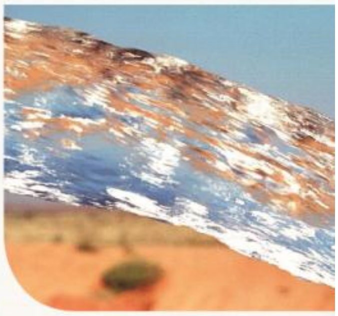
H3-LEVEL HYDROGEOLOGICAL ASSESSMENT OF THE THUNDERBIRD PROJECT



REPORT FOR SHEFFIELD RESOURCES

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REVISION	AUTHOR	REVIEW	ISSUED
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1 INTRODUCTION

1.1 PROJECT DESCRIPTION

Sheffield Resources (Sheffield) is developing the Thunderbird Mineral Sands Project (the Thunderbird Project) located on the Dampier Peninsula in the Kimberley region of Western Australia (Figure 1). The Thunderbird Project is targeting a heavy mineral sands (HMS) resource (Figure 2) over a 47 year life of mine. Processing will be undertaken onsite and the HMS product will be transported by road to Derby Port for storage and subsequent export to overseas markets.

The Thunderbird Project mining method will be progressive, with mined areas undergoing progressive backfilling and rehabilitation. Up to 200 hectares (ha) of pit area will be open at any given time. Processing methods include initial ore-screening at the active mine face and ore-transfer in a slurry form to a primary processing plant (a wet concentrator plant [WCP]) in close proximity to the active mining face). The WCP will be moved a number of times as the active mining face moves during the project life to minimise slurry piping distances. A secondary processing plant (the Mineral Separation Plant [MSP]) will separate different minerals from the heavy minerals concentrate (HMC). The MSP will be located away from the mining area and will incorporate a combination of gravity, magnetic, chemical, low temperature roasting and electrostatic separation processes. Uneconomic sands and other waste streams from the MSP will initially be stored within a conventional above-ground tailings storage facility (TSF). Once there is sufficient mine void storage capacity, all further mine waste material will be returned to mine voids as backfill.

Mining will start in the northeast of the deposit (Figure 2) and progress over the 47 year mine life in NW–SE mining blocks, using large dozers and scrapers. Approximate ore mining depths will progressively increase over the life of the project (Table 1). The projected ore mining rate is up to about 24 MTPA. Process water will be supplied from local groundwater resources.

Table 1 – Mining depths

Mining year	Approximate base of ore (m RL)
1–7	100
8–15	80
16–22	60
23–29	50
30–36	40
37–43	30
44–47	20

The Thunderbird Project will also include support facilities (power, workshops, roads), an accommodation camp and a waste water treatment plant.

1.2 PREVIOUS WORK

Sheffield commissioned an initial hydrogeological assessment for the project (Pennington Scott, 2015). The initial assessment included:

- Drilling, construction and testing of three test production bores (TWB001, TWB002 and TWB003) in the vicinity of the proposed mine (Figure 2).
- Installation of slotted casing in RC exploration holes (THAC series bores, Figure 2).
- Preliminary numerical modelling.
- Flora and fauna surveys.

The flora and fauna surveys have since been augmented (Mattiske, 2016). The results from these assessments are incorporated in the present study.

1.3 SOURCES OF DATA

Several assessments of the hydrogeology and groundwater resources in the Broome area and western Dampier Peninsula were undertaken by the Geological Survey of Western Australia (GSWA) in the 1980s. The Broome hydrogeological map and explanatory notes (Laws, 1991) summarise data from these assessments and other hydrogeological data for the area. A review of the groundwater resources of the Dampier Peninsula was compiled by Department of Water (DoW) and provides a summary of the available data and an assessment of the status of the groundwater resources (Searle, 2012).

Groundwater bore information and groundwater licence information has been accessed from DoW databases. Petroleum exploration drilling data and geophysical logs have been accessed from Department of Mines and Petroleum (DMP) databases to provide stratigraphic data and other geological data.

The Water Corporation provided access to groundwater level and pumping data from bores installed for the Broome Town Water Supply Borefield, as well as data from previous borefield groundwater modelling assessments (Rockwater, 2008; 2010; 2013; 2014).

Various aerial electromagnetic (EM) and magnetic surveys have been undertaken by Woodside (Fugro Airborne Surveys, 2012) and Department of Water (DoW, 2016). The surveys have helped map the saltwater interface in the western part of the peninsula.

The previous work described in Section 1.2 has been incorporated into this assessment.

1.4 ASSESSMENT OBJECTIVES

Sheffield commissioned Rockwater to undertake this H3-level hydrogeological assessment. The assessment is undertaken to fulfil the requirements for an application to the DoW for a Section 5C licence to take groundwater for the Thunderbird Project. This assessment seeks to compile the available hydrogeological data, develop a conceptual and numerical model and predict the likely extraction requirements and associated drawdown.

2 PHYSIOGRAPHY AND CLIMATE

2.1 PHYSIOGRAPHY AND DRAINAGE

The Thunderbird Project catchments largely comprise flat sandy plains with some small rocky hills approximately 50 m high. The gradient on the plains is flattest at the western side of the Thunderbird Project catchments (averaging approximately 0.75%) and tends to increase to approximately 1% to the east. Ground elevations in the Thunderbird Project area range from 88–120 m AHD.

The Thunderbird Project is located on sand plains, including Pindan silty sand, with some areas of sandstone outcrop and irregular sand dunes. The Dampier Peninsula has an average annual runoff coefficient of between 0.00–0.07 (Petheram et al., 2009).

The majority of the Thunderbird Project is within the Fraser River South catchment (MBS Environmental, 2016). The proposed pit location extends slightly into the Fraser River catchment and the proposed accommodation camp location is entirely within that catchment. The Logue and Little Logue River catchments are crossed by the site access road and do not contain any other project infrastructure.

There are no declared surface water areas in either the Thunderbird Project area or the Logue and Fraser River catchments.

The nearest Public Drinking Water reserves are near Broome and Derby (Figure 1).

2.2 RAINFALL AND EVAPORATION

The Dampier Peninsula is in the western part of the Kimberley region. Most rainfall occurs during the wet season between November and April. Areal potential evapotranspiration is very high, averaging 3413 mm per year, and varies moderately across seasons (Bureau of Meteorology, 2001). It generally remains higher than rainfall, even in the wet season, resulting in water-limited conditions for vegetation (CSIRO, 2009).

Rainfall data sources for the Thunderbird Project area (Table 2, Figure 3) include the SILO composite dataset. SILO is a comprehensive archive of Australian rainfall and climate data that has been developed from ground-based observational data (see Jeffery et al., 2001). The SILO dataset is a continuous, daily time-step record that has been constructed using spatial interpolation algorithms to estimate missing data. Data are accessed online [dnr.gld.gov.au/silo]. The SILO dataset incorporates the data from nearby stations Country Downs, Kilto Station, Beagle Bay and Derby. All these stations show similar patterns of average rainfall over the long term, although there can be significant variations between the sites on any day due to local rainfall events. Rainfall data from Broome townsite (Table 2) are lower than that at the Thunderbird Project due to the Dampier Peninsula's north–south rainfall gradient (CSIRO, 2009).

The SILO composite dataset includes daily pan-evaporation data extrapolated from surrounding monitoring sites (Table 2). Mean monthly evaporation varies from a low of 241 mm in June to a high of around 355 mm from October to December. Mean evaporation is higher than mean rainfall throughout the year.

Table 2 – Rainfall and evapotranspiration

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Rainfall													
Mean 1930-1996[1]	191.0	181.5	122.8	27.2	26.2	12.0	6.3	2.4	1.2	3.5	13.3	69.4	656.8
Mean 1997 – 2015[1]	243.7	219.3	170.0	26.0	28.0	18.0	11.7	3.2	0.4	11.7	23.4	117	872.4
Mean 1997 – 2015[2]	229.6	209.6	122.5	33.2	28.3	20.9	13.8	3.9	1.1	1.2	11.1	90.0	765.2
Evaporation[1,3]													
Mean	248	197	220	219	207	182	197	224	250	283	289	285	2801

1. SILO data for the Thunderbird Project (Jeffrey et al., 2001).
2. Broome township.
3. Evaporation, as would occur if there was an unlimited water supply from an area so large that effects of upwind boundary transitions are negligible and local variations are integrated to an area average.

2.3 VEGETATION AND LANDUSE

Vegetation

The Sheffield Project lies within the Pindanland subregion of the Dampierland bioregion. Mattiske (2016) notes that vegetation assemblages in the Thunderbird Project area include a 14.46 ha area of vegetation unit MaMvEtCPCc (*Melaleuca alsophila* or *Melaleuca viridiflora* and *Eucalyptus tectifica* low, open woodland, over *Chrysopogon pallidus* sparse tussock grassland and *Cyperus conicus* sparse sedgeland). Mattiske (2016) summarises that the Thunderbird Project area does not contain obvious areas of vegetation consistent with permanent water associated with springs. Mattiske (2016) cites previous assessments that state that areas of permanent fresh water are rare on the Dampier Peninsula, but where they occur they support groves of *Melaleuca cajuputi* and *Melaleuca viridiflora*, together with aquatic species such as *Nymphaea violacea*, *Nymphoides indica* and *Nymphoides beaglensis*. Mound springs, sometimes raised about two metres above the surrounding plain, are situated near the Beagle Bay community. They support large fern colonies of *Cyclosorus interruptus* and *Lygodium microphyllum*. Mattiske (2016) notes previous assessments that conclude that this is likely to represent vegetation which may be encountered at the Lolly Wells Spring wetland complex. This type of vegetation is unlikely to be present within the Thunderbird Project area.

Mattiske's (2016) June 2016 field survey revisited an area previously claimed to potentially constitute a priority ecological community (PEC). The survey noted that the area was dry and consisted of *Melaleuca viridiflora* and *Eucalyptus tectifica*, low, open woodland, over *Chrysopogon pallidus*, sparse tussock grassland and *Cyperus conicus* sparse sedgeland. Mattiske (2016) concludes that this portion of the Thunderbird Project area is a low-lying section of land which acts as a drainage area during periods of rainfall and not a potential PEC.

Mattiske (2016) concludes that: the vegetation communities mapped and species recorded in the Thunderbird Project Area are consistent with historical mapping; and that the majority of the Thunderbird Project Area comprised red sandy flats supporting pindan vegetation. The priority taxon *Triodia caelestialis* (P3) was recorded widely across the survey area. A second priority taxon, *Pterocaulon intermedium* (P3), was recorded infrequently, and was not associated with any specific vegetation community delineated. Both taxa are expected to be recorded external to the Thunderbird Project area boundary, and hence impacts within the project area are considered to be low.

Land use

Within the Dampierland bioregion there are 132 pastoral leases which collectively occupy 27,507 km^2 (55.4%). Pastoralism is the most extensive land use in the bioregion. Areas set aside for conservation account for 284 km^2 (0.6%) of the Dampierland bioregion, consisting of a single nature reserve, Coulomb Point Nature Reserve. Aboriginal reserves and heritage areas occupy 2,990 km^2 (6.0%) of the bioregion. Mining and exploration leases collectively occupy 43.8% of the bioregion. The remaining area in the Dampierland bioregion is predominantly made up of Unallocated Crown Land and road reserves.

The dominant land uses are grazing, unallocated crown land, crown reserves and native pastures. The study area lies within the Mt Jowlaenga pastoral lease and is frequently grazed by cattle.

3 GEOLOGY

3.1 REGIONAL GEOLOGY

The western Dampier Peninsula (Figure 1) is located within the Fitzroy Trough in the north of the Canning Basin.

The Fitzroy Trough is bounded by the Beagle Bay Fault in the north and the Fenton Fault in the south (Figure 1), which are near-vertical normal faults (Searle, 2012). The faults extend through the Triassic and older sediments. The faults’ prevalence in younger sediments is unknown.

The major fold within the Trough is the Baskerville Anticline, in the centre of the Dampier Peninsula. The anticline strike east-west and plunge to the west. Strata on the southern limb dip gently to the south-west and strata on the northern limb dip gently to the north-west.

3.2 STRATIGRAPHY

The stratigraphy of the western Dampier Peninsula (Table 3) is based on GSWA mapping and the recent DoW Dampier Peninsula review (Searle, 2012).

The main geological units of interest in this assessment are the Broome Sandstone and the Mowanjum Sand. The Broome Sandstone is mainly concealed at the surface by the younger units. It outcrops at some locations across the Peninsula, mostly along the shoreline. Outcrops of various facies of the Broome sandstone, mapped by Sheffield near Thunderbird, are shown in Figure 4.

3.3 SUPERFICIAL UNITS

The Mowanjum Sand (Searle, 2012) occurs at the surface or beneath a veneer of other superficial units within the study area. It consists of red-brown, fine grained (very fine to medium) silty sand. It is generally between 8 and 14 m thick (maximum 29 m) in the holes drilled by Wright (2013) near the Broome townsite. At Thunderbird it is typically 6 to 12 m thick and unsaturated. The red-brown sand is colloquially termed ‘Pindan’. The Mowanjum Sand is a widespread sheet deposit of Quaternary age and unconformably overlies a weathered contact on the Broome Sandstone. It is overlain in places by thin younger deposits.

Various other unconsolidated deposits of sand, limestone, silt, clay, gravel and conglomerate occur along beaches, tidal flats and are associated with the dunes.

Table 3 – Stratigraphy of the Dampier Peninsula (modified after Searle, 2012)

Age	Formation	Max. or estimated onshore thickness	Main lithologies	Extent
Quaternary	Mowanjum Sand ('Pindan')	10 m	Fine grained (very fine to medium) silty sand.	Widespread across the peninsula.
Late Cretaceous	Emeriau Sandstone	30 m	Fine to coarse grained poorly sorted sandstone, minor conglomerate, commonly ferruginous.	North-west of the peninsula only near Bobbys Creek and Lollywell Springs
Early Cretaceous	Broome Sandstone[1]	384 m[1]	Fine to coarse grained sandstone, gravel, some siltstone, mudstone and conglomerate. Heavy minerals near top & base.	West and central part of the Dampier Peninsula, except where it has been eroded away towards the east.
Early Cretaceous to Late Jurassic	Jarlemai Siltstone	240 m	Shallow marine laminated pink and purple siltstone with a sugary texture, massive and partly sandy mudstone, limestone. Includes thin coal seams.	Underlies the whole of the study area.

1: The unit follows Towner and Gibson's (1980) usage and includes the "Jowlaenga Formation" basal transitional unit

3.4 EMERIAU SANDSTONE

The Emeriau Sandstone consists of fine- to coarse-grained, poorly sorted sandstone and conglomerate. It is of Late Cretaceous age and is only present in the north-west of the Dampier Peninsula, about 60 km north-west of the Thunderbird Project (Figure 4). It overlies the Broome Sandstone.

3.5 BROOME SANDSTONE

The Broome Sandstone is present over the west and central part of the Dampier Peninsula, except where it has been eroded away towards the east and over the nose of the Baskerville anticline. To the west, the Broome Sandstone extends offshore beneath the Indian Ocean. The unit described here follows Towner and Gibson's (1980) usage and includes the basal transitional unit known as the Jowlaenga Formation.

The sediments of the Broome Sandstone and basal Jowlaenga Formation are of Early Cretaceous age. They are overlain by superficial units comprising shoreline, aeolian and alluvial deposits; mainly the Mowanjum Sand (‘Pindan sand’). The contact with the Mowanjum Sand is weathered and is frequently difficult to recognise in drill cuttings. The

Broome Sandstone is underlain by the Jarlemai Siltstone, which is of Late Jurassic to Early Cretaceous age. The formation has a maximum onshore recorded thickness within the study area of 388 m in Moogana 1 (Table 4) where the top of the Jarlemai Siltstone was intersected at -351 m AHD based on data in DMP's WAPIMS online geological database [dmp.wa.gov.au; accessed August 2016].

Broome Sandstone (upper part)

The Broome Sandstone consists of weakly cemented, fine- to coarse-grained quartzose sandstone, with minor beds of siltstone and claystone, thin coal seams, and minor pebble conglomerate (Laws 1991). Vogwill (2003), reports that these lithologies are contained within four subfacies, three upper deltaic facies ('Broome Sandstone 1–3') and a lower fluvial subfacies ('Broome Sandstone 4') in the south-west of the Peninsula. The fluvial facies comprises mainly coarse grained sand and granule-sized particles with minor siltstone and claystone, while the upper deltaic facies is mainly medium- to coarse-grained sand with abundant silt.

The Broome Sandstone is characterised in geophysical logs by low gamma radiation and high resistivity where the formation is saturated by fresh groundwater. Gamma-radiation signatures have higher intensity where there are intercalated siltstone and claystone beds. Gamma-radiation signatures have lower intensity where pebble conglomerate beds are present.

Heavy mineral sands (HMS)

The lower part of the Broome Sandstone contains high grades of fine-grained heavy mineral sands (HMS) at the Thunderbird Project. The HMS section of the Broome Sandstone at the Thunderbird Project is relatively thick (35–55 m) and is characterised by very high gamma radiation counts (commonly above 200 API counts). The HMS lithology of the Broome Sandstone is comparably finer-grained to that of the upper section of the Broome Sandstone.

The Thunderbird Project HMS resource area is approximately 4.0 x 5.0 km, with the base of the mineralised sand body ranging from about 110 m AHD in the north to about 0 m AHD in the south. Based on geophysical correlations and resource drilling, the HMS are likely to be present further south (to a basal elevation of about -65 m AHD [161 metres below ground level] at bore HG C).

Basal transitional unit

The Broome Sandstone basal transitional unit (also referred as the Jowlaenga Formation) is very similar lithologically to the upper part of the Broome Sandstone although it contains more silts and clays. It can be difficult to differentiate in drill cuttings. The transition however is recognisable in geophysical logs by a progressive increase in gamma-intensity and a decrease of resistivity with depth. Resource exploration drilling data show an increased concentration of very-fine grained sediment (slime) in the basal transitional unit.

Based on Rockwater's interpretation of available geophysical logs and data near the study area, the transitional unit is generally 15–30 m thick. This interpretation is in general agreement with the maximum recorded thickness of 40 m for the Jowlaenga Formation in Geoscience Australia's online geological database [www.ga.gov.au; accessed August 2016].

Top of Jarlemai structure contours

Several hydrogeological drilling programs have been carried out by the GSWA and DoW targeting the Broome Sandstone. Most of the bores were geophysically logged. The drilling programs include:

- A 1984 regionally-focused drilling program (Laws 1984). Eight bores (bores HG A to HG I) were drilled to the base of the formation and completed as monitoring bores.
- A second drilling program was carried out in 1985 (Laws 1985) to obtain data near proposed horticultural lots projects at 12 Mile. Six sets of bores (bores HCL 1 to HCL 6) were drilled to the base of the formation and completed as shallow and deep monitoring bores.
- A third drilling program was carried out in 2013 and 2014 (personal communication, Glenn Bathols, DoW, 2016) to improve the data coverage in the north of the Dampier Peninsula. Seven sets of bores (bores DPB01 to DPB07) were drilled and completed at various depths within the Broome Sandstone. As no completion report is available for these bores yet, they were given a lower confidence level when interpolating the top of Jarlemai (Figure 5).

Table 4 – Base of the Broome Sandstone in selected bores

Bore ID	Easting	Northing	Ground Level*	Total Depth	Top of Jarlemai	
					m bgl (m AHD)	m bgl (m AHD)
	m MGA	m MGA	m AHD	m bgl	Previous	This study
HG A	496000	8013000	52	64.5	54 (-2)[a]	51 (1)
HG B	498100	8043400	64	129.5	126 (-62)[a]	114 (-50)
HG C	495600	8062500	96	169.5	156 (-60)[a]	170 (-74)
HG D	485000	8097200	92	170	158 (-66)[a]	No change
HG E	484000	8109000	38	245	217 (-179)[a]	No change
HG G	469300	8080000	192	169	158 (+34)[a]	No change
HG H	470197	8061136	116	178	164 (-48)[a]	152 (-36)
HG I	470200	8022000	17	131	No data	114 (-97)
HCL 1	432010	8019956	23	182	176 (-153)[a]	No change
HCL 2	429385	8023663	42	192	182 (-140)[a]	No change
HCL 3	435084	8030119	43	174	164 (-121)[a]	No change
HCL 4	441157	8025663	38	156	150 (-112)[a]	No change
HCL 5	424892	8044421	42	240	231 (-189)[a]	No change
HCL 6	430312	8052881	126	213	201 (-75)[a]	187.5 (-61)
Keelindi 1	416625	8017705	24	501	292 (-268)[b]	No change
TTP 02	470165	8112992	66	221	No data	215 (-149)
JPP BP 01	411581	8063945	27	248	No data	238 (-211)
DPB01A	464362	8100538	134	217	155 (-21)[c]	174 (-40)
DPB02A	469055	8088035	154	144	134 (+20)[c]	No change
DPB03A	437457	8062345	196	192	174 (+22)[c]	No change
DPB04A	440574	8119016	12	270	190 (-178)[c]	218 (-206)
DPB06A	436007	8111087	40	360	140 (-100)[c]	180 (-140)
DPB07A	451002	8110050	111	421	140 (-29)[c]	250 (-139)
Roebuck Bay 1	442807	7992119	41	1219	148 (-107)[d]	No change
Freney 1	444073	8008087	7	1115	158 (-151)[d]	No change
Crab Creek 1	449634	8007726	14	1778	204 (-191)[d]	143 (-130)
Cow Bore 1	470897	8013335	21	2940	115 (-94)[d]	No change
Barlee 1	469692	8031207	23	2469	44 (-21)[d]	55 (-32)
Yulleroo 1	490464	8026075	56	4572	66 (-10)[d]	61 (-5)
Fraser River 1	517377	8074399	58	3092	Eroded away[d]	No change
Fraser River S-1	522118	8067270	44	366	Eroded away[d]	No change
Jum Jum 1	508925	8107054	97	2599	254 (-157)[d]	258 (-161)
Puratte 1	525477	8110870	33	3750	195 (-162)[d]	No change
Padilpa 1	520671	8118662	52	2184	195 (-158)[d]	No change
Moogana 1	467219	8127426	38	2213	388 (-351)[d]	No change
Curringa 1	472611	8139065	60	2335	350 (-290)[d]	No change
Perindi 1	421631	8139438	21	1867	470 (-449)[d]	No change
Minjin 1	433975	8142382	33	1850	442 (-409)[d]	No change
Kambara 1	440189	8148944	24	3147	397 (-373)[d]	No change
Pender 1	482532	8155985	24	912	182 (-158)[d]	221 (-197)
Pearle 1	397127	8026170	32	2032	342 (-310)[d]	372 (-340)
Santos DH6	485000	8097500	115	150	95 (20)[e]	No change
Santos DH9	433374	8060859	No data		No data (-23)[f]	No change

Bore ID	Easting	Northing	Ground Level*	Total Depth	Top of Jarlemai	
					m bgl (m AHD)	m bgl (m AHD)
	m MGA	m MGA	m AHD	m bgl	Previous	This study
Santos DH10	452440	8070940	No data		No data (8)[f]	No change
Santos DH11	463178	8057134	No data		No data (-53)[f]	No change
2-88 Nilli Bubbaca	518075	8048258	61	36	34 (27)[c]	No change

a: Laws (1991); b: Rockwater (1985); c: DoW (2016); d: DMP WAPIMS database (accessed April 2016); e: Santos (1983); f: Pennington Scott (2015)
* RL is defined as the height of the drilling table for oil wells (generally about 1.5 m above ground level)

The full section of the Broome Sandstone was penetrated in other deep water bores in the study area. These bores include Keelindi 1 (Rockwater 1985), Water Corporation production bore 3/87 and the original town water supply artesian bore SE6. There are geophysical and/or lithological logs for all three bores. Oil and gas wells in the study area also fully penetrate the formation and the Broome Sandstone section was geophysically logged in most instances.

The depth of the top of Jarlemai Siltstone in these bores was identified from the geophysical logs (Table 4). These depths were obtained from Laws (1991), Department of Mines and Petroleum (DMP) WAPIMS database (for oil wells) or unpublished data held by Rockwater. The depths of the base of the Broome Sandstone were re-interpreted in some instances by Rockwater for the purpose of the present project based on recent drilling and geophysical data. Regional-scale and site-scale geophysical correlations are shown in Figure 6.

Sheffield also provided the following data which were used in deriving the structure contours:
- Top of Jarlemai Siltstone inferred from fine content (‘slime’) and detailed lithological interpretation of deep resource drilling near Thunderbird and regional drilling investigations; and
- The Broome Sandstone/Jarlemai Siltstone contact as mapped by Sheffield geologists (shown in detail in Figure 5).

Structure contours on the top of the Jarlemai Siltstone were calculated from the bore data and other data available using geostatistical kriging methods (Figure 5). They indicate an asymmetric east-west trending anticline that probably developed over the pre-existing Baskerville anticline (Laws 1991). Some erosion may also have occurred, particularly south of the Thunderbird Project (Figure 5, Figure 6), but the overall structure is an anticline-like feature. Resource drilling data near the Thunderbird Project were used to refine the top of Jarlemai structure contours and were compared to the measured groundwater levels and high resolution (25 cm) digital elevation model (DEM). Regional section B-B’ (Figure 6) highlights geophysical correlations between various sub-units within the Broome Sandstone and the Jarlemai Siltstone.

3.6 JARLEMAI SILTSTONE

The Jarlemai Siltstone is a shallow marine deposit of early Cretaceous to late Jurassic age that is unconformably overlain by the Jowlaenga Formation (Gibson 1983). The formation is up to 218 m thick (in the bore Fraser River 1) and has an average thickness of about 100 m in the Dampier Peninsula.

The formation is primarily a mudstone, consisting of silty claystone, sandy and fossiliferous siltstone, and clayey sandstone. The siltstone and claystone are medium to dark grey, brownish grey and light brown, but can be oxidised dark red-brown, purple and yellow coloured, and is micaceous and pyritic. Sands are light grey, coarse to medium grained, loose to friable, sub-rounded to rounded. Shell fragments, including pelecypods, brachiopods and foraminifera are common, and the formation is calcareous through the middle portion.

4 HYDROGEOLOGY

4.1 SETTING

The Broome aquifer is hosted in the Broome Sandstone and the saturated parts of the overlying Emeriau Sandstone and Mowanjum Sand, which generally are in hydraulic continuity. It is a major unconfined to semi-confined aquifer that supplies groundwater to the Broome townsite, rural subdivisions, horticultural areas and pastoral properties. The Jarlemai Siltstone underlies the Broome aquifer and acts as a major aquiclude between it and the Alexander Formation (part of the Wallal aquifer) below.

4.2 BROOME AQUIFER

Groundwater levels (regional)

Groundwater levels in the Broome aquifer range from about 75 m AHD near the centre of the Dampier Peninsula to about 0–1 m AHD at the coast. Groundwater level contours were broadly mapped for the reference year 1997/1998 (Figure 7) to be used as starting heads for the modelling assessment. Assessments for this mapping include the following methods:

- Groundwater level data referenced to the Australian Height Datum (AHD) from 1997/1998 were used when available (22 data points were used).
- Good quality groundwater level data referenced to AHD but not collected in 1997/1998 were used in the assessment and were adjusted for inter-decadal variations of rainfall (44 data points were used).

- Groundwater level data of good quality that are referenced to ground level but not collected in 1997/1998 were used after the data had been adjusted for: inter-decadal variations of rainfall; and the level had been referenced to AHD using the DEM-H-extrapolated ground levels for the selected bores (19 data points were used).

Groundwater level data are most concentrated in the Broome townsite region. In the northern and eastern parts of the study area there are regions with sparse groundwater monitoring data. The contours (Figure 7) imply that regional groundwater flow is towards the coast under an average hydraulic gradient of 0.00085 (that is, 0.85 m per km).

Temporal groundwater level data are available from monitoring bores surrounding the Water Corporation Broome borefield and the Horticultural Lot (HCL) monitoring bores located in the south-western portion of the study area (Figure 8, Figure 9 and Figure 10).

Groundwater level measurements in the Broome borefield monitoring bores commence in the late 1960s, with measurements generally recorded monthly. However, these bores are within the influence of the Broome borefield and were not used for this study. The HCL bores were installed in the mid-1980s. Groundwater level measurement frequencies for these bores vary from six-monthly to several years between measurements. Groundwater levels from selected bores from the HG series located near the proposed development (HG H and HG B) are presented in Figure 10. Monitoring bore locations are shown in Figure 7.

Variations in groundwater levels in the HCL and HG monitoring bores, although within close proximity to production bores, appear to closely correspond to variations in rainfall. Groundwater levels in these bores (Figure 8, Figure 9 and Figure 10) vary by about 3 m in response to inter-decadal variations in rainfall. This is evident when comparing the cumulative rainfall variation with the groundwater levels. The groundwater-level trends closely match the trends in cumulative-deviation-from-mean annual rainfall, with an apparent lag of 2 to 3 years as observed in other studies (CSIRO, 2009; Rockwater, 2013, 2014).

Groundwater levels (mining area)

The water table elevation over the Thunderbird deposit ranges from about 62 m AHD in the south (near bore THAC 380) to about 75 m AHD in the north at the edge of the deposit.

Groundwater in the Broome aquifer flows to the south in the Thunderbird deposit region. The hydraulic gradient is steep across the HMS deposit (0.0016; that is, 1.6 m per km) and decreases to the south (0.0007; that is, 0.7 m per km) where the upper Broome Sandstone is the main component of the aquifer. Groundwater level contours are shown in Figure 11.

Groundwater levels trends in selected monitoring bores in the mine area (Figure 12 and Figure 13) also appear to closely match the trends in cumulative deviation from mean annual rainfall.

The depth to groundwater is in excess of 20 m over most of the project area. A localised seasonal surface water ponding area, identified by traditional owners about 3 km to the southeast of the mine, exhibits water levels in the Broome aquifer of about 18 m below land surface and is therefore unlikely to be connected to the regional Broome aquifer. This feature is identified as 'Nearby soak' (see Section 5.2) and is likely to be related to surface water ponding. However, monitoring bores are proposed to further assess this region.

Depths to groundwater in river valleys associated with the Fraser River South, about 8 km south-east of the mine, range from less than 5 m to more than 20 m (based on monitoring locations including those shown in Figure 11). Monitoring bores are proposed to further assess this region (Section 9).

Hydraulic parameters

The HG-series bores that were commissioned by Department of Mines and Petroleum (HCL 1–6) were test-pumped. The results (Laws, 1985) indicated that the hydraulic conductivity of the Broome aquifer at those bores ranges from 12–23 m/d, averaging 15 m/d. Test-pumping in the Beagle Bay area showed similar hydraulic conductivities (11–29 m/d) (Rockwater, 2004). Searle (2012) reported hydraulic conductivities ranging from 2–42 m/d (generally about 15 m/d) over the entire Dampier Peninsula. The Broome aquifer therefore has moderately high hydraulic conductivity, although significant variability occurs.

Rockwater has undertaken re-assessments of the Pennington Scott (2015) pumping-test data for bores TWB001, TWB002 and TWB003 (Appendix I, Table 5). The results generally agree with reported hydraulic conductivity data for the Broome aquifer sandstone and suggest that the HMS have a comparatively lower hydraulic conductivity value (around 1 m/d) whereas the Broome aquifer basal transitional unit has an intermediate hydraulic conductivity (around 5–10 m/d).

Table 5 – Summary of hydraulic parameters from 2015 drilling program

Bore	Transmissivity (m^2/day)	Screen length (m)	Hydraulic conductivity (m/day)	Hydrogeological unit
TWB001	1238	36	34	100% Broome aquifer sandstone
TWB002	39.86	36	1.1	100% Heavy mineral sands
TWB003	214.3	36	6.0	86% Heavy mineral sands 14% Broome aquifer basal transitional unit

Groundwater recharge, storage and discharge

Aquifer systems on the Dampier Peninsula are recharged by direct rainfall infiltration. Recharge to the aquifer was estimated to be 4–5% of the 5-year average rainfall in 1991 (Laws, 1991); that is, about 20–25 mm/annum. Minor seasonal surface water ponding areas may occur locally in the overlying Pindan sand.

Groundwater discharge occurs over a saltwater wedge to the coast in Gantheaume and Roebuck Bays and to wetlands along Dampier Creek and depressions in Roebuck and Buckleys Plains. Groundwater also discharges via bores, including: the town water supply borefield operated by the Water Corporation; bores used for horticulture at the 12 Mile, Coconut Wells and Skulthorpe areas; and private and shire bores (Section 5.1). Groundwater users are shown in Figure 15, based on the available locations of indicative drawpoints for the majority of the active licences.

Groundwater quality

Groundwater in the Broome aquifer is predominantly of sodium-chloride type, with some elevated levels of bicarbonate (indicating recent recharge), and sulphate and magnesium (associated with the saltwater wedge and possibly areas of trapped seawater around formerly more-extensive tidal inlets) (Laws 1991). Comparatively high nitrate levels, often greater than 40 mg/L (Laws 1991), are probably a mobilisation into the groundwater of nitrate resulting from nitrate fixation by native acacias and termite activity.

Fresh to slightly brackish groundwater in the Broome aquifer is underlain by a saltwater wedge which extends inland from the coast. The current wedge position near Broome is inferred from Department of Water’s recent TDEM survey along the Dampier Peninsula coastline. Project-scale groundwater quality is assessed in Pennington Scott (2015) and reproduced in Table 6.

Table 6 – Project-scale groundwater quality analyses

Analyte	Units	TWB001[1]	TWB002[1]	TWB003[1]
Inorganics	mg/L			
Ammonia as NH3-N	mg/L	<1	<1	<1
Bicarbonate as CaCO3	mg/L	29	22	25
Calcium	mg/L	2	2	3
Carbonate as CaCO3	mg/L	<1	<1	<1
Chloride	mg/L	60	30	70
Conductivity at 25°C	uS/cm	250	160	290
Fluoride	mg/L	<0.20	<0.20	<0.20
Ion Balance		0.98	1.02	1.03
Magnesium	mg/L	5	3	6
Nitrate NO3-N	mg/L	0.7	0.4	0.7
pH		6.3	6.1	5.8
Potassium	mg/L	3	5	6
Silica as SiO2	mg/L	36	37	64
Sodium	mg/L	40	20	40
Sulfate	mg/L	<5	<5	<5
Total Dissolved Solids (Evap)	mg/L	150	110	200
Trace Elements				
Aluminium	mg/L	0.043	0.05	14
Arsenic	mg/L	<0.005	<0.005	<0.005
Barium	mg/L	0.08	0.082	0.13
Beryllium	mg/L	<0.001	<0.001	<0.001
Boron	mg/L	0.12	0.11	0.16
Cadmium	mg/L	<0.002	<0.002	<0.002
Chromium	mg/L	<0.005	<0.005	0.015
Cobalt	mg/L	<0.005	<0.005	<0.005
Copper	mg/L	<0.005	<0.005	<0.005
Iron	mg/L	0.37	0.016	1.2
Lead	mg/L	0.002	<0.001	0.004
Manganese	mg/L	0.012	0.002	0.008
Molybdenum	mg/L	<0.005	<0.005	<0.005
Nickel	mg/L	0.009	0.006	0.01
Selenium	mg/L	<0.005	<0.005	<0.005
Silver	mg/L	<0.001	<0.001	<0.001
Tin	mg/L	<0.010	<0.010	<0.010
Zinc	mg/L	1.7	0.071	0.062

1. Data source: Pennington Scott (2015). Bores TWB001, TWB002 and TWB003 are test production bores in the greater project region, as described in Pennington Scott (2015).

