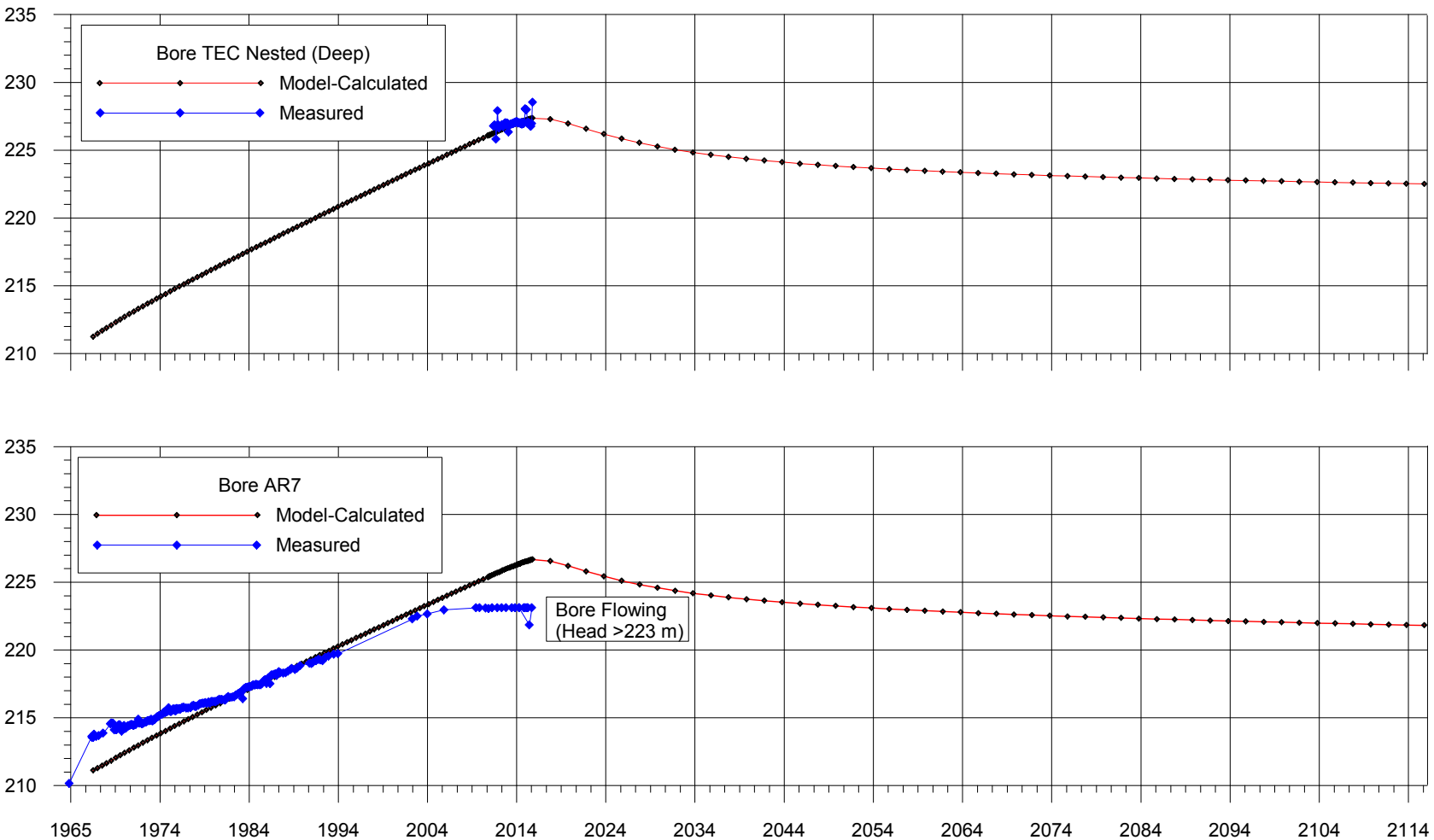
Figure 16



Client: Karara Mining Ltd
 Project: Yandanooka Borefield
 Date: March 2017
 Dwg. No: 319-3/17/1-16