5 EXISTING GROUNDWATER USE AND POTENTIAL GDES

5.1 EXTRACTION

The Thunderbird Project is located in the Canning–Pender sub-area of the Canning-Kimberley Groundwater Area. This sub-area encompasses the majority of the Dampier Peninsula except for the area near Broome which is classified as the Broome Groundwater Area. Licensing policy and management in the Broome Peninsula region is outlined in DoW (2010).

The Broome aquifer in the Canning-Pender sub-area of the Canning-Kimberley Groundwater Area has 95.4% of its available groundwater resources of 50 GL/yr available for allocation (Table 7). Licence entitlements within the sub-area total 2.3 GL/yr, with one major user (Kilto Station, 2 GL/yr) located about 40 km to the south-west of the Thunderbird Project.

Table 7 – DoW Broome Aquifer groundwater resources

Canning-Kimberly Groundwater Area			
Sub area	**Allocation limit (GL/yr)**	**Licensed entitlements (GL/yr)**	**Balance available (GL/yr)**
Canning-Pender	50.0	2.3	47.7
Broome	51.2	42.0	9.2

Note: Data current at 9-June-2016. Provided by DoW

Water Corporation's Broome borefield

The Broome borefield is located about 12 km north-east of Broome. It is operated by Water Corporation. It was commissioned in the 1960s and initially consisted of three production bores extracting about 0.4 GL/yr. Borefield extraction has increased as the population of Broome has expanded and the borefield now consisted of about 20 production bores extracting about 5 GL/yr (Figure 15). The Water Corporation's current groundwater licence allocation is 6.2 GL/yr.

The borefield also contains six monitoring bores that are regularly monitored to provide aquifer-response data for borefield operation. A Priority 1 Drinking Water Protection Zone (DWPZ) extends north and east from the borefield in the Town Water Reserve (Figure 15).

Pennington Scott (2015) identified a number of proximal bores, including unregistered stock and domestic bores (Table 8; Figure 15).

Table 8 – Proximal bores, as described by Pennington Scott (2015)

Bore name	Coordinates, MGA94, Zn 51	
	mE	mN
1-90	503,942	8,081,714
Daniel's	521,989	8,085,880
Fraser River (No. 1 WW)	516,976	8,075,465
Fraser River No. 1	517,119	8,074,460
Claypan bore	514,899	8,064,476
Salt	515,687	8,064,979
Bakers (Yeeda) bore	517,835	8,056,647
Mt Clarkson (new)	530,511	8,060,813
Orange Flat	527,002	8,044,508
Homestead	503,788	8,072,865
Lanigans	504,406	8,061,506

5.2 POTENTIAL GROUNDWATER DEPENDENT ECOSYSTEMS

Pennington Scott (2015) undertook a preliminary review of potential groundwater dependent ecosystems (GDEs), based on general site observations and initial interpreted groundwater and topographic elevations. The Pennington Scott (2015) locations (Figure 15) are described for reference as follows:

- An intermittent soak about 3 km to the south-east of the mining region. Vegetation assessments by Ecologia (2014) and follow up assessments by Mattiske (2016) describe vegetation in this location as paperbarks and *Eucalyptus tecifica* open woodland over sparse tussock grassland or sedgeland (see Section 2.3). Groundwater levels in the Broome aquifer are about 18 m below land surface in this region. This intermittent soak is therefore unlikely to be connected to the regional Broome aquifer and is more likely related to localised seasonal surface water ponding. As outlined in Section 9, additional monitoring bores are recommended to further assess these conclusions.
- River valleys associated with the Fraser River South. This feature is about 8 km south-east of the mining region and has depths to groundwater ranging from less than 5 m to more than 20 m. This region consists of a lower-transmissivity basal transitional unit (also referred to as the Jowlaenga Formation) (Figure 16). As outlined in Section 9, additional monitoring bores are recommended to further assess this region.
- Jarlemai Siltstone 'soaks'. The Fraser River North has developed over the Jarlemai Siltstone to the north-east of the mining region. The Jarlemai Siltstone has low hydraulic connectivity (an aquitard) and therefore these 'soaks' are unlikely to be impacted by Broome aquifer groundwater extraction.

Stygofauna and troglofauna

Stygofauna and troglofauna assessments by Ecologia (2014) are outlined in Pennington Scott (2015). Subterranean fauna surveys included 90 net hauls from 15 drill holes sampling for stygofauna and a program of 12 traps and 12 scraping hauls at six drill holes sampling for troglofauna.

As outlined in Pennington Scott (2015), Ecologia (2014) identified only one type of stygofauna (Naididae worms). Pennington Scott (2015) notes that these are classified by Ecologia (2014) as opportunistically stygal.

As outlined in Pennington Scott (2015), Ecologia (2014) identified only two troglofauna species: a centipede and a rover beetle. Overall troglofauna were generally found to have low diversity and abundance in the Project area. Pennington Scott (2015) concludes that while groundwater level fluctuations may have some impact on humidity in troglofauna habitat, troglofauna are generally fairly robust to changes in groundwater levels.

Pennington Scott (2015) summarised that, given the wide extent of the Broome aquifer across the Canning Basin, the lack of any significant obligate stygofauna identified within the study area and the relatively localised impact on aquifer saturated thickness due to the Project, it is unlikely that the groundwater extraction for the Project will have unacceptable impacts on subterranean fauna.

6 GROUNDWATER ASSESSMENTS

A 2014–2015 field program included the following groundwater assessments:

- 32 monitoring bore sampling points (Pennington Scott, 2015)
- 5 monitoring bores assess Broome aquifer water levels proximal to interpreted soaks (Pennington Scott 2015)
- 3 test dewatering bores (Pennington Scott, 2015)
- test pumping (step-rate and 7-day constant-rate) of 3 production bores (Pennington Scott 2015).

2016 groundwater assessments undertaken as part of the current H3-level of hydrogeological assessment include:

- geophysical logging (natural gamma-ray) of six selected cased RC holes; three test production bores installed by Pennington Scott; and one regional DoW bore
- a regional-scale and local-scale review of geological and hydrogeological data for the Dampier Peninsula
- installation of monitoring bores around intermittent soaks (awaiting traditional owners' approval; to be undertaken FY2016–2017).

The following bores were logged using a portable Auslog 1-conductor winch and a calibrated Auslog 43 mm natural gamma-ray tool:

- THAC252 (blocked at 67 m)

- THAC280 (blocked at 48.5 m)
- THAC285 (blocked at 47 m)
- THAC286 (blocked 55.5 m)
- THAC389 (blocked at 38.5 m)
- THAC390 (blocked at 49.5 m)
- TWB01
- TWB02
- TWB03
- HG C (blocked at 113.5 m).

Hydrostratigraphic correlations were compared to resource drilling data (including the ‘percentage slime’ and percentage HMS). The resulting depths to each hydrostratigraphic unit (Table 9) were used to augment the project-scale hydrogeological data.

The depths of geophysical logs were dictated by bores’ open depths. Several cased RC holes were collapsed or filled with fine sand. The regional DoW bore HG C, which is constructed of mild steel, appears to have collapsed at 113.5 m depth (monitoring data from this bore may therefore have lower reliability). Geophysical logging results are summarised in cross-sectional format in Figure 16.

Table 9 – Base of the hydrostratigraphic units in logged bores

Bore ID	Easting	Northing	Ground level	Cased depth	Top of HMS	Base of HMS	Top of Jarlemai
	m MGA	m MGA	m AHD	m bgl	m bgl (m AHD)		
THAC 252	493371	8072975	118	96 (67)*	54 (64)	95 (23)	?
THAC 280	501617	8069963	110	60 (48.5)*	absent		29 (81)
THAC 285	502291	8069276	111	54 (47)*	absent		23 (88)
THAC 286	501289	8069582	108	60 (55.5)*	12 (96)	20 (88)	41 (67)
THAC 389	495903	8068221	95	42 (38.5)*	69 (26)	?	?
THAC 390	497643	8070678	95	52 (49.5)*	7 (88)	30 (65)	?
TWB 01	8067215	492457	113	84	?	?	?
TWB 02	8071304	494596	103	78	47 (56)	80 (23)	?
TWB 03	8069681	496489	95	78	19 (76)	72 (23)	?
HG C	8062500	495600	96	169.5 (113.5)*	146 (-50)	164 (-68)	170 (-74)

*: parenthesis = blocked depth

7 PROPOSED GROUNDWATER USE

7.1 WATER SOURCES

Water for the project will be supplied from the following:

- Project specific bores
- Mine dewatering

Table 10 summarises the anticipated sources of project water over the life of the project.

Table 10 – Thunderbird Project water volumes

Input	Quantity (GL/yr)		
	Stage 1 (Year 1–3)	**Stage 2 (Year 4-15)**	**Stage 3 (Year 15+)**
Water sources			
Mine dewatering		0	10.7–32.7
Borefield abstraction	5.2–12.2	10.7	
Total	**5.2–12.2**	**10.7**	**10.7–32.7**
Aquifer injection			
Aquifer injection		0	0 to -22
Net total	**5.2–12.2**	**10.7**	**10.7**

7.2 WATER USE

Construction

Up to 120 m^3/h of water will be required for construction activities at the Mine Site over the two year construction schedule. Construction water will be sourced from groundwater bores; with the three existing test production bores a priority source.

Operations

Project water requirements during operations (Table 11) during steady-state operations will be up to 1219 m^3/h.

Table 11 – Project water requirements

Demand	Quantity (m^3/h)		
	Year 1	Year 2&3	Year 4+
Ore processing	1252	456	1082
Accommodation village	25	28	23
General mine use (incl. dust suppression)	114	114	114
Total water demand	**1391**	**598**	**1219**

Water discharge

Excess dewatering volumes (from about Year 32 onwards) will be discharged via aquifer injection. No other sources of water other than dewatering-bore water will be used for aquifer injection (for example, stormwater and sewage water will not be directed to the injection bores). The proposed injection sites are situated along the mine-access road corridor (Figure 2). The location of the proposed injection borefield is based on: opportunities to reduce the land-disturbance footprint by utilising existing infrastructure corridors; the region's relatively large depth to groundwater (about 30 m), and proximity to the Fraser River South Valley, whereby aquifer injection could mitigate potential drawdown impacts. Up to 15 injection bores will be constructed and connected to a water reticulation pipeline (or double pipeline) laid next to the road within the existing road-clearing corridor. Injection bores will be about 50 m deep with screen intervals targeting the Broome aquifer.

Water infrastructure

Process water will be sourced from mine dewatering and the water supply borefield (see below). As mining is above the water for the first 15 years, process water will be sourced from a make-up borefield adjacent to the mining void and stored in a process water dam located within the processing area.

The water supply and dewatering borefield will operate to achieve the dual aims of (1) providing process water and (2) dewatering below-watertable ore regions from Year 16 onwards. The borefield will initially be situated immediately south of the mining region and will progressively incorporate near-pit dewatering bores as below-watertable regions are included in the mining schedule. Bores will be constructed to about 120 m depth and target the Broome aquifer. For the first 15 years, up to 17 bores will be required to achieve sufficient process water supplies. In peak dewatering years (after Year 30) up to 40 bores may be required to maintain dry mining conditions. Additional sump-dewatering may be required as a contingency. The dewatering borefield will be linked via an intra-borefield polyethylene pipeline. The intra-borefield pipeline will transfer water to the ore processing facility and will include water storages and lie within a 12 m-wide pipeline corridor. Polyethylene pipeline will also connect the ore processing facility water storages to the injection borefield. The polyethylene pipeline will be up to 650 mm nominal diameter and may include dual-pipeline intervals along key sections of the pipeline route. Intermediate pressure-regulation/dust suppression offtake dams will be included in the injection pipeline corridor. The pipeline corridor will be up to 40 km long (including pipelines to the aquifer injection bores).

The water supply borefield will be powered by a reticulated electricity power line system that connects the bores' control panels to the central minesite power grid.

A dedicated bore will provide the accommodation village's potable water supply. The bore will be proximal to the accommodation village and up-gradient of potential contaminant sources (for example, sewage treatment ponds). The bore will be connected to a polyethylene of up to 150 mm nominal diameter.

A network of 20 local-scale and regional-scale monitoring bores (Section 9) will be established to assess potential groundwater drawdown and mounding impacts.

8 GROUNDWATER FLOW-MODELLING

8.1 MODEL OBJECTIVES

Rockwater was engaged by Sheffield to assess dewatering and extraction volumes associated with the proposed Thunderbird Project and the related drawdown and mounding. The groundwater model was developed with reference to the Australian groundwater modelling guidelines (Barnett et al., 2012) and has been designed to meet the key requirements of a Class 3-confidence-level classification (Table 12), where possible, for regional features.

Table 12 – Key indicators for a Class 3 model classification

No.	Key indicator[1]
1	Key calibration statistics are acceptable and meet agreed targets (a <5% SRMS groundwater head error is adopted as a calibration target for this assessment)
2	Model predictive time frame is less than 3 times the duration of transient calibration
3	Stresses are not more than 2 times greater than those included in calibration
4	Temporal discretisation in predictive model is the same as that used in calibration
5	Mass balance closure error is less than 0.5% of total
6	Model parameters consistent with conceptualisation
7	Appropriate computational methods used with appropriate spatial discretisation to model the problem
8	The model has been reviewed and deemed fit for purpose by an experienced, independent hydrogeologist with modelling experience

1. From Table 2-1, Barnett et al. (2012)

Modelling has been undertaken with special reference to assessments of:

- Groundwater flow characteristics over the greater Dampier Peninsula region.
- Project-scale model refinement.
- A mine life of 47 years duration.
- Scenario modelling incorporating CSIRO (2009) climate change predictions.
- Groundwater dynamics with special reference to Water Corporation's Broome Borefield and other users down-gradient of the proposed borefield (Figure 1).
- Model-predictive outcomes presented with associated predictive uncertainty.

The implementation of these model objectives is outlined in Sections 8.2 and 8.3.

8.2 CONCEPTUAL MODEL

The hydrogeological conceptual model on which the numerical model is based features the following characteristics and assumptions.

Hydrostratigraphy

The Broome aquifer is represented in the model by up to four layers: an uppermost unconfined layer and three semi-confined layers (Table 13). Geological unit thicknesses in the unsaturated north-east portions of the Thunderbird area (where the Jarlemai Siltstone is close to the ground level) may be less than 5 m. Conceptual layers are shown in Figure 14, Figure 16 and Appendix I-1.

Table 13 – Model layer description

Layer number	Description
1	Superficial deposits (sand, tidal flats) where saturated conditions occur and the top of the Broome aquifer elsewhere. The top of the layer represents the ground surface and was derived from the available topographic data (Figure 1). The layer has a uniform thickness of 10 m.
2	Broome aquifer; HMS deposits where they underlie directly Pindan superficial sediments.
3	HMS where present near Thunderbird and the Broome aquifer elsewhere. The top and bottom of the layer are inferred from data provided by Sheffield near Thunderbird.
4	Transitional Broome aquifer basal unit where present near Thunderbird and the Broome aquifer elsewhere. The base of Layer 4 is the top of the underlying, impermeable Jarlemai Siltstone (Figure 5).
5	The Jarlemai Siltstone. Layers 1 to 4 also represent the Jarlemai Siltstone where the Broome aquifer is absent.

Aquifer properties

Pre-calibration aquifer properties are based on existing data (Table 17). Areas of equivalent aquifer properties are represented with reference to previous modelling assessments, including Vogwill (2003), Rockwater (2008; 2013; 2014) and Pennington Scott (2015). Typical hydraulic conductivity anisotropy ratios (K_z/K_{xy}) for sand/sandstone aquifers (10%) are replicated for this modelling assessment.

Conceptual groundwater flow and boundaries

Groundwater flow in the Broome aquifer is radial from the groundwater mound, near the centre of the peninsula, towards the coast, where discharge occurs to the ocean over a salt-water wedge (Figure 7). Groundwater discharge also occurs in shallow tidal areas and depressions such as Dampier Creek, the Roebuck and Buckleys plains. Evaporation greatly exceeds recharge in these areas and groundwater salinity can reach seawater concentrations. This flow system is predominantly represented by rainfall recharge applied to Layer 1. Local-scale recharge heterogeneities (for example, local-scale Pindan sands and other surface deposits) may locally retard infiltration and cause perching or surface ponding of rainfall and runoff; however, recharge throughflow is generally assumed to be unsaturated and transmitted to the water table in the underlying Broome aquifer. In shallow tidal areas and drainages such as Dampier Creek, Roebuck and Buckleys plains, low-permeability Holocene and Pleistocene tidal and supratidal deposits occur a few metres below the water table and were included in the model in Layer 1 (tidal flats in Figure 4).

The available temporal groundwater level data (Figure 8 to Figure 13) indicate that medium- to long-term groundwater level variations correspond to variations in rainfall of similar periods (Figure 3) and these have been incorporated into the model. Recharge rates were modelled based on climate data (Section 2.2) and CSIRO’s (2009) recharge assessments. Two rainfall zones were included in the model based on the Project and near the Broome townsite (see Section 2.2) rainfall datasets.

Seawater-interface dynamics were approximated based on a constant-head boundary with reference to time-averaged tidal ranges. The influence of tides leads to elevated time-averaged water table heights above mean sea level in the near shore area (Carey et al., 2009). The adopted tidal water over-height (TWOH) obtained through model calibration is 1 m above the mean sea level (within the range reported by Carey et al. [2009]). The seawater interface is distant to the groundwater impact area; therefore, coastal density-driven flow is not incorporated in the model. Areas of the Broome aquifer below the salt-water interface were set as very low hydraulic conductivity so as not to contribute to modelled groundwater flow.

Other groundwater users’ extraction is modelled based on groundwater allocations (Figure 15) provided by DoW and used by Rockwater for other assessments in the region (Rockwater, 2008; 2010; 2012; and 2014). Extraction from the Water Corporation Broome borefield has also been incorporated in the model.

8.3 DESCRIPTION OF NUMERICAL MODEL

Model code

The model utilises FEFLOW (version 7.0), the industry-standard finite-element three-dimensional groundwater-flow model code. The SAMG Solver for FEFLOW was selected to solve the groundwater-flow equations. A head-change-criterion for convergence of 0.005 m was used. This head-change-criterion is chosen based on its applicability to flow systems with maximum seasonal groundwater level changes exceeding 1 m (groundwater levels near Water Corporation's Broome borefield vary from 3.5 to 7 m AHD from dry to wet years [Figure 8]). Numerical wetting-rewetting issues were addressed by applying a residual groundwater depth for unconfined layers of 1 m.

The residual criterion for convergence was set at 10^{-8} m^3/d (<0.02% of the annual groundwater throughflow). This criterion achieves numerical convergence while maintaining an appropriate water balance (water balance results are discussed in Section 8.6).

Model design

The numerical groundwater-flow model consists of a mesh of 873,305 triangular elements (Appendix II) and 5 layers (Table 13) covering an area of 45 km north–south and 40 km east–west. The model domain includes the entire Dampier Peninsula and a spatial buffer to the south of Thunderbird. The spatial buffer is incorporated to ensure that the limits of the model domain are sufficiently remote to minimise the impact of the assumed boundary conditions on the modelling results.

The model layer structure (Section 8.2) incorporates four layers (an uppermost unconfined layer and three semi-confined layers) to vertically discretise the Broome aquifer. The first layer's thickness was set uniformly at 10 m, which is the average thickness of superficial deposits overlying the Broome Sandstone. The thicknesses of layers 2–4 vary with the hydrostratigraphic units' thicknesses as inferred from the available data. The model-layers' minimum thickness is 5 m. This minimum-thickness requirement is to avoid numerical errors associated with excessively-contrasting model-layer thicknesses. The basal layer of the model (Jarlemai Siltstone) was set with a uniform thickness of 100 m (the average thickness of the formation).

Model stress periods were set at calendar-year intervals. Model time-steps were set at sub-annual intervals via FEFLOW's automatically time-stepping function.

Further model data are provided in Appendix I, including: rainfall recharge factors (Appendix I-2); boundary conditions (Appendix I-3 to Appendix I-5); and hydrostratigraphic units (Appendix I-6).

Model construction

Model construction commenced with the adoption of an initial uncalibrated model. The initial model setup features included:

Initial aquifer parameters

Average aquifer parameters and recharge rates reported by Laws (1985, 1991), Vogwill (2003) and used by Rockwater in other assessments in the region.

Boundary conditions

Model boundary conditions (Table 14; Appendix I-3) are based on the conceptual model described in Section 8.2 and are designed to simulate peninsula-scale and project-scale hydrogeological processes.

Table 14 – Model boundary conditions

Boundary	Description
Coastal areas	The water level along the model's coastal boundary was simulated as a constant-head boundary in all layers and incorporated the tidal water over-height (TWOH – see Section 8.2).
Southern boundary	Inflow through the southern boundary of the model is modelled as a constant-head boundary for all model layers. This is in accordance with the groundwater level contours (Figure 7). The magnitude of southern boundary fluxes is described in Section 8.6.
Groundwater discharge in low lying areas	Groundwater discharge in low lying areas is modelled for areas of frequent coastal tidal inundation and depressions, including Dampier Creek, and Roebuck and Beagle Bay. Groundwater discharge were applied to the portion of Slice 1 where groundwater is <10 m bgl (polygon shown in Appendix II). Discharge is modelled via two mechanisms: 1. FEFLOW seepage-face boundary conditions for the <10 m bgl polygon; and 2. Evapotranspiration for the <10 m bgl polygon, set at 100 mm/year. As outlined in Section 8.5, this evapotranspiration rate is based on model-calibration outcomes together with reference to previously-reported modelling assessments.
Bore pumping	The FEFLOW multi-layer well-function was used to simulate groundwater extraction over the transient-calibration period. Existing users' extraction used the average annual pumping rates for each Water Corporation production bore; whereas licensed private bores (including those at '12 Mile') were modelled at the annual licence allocation rate. Total modelled extraction was 12.5 GL/year, including 5.0 GL/year from the Water Corporation borefield. Water supply and groundwater injection for the Thunderbird Project were similarly modelled using the FEFLOW well-function.
Mine dewatering	Mine dewatering in predictive modelling assessments was modelled using time-varying Constant-head boundary conditions. Constant-head levels were set to follow Sheffield's mining sequence (Figure 18) for the duration of the below-watertable phase of the Thunderbird Project. Constant-head levels were set to the resource's

Boundary	Description
	base level at the corresponding time period (Table 1). Constant-heads' groundwater-flux results are appropriate to the (annual) time-steps used in this modelling assessment; however, sub-annual assessments of dewatering volumes require a further-refined boundary condition.
Rainfall recharge	Recharge was applied on an annual basis, with the value applied related to the amount that the two-year annual average rainfall was above or below the average annual rainfall using the recharge multiplier presented in Appendix I-2. For the calibration periods, modelled average recharge rates range from 3.7–4.7% of total rainfall for the Pindan soils, in acceptable agreement with the rates of 4–5% reported by Laws (1991), Vogwill (2003) and used by Rockwater in other assessments in the region. The rate of recharge to groundwater in the area from direct infiltration of rainwater is assumed to range from 16.5–22.5 mm for the historic (1930-1996) average rainfall. Recent modelling undertaken by CSIRO (2009), using the WAVES vertical flux recharge model, indicates that recharge is comparatively higher in wetter years than it is in drier years: • a 19% decrease in rainfall results in a 13–24 % decrease in recharge; whereas • a 10% increase in rainfall results in a 51% increase in recharge. Results from CSIRO modelling were incorporated in the present model via a recharge factor ranging from 0.25–3.5 (see Appendix I-2). Using actual rainfall data for recent years (1997-2016) and historic and WAVES vertical flux recharge factors, the average rainfall recharge was estimated to range from 3.7–4.7% (Table 16) of the annual rainfall (other than for coastal sands and mud flats – see below). This assessment is within the range of estimates based on chloride ratios (4 to 5%) and from interpretation of the flow net for the aquifer (Laws 1991), the exceptions being: • An area north of Broome (Superficial Sands unit in Figure 4) that is covered by sandier soils when compared to the remainder of the model domain. This area has been modelled with a high rate of recharge (24–34%), similar to the rate of recharge in coastal dunes areas as estimated by Laws (1991). • The Roebuck plains mud flats. No rainfall recharge is applied to this area because evapotranspiration greatly exceeds recharge (Vogwill, 2003).
Tailings seepage	Seepage from the tailing ponds was modelled using an injection well set in the ore layer (Layer 4). Seepage rate follow those set out in Table 19 with locations shown in Figure 18. Further details are provided in Section 8.7.

8.4 MODEL CALIBRATION

Model calibration was undertaken using PEST parameter uncertainty and uncertainty analysis (Doherty, 2015) as an initial guide in the preliminary steady-state model. Steady-state calibration was then continued via manual-input iterative parameter updates. The transient model was calibrated via manual-input iterative parameter updates. Calibration was undertaken until a close correspondence between model-calculated and measured groundwater levels was achieved, as described below (Appendix I-1 to Appendix I-6).

PEST sensitivity

Following model construction, a steady-state sensitivity assessment was initially undertaken using PEST to identify the parameters sensitive in model calibration; that is, changes to which model parameters most affect the model calibration results. This was done in PEST by measuring the magnitude of the sensitivity of all observations to particular parameters. These sensitivities are calculated as a by-product of the Jacobian matrix during each iteration of parameter estimation optimisation. Calibration sensitivity assessments suggested that recharge was the most sensitive factor in calibration, followed by assigned evapotranspiration. Hydraulic conductivity was comparatively less sensitive. As is outlined below, transient model calibration and model results are more so sensitive to aquifer parameters. Once a realistic recharge and evapotranspiration distribution was achieved these parameters were held relatively constant and the model hydraulic-conductivity distribution was refined within reasonable limits using trial and error, initially in the steady-state model and then in the transient model.

Steady-state calibration

The steady-state model was used to simulate stresses on the aquifer prior to 1997, when substantially increased abstraction from the Water Corporation's Broome borefield commenced.

This phase of the calibration used a constant annual rainfall of 689 mm/year near Broome and 758 mm/year near the Thunderbird Project. These rainfall rates are based on the 1995-1996 measured rainfall for the Broome townsite (600 to 687 mm/year) and Thunderbird (756 to 806 mm/year).

Historic extraction volumes (Table 15) were incorporated in this and subsequent stages of the modelling assessment.

Table 15 – Other users' modelled extraction

Borefield	Rate (GL/yr)[1]
Broome Borefield (13 bores)	2.9
12-Mile horticultural lots	0.6
Skulthorpe horticultural lots	4.2
Broome townsite private extraction	0.8
Other private extraction	4
Total	12.5

1. Data sources are described in Section 8.2

Model parameters were varied and modelled groundwater levels were assessed. Model results were compared with regional and Project-scale groundwater levels (Figure 7). Groundwater levels (m AHD) from the final calibrated steady-state model (Figure 17) were used as the starting point for the transient model. This set of heads has a scaled-root-mean-square (SRMS) error of 4.8% against bores used in transient model calibration.

Transient calibration, 1997-2016

The model was calibrated in transient mode to groundwater level hydrographs for eight representative regional bores in the study area for the period 1997 to 2016 (HCL 1–6, HG B, HG H; Figure 8, Figure 9 and Figure 10) as well as five monitoring bores within the Thunderbird area (THAC243, 252, 357, 376, 441; Figure 12 and Figure 13).

Modelled and observed groundwater-level data (Appendix II-1 to Appendix II-5) for the eight representative regional bores have SRMS errors for groundwater levels from 0.36% (THAC 243) to 10.70% (HCL 6) (average 2.57%). The average SRMS for the monitoring bores within the Thunderbird area is 1.22%. This SRMS is below the model target of 5% as outlined in Section 8.1.

Groundwater-level trends are generally closely matched. An exception is the region of Bore HCL 6, where model-predicted groundwater levels are slightly higher than the observed values. This may be due to: local variations in hydraulic conductivity; inaccurately recorded bore or aquifer data; or unrecorded local groundwater extraction. Measured versus modelled groundwater levels (scatterplot, Appendix II-6) suggest a net equivalence between groundwater observations and model results.

8.5 ADOPTED AQUIFER PARAMETERS

Adopted model parameters are presented in Table 16 and Table 17. Aquifer parameters and recharge zones adopted in the model are presented in Appendix I-3.

Table 16 – Summary of recharge rates adopted in this and other assessments

Zone	Units	This assessment		Pennington Scott (2015)	Rockwater (2014)	Laws (1991)	Vogwill (2003)
		Steady-state	Transient				
Pindan (Broome)	mm/yr	16.5 (2.8%)[1]	29 (3.7%)[2]	6–38.5	26	24–30	20
Pindan (Thunderbird)	mm/yr	22.5 (3.0%)[1]	42 (4.7%)[2]	17	no data	no data	no data
Roebuck Plains	mm/yr	-100	-100	-182.5	no data[3]	no data	no data[3]
Dunes/superficial sands	mm/yr	182.5 (24%)[1]	320 (36%)[2]	no data	187	200	no data

1: As a fraction of 1996 rainfall
2: As a fraction of 1997-2016 rainfall
3: The modelling used Modflow's Drain Package

Table 17 – Summary of aquifer parameters adopted in this and other assessments

Aquifer/ aquitard unit	Source	Horizontal hydraulic conductivity Kh (m/d)	Vertical hydraulic conductivity Kv (m/d)	Specific yield Sy (-)	Specific storage coefficient Ss (1/m)
Tidal flats	**This assessment**	**5**	**0.5**	**0.1**	**1×10^{-6}**
	Rockwater (2014)	0.01–0.1	0.001–0.1	0.25	$1x10^{-5}$
	Vogwill (2003)	0.1	0.1	0.35	2×10^{-3}
Broome aquifer sandstone	**This assessment**	**10–30**	**1–3**	**0.1**	**1×10^{-6}**
	Rockwater (2014)	15–25	1.5–2.5	0.15–0.2	$1x10^{-5}$
	Rockwater (2008-2012)	5–23	0.5–2.3	0.08–0.1	$1x10^{-5}$
	Laws (1991)	12–23	no data	no data	no data
	Leech (1979)	3–15	no data	0.1–0.3	no data
	WMC (1999)	25–45	no data	no data	no data
	Searle (2012)	2–42	no data	no data	no data
	Vogwill (2003)	9–26	0.9–13	0.25–0.33	2×10^{-4}
	Pennington Scott (2015)*	7.5–9.5	0.075–0.095	0.15–0.20	$1x10^{-6}$
HMS	**This assessment**	**0.5–6**	**0.05–0.6**	**0.1**	**1×10^{-6}**
	Pennington Scott (2015)*	1	no data	no data	no data
Basal transitional Broome aquifer unit	**This assessment**	**3–6**	**0.3–0.6**	**0.1**	**1×10^{-6}**
	Pennington Scott (2015)	0.65	0.0065	0.03	$1x10^{-6}$
Jarlemai Siltstone	**This assessment**	**10^{-6}**	**10^{-7}**	**0.1**	**1×10^{-6}**
	Pennington Scott (2015)	0.005	0.0005	0.03	$1x10^{-6}$

*: As re-interpreted by Rockwater (see Appendix I)

8.6 WATER BALANCE

The model employs annual time steps, with the only significant variants during the model calibration period being recharge and extraction; recharge was varied using the rainfall multipliers shown in Appendix I-2.

Water balance results for the calibrated model in 2016 (Table 18) suggest that Broome aquifer groundwater fluxes are relatively small in the Thunderbird Project area (2 GL/year, of which 96% is derived from rainfall infiltration in the study area) compared to those of the entire peninsula.

Storage within the Broome aquifer increased by about 0.76 GL/year in the Thunderbird model area (Table 18). This model result is because 1997–2016 rainfall (Figure 3) was slightly above the long-term average. Similarly, storage increased by 182 GL/year (24% of outflow fluxes) for the entire model area due to higher-than-average rainfall over 1997–2016.

Peninsula-scale discharge fluxes include fluxes into the ocean over the saltwater wedge (57%) and drainage to tidal flats (11%). Total bore extraction over the entire Peninsula (12 GL/year) is about 2% of total outflow fluxes.

The maximum water balance error is ±0.15%. The target water balance error (Section 8.1) is ±0.5%.

Table 18 – Model water balance

1997–2016 (entire model)	
Inputs	**GL/yr**
Inflow from southern boundary	135
Recharge	582
Total	717
Outputs	
Net change in storage	182
Outflow to ocean / low lying areas	439
Bore extraction	12
Discharge to tidal flats	83
Total	716
1997–2016 (Thunderbird area)	
Inputs	**GL/yr**
Recharge	1.94
Total	1.94
Outputs	
Net change in storage	0.76
Outflow to regional model	1.18
Total	1.94

8.7 PREDICTIVE MODELLING

The calibrated model was used as a predictive tool to assess the Thunderbird Project's proposed water management.

Method

Predictive modelling is based on future CSIRO climate predictions (CSIRO, 2009). The CSIRO assessment is part of the 'Water Availability for the Fitzroy Region' project. Predicted future rainfall include 532 mm/year (dry-climate scenario, -19% variation compared to the long-term rainfall average for years prior to 1996), 644 mm/year (base-case scenario; -2% variation) and 696 mm/year (wet-climate scenario, +6% variation). These scenarios were chosen to best correspond to the 10th, 50th and 90th percentile of CSIRO's (2009) 45 scenario simulations.

Groundwater abstraction during Stage 1, 2 and 3 (Table 10) of the proposed Thunderbird Project were modelled using:

- Stage 1 and 2: nine multi-layer wells down-gradient from the mine for borefield abstraction (Figure 18).

- Stage 3: 32 zones of constant-head boundary in the ore layer from mining Year 16 to mining Year 47 (the head of each zone was set according to the base of ore for each mining year [Table 1; Figure 18]).

TSF seepage

Seepage from the tailings storage facilities (TSFs) was modelled using wells in the ore layer. The location of the tailings storage facility (TSF) progresses with mining. Tailings seepage was simulated based on the mining schedule, with the TSF location (after the start-of-mining TSF location) moving along NW–SE mining blocks, with a 1 year lag behind the active mining zone (Figure 18). Modelled seepage rates (Table 19) equal the water to TSF minus entrained water minus evaporation. Seepage-calculation parameters were assessed based on the following:

- Net water to the TSF. This value represents the component of the total net water demand that reports to the TSF. It equals the net water demand minus 2.2 GL/year (water used for dust suppression, camp use and water losses from the processing plant).
- Entrained water. Mine tailing will be saturated when deposited. Though this water will likely return to the groundwater system in the long term, this modelling assessment assumes that this water does not return to the groundwater system over the modelled period. It is therefore accounted for as a deficit from the water balance. Entrained water is calculated as follows:
  - Years 1–7: Average mining rate (14.6 MTPA) x 0.93 (the proportion of ore material that reports to the TSF) x 1.602 (average S.G. of dry ore) x 0.33 (effective porosity, assuming unsaturated conditions).
  - Year 8–15: As above, but with an average mining rate of 24 MTPA.
  - Year 16+: As above, but with an 'additional' effective porosity of 0.45 (TSF materials' water content) minus 0.33 (= 0.15). This represents the additional moisture content that is entrained as saturated ore is processed and added to the TSF.
- Evaporation. TSF evaporation is assessed based on plan view area of tailings with standing water (50 Ha), multiplied by the average annual evaporation for days with evaporation greater than daily rainfall (2498 mm), multiplied by 0.9 (a coefficient for converting theoretical pan evaporation to pond evaporation).

Table 19 – Modelled rates of seepage

Year	Net water to TSF (GL/yr)	Entrained water (GL/yr)	Evaporation (GL/yr)	Seepage rate (GL/yr)[1]
1-7	7.1	2.8	1.11	3.36
8-15	8.5	4.6	1.11	2.80
16+	8.5	2.1	1.11	5.31

1. **Net water to the TSF** minus **Entrained water** minus **Evaporation**.

Aquifer injection

Aquifer injection was modelled using five multi-layer wells. Well locations are shown in Figure 18. The modelled injection rate was based on the modelling water budget, with dewatering in excess of 10.7 GL/year modelled as injection in the injection borefield.

Null Scenarios

Null scenario models were run for the base-case predictive scenario as well as the different climate and recovery scenarios. These null scenario models were the same as the predictive models but with no mining and associated extraction/dewatering simulated. Heads from these models were used to calculate drawdown by subtracting the calculated head results from the predictive-model heads for the appropriate time period.

Groundwater levels

Drawdown and mounding results are presented in Figure 19 (Year 15), Figure 20 (Year 32) and Figure 21 (Year 47) and are summarised in Table 20 for key locations. Drawdown at the Fraser River South Valley (Year 47) is shown in long-section in Figure 23, together with regional-scale groundwater levels and drawdown to Broome. The drawdown results for mining year 47 (Figure 21) are also presented in depth-to-groundwater format (Figure 22).

Table 20 – Summary of modelled drawdown and mounding at key locations

Assessment area	Mining year		
	Year 15 (Figure 19)	Year 32 (Figure 20)	Year 47 (Figure 21)
Borefield drawdown or mounding			
Borefield drawdown	≤11 m	≤20 m	≤43 m
Injection borefield mounding	N/A	N/A	≤12 m
TSF-seepage mounding	≤20 m	≤11 m	≤3 m
Broome aquifer drawdown in the vicinity of interpreted seasonal surface water ponding areas			
'Nearby Soak'^	≤3.7 m	≤3.8 m	≤6 m
Fraser River South Valley^	~2 m	≤2.6 m	≤2.7 m

For each climate scenario (10th percentile, base case and 90th percentile), the numerical model was run with and without the proposed water management operation. Modelled heads for each model run were compared for mining Years 15 and 47 to assess the likely drawdown and mounding impacts of the proposed mining activities. Modelled differences between the three climate scenarios are presented in Table 21 for key assessment locations. These data show relatively small differences in model results for various climate scenarios, as would be expected given that most of the dewatering water comes from aquifer storage rather than recharge. The drawdown extent is maximal under the high-rainfall scenario which requires extra dewatering effort. Conversely under the dry-rainfall scenario less dewatering effort is required.

Table 21 – Summary of drawdown uncertainty at key locations for various climate scenarios

Assessment area^	Change in drawdown/mounding (metres)[1]			
	Year 15		Year 47	
	Dry climate[2]	Wet climate[3]	Dry climate[2]	Wet climate[3]
'Nearby Soak'	-0.02	0.01	-0.34	0.21
Fraser River South Valley	-0.01	0.01	-0.08	0.06

^ See Figure 15
1. Positive numbers represent increased drawdown; negative numbers represent reduced drawdown
2. 10th percentile of CSIRO's (2009) 45 scenario simulations
3. 90th percentile of CSIRO's (2009) 45 scenario simulations

Water management volumes

Predicted annual water-management volumes are presented in Figure 24 for the base-case scenario. The modelling results show the project water supply requirements, of 10.7 GL/yr, initially being met by the water supply borefield (Years 1–15) and then increasingly incorporating combined dewatering and water supply sources. From Year 32, the dewatering volumes exceed water demand; therefore, aquifer injection is modelled in the injection borefield, peaking in mining Year 47 with dewatering of about 30 GL and injection of 22 GL/yr. The impact of the climate scenario on the dewatering volumes (Figure 25) is predicted to be small (~±5%).

Post-mining aquifer recovery

Post-mining aquifer recovery was simulated via the transient response of aquifer recovery from Year 47 onwards. This modelling did not include borefield extraction or injection. Predicted drawdown/mounding contours (Figure 26 and Figure 27) show that at 2 years post-mining the magnitude of drawdown has declined markedly from >40 m at the end of mining to <8 m. Residual groundwater mounding is negligible at 2 years post-mining. After 10 years post-mining, the residual drawdown is confined to an area close to the mining area and the magnitude is < 2.5 m.

8.8 PREDICTIVE UNCERTAINTY

A range of potential model outcomes were assessed via a predictive uncertainty assessment. This assessment was undertaken by choosing a distribution of model parameters and running iterative model scenarios based on these possible model distributions. This reflects the many variations of model parameters that can be used to achieve in a calibrated model (Barnett et al., 2012). The assessment methodology is described in detail in Table 22.

Table 22 – Predictive uncertainty methodology

Step	Description
1	**Select a representative model year**
	One model year (approximating mining year 40) was selected for use in the predictive uncertainty analysis process. Mining Year 40 was chosen because: its dewatering depth (about 30 m RL) is about average for the below-watertable component of the mining schedule; and it has about an average predicted dewatering rate for mining from 30 years onwards.
2	**Run the representative model year for a variety of parameters**
	This one mining year was modelled with a variety of input parameters. A Monte Carlo type approach was used whereby model parameters (that are applicable to the impact assessment) were randomly varied following a normal distribution function for 40 iterations. The parameters from the calibrated model were used as the population mean which were then varied with a standard deviation equal to a quarter of each model parameter. The assessment results (Table 23) were compared with respect to their frequency of occurrence (Figure 28). These data suggest that Scenario 10 in Table 23 represents the upper 97.5 percentile of possible model outcomes with respect to dewatering volumes.
3	**Select an appropriate outlier model result, run it for the full model period (47 years)**
	The transient model was run for 47 years with Scenario 10 (Table 23, representing the upper 97.5 percentile model result). These water balance results are compared to the base-case results (Figure 29). Drawdown and mounding results for Scenario 10 (Table 23) were compared to non-extraction and non-injection model results with model parameters to show drawdown at key model locations (Table 24).

Table 23 – Summary of model predictive uncertainty analysis

Scenario	Hydraulic conductivity (m/d)								Storage		Dewatering (GL/year)	Drawdown (m)	
	Layer 1 Broome Sst	Layer 2 Broome Sst	Layer 3 Broome Sst	Layer 3 HMS(i)	Layer 3 HMS(ii)	Layer 4 Broome Sst	Layer 4 Trans(i)	Layer 4 Trans(ii)	Specific yield (-)	Specific storage constant (1/m)		Fraser River South	Nearby Soak
Base case	**10.0**	**21.0**	**21.0**	**3**	**6**	**21.0**	**0.5**	**6**	**0.10**	**1.00E-06**	**16.91**	**1.66**	**3.53**
											Change from Base Case		
1	8.3	22.9	20.2	2	7	24.0	0.6	6.6	0.07	9.44E-07	6.7%	3.6%	2.5%
2	13.2	27.8	22.9	4	6	21.9	0.6	6.6	0.11	1.03E-06	-1.6%	-2.4%	1.7%
3	6.2	26.4	24.1	3	5	21.9	0.4	7.9	0.06	1.02E-06	-5.3%	15.7%	4.2%
4	12.5	21.1	21.7	3	5	13.1	0.5	5.3	0.10	1.38E-06	-33.1%	-3.0%	-2.0%
5	12.9	25.0	3.8	2	6	20.2	0.7	6.3	0.09	5.53E-07	-19.5%	-5.4%	5.4%
6	13.8	21.9	26.5	3	7	25.6	0.6	3.9	0.08	3.45E-07	0.1%	4.8%	-9.3%

Scenario	Hydraulic conductivity (m/d)								Storage		Dewatering (GL/year)	Drawdown (m)	
	Layer 1 Broome Sst	Layer 2 Broome Sst	Layer 3 Broome Sst	Layer 3 HMS(i)	Layer 3 HMS(ii)	Layer 4 Broome Sst	Layer 4 Trans(i)	Layer 4 Trans(ii)	Specific yield (-)	Specific storage constant (1/m)		Fraser River South	Nearby Soak
7	11.1	15.4	33.8	3	7	17.2	0.5	5.2	0.08	8.68E-07	-33.4%	5.4%	-6.8%
8	9.0	24.7	19.5	2	7	25.0	0.5	7.6	0.12	1.13E-06	-3.0%	1.2%	1.1%
9	11.5	29.2	23.1	3	4	16.9	0.6	7.9	0.13	1.13E-06	9.6%	-1.8%	2.5%
10[A]	12	34	23.8	3	6	27.2	0.6	3.8	0.13	1.63E-06	27.6%	-10.2%	8.2%
11	9.2	18.3	19.1	3	8	23.7	0.5	3.7	0.08	8.55E-07	1.9%	-1.8%	2.0%
12	12.7	25.2	12.6	3	6	15.6	0.4	5.4	0.05	7.65E-07	-31.0%	0.0%	0.3%
13	12.6	22.3	17.7	4	2	22.1	0.4	5.9	0.13	2.03E-07	3.5%	-4.8%	5.4%
14	9.9	22.1	20.2	3	7	11.8	0.5	7.7	0.10	1.04E-06	-36.7%	1.8%	-2.3%
15	14.3	18.5	22.5	4	6	25.2	0.5	5.6	0.13	1.18E-06	7.5%	-4.2%	1.7%
16	7.1	18.3	23.4	2	7	14.3	0.5	6.5	0.11	1.44E-06	-25.3%	1.8%	-3.7%
17	10.0	15.9	23.5	3	8	12.6	0.5	5.8	0.09	7.15E-07	-40.3%	1.8%	-2.8%
18	9.0	27.2	18.8	5	8	33.8	0.5	6.3	0.09	6.96E-07	30.2%	3.6%	14.2%
19	13.1	6.00	26.4	2	6	22.5	0.4	5.9	0.11	1.30E-06	5.1%	3.0%	-5.9%
20	13.3	20.1	11.8	3	5	28.6	0.6	6.2	0.10	6.22E-07	-4.8%	-1.8%	1.1%
21	9.4	15.5	21.6	2	3	26.8	0.5	5.2	0.06	1.36E-06	2.0%	4.8%	5.4%
22	15.2	20.6	20.2	3	5	15.0	0.3	6.7	0.06	3.23E-07	-29.5%	4.2%	-5.7%
23	13.4	18.8	29	2	4	28.8	0.4	4.9	0.13	6.77E-07	14.7%	-4.2%	2.8%
24	9.8	27.7	19.3	2	5	24.0	0.5	8.2	0.07	4.33E-07	7.9%	7.8%	6.2%
25	11.0	28.1	20.8	3	6	20.0	0.7	4.5	0.09	1.16E-06	-4.4%	-4.8%	4.0%
26	6.4	20.9	26	4	5	15.5	0.5	7.4	0.09	1.83E-07	6.9%	-4.2%	2.3%
27	7.8	25.9	0.2	3	4	16.8	0.4	5.3	0.10	6.39E-07	-39.4%	-9.0%	5.9%
28	7.6	15.0	21.9	3	7	21.0	0.4	7.4	0.13	1.05E-06	-16.0%	3.6%	-3.7%
29	10.5	32.3	25.4	3	6	22.3	0.6	4.3	0.06	1.50E-06	6.9%	1.8%	4.5%
30	8.5	20.2	18.3	1	8	15.2	0.6	3.4	0.09	7.86E-07	-21.9%	-5.4%	0.3%
31	10.7	21.7	8.4	2	5	31.8	0.4	4.4	0.13	7.84E-07	9.9%	-7.2%	7.9%
32	6.0	16.2	18.9	3	9	19.1	0.6	5.6	0.13	1.17E-06	-25.1%	0.0%	-1.4%
33	9.1	25.6	19.2	3	9	26.5	0.6	6.4	0.10	1.34E-06	17.1%	1.8%	8.2%
34	9.0	23.3	17.5	3	6	14.8	0.4	5.4	0.09	1.53E-06	-3.4%	1.2%	0.0%
35	12	22.1	23.8	3	8	22.0	0.7	6.7	0.12	4.44E-07	6.4%	0.0%	2.3%
36	7.4	26.4	28.3	3	7	22.1	0.5	7.3	0.11	9.55E-07	-18.1%	4.2%	-1.1%
37	10.6	16.3	23.2	4	5	29.4	0.6	6.9	0.13	1.67E-06	-5.9%	1.2%	-2.0%
38	7.1	18.6	19.8	4	7	24.6	0.6	1.9	0.11	9.74E-07	6.7%	-9.6%	0.0%
39	13.1	18.3	19	2	5	20.2	0.7	4.6	0.09	7.73E-07	-17.9%	-3.6%	-1.1%
40	9.7	23	23.2	3	5	14.2	0.4	6.3	0.09	9.60E-07	-24.7%	1.2%	-2.5%
Average	10.6	21.5	20.3	3	6	21.1	0.5	6	0.1	9.00E-07	-6.6%	0.0%	1.1%
Min	5.4	6	0.2	1	2	11.8	0.2	1.9	0.03	2.00E-07	-40.3%	-10.2%	-9.3%
Max	16.8	34	33.8	5	9	33.8	0.7	11	0.13	2.00E-06	30.1%	15.7%	14.2%

A. Predictive uncertainty scenario representing the 97.5 percentile result

The predictive uncertainty results suggest that:

The 97.5 percentile of dewatering and mounding results (

- Table 23, Scenario ‘10’) is within about ±10% for drawdown at the ‘Nearby soak’ and Fraser River South.
- The 97.5 percentile of dewatering volumes is up to an average of 16% greater over the 47-year life of the Thunderbird Project (that is, the average increase in dewatering volumes in Figure 29 is 16% for the 97.5 percentile). Peak dewatering rates towards the end of the mine sequence may be up to 8 GL higher under the 97.5 percentile scenario.

Table 24 – Additional modelled drawdown at key model locations, P97.5 scenario

Assessment area^	Additional drawdown (m)[1]
‘Nearby Soak’	0.33
Fraser River South Valley	0.37

^ See Figure 15

1. Compared to base case (Table 20)

8.9 MODEL LIMITATIONS

Limitations and uncertainty associated with the model include gaps in available data. Data gaps include the uneven distribution of monitoring bores and the absence of dedicated monitoring bores with long-term groundwater level data in the Thunderbird Project area. Aquifer characteristics are therefore inferred based on published data for some parts of the model.

Temporal groundwater-level measurements are concentrated in coastal locations, including bores near the Water Corporation borefield area and the HCL monitoring bores along the western margin of the model area. Temporal groundwater-level data may contain data gaps and limited measurements. Groundwater level measurements for the immediate mining area are limited (but will contain over 30 years of monitoring data by the time pit-dewatering is required).

Bore abstraction is a component of model-calibration; however, these data are limited to the Water Corporation borefield. Private groundwater extraction has been taken to be the licensed allocations from the DoW database–actual extraction data are not available. There is little or no extraction for much of the modelled area. Groundwater use within the model domain (12.5 GL/yr; Table 15) is comparable to the average modelled extraction for the Thunderbird project (12.4 GL/yr); however, model stresses of about 30 GL/yr are predicted to occur late in the project cycle. Peak-dewatering model stresses are therefore in excess of calibration model stresses. Dewatering will occur 15 years into the mining schedule; therefore there are opportunities for model-refinement if necessary.

An assessment of the model with respect to key indicators (Table 25) suggests that the model objectives (Section 8.1) were largely met, with the following exceptions:

- Only limited monitoring data exist for the immediate mining area, as is the case for most new mining projects. Therefore, the mining area does not meet the calibration period requirements.
- Model stresses are more than two times the calibration stresses for peak dewatering periods late in the project cycle.
- A peer review has not been completed at the time of report writing.

Given these limitations and uncertainties, the modelling assessment has adopted a predictive uncertainty assessment whereby a variety of model outcomes are presented for a variety of potential model configurations.

Table 25 – Model assessment with respect to key indicators

No.	Key indicator[1]	Comment
1	Key calibration statistics are acceptable and meet agreed targets (a <5% SRMS groundwater head error is adopted as a calibration target for this assessment)	The SRMS groundwater head error is <5% (Section 8.4).
2	Model predictive time frame is less than 3 times the duration of transient calibration	The model calibration period using regional data is 18 years, the predictive time frame is 47 years (2.6 times the calibration period). However, only limited groundwater data are available for the immediate mining area.
3	Stresses are not more than 2 times greater than those included in calibration	Groundwater use within the model domain is currently about 12.5 GL/yr (Table 15), whilst the average modelled extraction for the Thunderbird project is 12.4 GL/yr. However, model stresses of about 30 GL/yr are predicted to occur late in the project cycle.
4	Temporal discretisation in predictive model is the same as that used in calibration	Temporal discretisation for both the calibration and predictive models is annual.
5	Mass balance closure error is less than 0.5% of total	The model mass balance closure error is ±0.15% (Section 8.6).
6	Model parameters consistent with conceptualisation	Model parameters (Table 16 and Table 17) are consistent with the hydrogeological characteristics described in Section 4 and are consistent with those derived from previous assessments.
7	Appropriate computational methods used with appropriate spatial discretisation to model the problem	A finite element model code was utilised whereby spatial discretisation ranged from 500 metres (distant model regions) to 40 metres (mining region), reflecting the model's varying scales of assessment.
8	The model has been reviewed and deemed fit for purpose by an experienced, independent hydrogeologist with modelling experience	Recommended; to be completed.

1. From Table 2-1, Barnett et al. (2012)

9 ASSESSMENT OF IMPACTS AND PROPOSED MANAGEMENT APPROACH

Impact assessment items are summarised in Table 26 based on site characteristics (Section 4) and model results (Section 8).

Table 26 – Description of potential impacts

ID	Potential impact	Impact description
	Groundwater drawdown	
1	Drawdown in the Fraser River South valley	Groundwater drawdown has the potential to impact on vegetation communities in the Fraser River South valley. Groundwater drawdown of up to about 3 m is predicted (Figure 21) in later stages of the mining sequence. Groundwater drawdown at the Fraser River South valley is predicted to be a gradual process over the Thunderbird Project's 47 year duration. Vegetation communities in this region are likely to experience seasonal variability in groundwater levels.
2	Localised seasonal water ponding locations	Localised seasonal water-ponding locations have been identified in the greater Thunderbird Project region (Section 5.2). These features are unlikely to be impacted by Broome aquifer drawdown, as is outlined in Section 5.2, as they are likely to be disconnected from the Broome aquifer.
3	Impact on existing groundwater users	Groundwater drawdown is not predicted to extend towards other existing groundwater users. The nearest licensed users and nearest known indigenous heritage sites are about 25 km from the Thunderbird Project, outside the modelled drawdown related to the Thunderbird Project.
4	Potentially acid forming (PAF) materials	Two samples of PAF material have been identified in regions that are included in the final stages of the mining schedule. Pit dewatering has the potential to expose PAF materials to oxidation and acidification. PAF materials have the potential to cause down-gradient acidification when oxidised.
5	Subterranean fauna	Groundwater drawdown has the potential to impact on stygofauna and troglofauna, should these be present in any significant way in that part of the aquifer being temporarily dewatered. Subterranean fauna assessments (Section 5.2) identified only one type of stygofauna which are classified as opportunistically stygal. Troglofauna assessments (Section 5.2) identified only two troglofauna species. Overall troglofauna were generally found to have low diversity and abundance in the Thunderbird Project area. Pennington Scott (2015) conclude that, given the wide extent of the Broome aquifer across the Canning Basin, together with the lack of any significant obligate stygofauna identified within the study area and the relatively localised impact on aquifer saturated thickness due to the Thunderbird Project, it is unlikely that the groundwater extraction for the Thunderbird Project will have unacceptable impacts on subterranean fauna.
	Groundwater mounding	
6	Injection region mounding	Groundwater mounding of up to about 11 m is predicted (Figure 21) in the injection borefield region. However, the unsaturated zone is more than 30 metres deep in this region. Groundwater mounding is therefore not predicted to result in surface-waterlogging or other mounding impacts.
7	Tailings co-disposal mounding	Mounding due to seepage from tailings co-disposal is likely to occur, especially in the first 15 years of mining. Modelling assessments suggest that mounding may be up to about 20 m (Figure 19). Tailing mounding occurs in

ID	Potential impact	Impact description
		regions where the unsaturated zone is relatively deep (about 40 m) and in areas already disturbed by mining operations.
	Other	
8	Contaminant risks	Groundwater contamination from project-related activities has the potential to impact on downgradient receptors. Contaminant risks include diesel and oil spills.

Proposed management approaches for potential impacts (Table 26) are outlined in Table 27.

Table 27 – Summary of impacts and management strategies

ID	Potential impact	Impact summary	Recommendation	Management strategy[2]
	Groundwater drawdown			
1	Drawdown in the Fraser River South valley	Groundwater drawdown of about 3 m is predicted in later stages of the mining sequence	- Undertake further baseline monitoring (R1)[1] - Set trigger levels (R2)[1] - Re-calibrate the numerical model after 2 years' operation and revise drawdown predictions (R3)[1]	Alter the location and/or timing of aquifer injection (Strategy A)
2	Localised seasonal water ponding locations	Localised seasonal water ponding locations are not likely to be impacted by Broome aquifer drawdown	- Install monitoring bores in the shallow strata (R4)[1] - Set trigger levels (R2)[1] Undertake baseline monitoring (R1)[1]	Alter the location and/or timing of aquifer injection (Strategy A)
3	Impact on existing groundwater users	Groundwater drawdown is not predicted to extend towards areas of other groundwater users	- Conduct the 'regional responses' monitoring outlined in Table 30 (R5)[1] - Conduct a census of stock and domestic bores with the drawdown cone of depression (R1)[1] - Set trigger levels (R2)[1]	Provide alternative water sources in the event that unexpected drawdown impacts upon existing groundwater users (Strategy B)
4	Potentially acid forming (PAF) materials	Two samples of PAF material have been identified in regions that are excluded from the final stages of the mining schedule	- Undertake further ore-characterisation during resource-definition and grade-control drilling (R6)[1] - Undertake high-frequency monitoring of changes in pH via the water conveyance system.	Alter the dewatering strategy where necessary to avoid acid-generating materials. In some instances this may result in delays or restrictions in mining (Strategy C)
5	Subterranean fauna	Drawdown is not predicted to impact upon subterranean	None	None

ID	Potential impact	Impact summary	Recommendation	Management strategy[2]
		fauna		
	Groundwater mounding			
6	Injection region mounding	Groundwater mounding is predicted to occur in regions of deep groundwater and is not anticipated to impact upon the injection region	- Undertake further baseline monitoring (R1)[1] - Set trigger levels (R2)[1]	Alter the location and/or timing of aquifer injection (Strategy A)
7	Tailings co-disposal mounding	Groundwater mounding is predicted to occur in regions of deep groundwater and is not anticipated to impact the region	- Undertake further baseline monitoring (R1)[1] - Set trigger levels (R2)[1]	Alter the location and/or timing of tailings disposal; further seepage-recovery measures (Strategy D)
8	Contaminant risks	Contamination risk from (e.g.) diesel and oil spills	- Implement a spill-prevention and spill-response strategy - Include hydrocarbon-indicator analytes in the monitoring program (R8)[1]	Spill response strategies (Strategy E)

1. Recommendations are described in Table 28
2. Management strategies are described in Table 29

Project recommendations summarised in Table 27 are described in Table 28.

Table 28 – Recommendations

ID[1]	Recommendation	Description
1	Baseline monitoring	A baseline monitoring program should be implemented for groundwater levels in accordance with Department of Water guidelines. This includes the documentation of the strategy in a Groundwater Licence Operating Strategy. Groundwater level measurement frequencies should be at least monthly. Indicative monitoring locations are described in Table 30. The baseline monitoring program should include a census of stock and domestic bores within the drawdown cone of depression shown in Figure 21.
2	Trigger levels	Trigger levels should be implemented for key monitoring locations. Trigger levels should be developed in consultation with Department of Water and documented in a Groundwater Licence Operating Strategy. Indicative trigger levels may include: - Fraser River South valley (monitoring location 15 in Table 30): A 1.5^ m decrease (half of the predicted maximum drawdown) in groundwater levels beyond seasonal trends[2]. - Surface water ponding areas (monitoring location 17 in Table 30): A 0.5^ m decrease in groundwater levels beyond seasonal trends[2] in the shallow surface water ponding areas. The trigger is applicable when the

ID[1]	Recommendation	Description
		0.5^ m decrease is shown to be synchronous with groundwater level trends in the proximal Broome aquifer monitoring data. - Impact on existing groundwater users (monitoring locations 1,18&20 in Table 30): A 1^ m trigger for groundwater drawdown beyond seasonal trends[2]. - Injection region mounding (monitoring locations 4,5&6 in Table 30): groundwater levels of <10^ m below ground level. - Tailings mounding (monitoring location 3 in Table 30): groundwater levels of <10^ m below ground level.
3	Model re-calibration	The numerical model described in Section 8 should be updated at least before 2 years' operation. The updated model should include: updated model-calibration based on updated monitoring and hydrogeological data; and further-refined mine-scale discretisation of the model region. Model results should be used to further refine the water management objectives and practices.
4	Install monitoring bores (shallow surface water ponding areas)	Shallow monitoring points should be installed proximal to the shallow surface water ponding areas identified in Figure 15. Monitoring points should be low-impact and should be constructed in accordance with local heritage requirements.
5	Install monitoring bores (project-scale and regional)	Monitoring bores should be installed in consultation with Department of Water. Proposed monitoring locations are summarised in Table 30.
6	PAF ore characterisation	Further ore-characterisation should be undertaken during resource definition and grade control drilling, with special reference to the down-dip (end of mine life) PAF material regions.
8	Hydrocarbon-indicator monitoring	The Groundwater Licence Operating Strategy should include reference to hydrocarbon and hazardous material risks. Suitable strategies include hydrocarbon-indicator analyses in groundwater-quality sampling programs.

1. ID nomenclature used in Table 27

2. Triggers with reference to seasonal trends require synchronous baseline data to assess seasonal trends outside drawdown and mounding areas. Assessments of seasonal trends should be developed in consultation with Department of Water and documented in the Groundwater Licence Operating Strategy.

^ Indicative trigger level, to be finalised in consultation with Department of Water.

Table 29 – Management strategies

ID[1]	Management strategy	Management strategy description
A	Alter the location and/or timing of aquifer injection	This strategy involves moving the injection borefield or components of the injection borefield closer towards the Fraser River South valley. The proposed injection borefield would remain within the access road corridor. This strategy will maintain groundwater levels in the Fraser River valley region. If this strategy is required prior to below-watertable mining then the timing of injection may need to be altered.
B	Provide alternative water sources in the event that unexpected drawdown impacts upon existing groundwater users	In the event that unexpected drawdown impacts on existing groundwater users Sheffield Resources should provide alternative water sources. This may include: - Deepening existing bores or providing increased pumping capacity; and/or - Piping or transporting water from the Thunderbird Project to the existing user's water source.
C	Alter the dewatering strategy where necessary to avoid acid generating materials. In some instances this may result in delays or restrictions in mining	Changes may be required to the dewatering strategy in the event that PAF material is identified in a mining region. These changes may include: - Utilising sump pumping instead of bore pumping in key areas so that the dewatering front is minimised and the area of PAF exposure is reduced. - Restricting mining (leaving ore in the ground) in key PAF material areas to avoid PAF material oxidation.
D	Alter the location and/or timing of tailings disposal; further seepage-recovery measures	The following management strategies should be considered in the event of impacts from tailings disposal mounding: - Altering the location and/or timing of tailings disposal such that mounding triggers are met. - Implementing further seepage-recovery measures
E	Spill response strategies	A spill response strategy should be implemented, including: - Documented spill-response strategies. - Dedicated onsite spill-response equipment. - Staff training and education programs.

1. ID nomenclature used in Table 27

Table 30 – Proposed monitoring locations

No.	mE[1]	mN[1]	Monitoring target	Comment
Monitoring location				
1	483,182	8,058,300	Groundwater drawdown	Proposed far-field drawdown monitoring location
2	490,145	8,077,272		Proposed along-strike dewatering monitoring location
3	497,923	8,074,318	Tailings mounding	Proposed up-dip tailings mounding monitoring location
4	512,301	8,052,168	Groundwater injection[2]	Propose injection-area monitoring location
5	512,252	8,047,526		Propose injection-area monitoring location
6	508,908	8,056,937		Propose injection-area monitoring location
7	493,371	8,072,975	Near-mine drawdown	At/near exploration hole THAC252
8	493,082	8,067,978		At/near exploration hole THAC376
9	497,706	8,068,026		At/near exploration hole THAC441
10	493,947	8,074,446		At/near exploration hole THAC427

No.	mE[1]	mN[1]	Monitoring target	Comment
11	502,291	8,069,276		At/near exploration hole THAC285
12	499,400	8,078,237	Vegetation communities	Proposed Fraser River North headwaters monitoring location
13	503,500	8,066,540		Monitoring site for Fraser River South valley 1
14	505,399	8,063,495		Monitoring site for Fraser River South valley 2
15	504,225	8,065,611		Monitoring site for Fraser River South valley 3
16	502,505	8,078,177		Proposed Bunbarragut Creek headwaters monitoring location
17	498,857	8,067,354		Proposed monitoring site for 'Nearby soak'
18	498,100	8,043,400	Regional responses	DoW bore site HG B
19	495,600	8,062,500		DoW bore site HG C
20	469,300	8,080,000		DoW bore site HG G
Additional in-pit locations[3]				
A	497,168	8,072,071	Mining-region drawdown responses	At/near exploration hole THAC243
B	495,877	8,070,536		At/near exploration hole THAC357

1. Coordinate system MGA94, Zone 51. Monitoring locations are shown in Figure 30. Final bore locations to be reviewed in consultation with Department of Water.

2. Proposed injection monitoring sites will be commissioned one season prior to the injection phase of the water management system.

3. Sites with the resource footprint. Monitoring locations are likely to be moved during the course of mining due to the interaction between pit-progression and monitoring bore locations.

10 SUMMARY AND CONCLUSION

Sheffield Resources is developing the Thunderbird Mineral Sands Project (the Thunderbird Project) located on the Dampier Peninsula in the Kimberley region of Western Australia. The Thunderbird Project is targeting a heavy mineral sands (HMS) resource over a 47 year life of mine. Processing will be undertaken onsite, with process water supplied from local groundwater resources. The HMS resource lies within the Broome aquifer – a regional, unconfined aquifer that extends across a large portion of the Dampier Peninsula. Later stages of the mining sequence will target below-watertable ore and a dewatering program will be required. Dewatering volumes are predicted to exceed process water requirements for some periods; therefore, aquifer injection will be used as a water management strategy.

Hydrogeological conditions within the project area have been assessed via previous drilling and aquifer testing programs. Regional hydrogeological conditions have been collated from a variety of studies. A numerical modelling assessment of the Thunderbird Project has been undertaken. The model incorporates both project-scale hydrogeology and mine sequencing and also hydrogeological processes for the greater Dampier Peninsula. The model was developed with reference to the Australian groundwater modelling guidelines. FEFLOW finite-element model code was utilised to represent hydrogeological conditions. Model parameters are based on site-specific data and regional reference data. Model calibration was based on local and regional monitoring data. The model incorporated existing groundwater users on the Dampier Peninsula, including the Broome town borefield.

Predictive modelling assessments were undertaken for the proposed water management strategy. Predictive assessments incorporated a variety of potential future climate scenarios, based on CSIRO's summary of climate predictions. The impact of parameter uncertainty was assessed via predictive uncertainty assessments. Model results suggest that drawdown of up to about 3 m may be expected at the Fraser River South valley, about 8 km south-east from the mine. Groundwater drawdown at the Fraser River South valley is predicted to be a gradual process over the Thunderbird Project's 47 year duration. Vegetation communities in this region are likely to experience seasonal variability in groundwater levels. Groundwater drawdown is not predicted to impact on existing licenced groundwater users, including the Broome town water supply. Drawdown results are relatively insensitive to future climate scenarios and model-parameter uncertainty. Dewatering volumes are predicted to peak in later stages of the mining sequence, with about 30 GL/year dewatering predicted in mining year 47. Predictive uncertainty assessments suggest that a 97.5 percentile uncertainty scenario would result in dewatering volumes of up to 16% greater on average over the 47-year mine life, with peak dewatering rates up to 8 GL greater towards the end of the mine sequence.

The following recommendations are provided:

- A baseline monitoring program should be established in accordance with Department of Water guidelines. Groundwater level measurement frequencies should be at least monthly. The baseline monitoring program should include a census of stock and domestic bores within the drawdown cone of depression.
- Trigger levels should be implemented for key monitoring locations. Trigger levels should be developed in consultation with Department of Water and documented in a Groundwater Licence Operating Strategy. Indicative trigger levels are provided in this report.
- The numerical model should be updated at least before 2 years' operation. The updated model should include: updated model-calibration based on updated monitoring and hydrogeological data; and further-refined mine-scale discretisation of the model region. Model results should be used to further refine the water management objectives and practices.
- Monitoring bores should be installed in consultation with Department of Water. Shallow monitoring points should be installed proximal to the identified shallow surface water ponding areas. Monitoring points should be low-impact and should be constructed in accordance with local heritage requirements.
- Further ore-characterisation should be undertaken during resource definition and grade control drilling, with special reference to the down-dip (end of mine life) PAF material regions.
- The Groundwater Licence Operating Strategy should include reference to hydrocarbon and hazardous material risks. Suitable strategies include hydrocarbon-indicator analyses in groundwater-quality sampling programs.