HYDROGRAPHS for BORES RMB1 to RMB3
 Measured, and Predicted for 23 GL/a

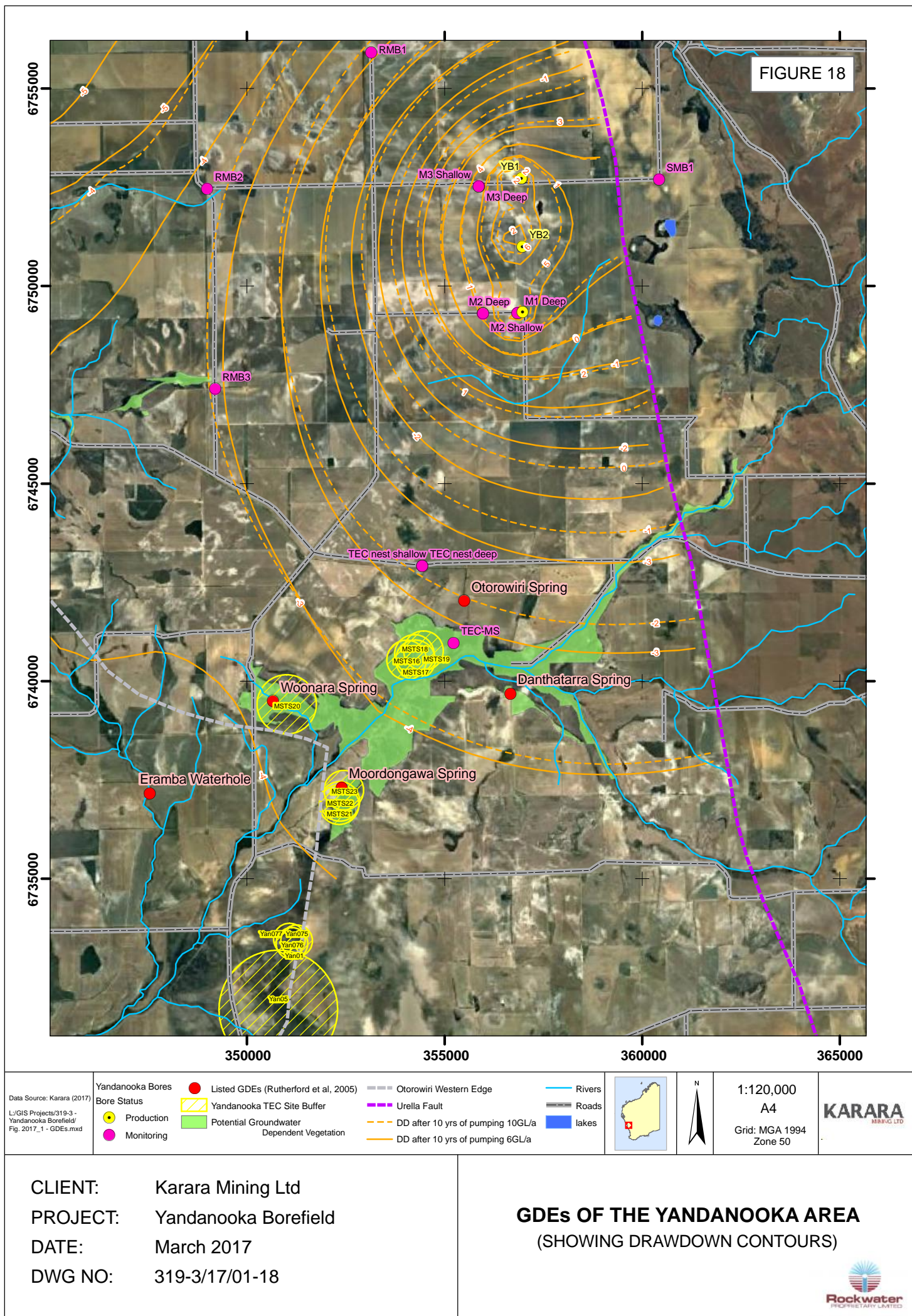
Figure 17



predicted WLS 23GL - TEC Nested Deep, AR7.grf

Client: Karara Mining Ltd
 Project: Yandanooka Borefield
 Date: March 2017
 Dwg. No: 319-3/17/1-17

HYDROGRAPHS for ARROWSMITH BORES
 TEC NESTED Deep, and AR7
 Observed, and Predicted for 23 GL/a



APPENDIX I:
Measured and Model-Calculated Groundwater Levels, Rockwater (2010)