Dated: 23 December 2016 Rockwater Pty Ltd

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FIGURES

Figure 1

I:464-0/Surfer/16-02/Figure 1.srf

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

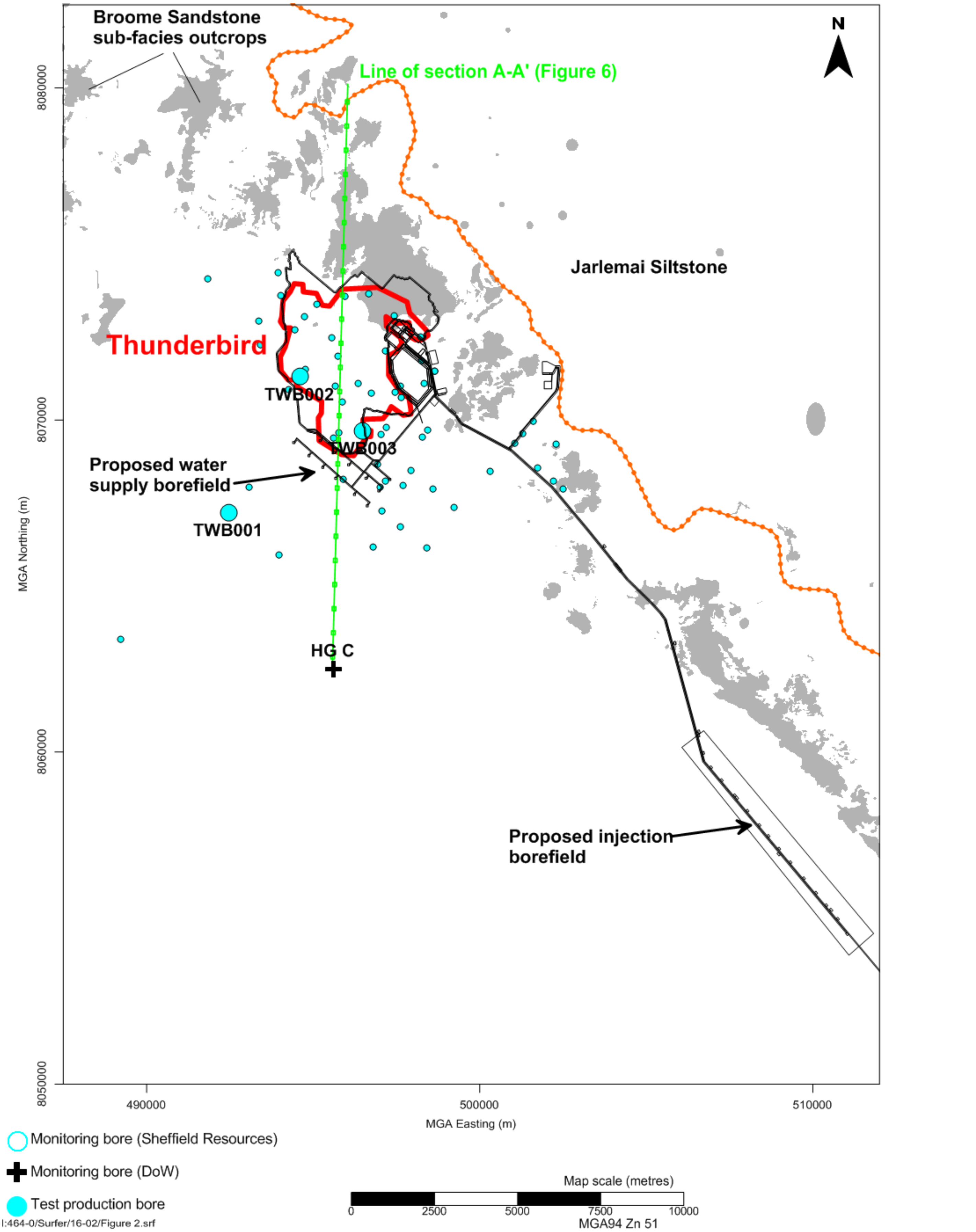
DATE: October 2016

Dwg No: 464-0/16/02-1

SITE LOCATION

Rockwater PROPRIETARY LIMITED

Figure 2



CLIENT: Sheffield Ressources

PROJECT: Thunderbird H3 hydrogeological assessment

DATE: December 2016

Dwg No: 464-0/16/02-2

SITE SETTING

Rockwater PROPRIETARY LIMITED

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

DATE: October 2016

Dwg No: 464-0/16/02-3

HISTORICAL RAINFALL

464-0/Grapher/Figure 03.grf

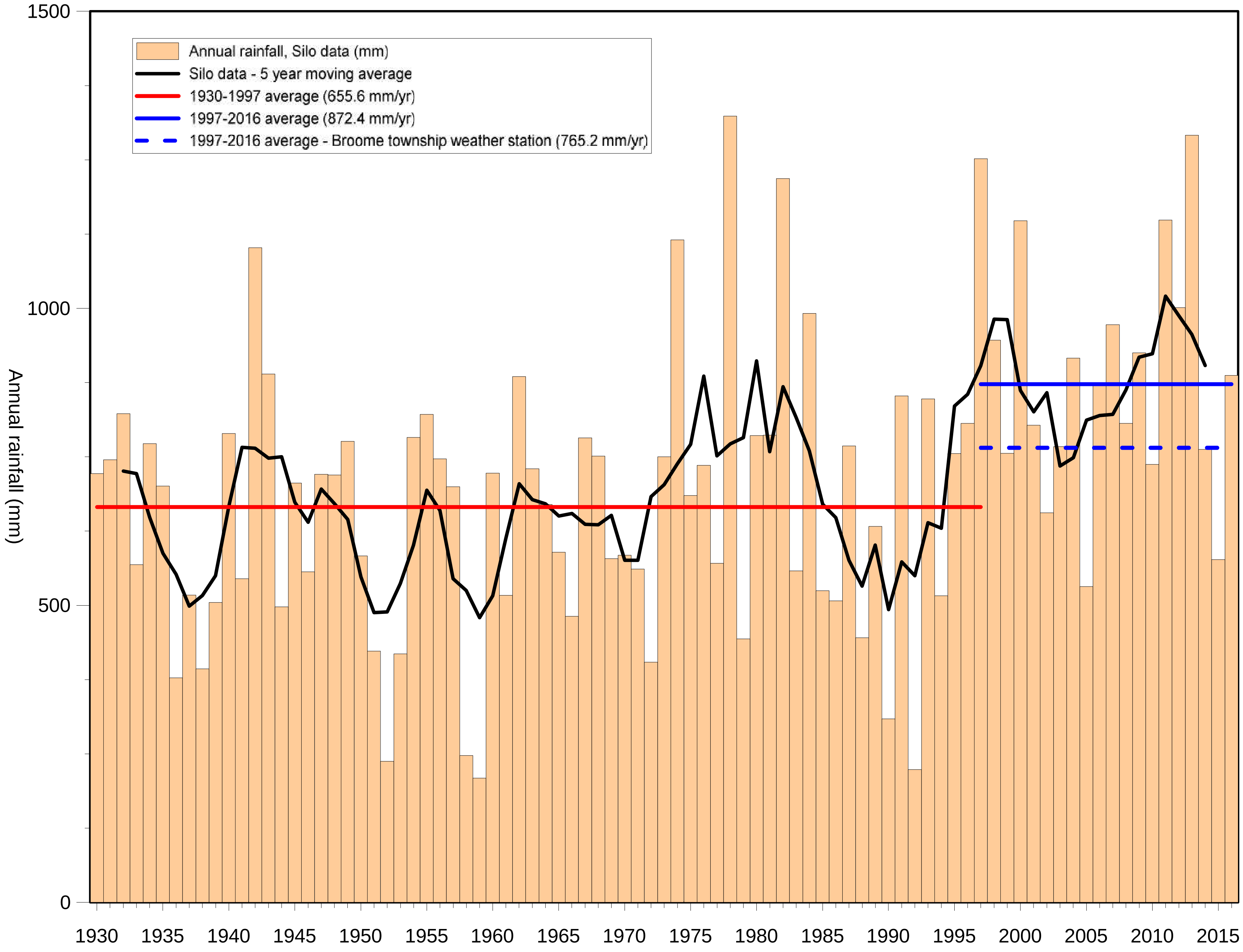
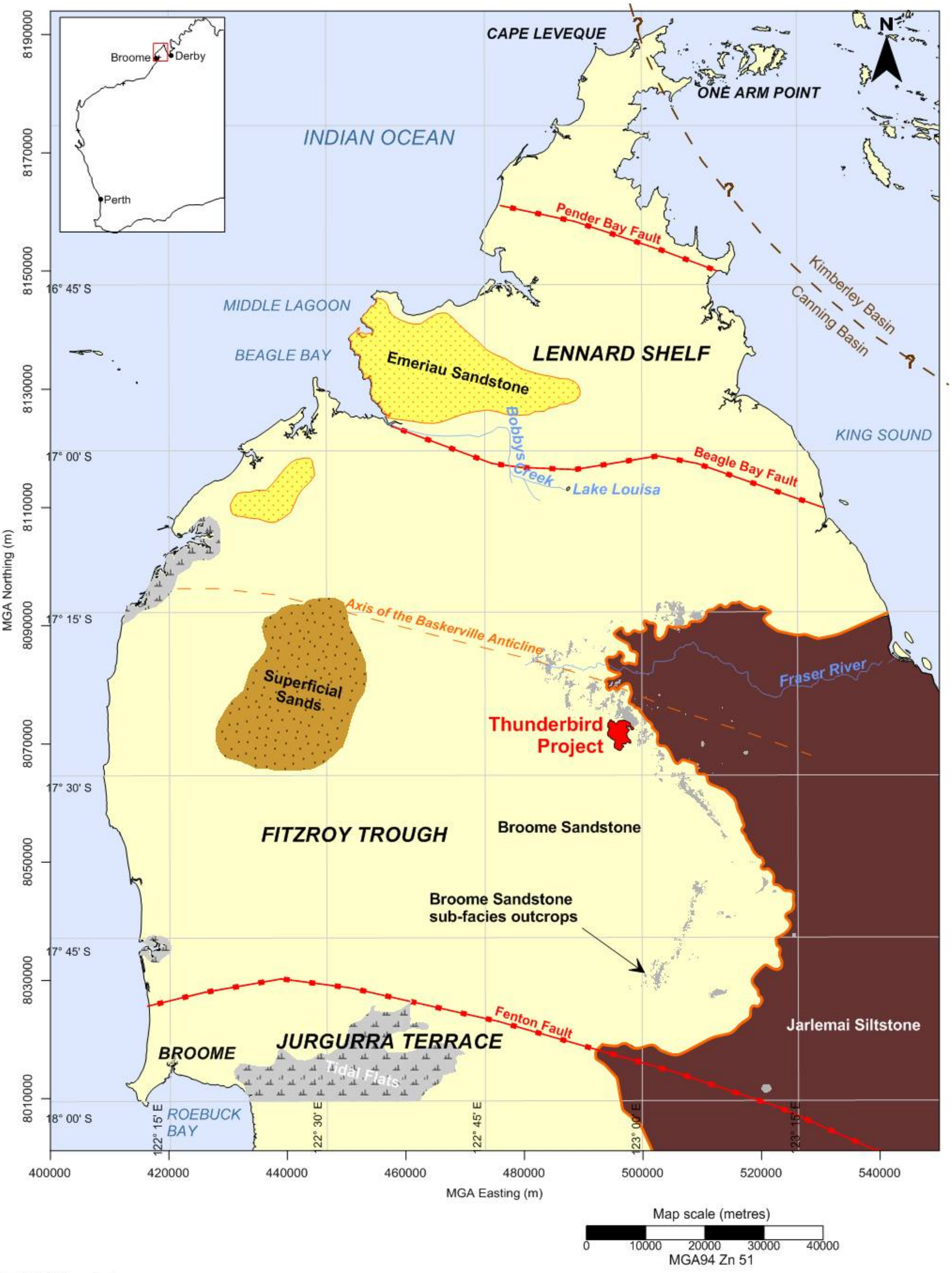


Figure 3

Figure 4



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CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

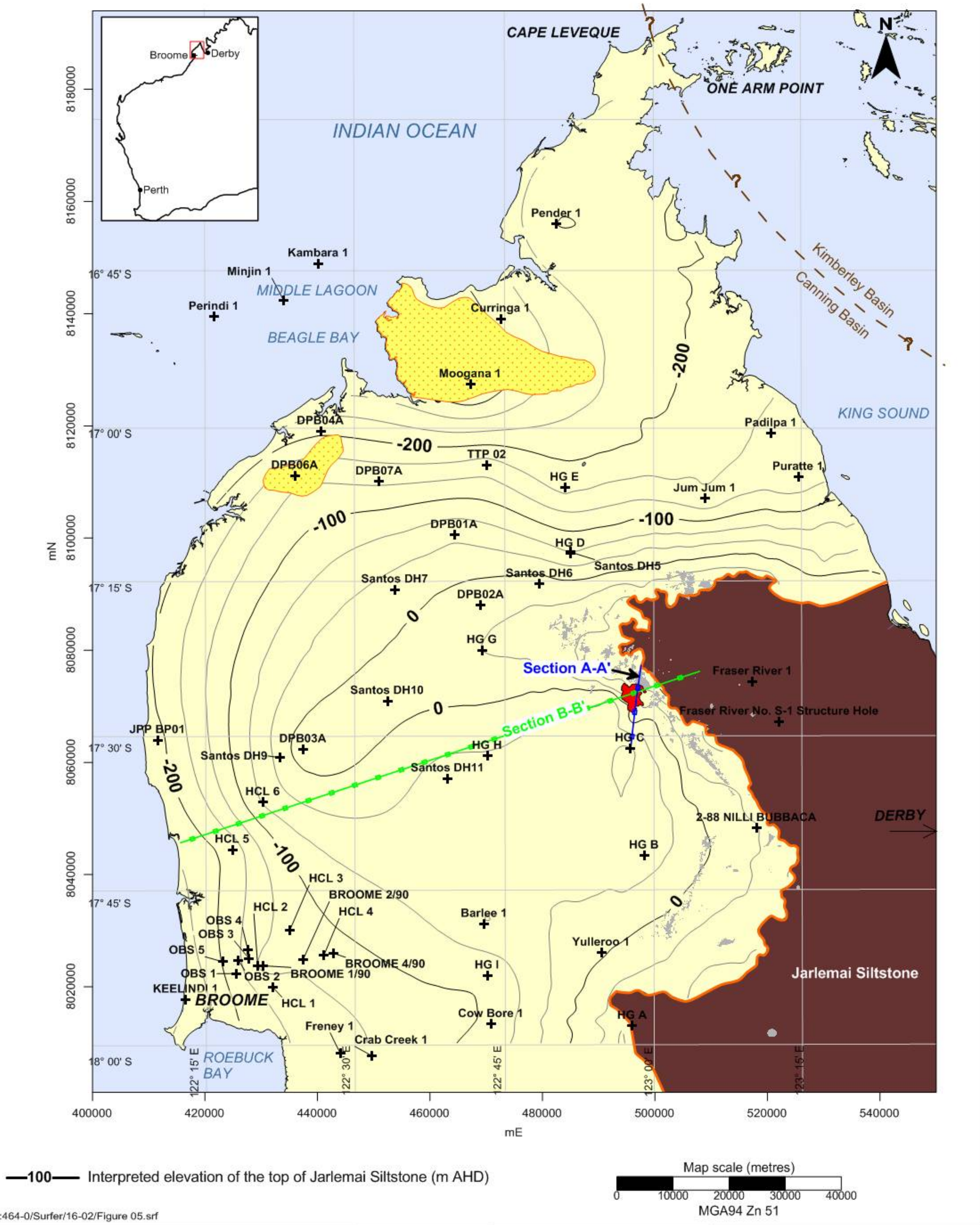
DATE: October 2016

Dwg No: 464-0/16/02-4

REGIONAL GEOLOGICAL SETTING

Rockwater PROPRIETARY LIMITED

Figure 5



I:464-0/Surfer/16-02/Figure 05.srf

CLIENT: Sheffield Resources

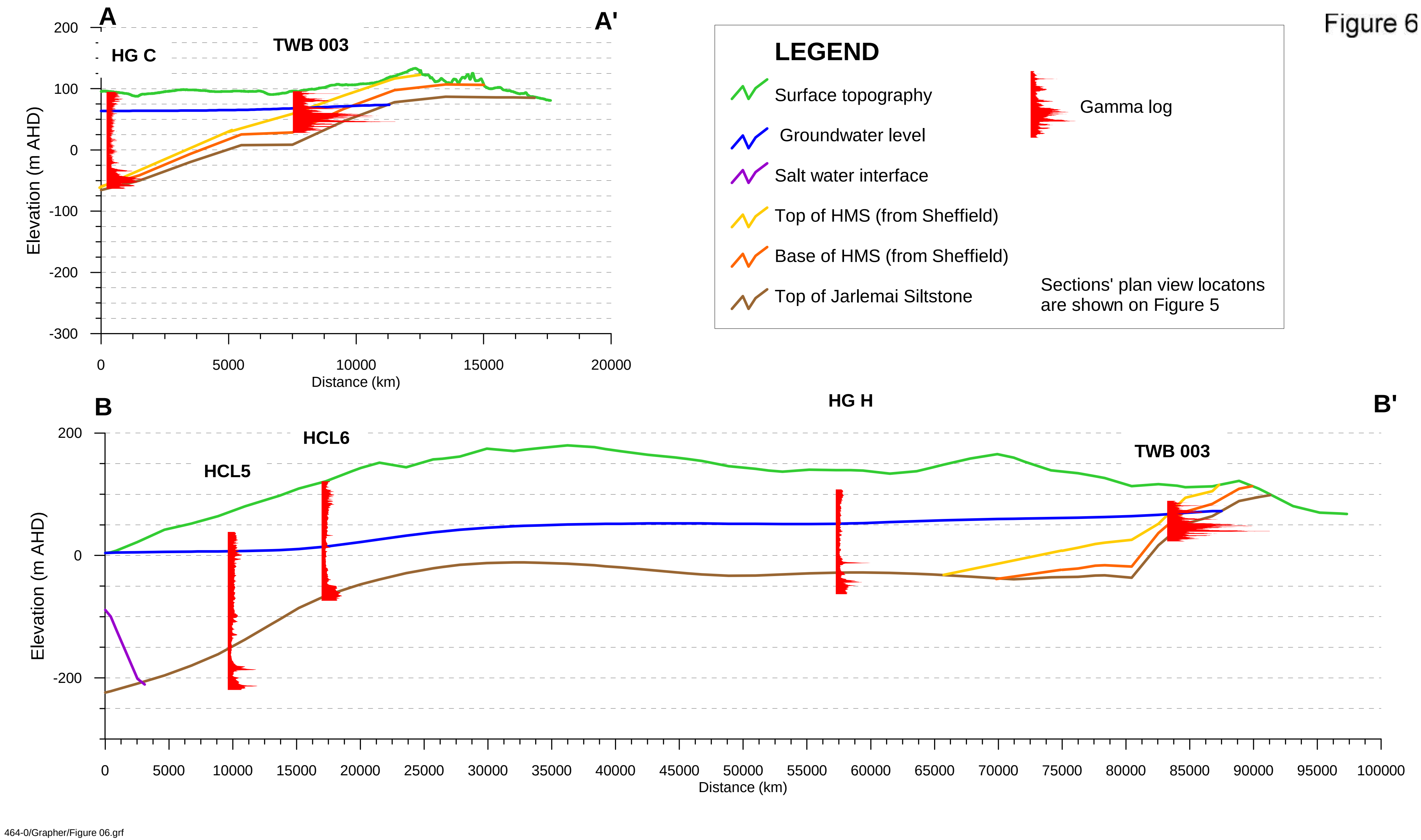
PROJECT: Thunderbird H3 hydrogeological assessment

DATE: October 2016

Dwg No: 464-0/16/02-5

TOP OF JARLEMAI SILTSTONE

Rockwater PROPRIETARY LIMITED



Client: Sheffield Resources

Project: Thunderbird H3 hydrogeological assessment

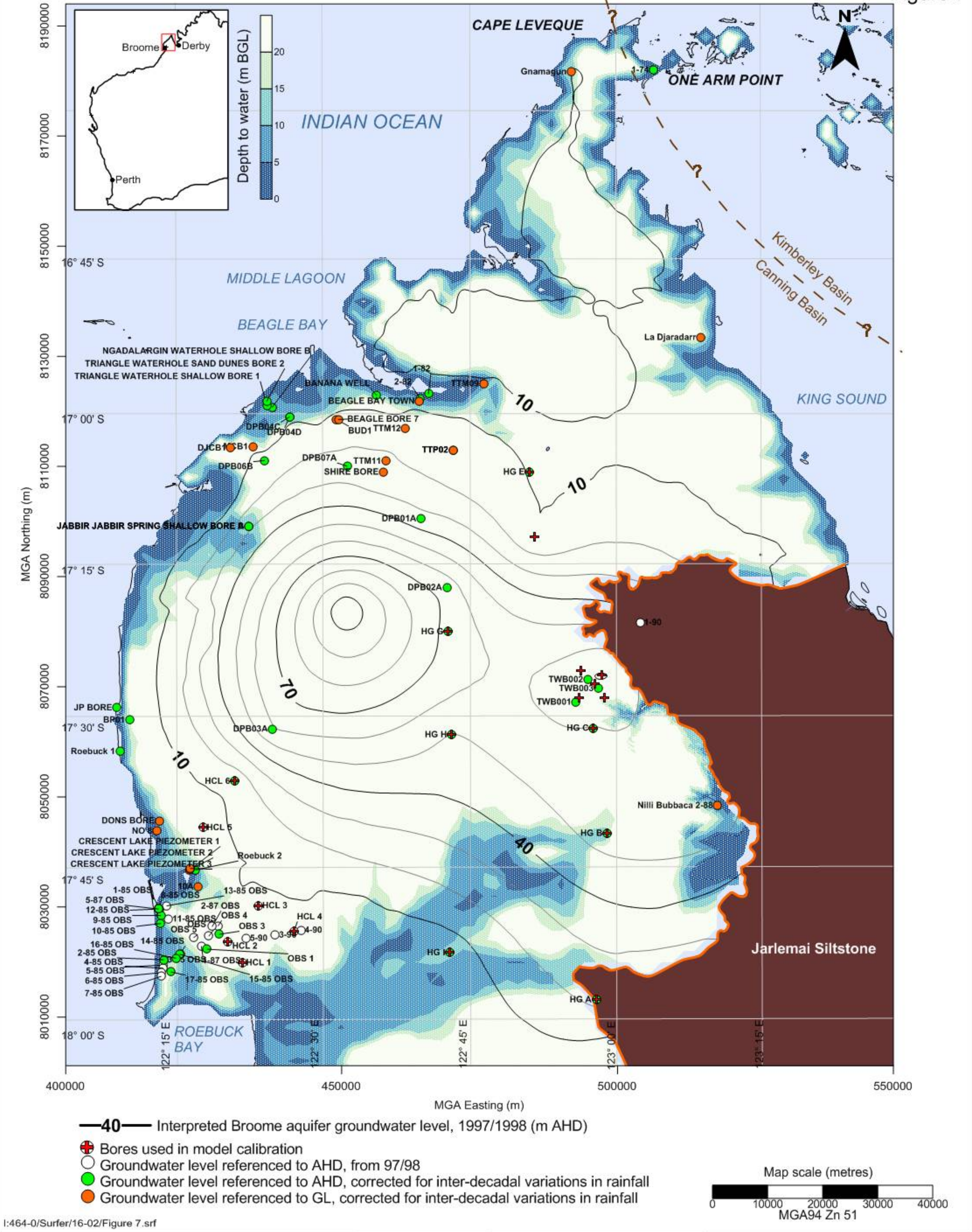
Date: October 2016

Dwg. No: 464-0/02/02-6

HYDROGEOLOGICAL CROSS-SECTIONS A-A' AND B-B'

Rockwater

Figure 7



CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

DATE: October 2016

Dwg No: 464-0/16/02-7

REGIONAL BROOME AQUIFER GROUNDWATER CONTOURS (YEAR 1997/1998)

Rockwater PROPRIETARY LIMITED

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

DATE: September 2016

Dwg No: 464-0/16/02-8

464-0/Grapher/16-02/Figure 08.grf

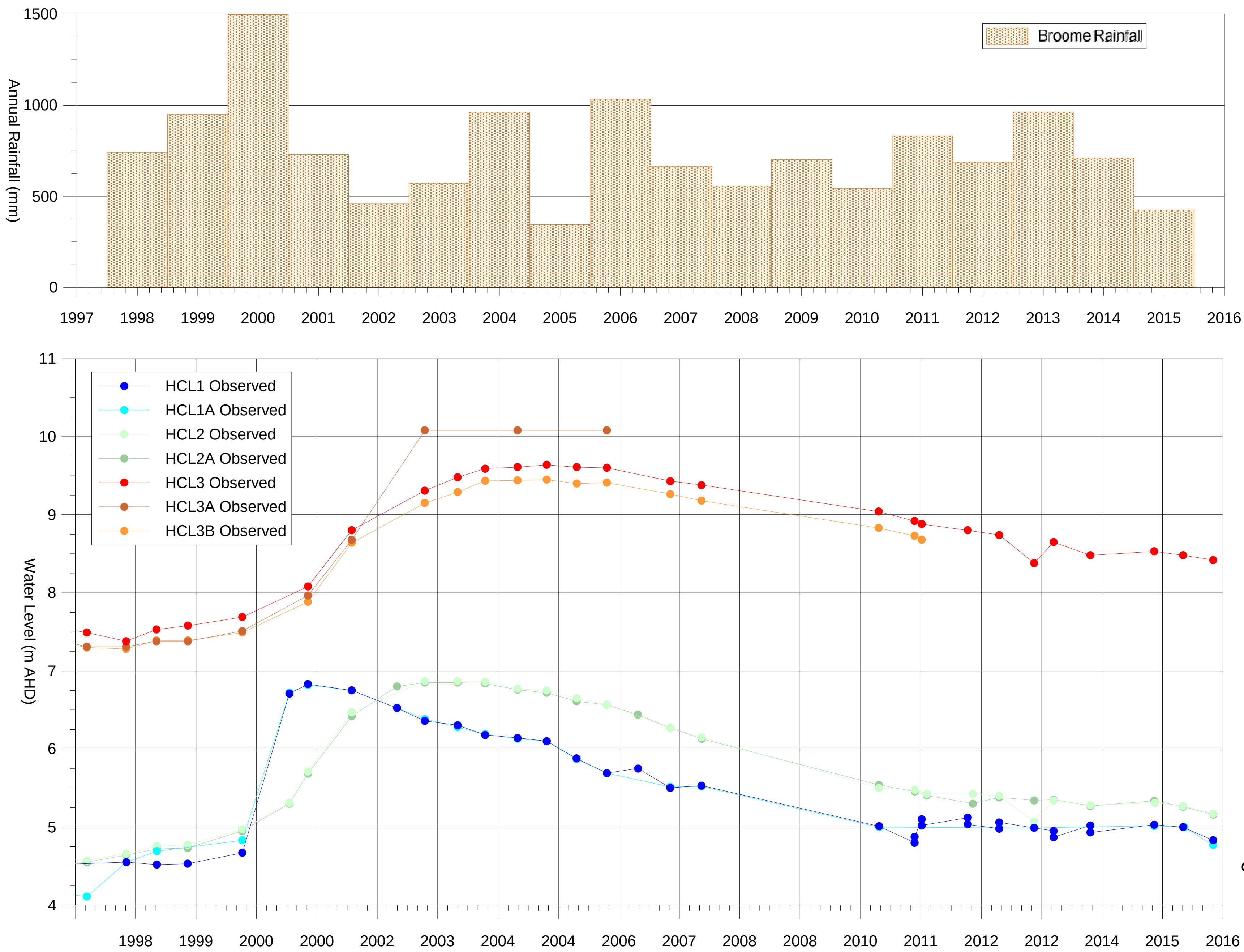


Figure 8

HCL 1, HCL 2 AND HCL 3
TEMPORAL GROUNDWATER LEVELS

Rockwater
PROPRIETARY LIMITED

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

DATE: September 2016

Dwg No: 464-0/16/02-9

464-0/Grapher/16-02/Figure 09.grf

HCL 4, HCL 5 AND HCL 6 TEMPORAL GROUNDWATER LEVELS

Rockwater

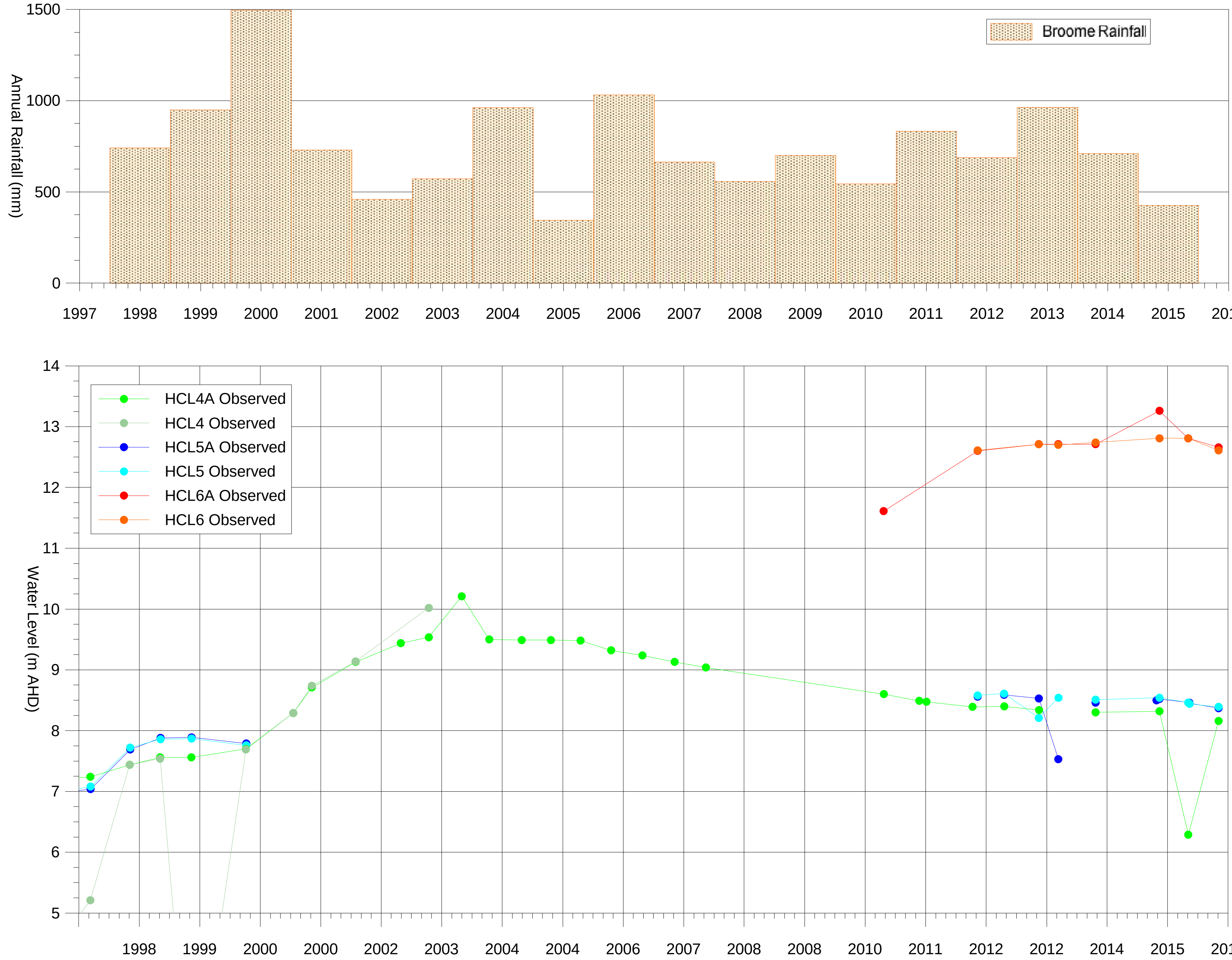


Figure 9

CLIENT: Sheffield Resources

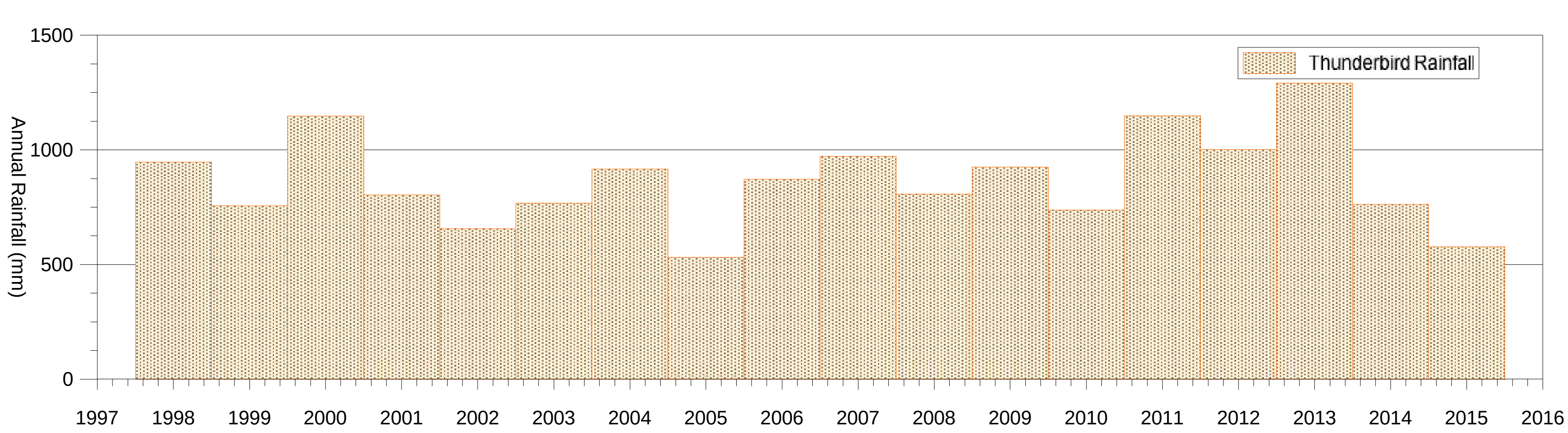
PROJECT: Thunderbird H3 hydrogeological assessment

DATE: September 2016

Dwg No: 464-0/16/02-10

HG B AND HG H
TEMPORAL GROUNDWATER LEVELS

Rockwater



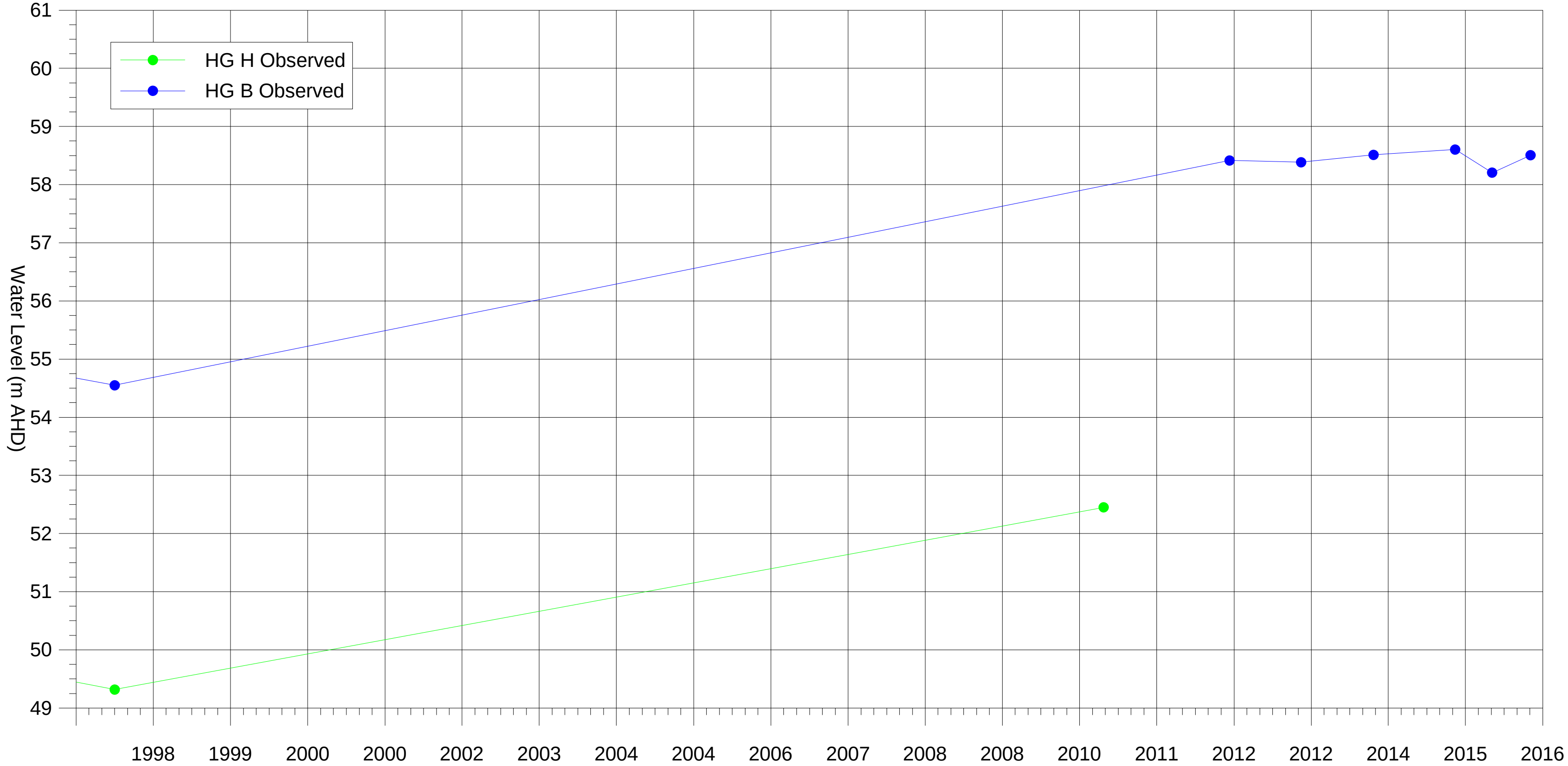
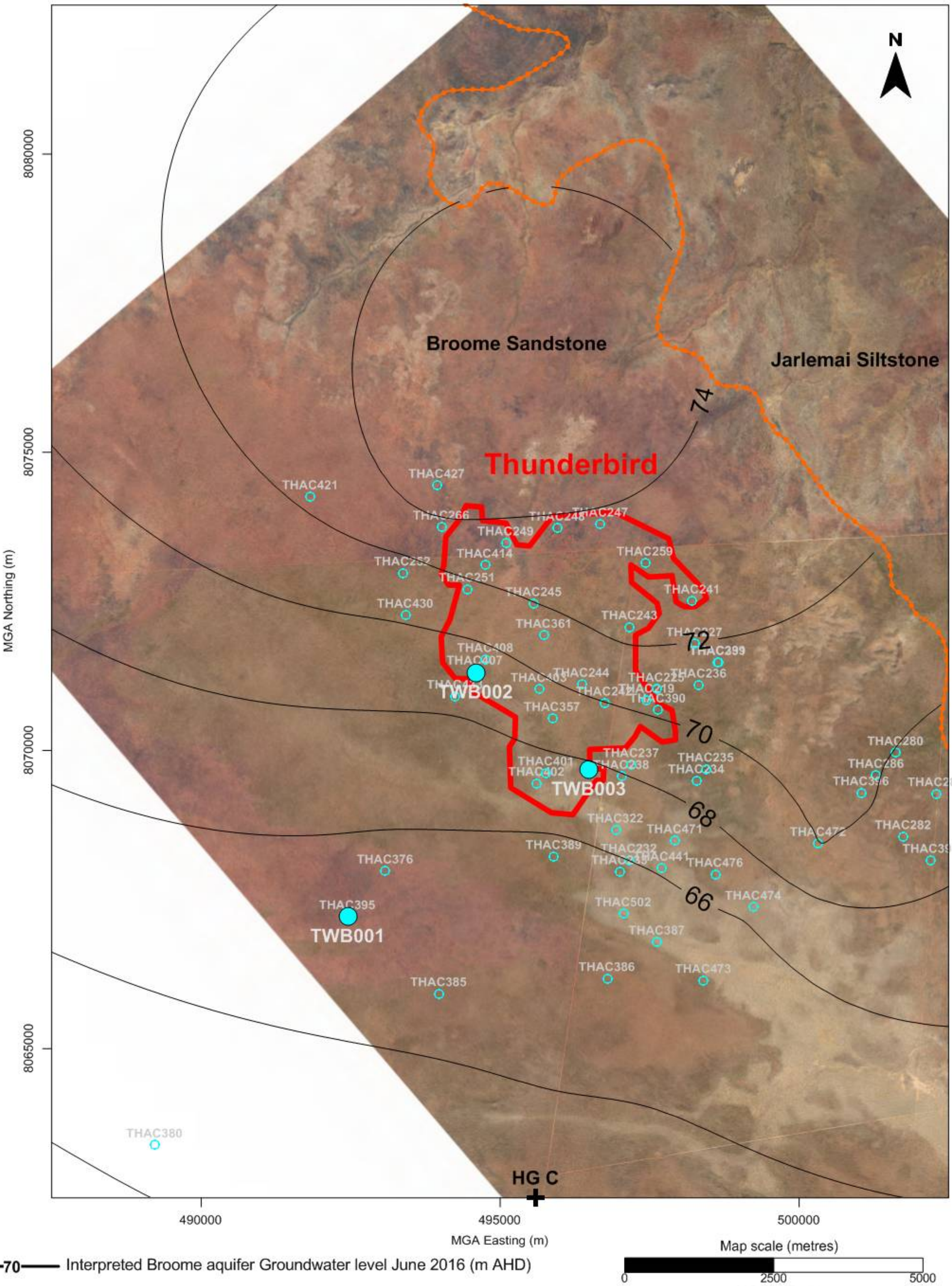


Figure 10

Figure 11



—70— Interpreted Broome aquifer Groundwater level June 2016 (m AHD)

Map scale (metres)

0 2500 5000

MGA94 Zn 51

I:464-0/Surfer/16-01/Figure 11.srf

CLIENT: Sheffield Ressources

PROJECT: Thunderbird H3 hydrogeological assessment

DATE: October 2016

Dwg No: 464-0/16/02-11

MINE AREA BROOME AQUIFER GROUNDWATER CONTOURS (2016)

Rockwater PROPRIETARY LIMITED

CLIENT: Sheffield Resources
PROJECT: Thunderbird H3 hydrogeological assessment Report
DATE: September 2016
DwgNo:464-0/16/02-12

THAC252, THAC357 AND THAC376 TEMPORAL WATER LEVELS

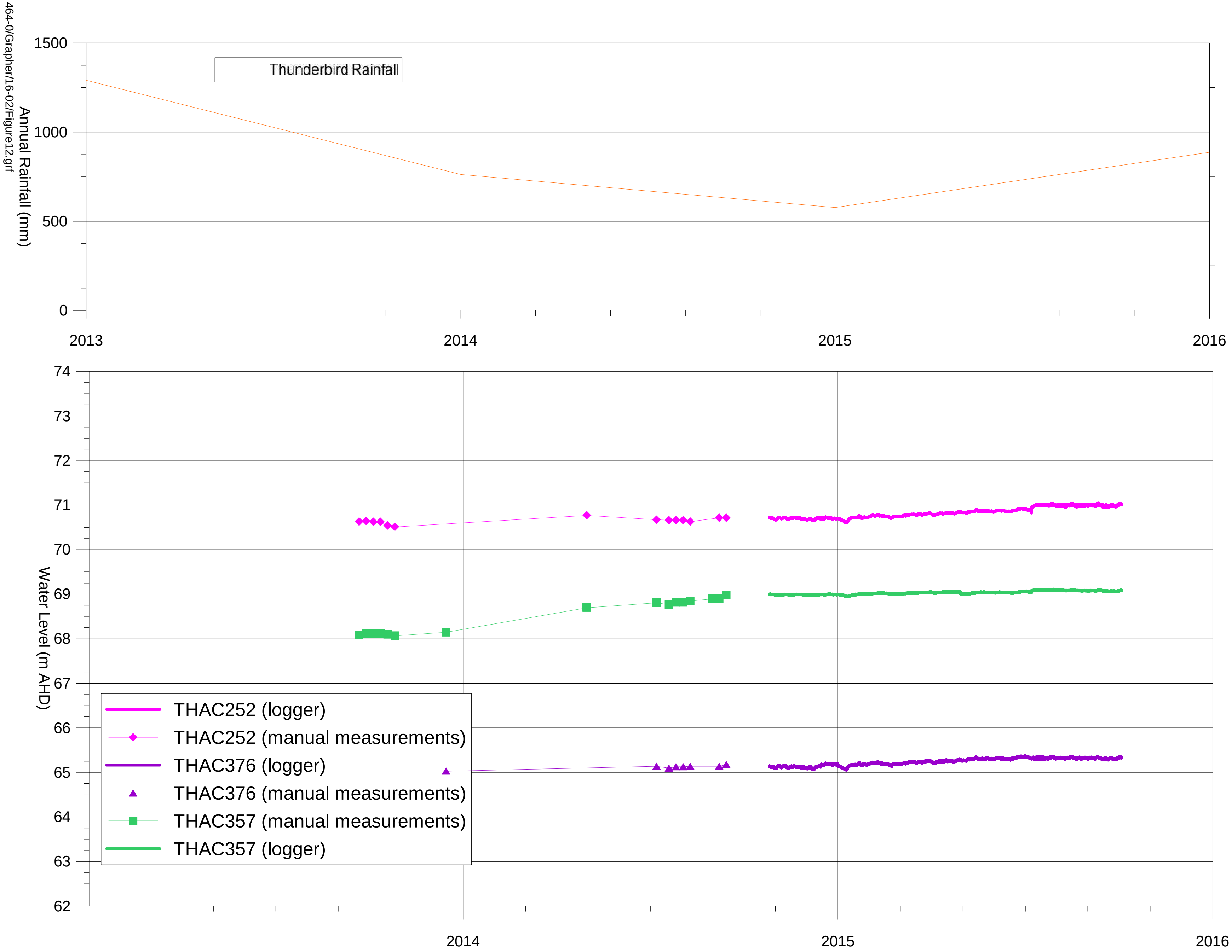


Figure12

Rockwater PROPRIETARY LIMITED

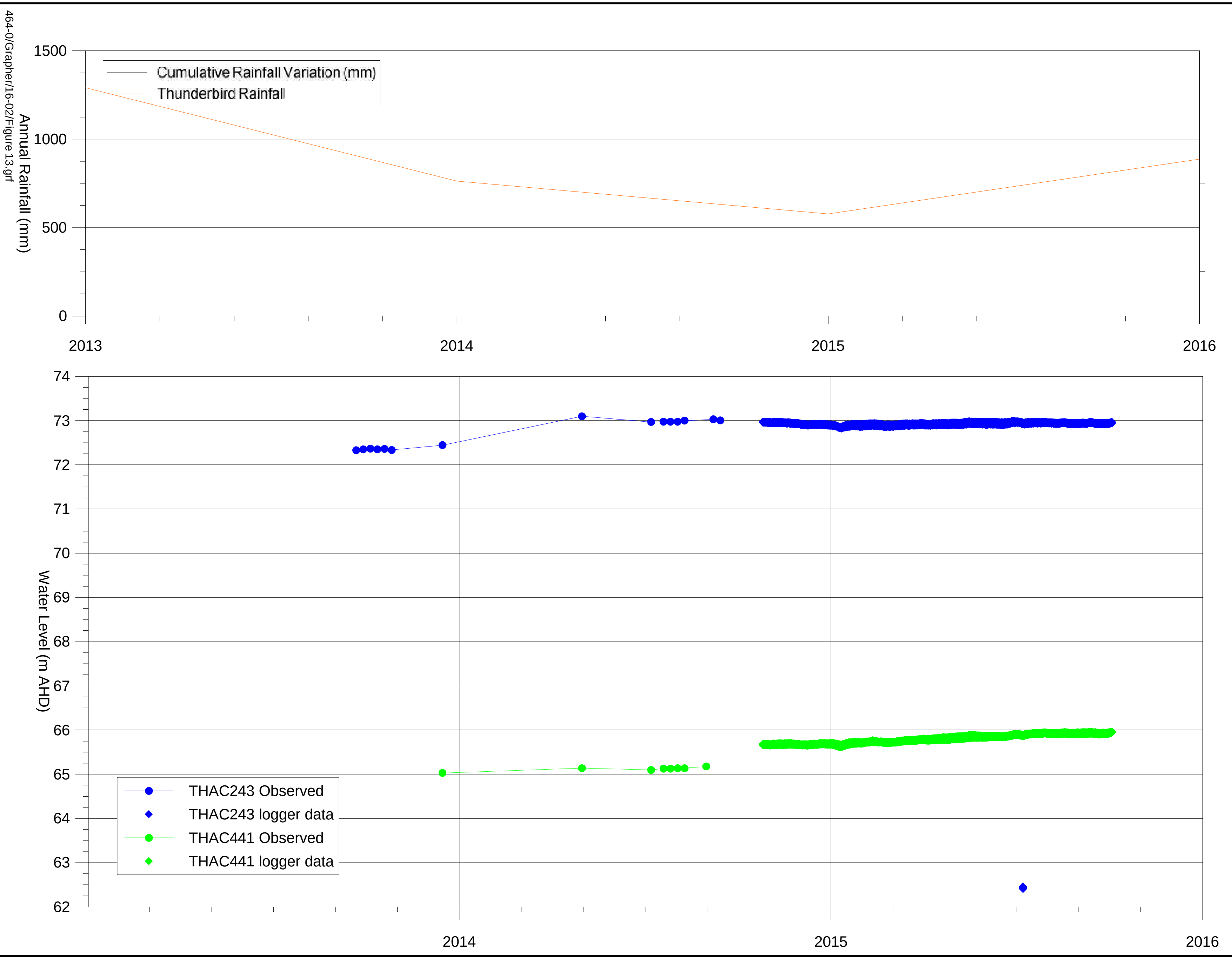


Figure 13

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

DATE: September 2016

Dwg No: 464-0/16/02-13

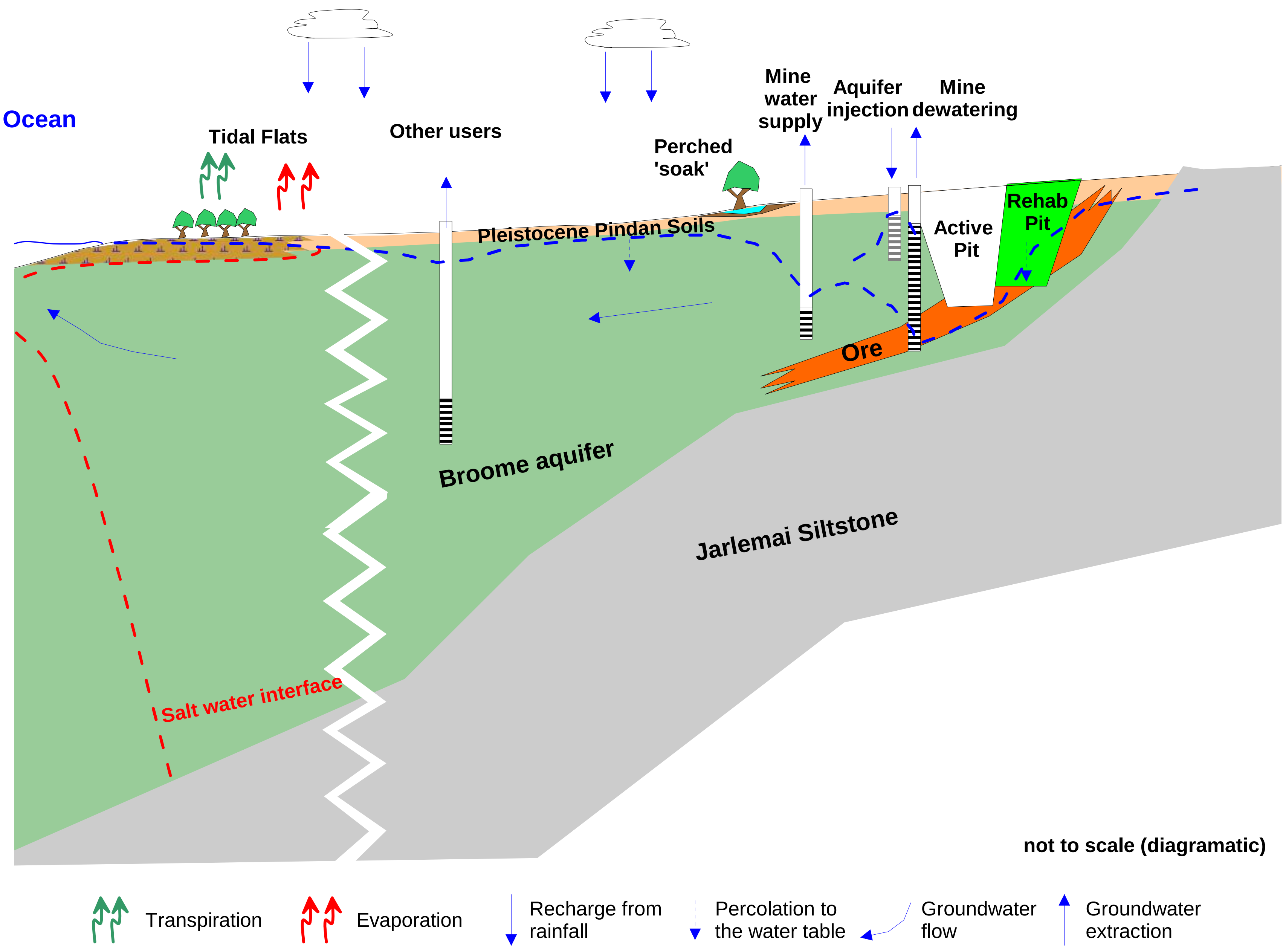
THAC243, THAC441
TEMPORAL WATER LEVELS

Rockwater PROPRIETARY LIMITED

CLIENT: Sheffield Resources
PROJECT: Thunderbird H3 hydrogeological assessment
DATE: October 2016
Dwg No: 464-0/16/02-14

I:464-0/Surfer/16-02/Figure 14.srf

DAMPIER PENINSULA

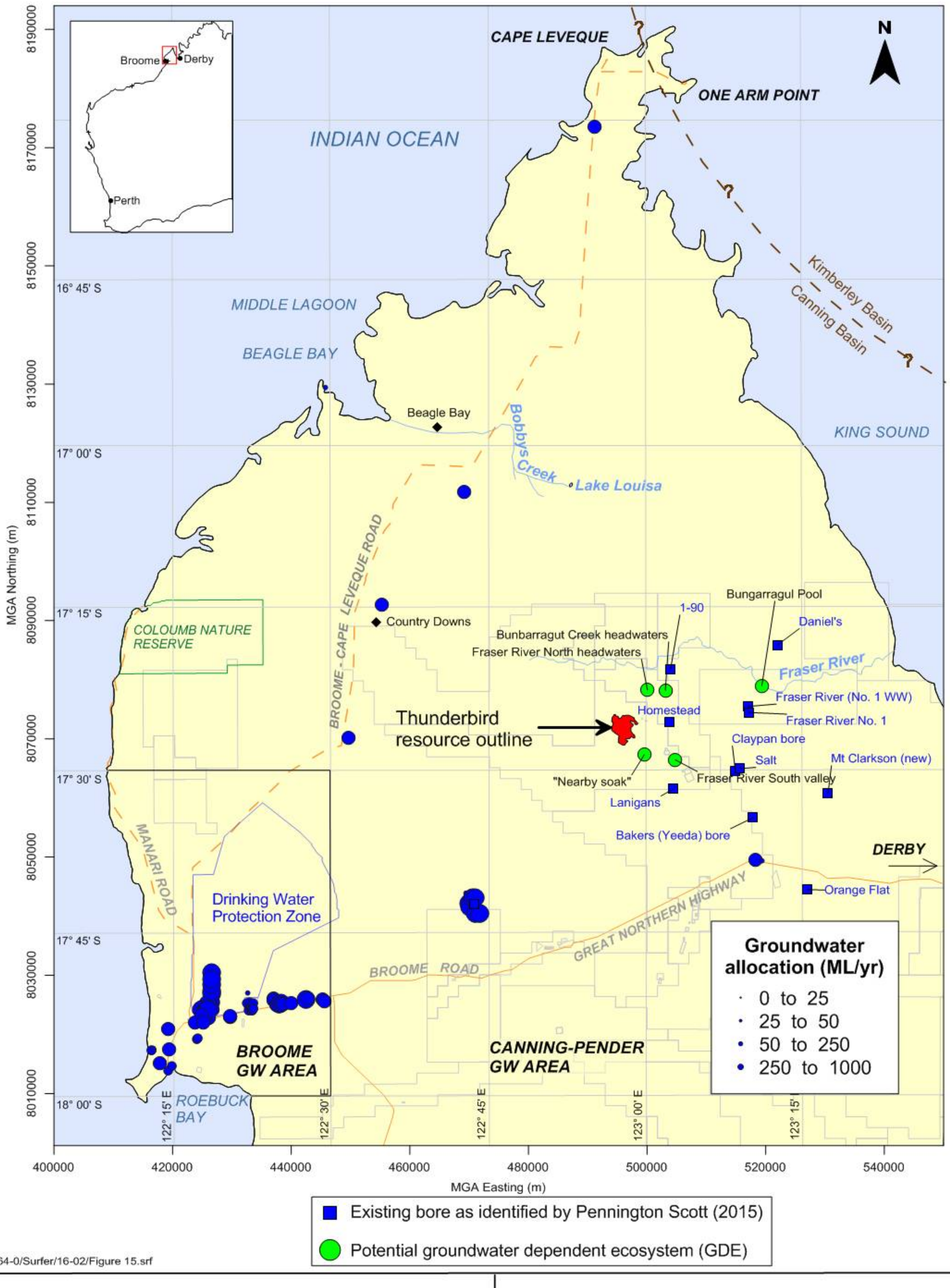


CONCEPTUAL HYDROGEOLOGICAL CROSS SECTION

Rockwater PROPRIETARY LIMITED

Figure 14

Figure 15

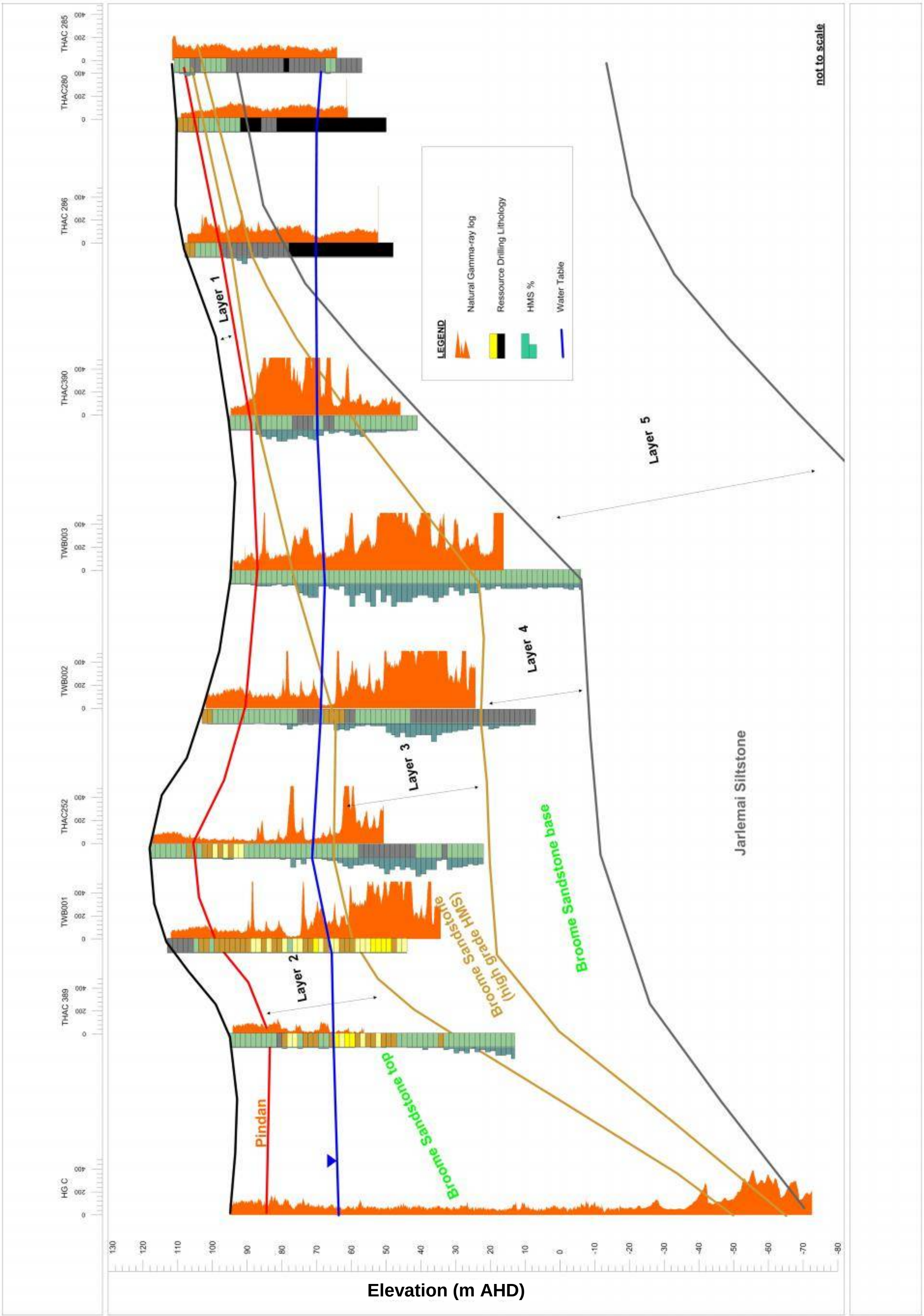


I:464-0/Surfer/16-02/Figure 15.srf

CLIENT: Sheffield Resources PROJECT: Thunderbird H3 hydrogeological assessment DATE: October 2016 Dwg No: 464-0/16/02-15	OTHER GROUNDATER USERS AND POTENTIAL GDES