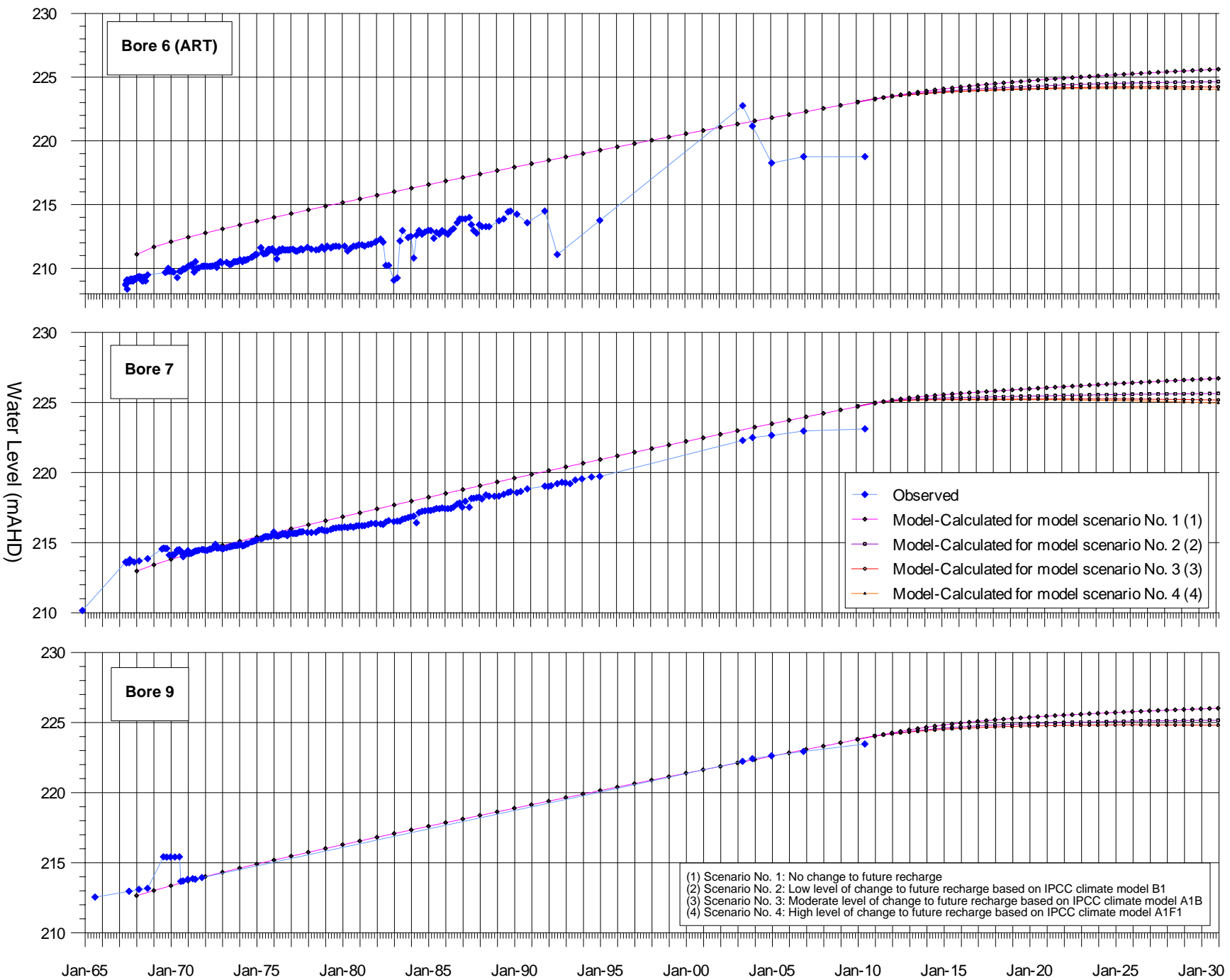


Figure APPI-i

I:\319-3\Grapher\10-001\Time-series Water Levels.xls\Ob and Modelled WLS - B6, 7, 9.gdt

Client: Karara Mining Ltd
 Project: Yandanooka Borefield
 Date: November 2010
 Dwg. No: 319-3/10/1-APP1-i

HYDROGRAPHS for ARROWSMITH BORES
 Bore 6(ART), Bore 7 and Bore 9
 Observed and Model-Calculated