Rockwater PROPRIETARY LIMITED

Figure 16



I:464-0/Surfer/16-01/Figure 16.srf

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

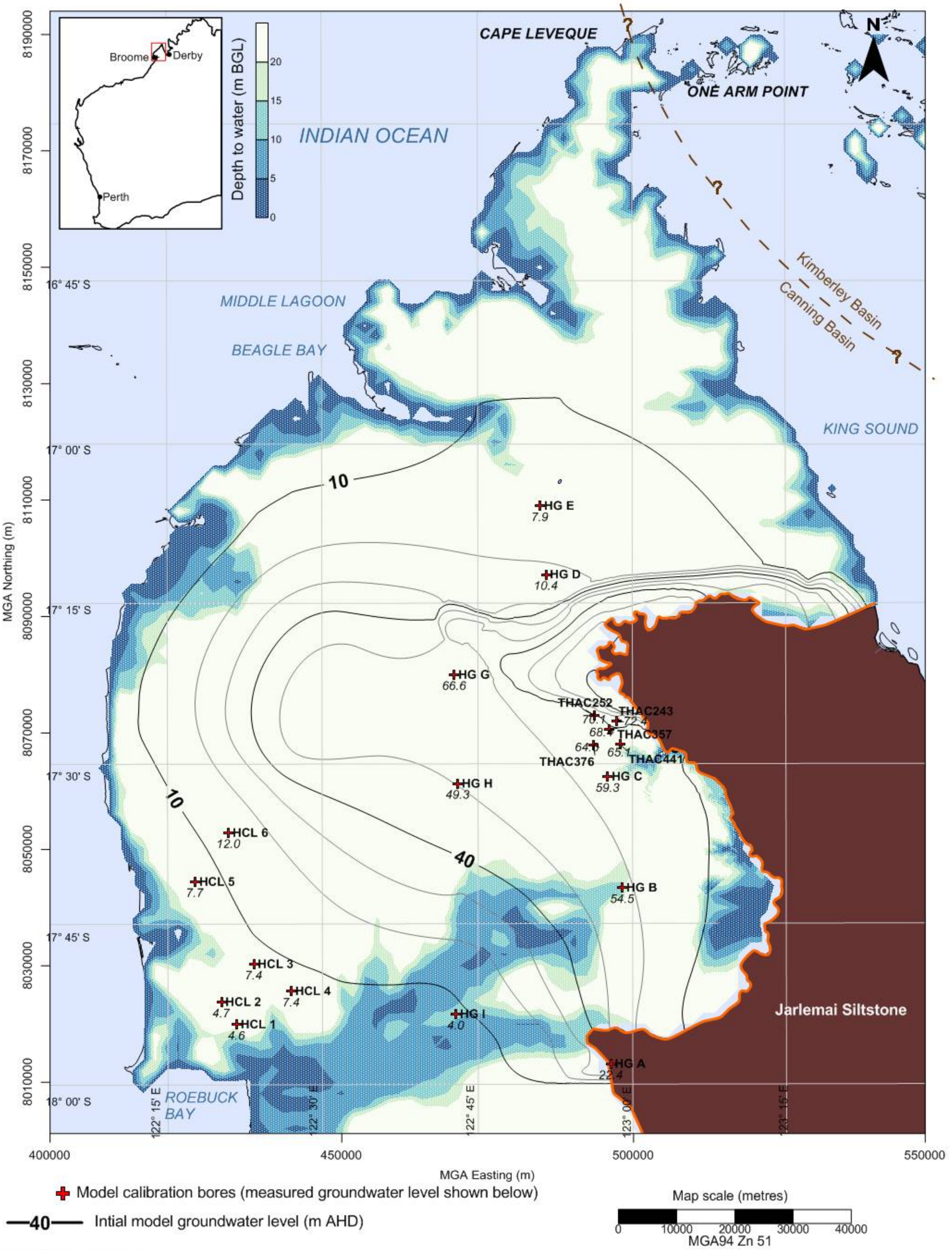
DATE: October 2016

Dwg No: 464-0/16/02-16

THUNDERBIRD PROJECT
GEOPYSICAL CORRELATIONS

Rockwater
PROPRIETARY LIMITED

Figure 17



I:464-0/Surfer/16-02/Figure 17.srf

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

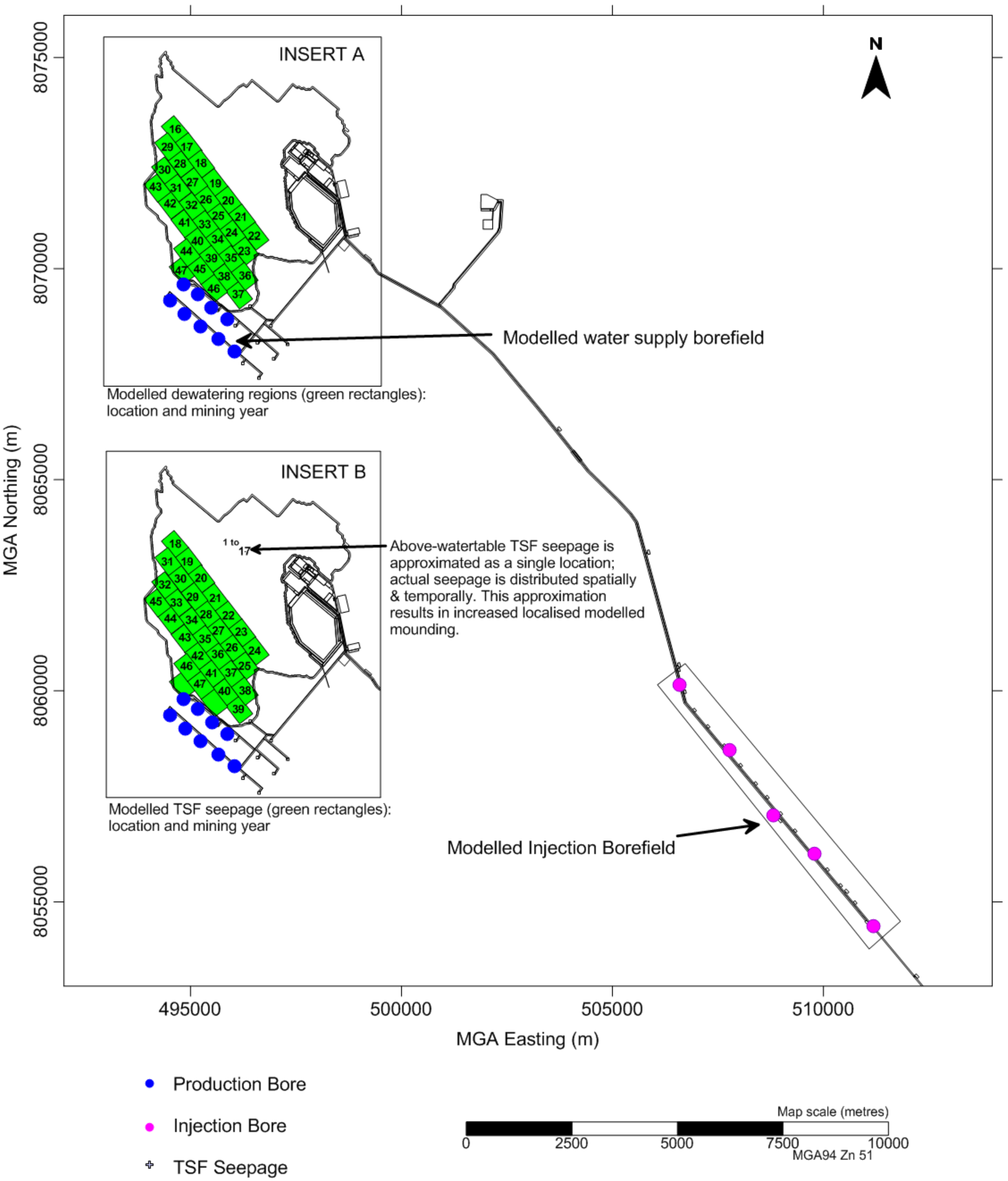
DATE: October 2016

Dwg No: 464-0/16/02-17

MEASURED GROUNDWATER LEVELS AND MODEL INITIAL CONDITIONS, 1997/98

Rockwater PROPRIETARY LIMITED

Figure 18



I:464-0/Surfer/16-02 H3/Fig 18.srf

CLIENT: Sheffield Ressources

PROJECT: Thunderbird H3 Assessment

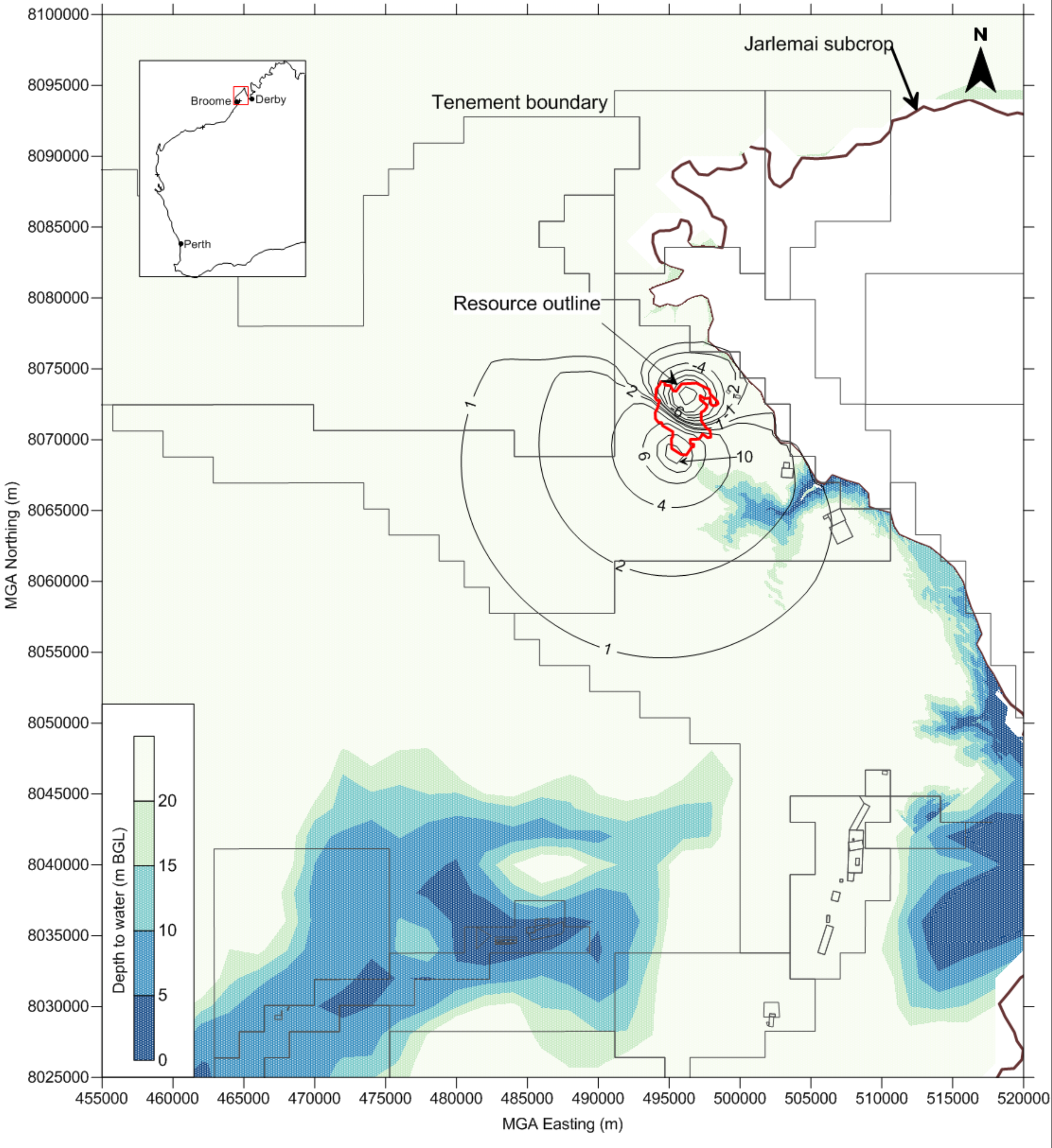
DATE: December 2016

Dwg No: 464-0/16/01-18

MODELLED DEWATERING, SEEPAGE AND BOREFIELD LOCATIONS

Rockwater PROPRIETARY LIMITED

Figure 19



I:464-0/Surfer/16-02 H3/Figure 19.srf

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

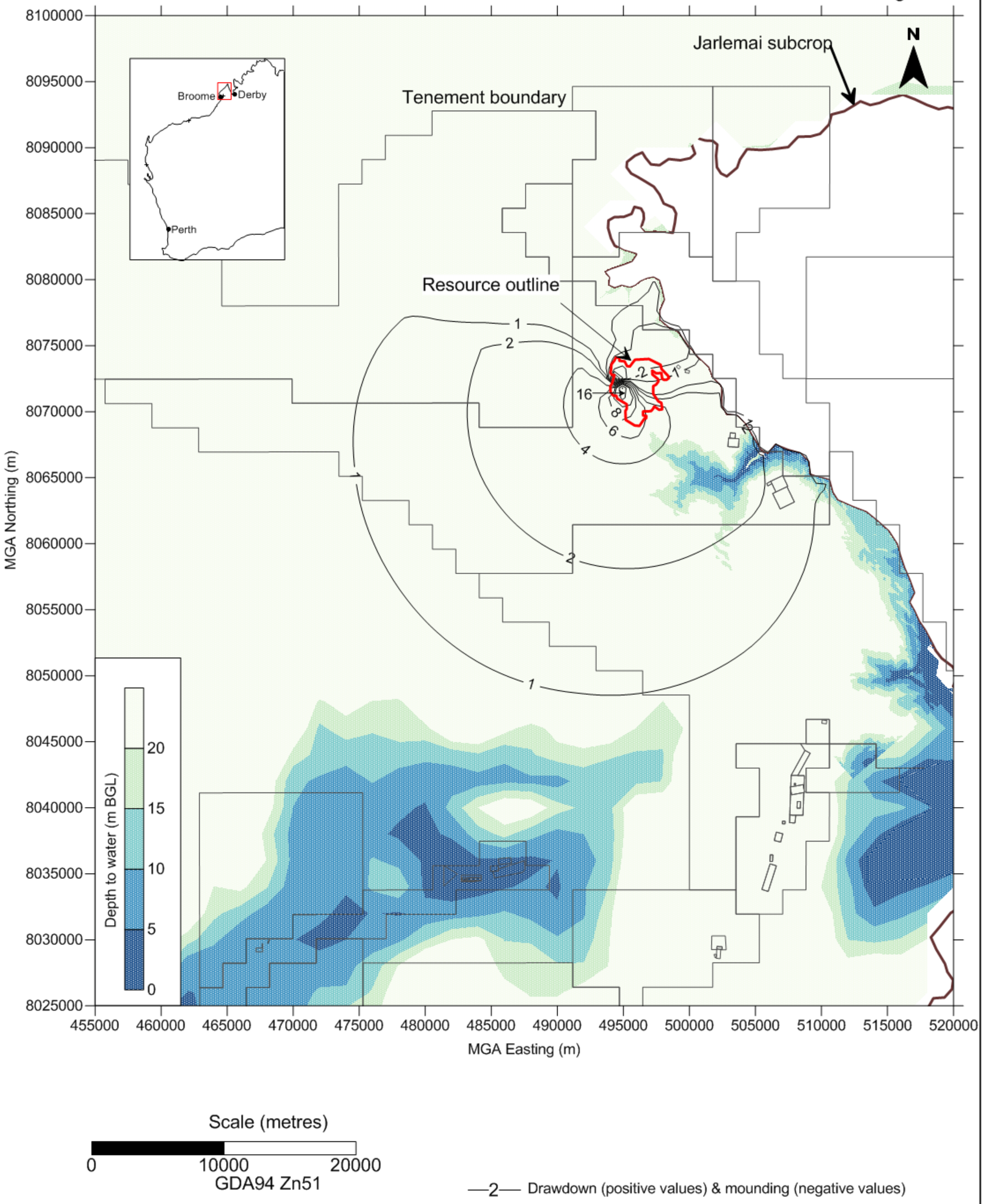
DATE: December 2016

Dwg No: 464-0/16/02-19

MODELLED DRAWDOWN AND MOUNDING, YEAR 15

Rockwater PROPRIETARY LIMITED

Figure 20



I:464-0/Surfer/16-02 H3/Figure 20.srf

CLIENT: Sheffield Resources

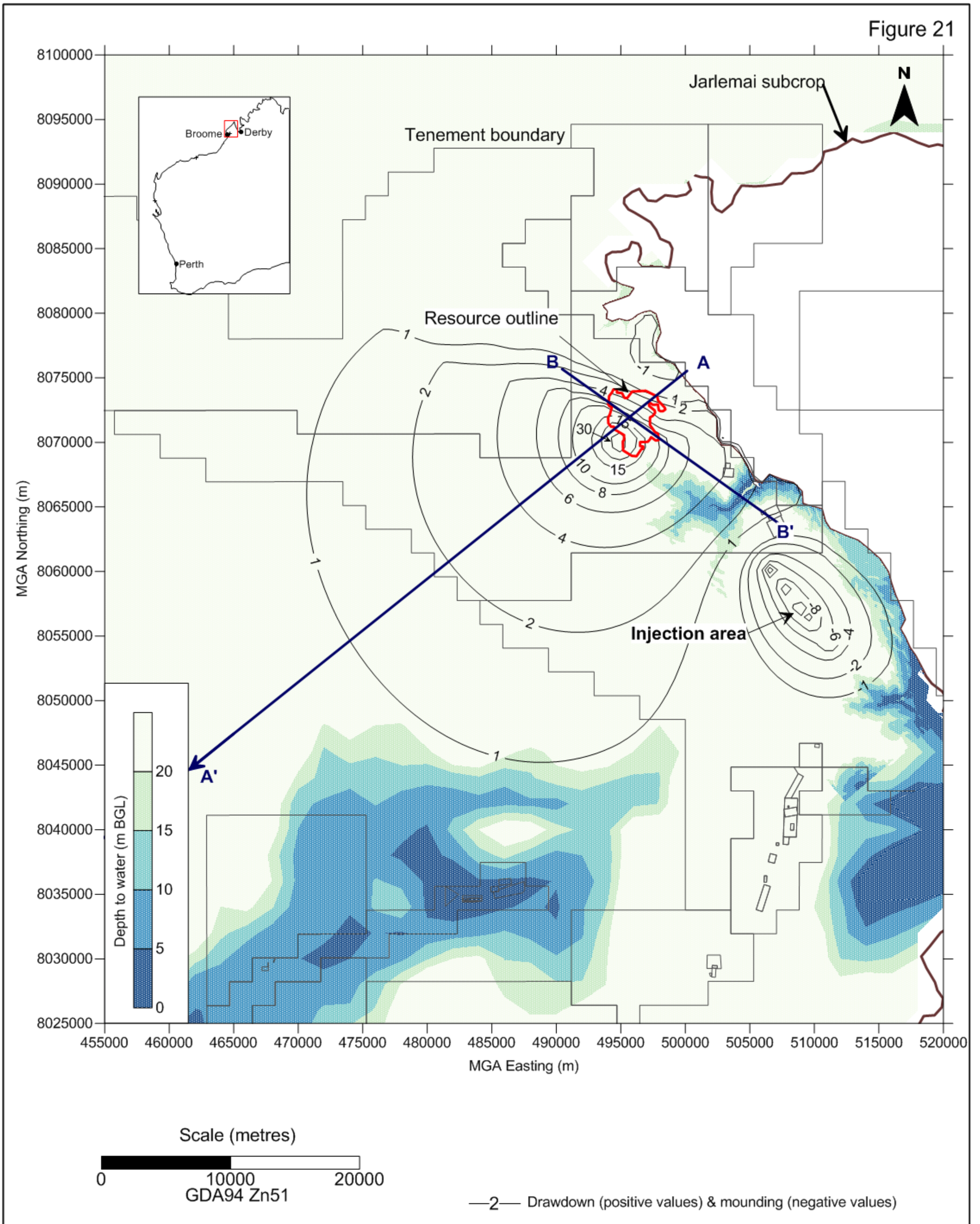
PROJECT: Thunderbird H3 hydrogeological assessment

DATE: December 2016

Dwg No: 464-0/16/02-20

MODELLED DRAWDOWN AND MOUNDING, YEAR 32

Rockwater PROPRIETARY LIMITED



I:464-0/Surfer/16-02 H3/Figure 21.srf

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

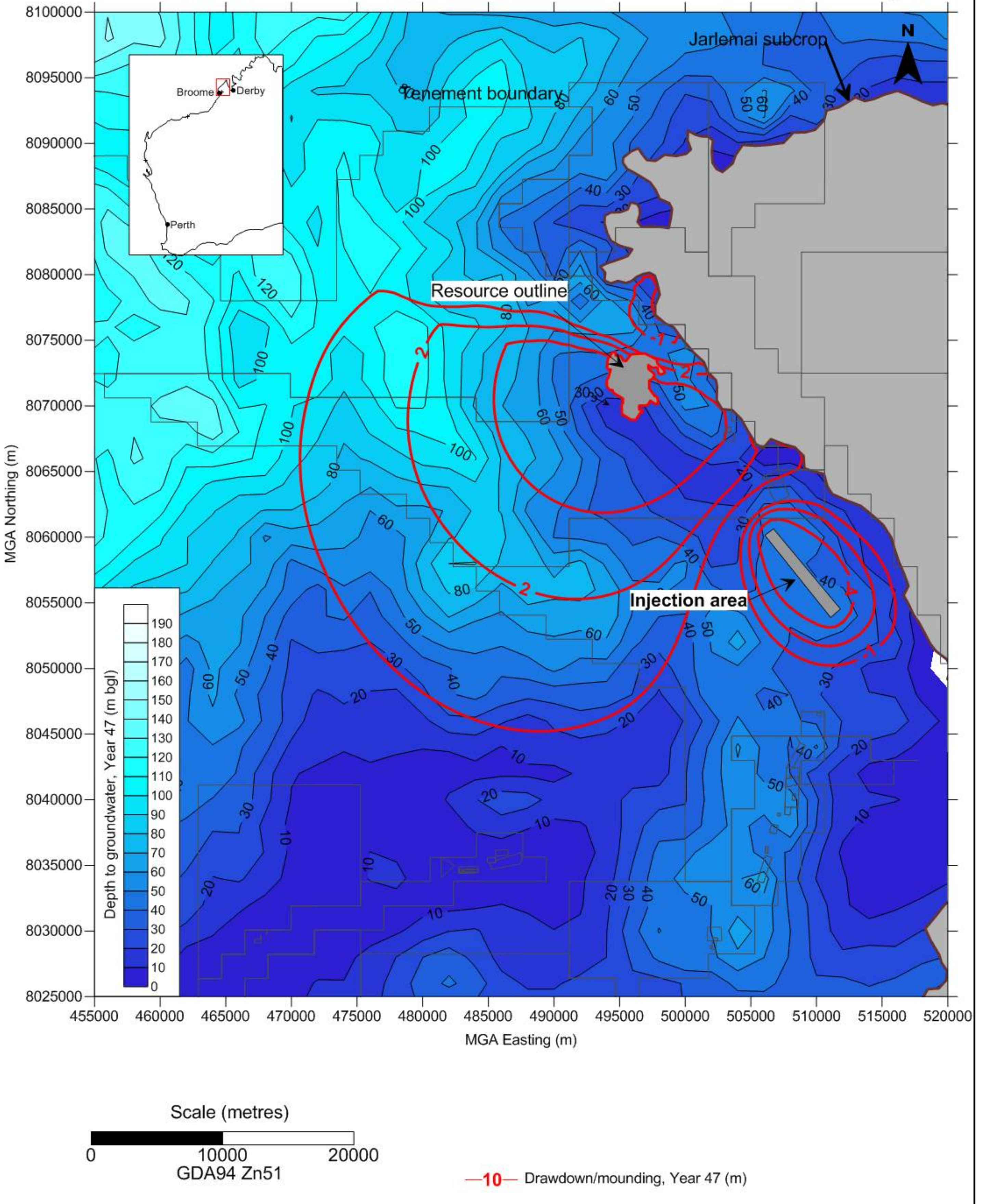
DATE: December 2016

Dwg No: 464-0/16/02-21

MODELLED DRAWDOWN AND MOUNDING, YEAR 47

Rockwater PROPRIETARY LIMITED

Figure 22



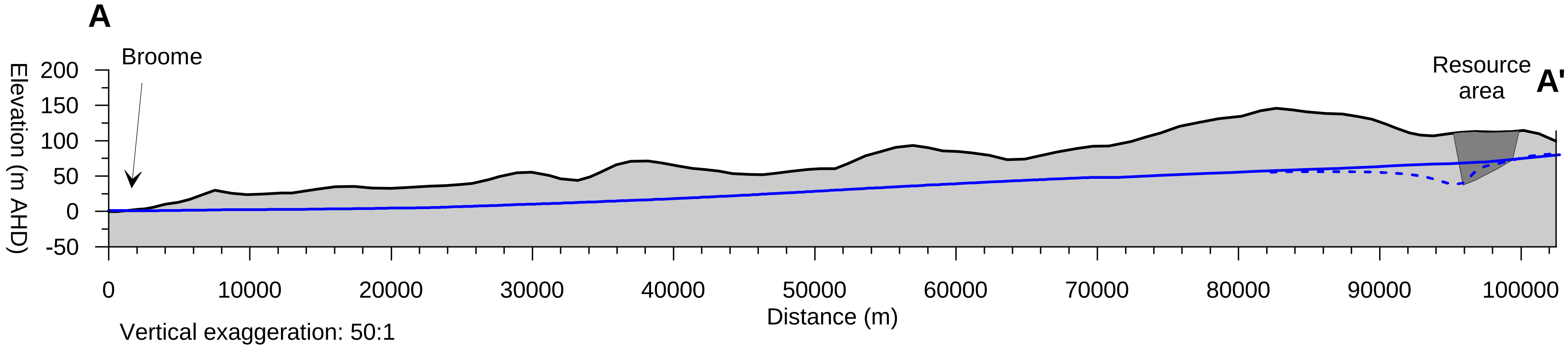
I:464-0/Surfer/16-02 H3/Figure 22.srf

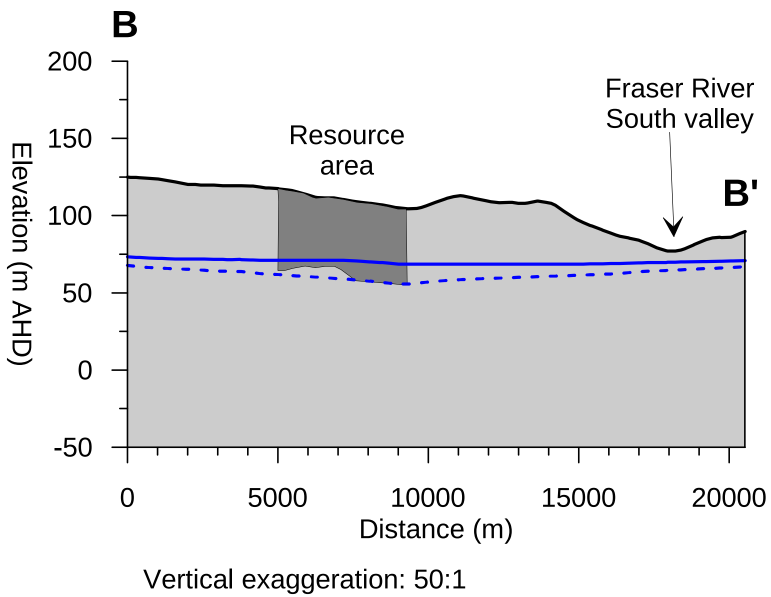
CLIENT: Sheffield Resources PROJECT: Thunderbird H3 hydrogeological assessment DATE: December 2016 Dwg No: 464-0/16/02-22	MODELLED DEPTH TO GROUNDWATER, YEAR 47 Rockwater PROPRIETARY LIMITED

CLIENT: Sheffield Resources
PROJECT: Thunderbird H3 hydrogeological assessment
DATE: October 2016
Dwg No: 464-0/16/2-23

464-0/Grapher/Figure 23.grf

DRAWDOWN CROSS SECTIONS





Groundwater level, pre-mining

Groundwater level, mining year 47

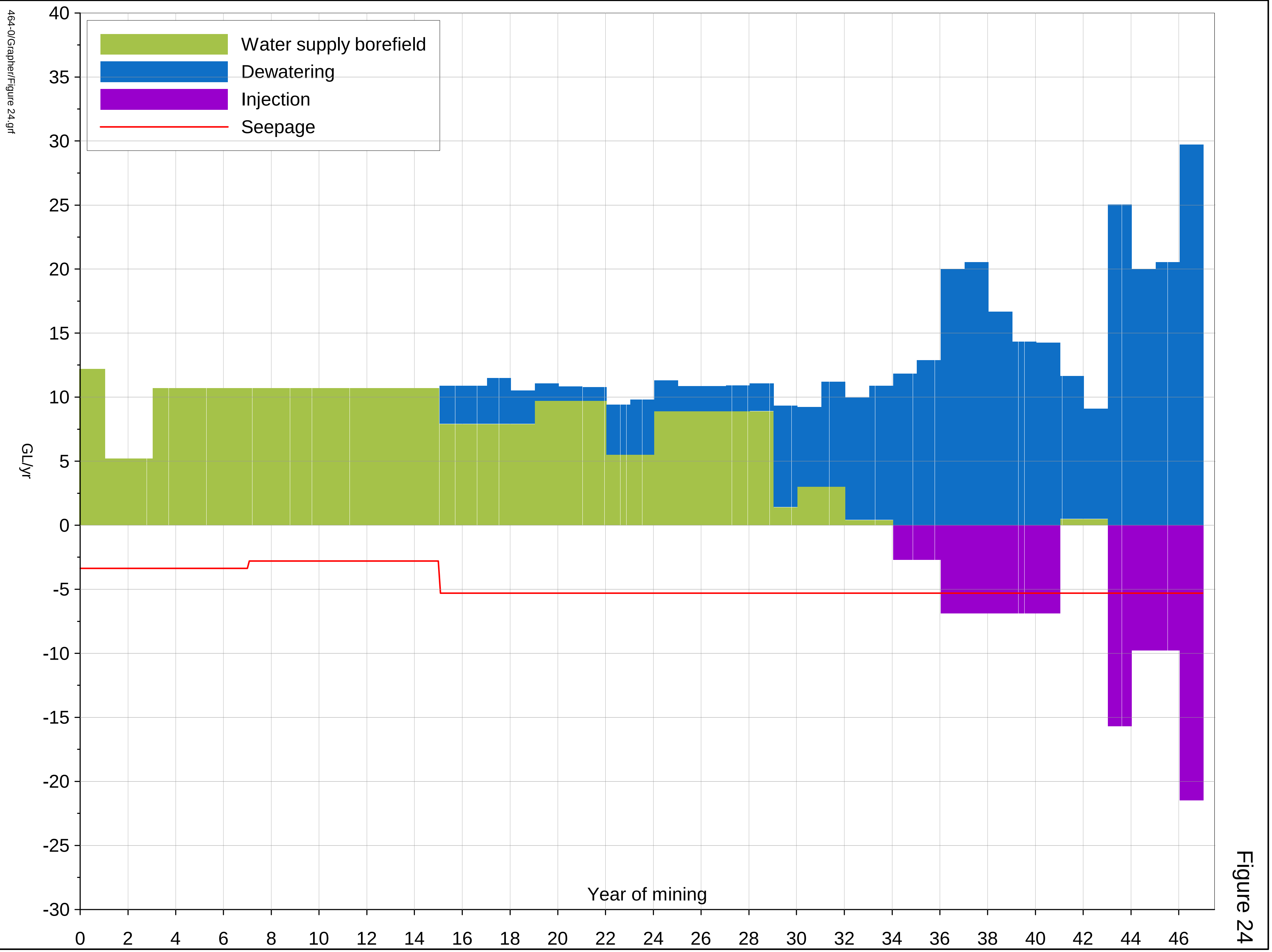
Section locations shown in Figure 23

Figure 23

Client: Sheffield Resources
Project : Thunderbird H3 hydrogeological assessment
Date : December 2016
Dwg. No: 464-0/16/1-24

PREDICTED WATER MANAGEMENT VOLUMES (BASE CASE)

Figure 24



Rockwater

Client: Sheffield Resources

Project : Thunderbird H3 hydrogeological assessment

Date : December 2016

Dwg. No: 464-0/16/1-25

PREDICTED PUMPING VOLUMES
(CLIMATE PREDICTIVE UNCERTAINTY
P10&P90)

Rockwater

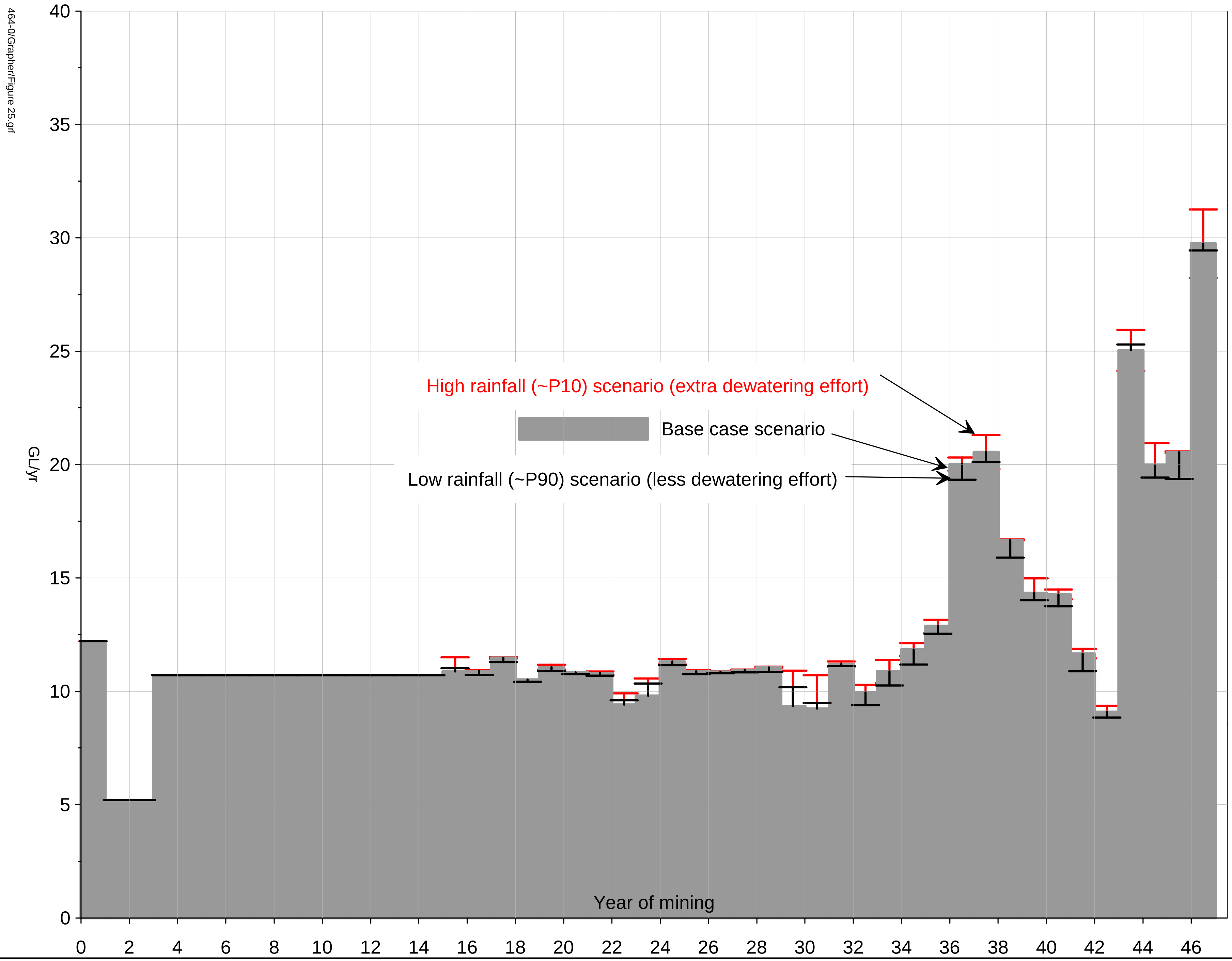
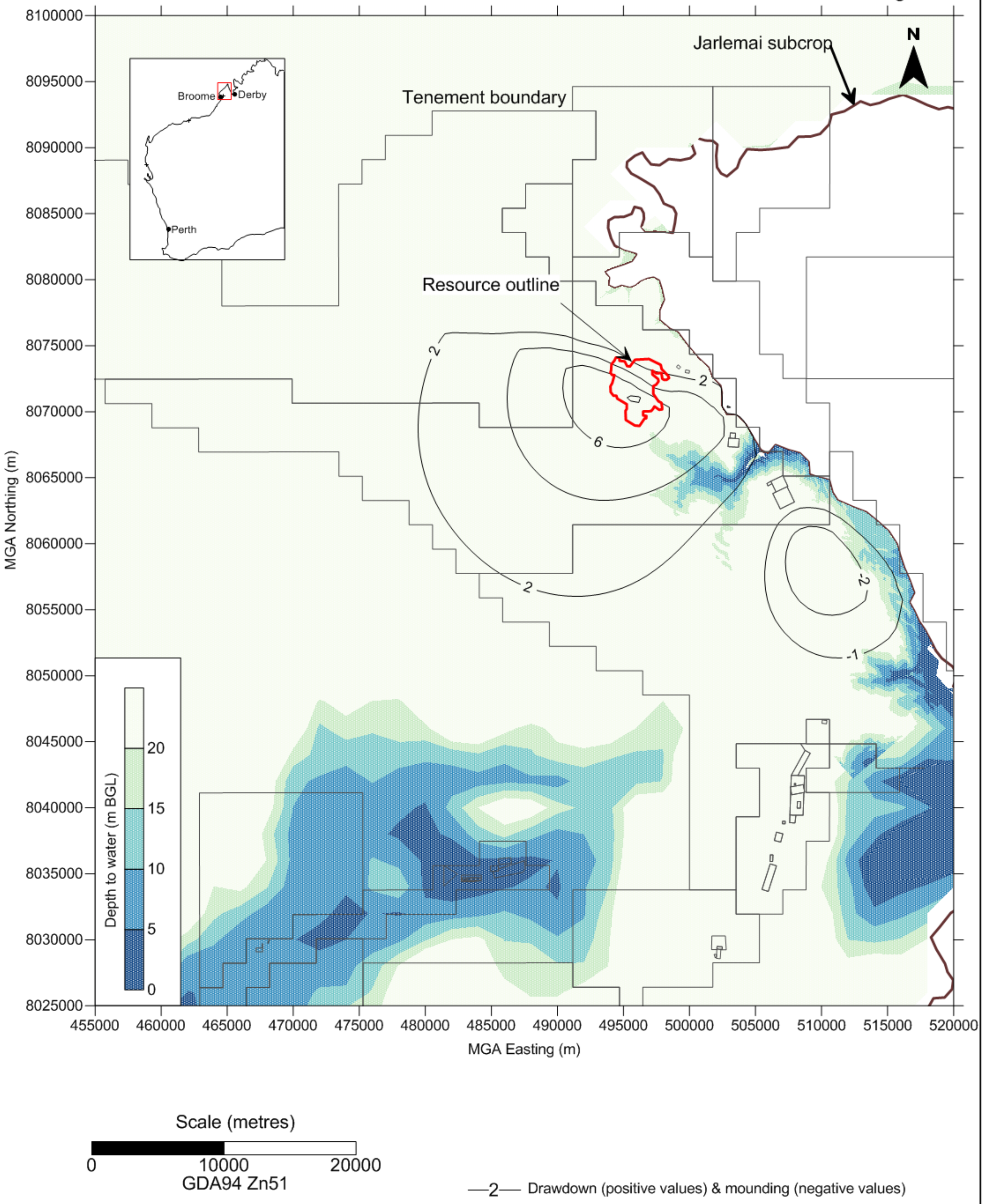


Figure 25

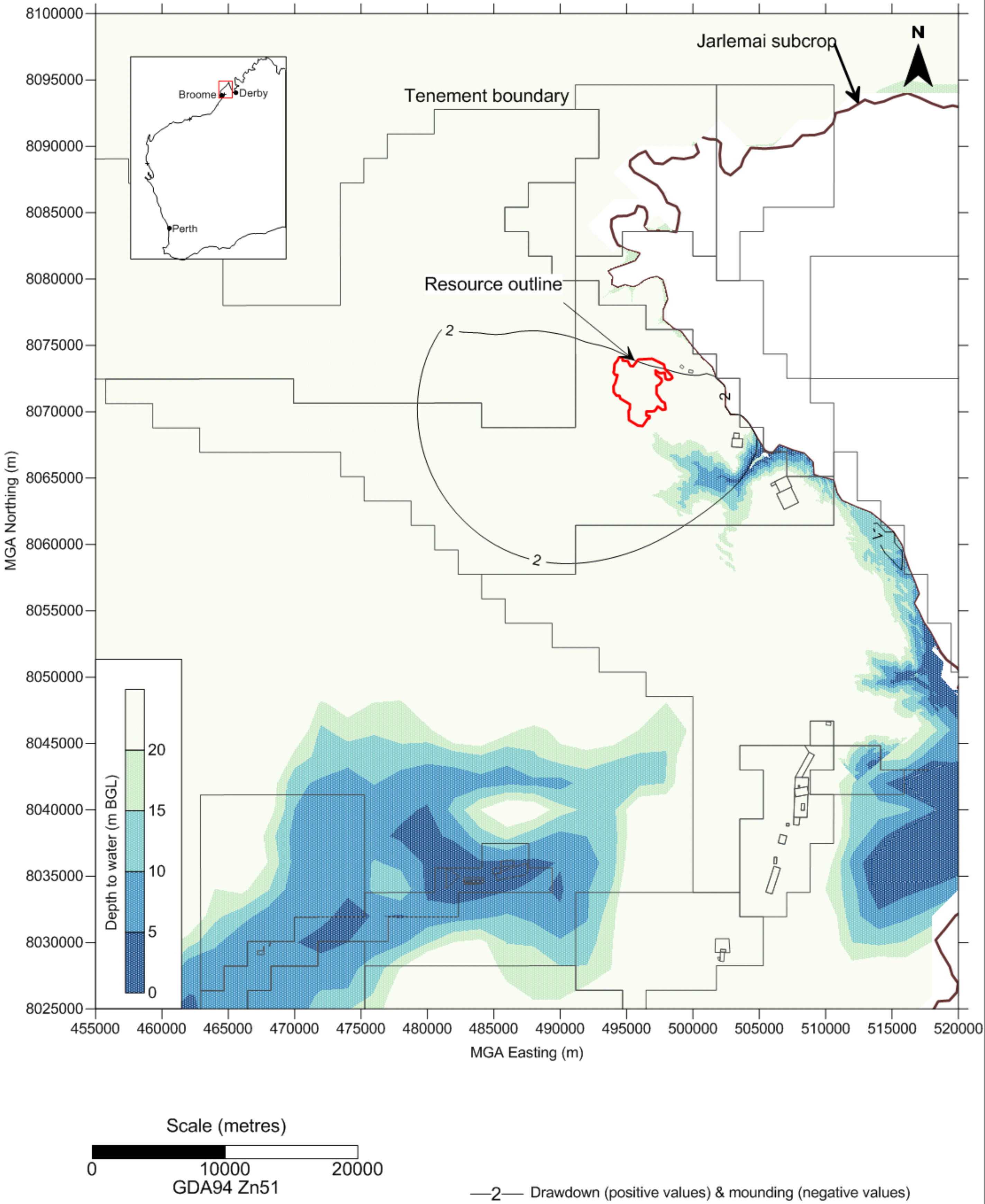
Figure 26



I:464-0/Surfer/16-02 H3/Figure 26.srf

CLIENT: Sheffield Resources PROJECT: Thunderbird H3 hydrogeological assessment DATE: December 2016 Dwg No: 464-0/16/02-26	AQUIFER RECOVERY, 2 YEARS POST MINING Rockwater PROPRIETARY LIMITED

Figure 27



I:464-0/Surfer/16-02 H3/Figure 27.srf

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

DATE: December 2016

Dwg No: 464-0/16/02-27

AQUIFER RECOVERY, 10 YEARS POST MINING

Rockwater PROPRIETARY LIMITED

Client: Sheffield Resources

Project: Thunderbird H3 hydrogeological assessment

Date : October 2016

Dwg. No: 464-0/16/2-28

464-0/Grapher/Figure 28.grf

DEWATERING UNCERTAINTY ANALYSIS, YEAR 40

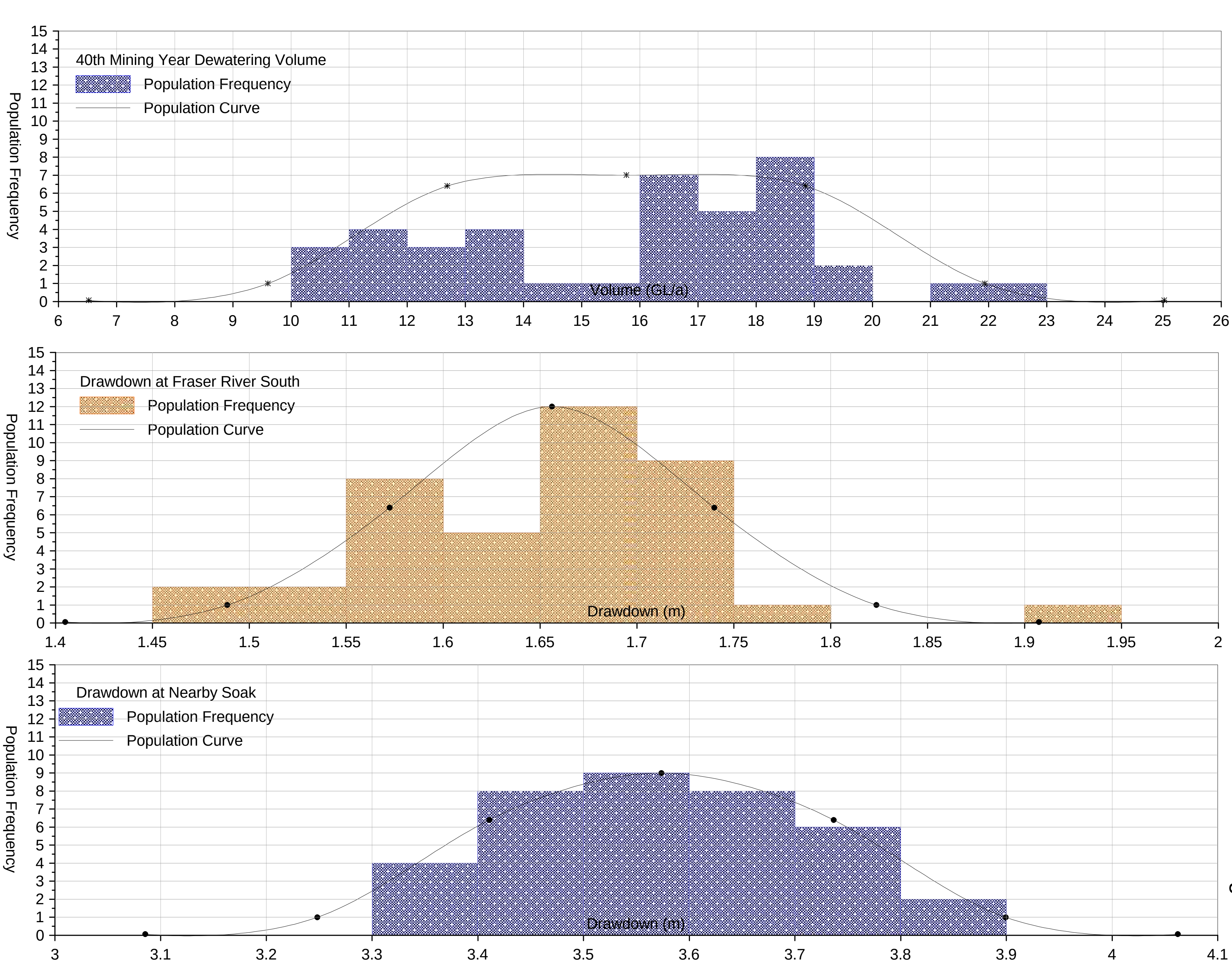
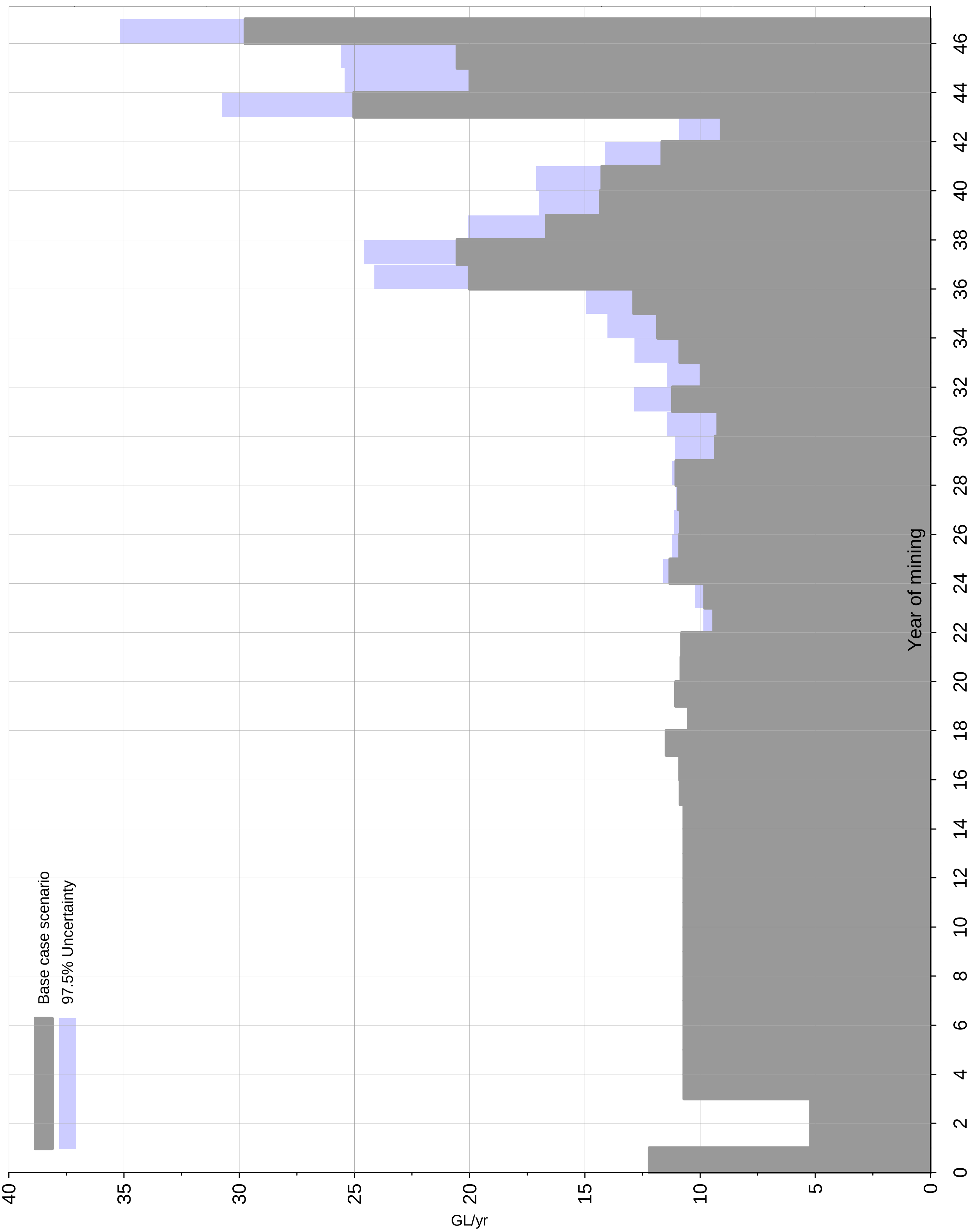


Figure 28

Figure 29



464-0/Grapher/Figure 29.grf

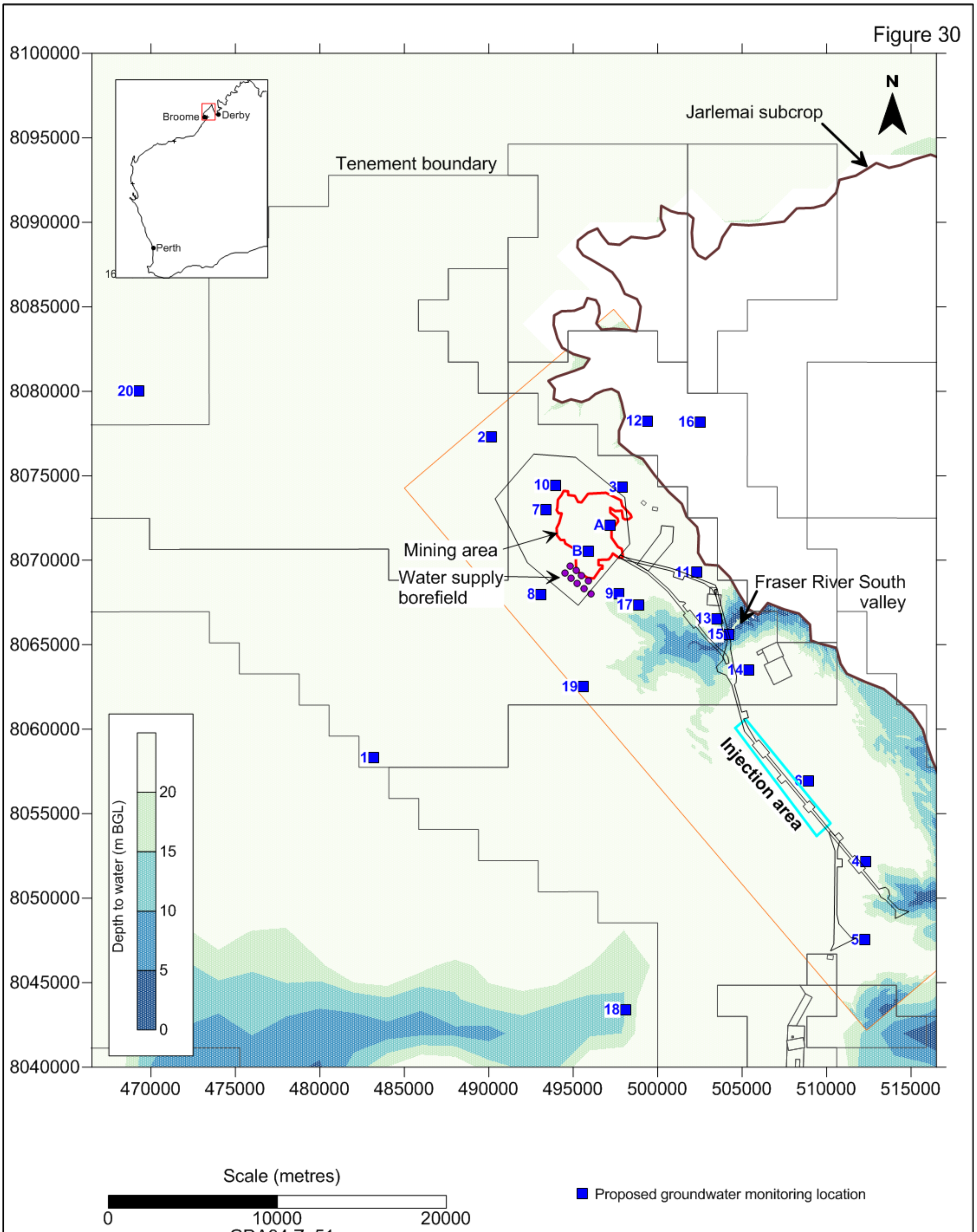
Client: Sheffield Resources

Project : Thunderbird H3 hydrogeological assessment

Date : December 2016

Dwg. No: 464-0/16/2-29

PREDICTED PUMPING VOLUMES (PARAMETER PREDICTIVE UNCERTAINTY P97.5)



I:464-0/Surfer/16-01/Figure 30.srf

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

DATE: December 2016

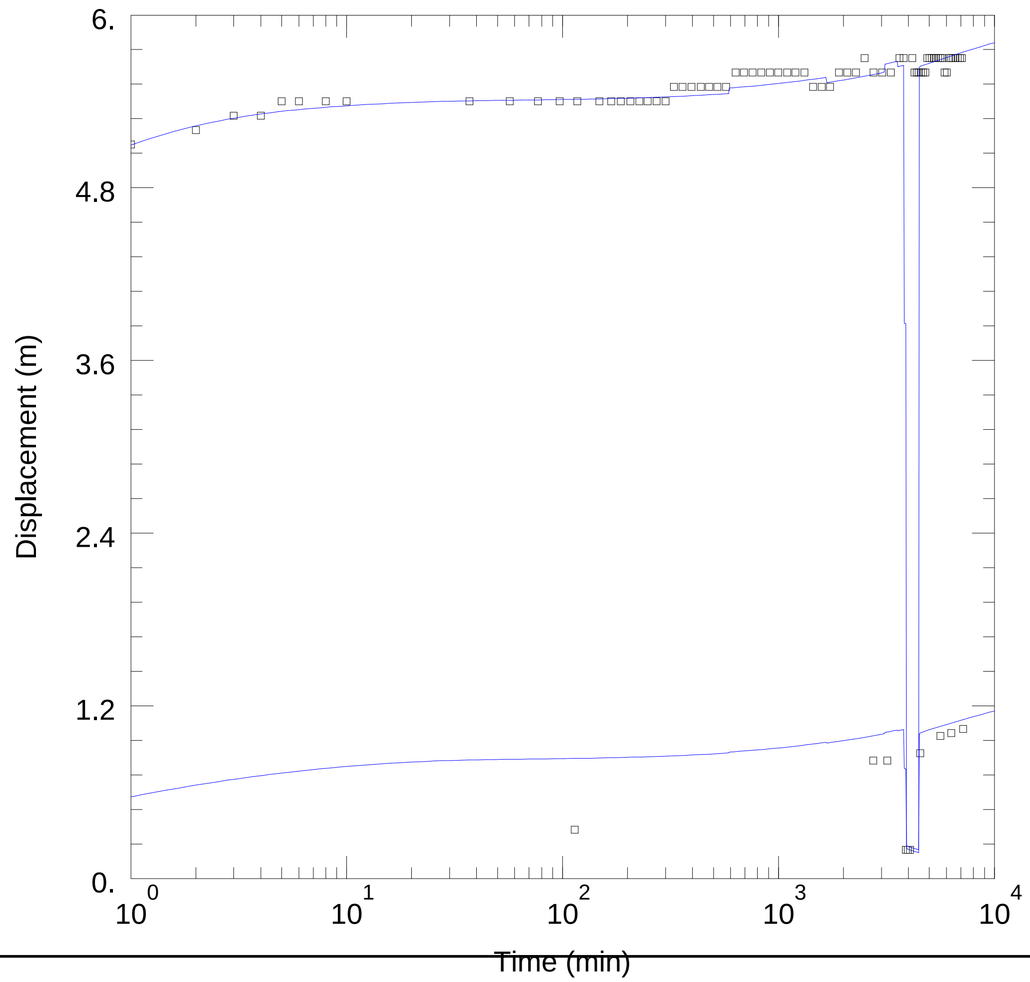
Dwg No: 464-0/16/02-30

PROPOSED MONITORING BORE LOCATIONS

Rockwater PROPRIETARY LIMITED

APPENDIX I

Re-interpreted pumping test data, Thunderbird Project



PROJECT INFORMATION

Company: Rockwater
Client: Sheffield Resources
Project: 464-0
Location: Thunderbird project
Test Well: TWB001
Test Date: 26/6/14

AQUIFER DATA

Saturated Thickness: 100. m

Anisotropy Ratio (Kz/Kr): 0.1935

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
TWB001	492457	8067215

Observation Wells

Well Name	X (m)	Y (m)
TWB001	492457	8067215
THAC395	492449	8067213

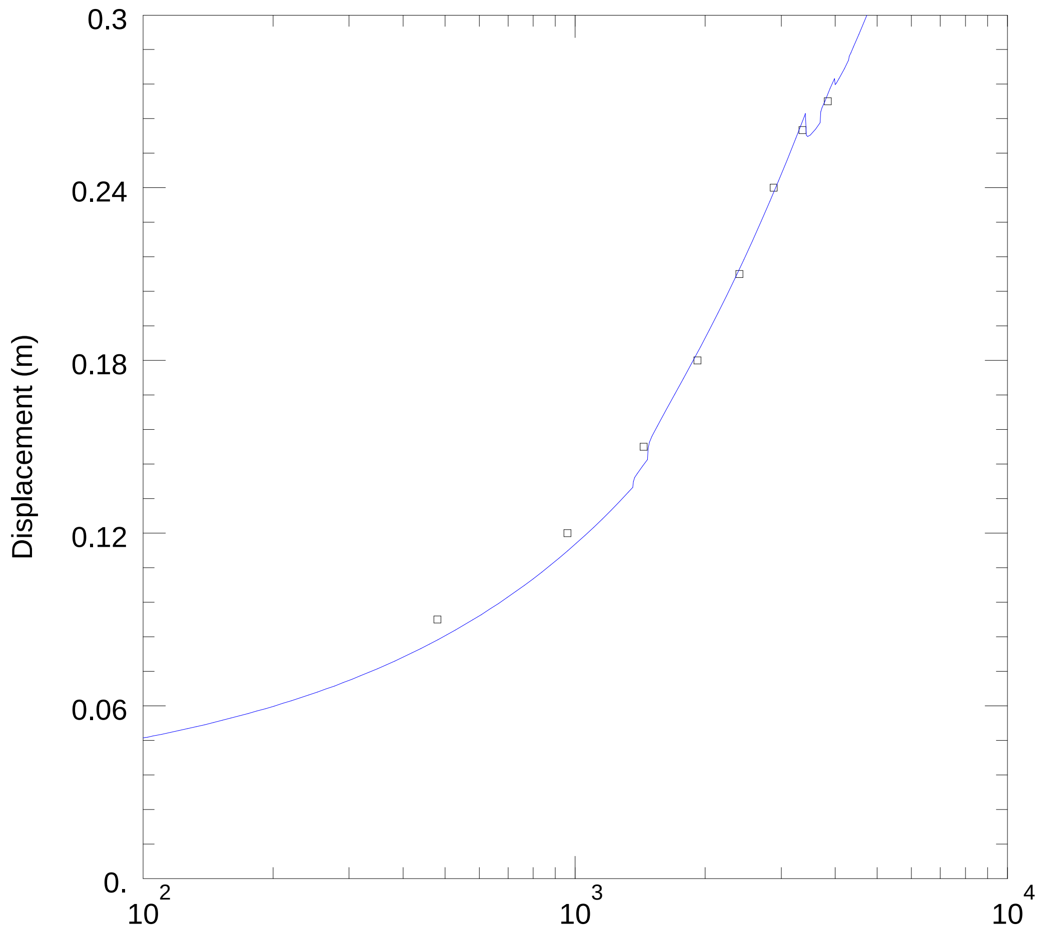
SOLUTION

Aquifer Model: Unconfined

Solution Method: Tartakovsky-Neuman

T = 1237.5 m^2/day
Sy = 0.17
kD = 1000.

S = 0.0007125
Kz/Kr = 0.1935



PROJECT INFORMATION

Company: Rockwater
Client: Sheffield Resources
Project: 464-0
Location: Thunderbird project
Test Well: TWB002
Test Date: 6 Oct 2014

AQUIFER DATA

Saturated Thickness: 100. m

Anisotropy Ratio (Kz/Kr): 0.8529

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
TWB002	494596	8071304

Observation Wells

Well Name	X (m)	Y (m)
THAC408	494759	8071525

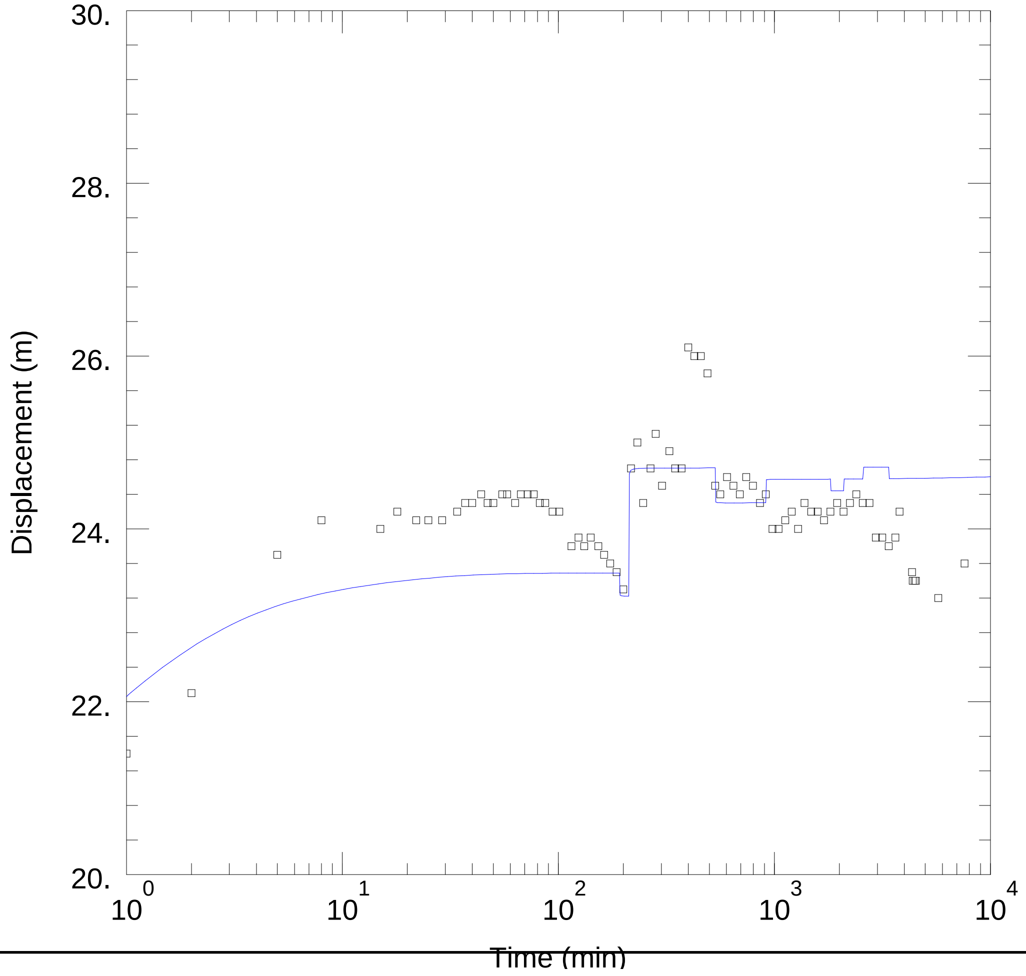
SOLUTION

Aquifer Model: Unconfined

Solution Method: Tartakovsky-Neuman

T = 39.86 m^2/day
Sy = 0.17
kD = 0.147

S = 1.0E-5
Kz/Kr = 0.8529



PROJECT INFORMATION

Company: Rockwater
Client: Sheffield Resources
Project: 464-0
Location: Thunderbird project
Test Well: TWB003
Test Date: 18 Oct 2014

AQUIFER DATA

Saturated Thickness: 100. m

Anisotropy Ratio (Kz/Kr): 0.0105

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
TWB003	0	0

Observation Wells

Well Name	X (m)	Y (m)
TWB003	0	0

SOLUTION

Aquifer Model: Unconfined

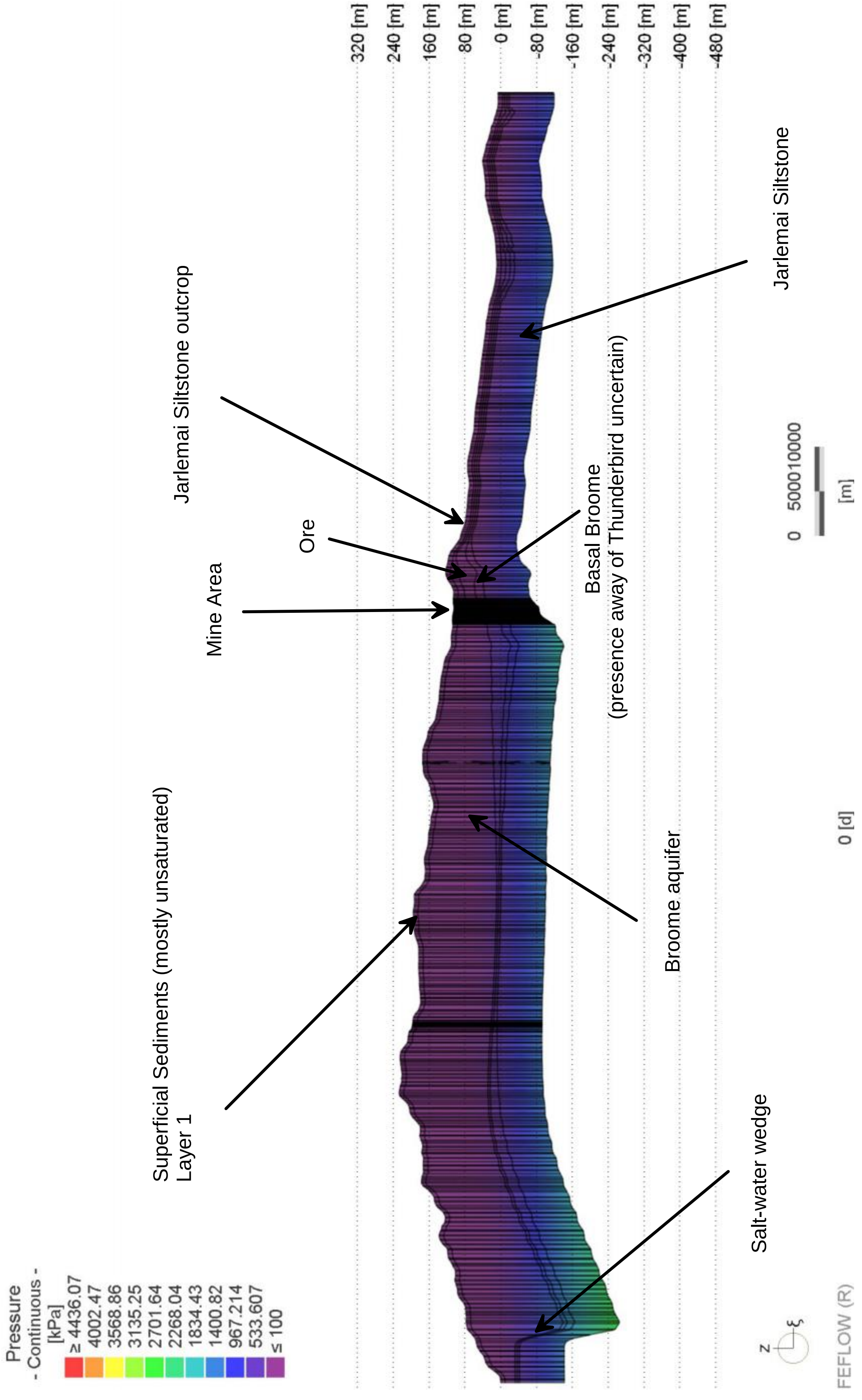
Solution Method: Tartakovsky-Neuman

T = 214.3 m^2/day
Sy = 0.17
kD = 1000.

S = 1.0E-5
Kz/Kr = 0.0105

APPENDIX II
Numerical model setup figures

Appendix I-1



I:464-0/Surfer/16-01/Figure 22.srf

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

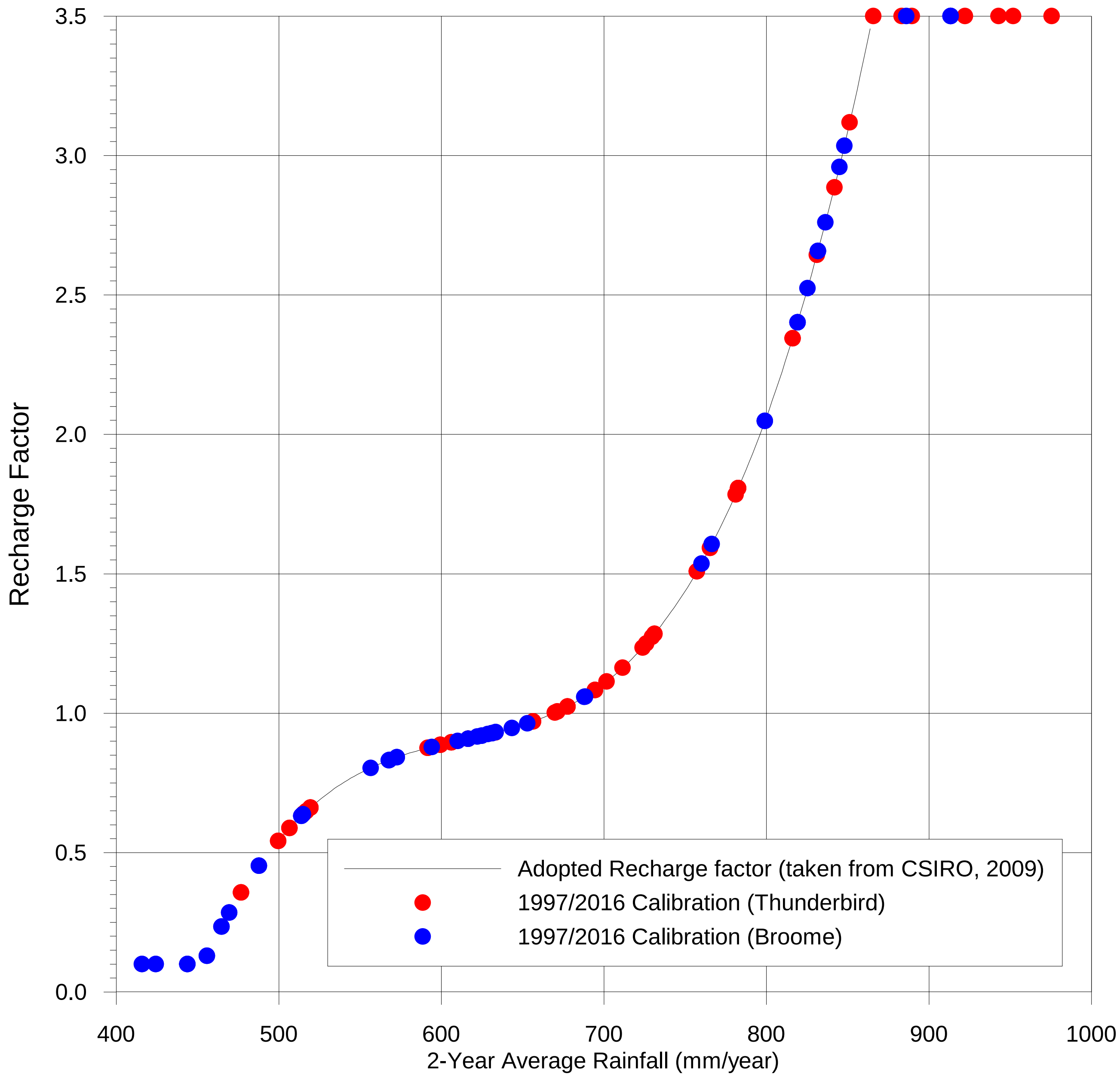
DATE: September 2016

Dwg No: 464-0/16/02-App I-1

MODEL LAYERS

Rockwater PROPRIETARY LIMITED

Appendix I-2



353-1//Grapher/App I/Recharge Factor

CLIENT: Sheffield Ressources

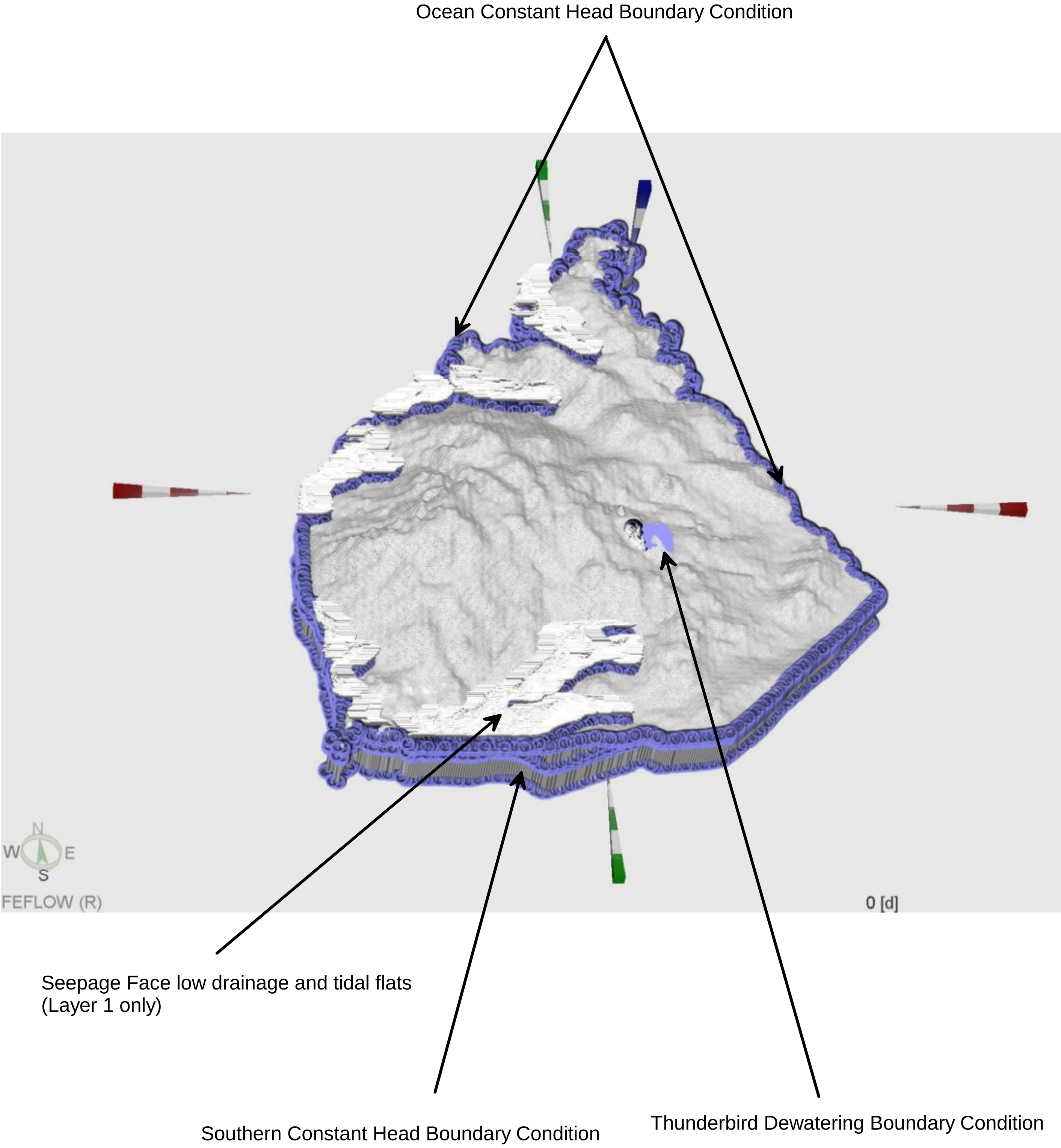
PROJECT: Thunderbird H3 Level of Assessment