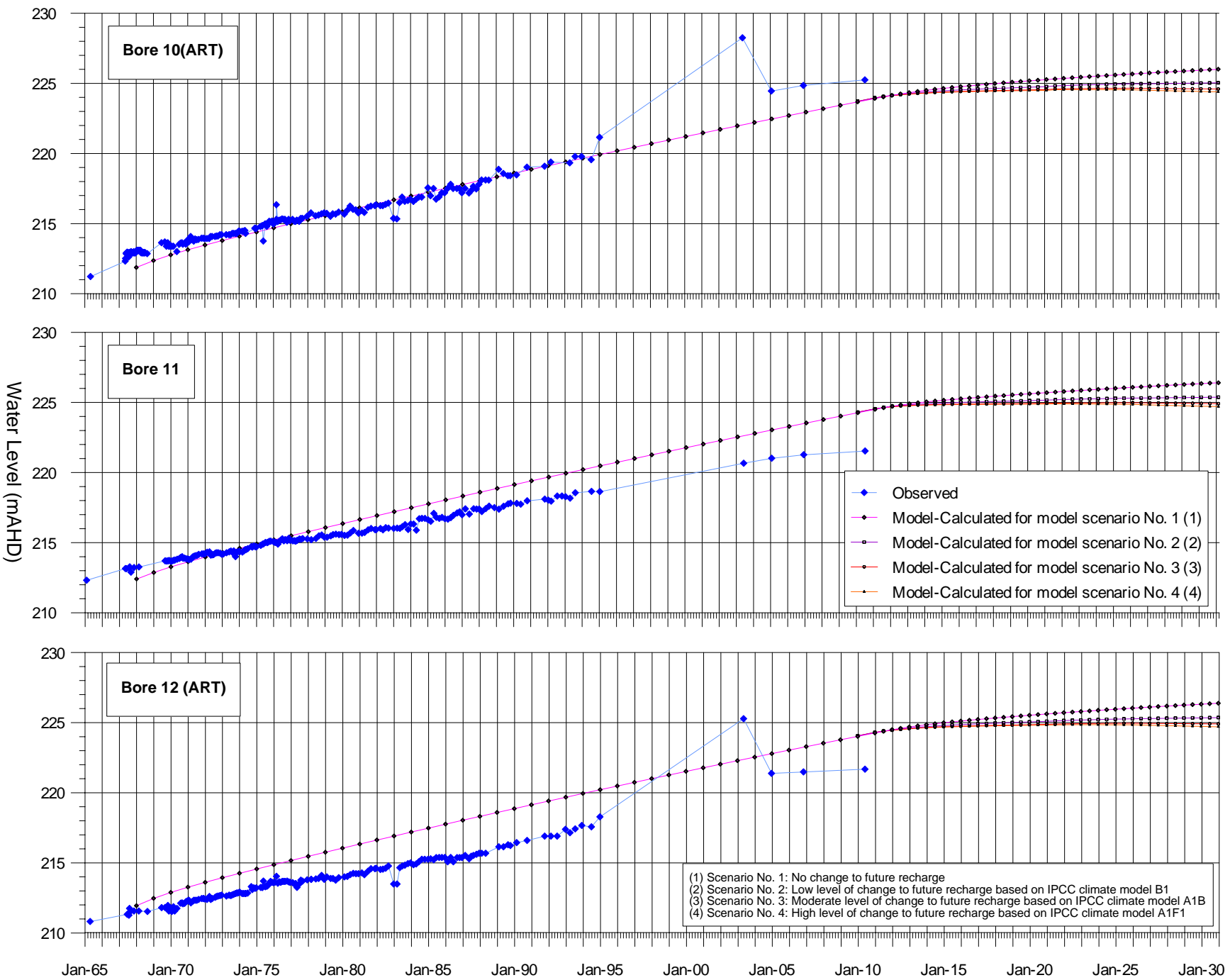


Figure APPI-ii

I:\319-3\Grapher\10-001\Time-series Water Levels.xls\Ob and Modelled WLS - B10.11.12.grf

Client: Karara Mining Ltd

Project: Yandanooka Borefield

Date: November 2010

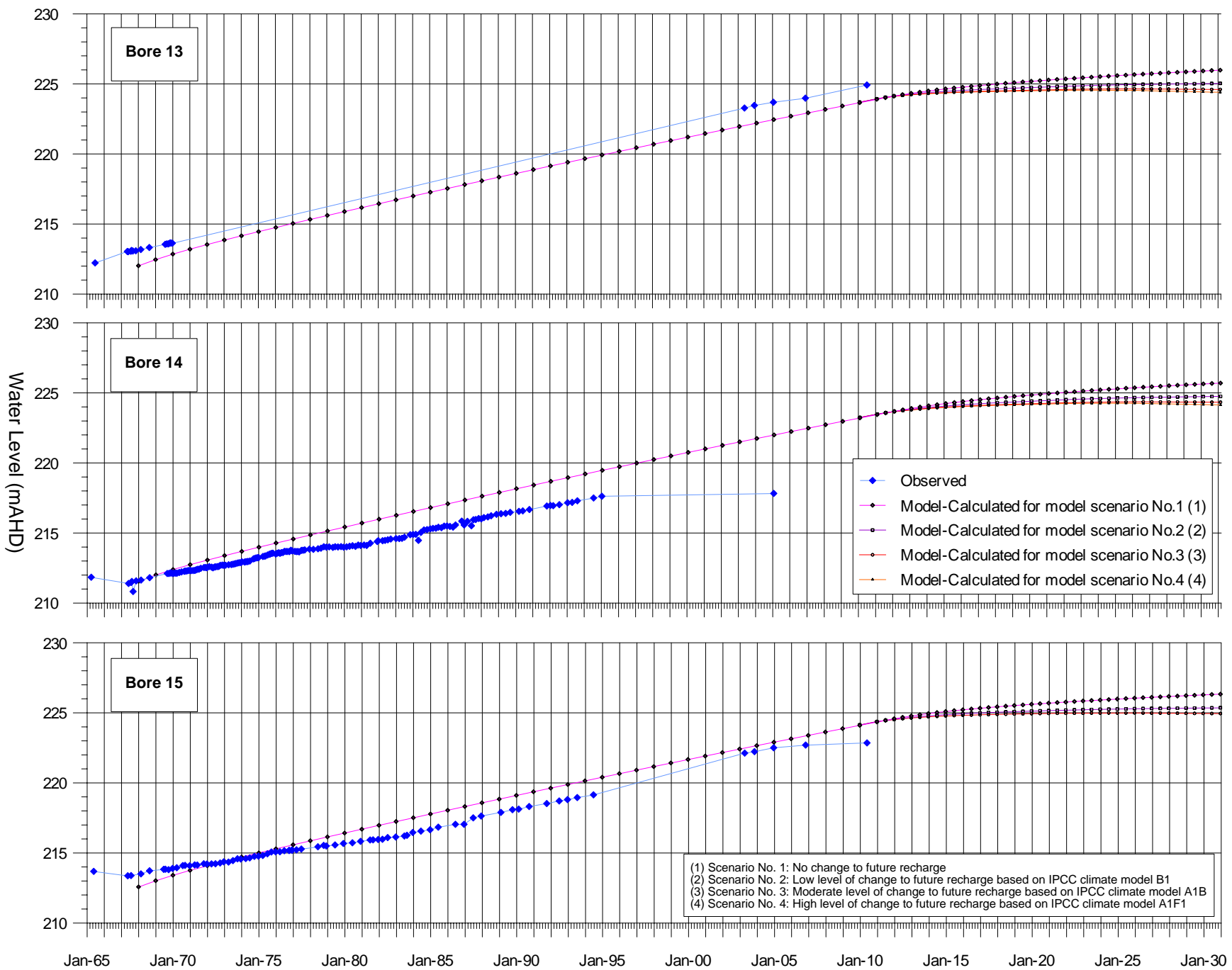
Dwg. No: 319-3/10/1-APP1-ii

HYDROGRAPHS for ARROWSMITH BORES

Bore 10(ART), Bore 11 and Bore 12(ART)

Observed and Model-Calculated

Figure APP1-iii



I:\319-3\Grapher\10-001\Time-series Water Levels.xls\Obs and Modelled WLS - B13,14,15.grf

Client: Karara Mining Ltd

Project: Yandanooka Borefield

Date: November 2010

Dwg. No: 319-3/10/1-APP1-iii

HYDROGRAPHS for ARROWSMITH BORES

Bore 13, Bore 14 and Bore 15

Observed and Model-Calculated