DATE: October 2016

Dwg No: 464-0/16/02- App I-2

ADOPTED
RECHARGE FACTOR

Rockwater



I:464-0/Surfer/16-01/Figure 22.srf

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

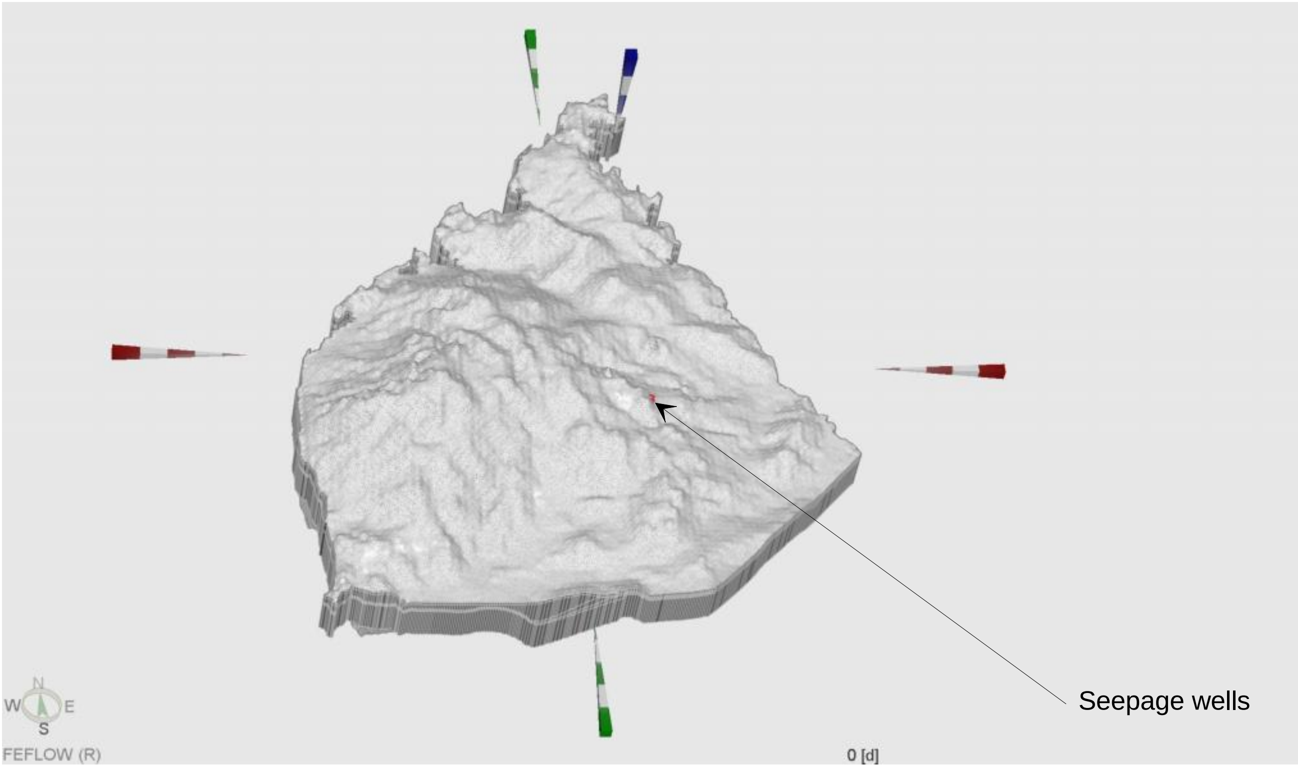
DATE: September 2016

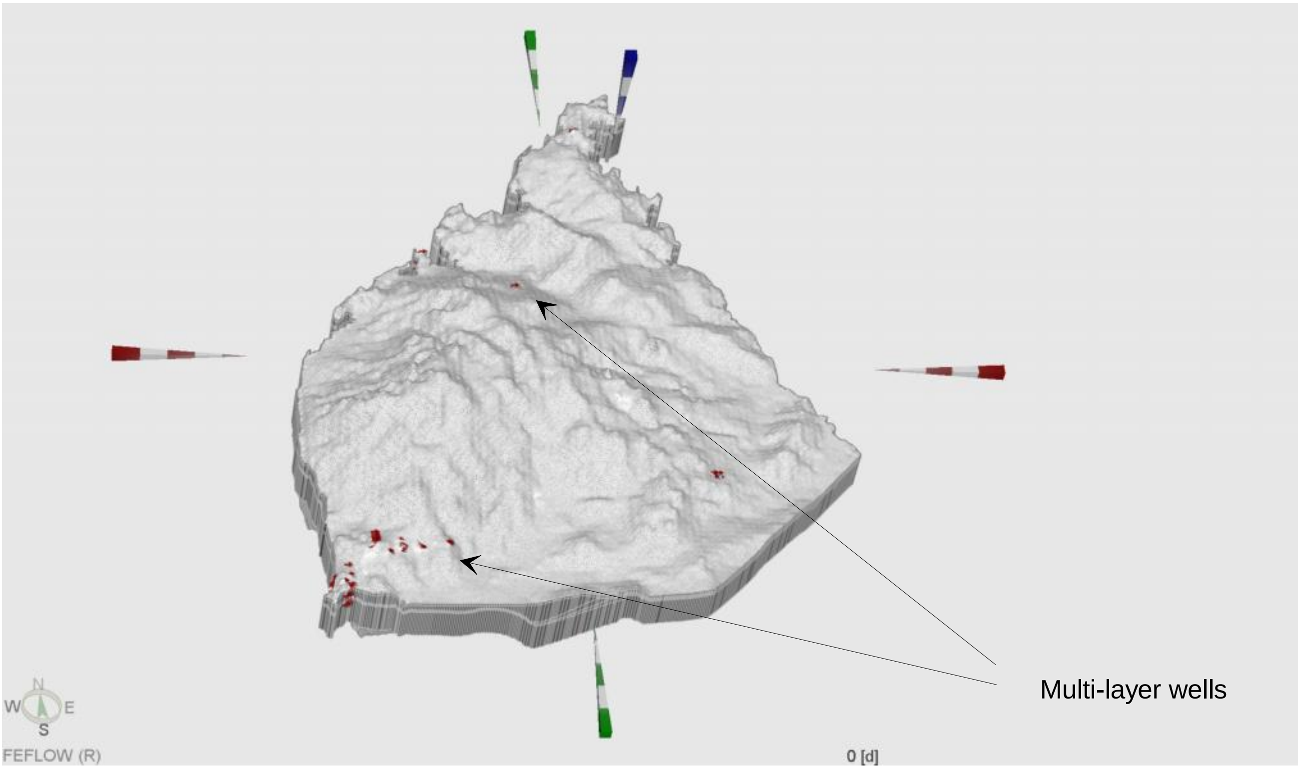
Dwg No: 464-0/16/02-App I-3

CONSTANT HEAD BOUNDARY CONDITIONS

Rockwater PROPRIETARY LIMITED

Appendix I-3





I:464-0/Surfer/16-01/Figure 22.srf

CLIENT: Sheffield Resources

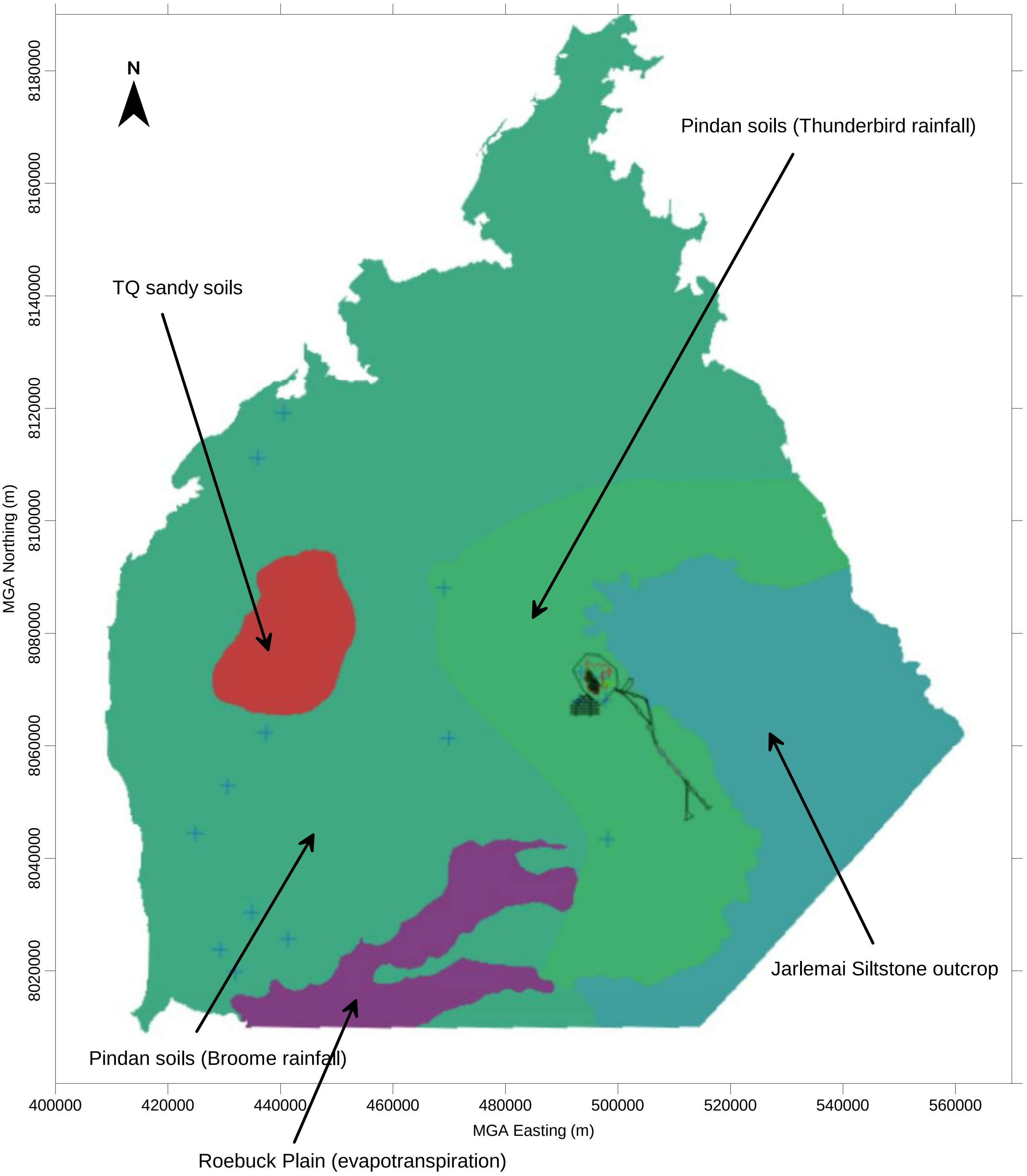
PROJECT: Thunderbird H3 hydrogeological assessment

DATE: September 2016

Dwg No: 464-0/16/02-App I-4

WELLS BOUNDARY CONDITIONS

Rockwater PROPRIETARY LIMITED



I:464-0/Surfer/16-01/Figure 22.srf

CLIENT: Sheffield Resources

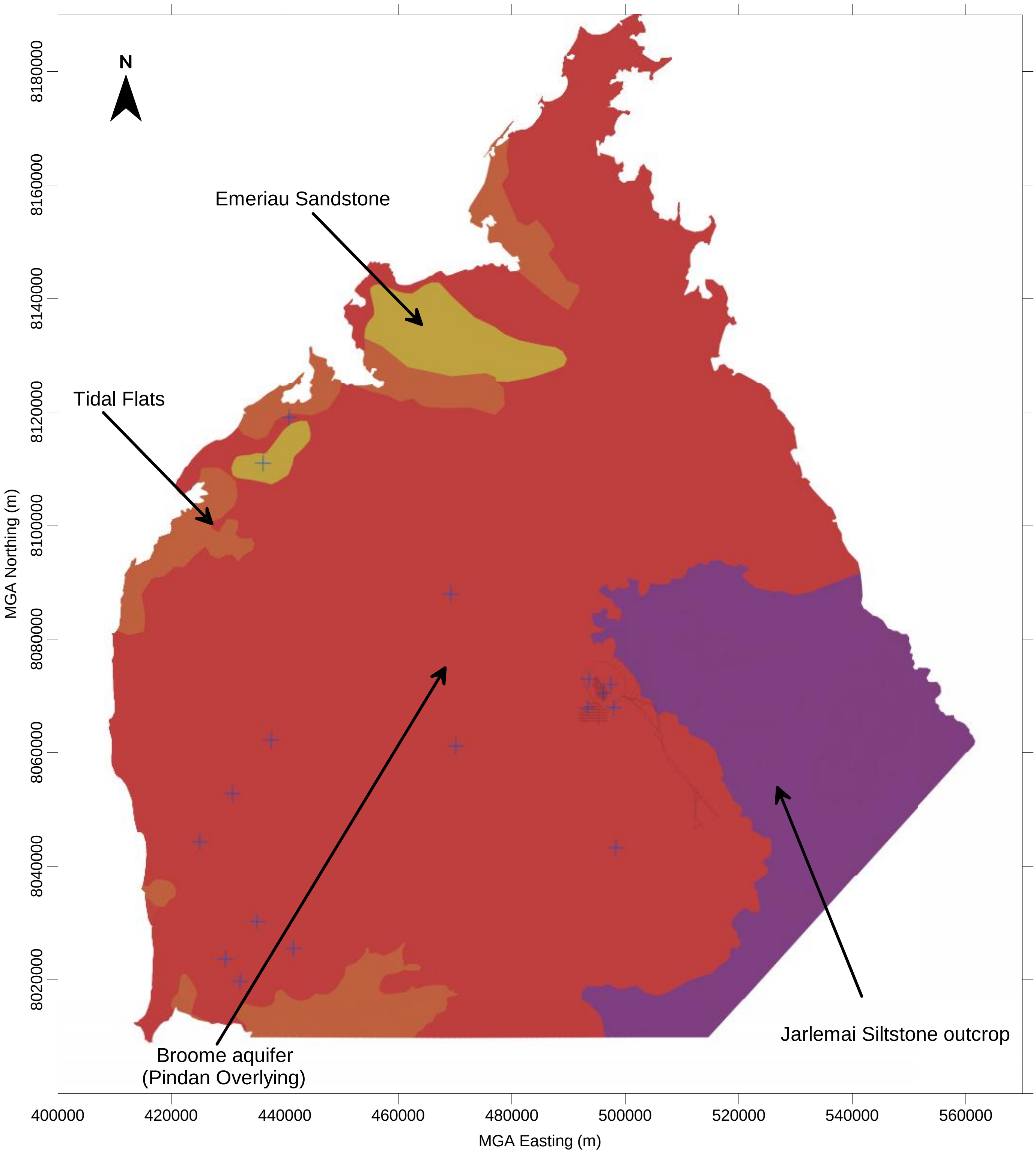
PROJECT: Thunderbird H3 hydrogeological assessment

DATE: December 2016

Dwg No: 464-0/16/02-App II-5

RECHARGE BOUNDARY CONDITIONS

Rockwater PROPRIETARY LIMITED



I:464-0/Surfer/16-01/Figure 22.srf

CLIENT: Sheffield Resources

PROJECT: Thunderbird H3 hydrogeological assessment

DATE: December 2016

Dwg No: 464-0/16/02-App II-6

HYDROSTRATIGRAPHIC UNITS

Rockwater PROPRIETARY LIMITED

APPENDIX III
Numerical model calibration figures

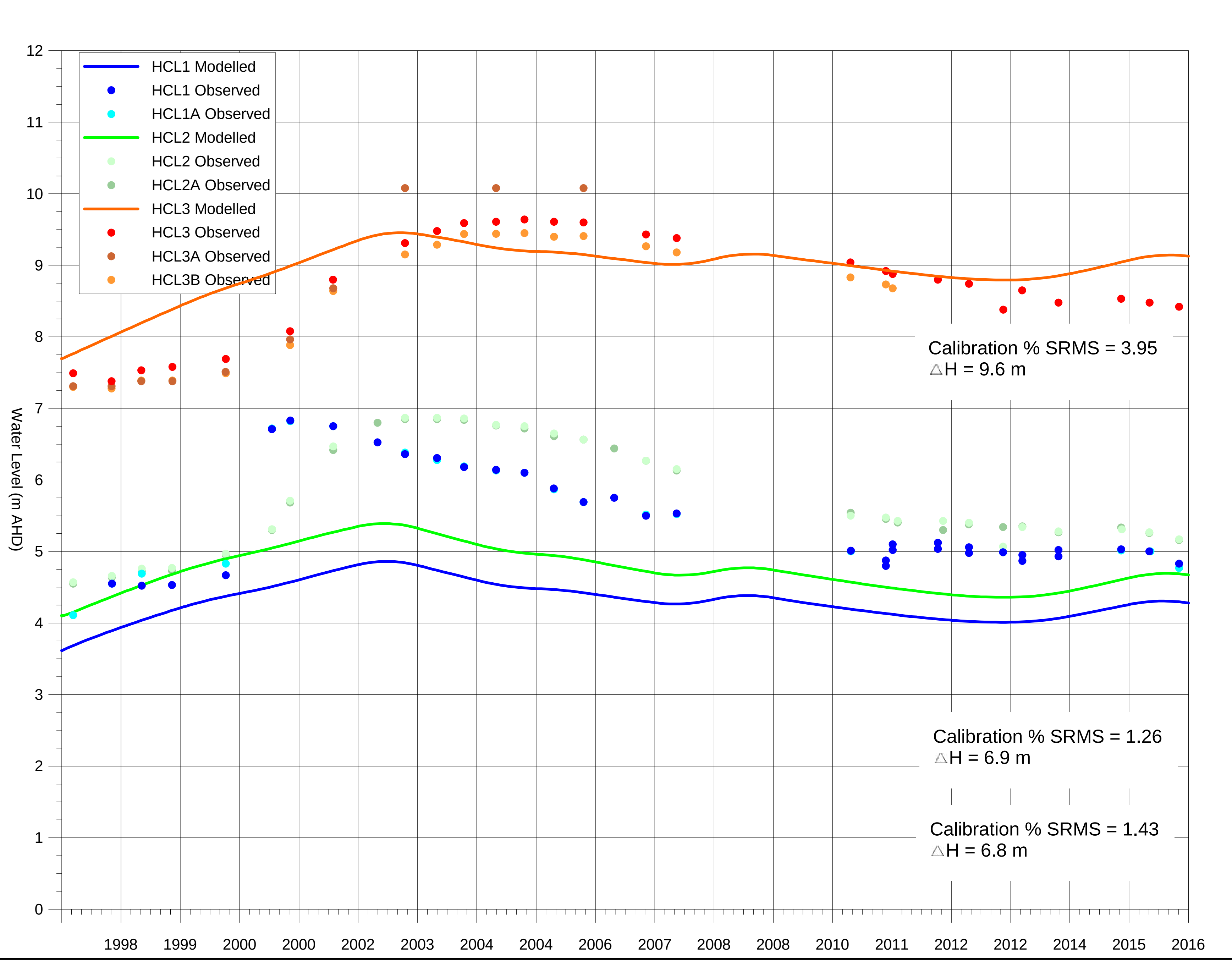
CLIENT: Sheffield Ressources

PROJECT: H3 Hydrogeological Assessment Report

DATE: October 2016

Dwg No: 464-0/16/02-App II-1

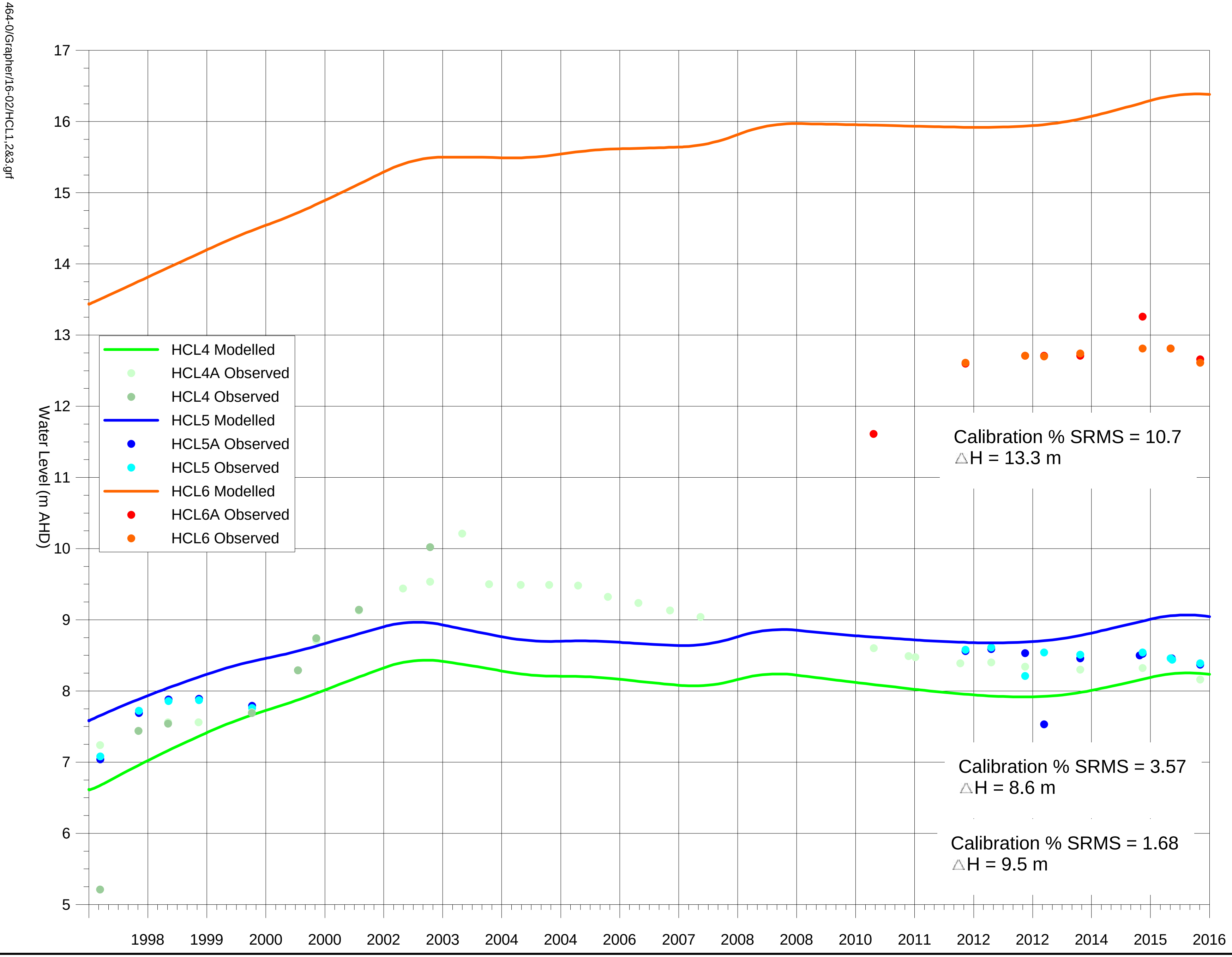
464-0/Grapher/16-02/HCL1,2&3.grf



COMPARISON BETWEEN MEASURED AND MODEL-CALCULATED WATER LEVELS IN OBSERVATION BORES HCL1, HCL2 & HCL3

Rockwater PROPRIETARY LIMITED

Appendix II-1



CLIENT: Sheffield Ressources

PROJECT: H3 Hydrogeological Assessment Report

DATE: October 2016

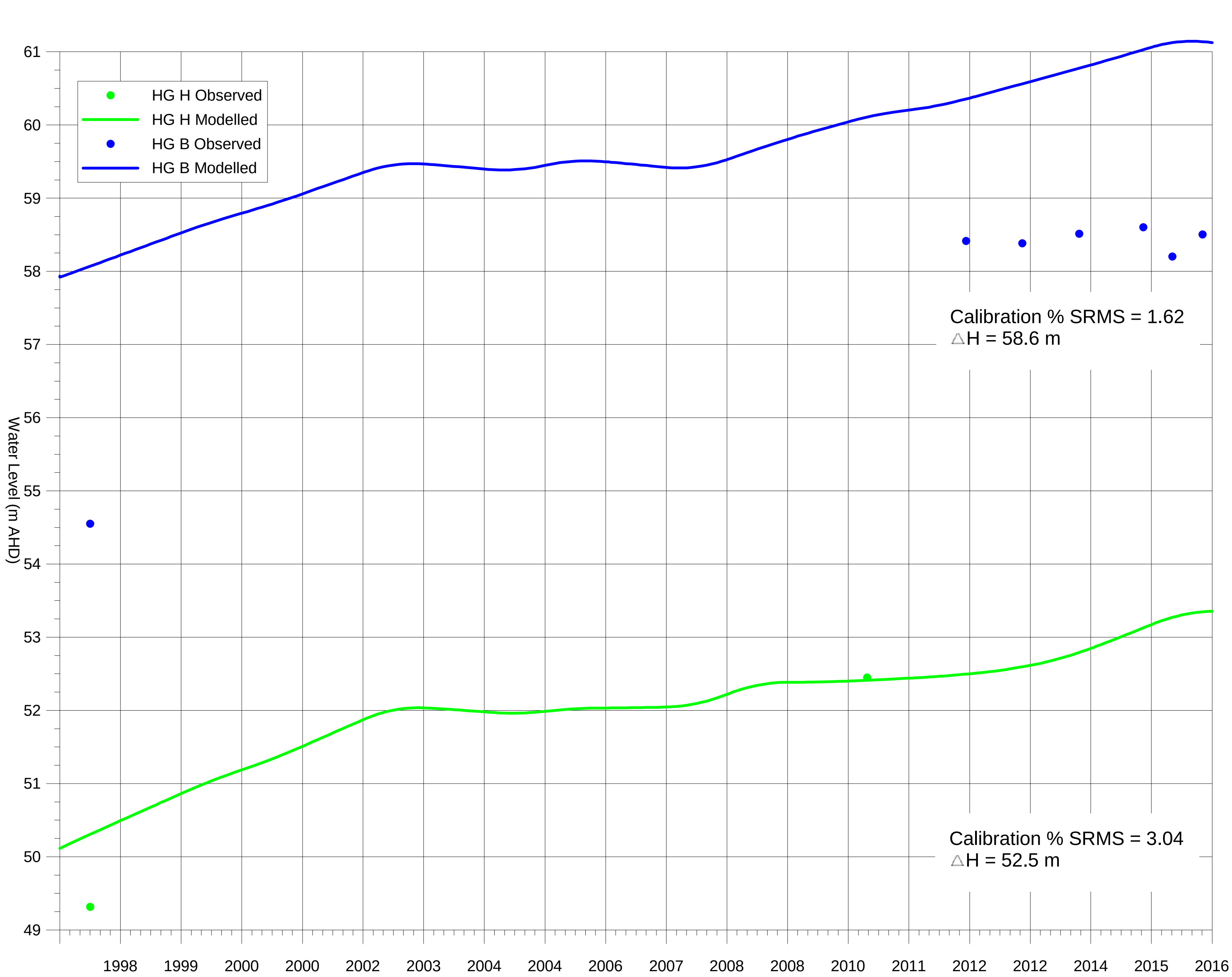
Dwg No: 464-0/16/02-AppII-2

COMPARISON BETWEEN MEASURED AND MODEL-CALCULATED WATER LEVELS IN OBSERVATION BORES HCL4, HCL5 & HCL6

Rockwater PROPRIETARY LIMITED

Appendix II-2

Appendix II-3



464-0/Grapher/16-02/HCL1,2&3.grf

CLIENT: Sheffield Ressources

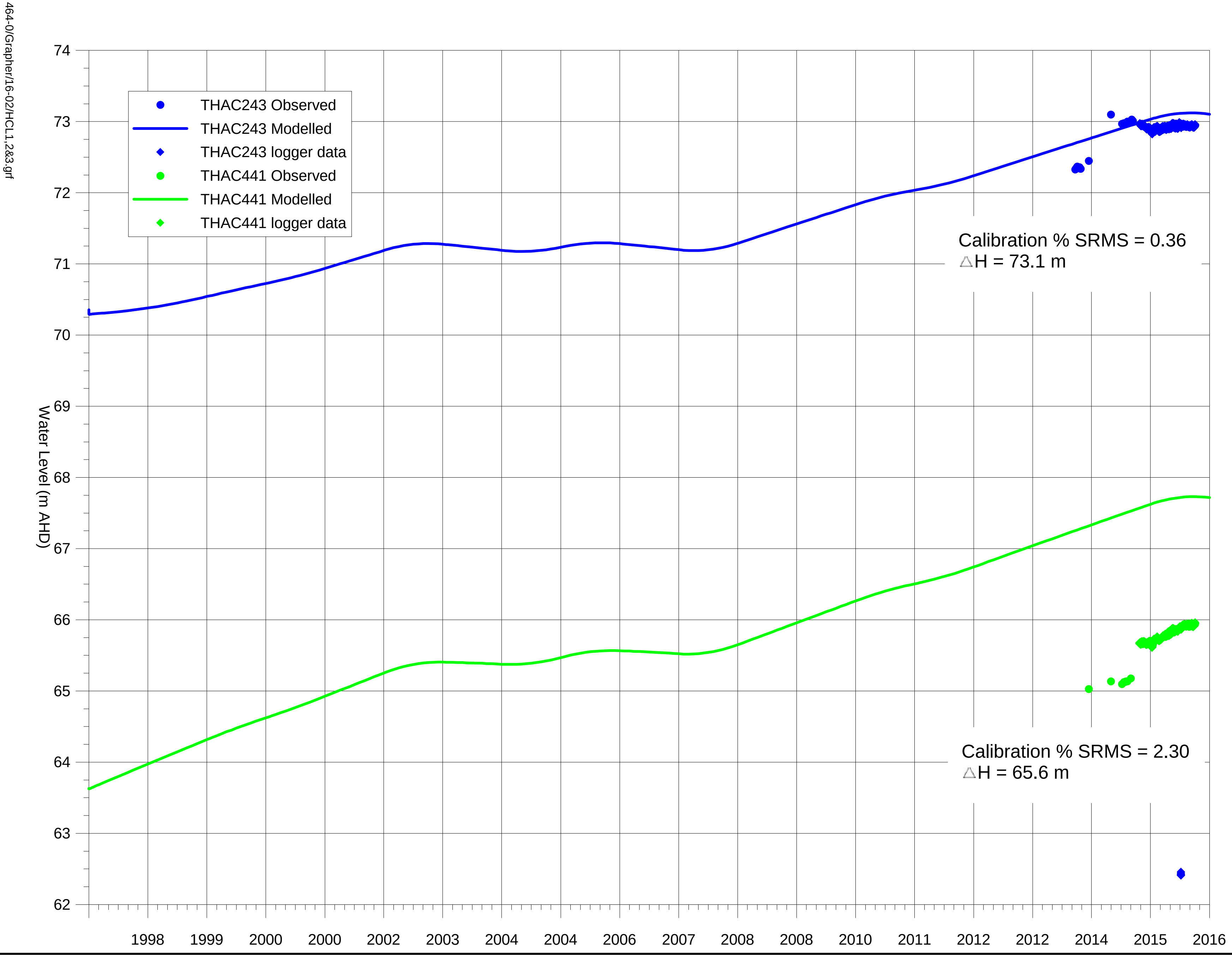
PROJECT: H3 Hydrogeological Assessment Report

DATE: October 2016

Dwg No: 464-0/16/02-App II-3

COMPARISON BETWEEN MEASURED AND MODEL-CALCULATED WATER LEVELS IN OBSERVATION BORES HG B & HG H

Appendix II-4



CLIENT: Sheffield Ressources

PROJECT: H3 Hydrogeological Assessment Report

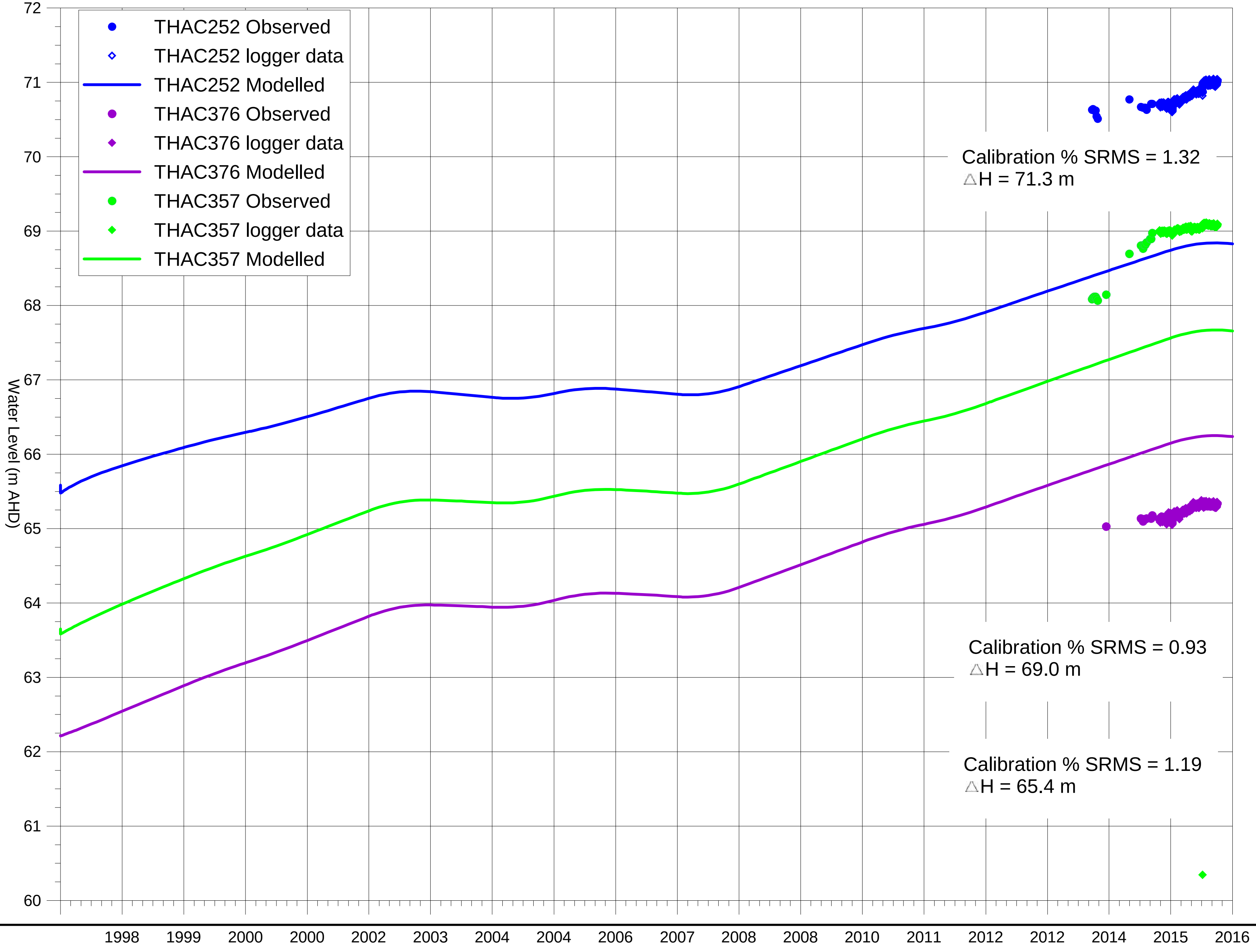
DATE: October 2016

Dwg No: 464-0/16/02-App II-4

COMPARISON BETWEEN MEASURED AND MODEL-CALCULATED WATER LEVELS IN OBSERVATION BORES HCL1, HCL2 & HCL3

Rockwater PROPRIETARY LIMITED

464-0/Grapher/16-02/HCL1,2&3.grf



CLIENT: Sheffield Ressources

PROJECT: H3 Hydrogeological Assessment Report

DATE: October 2016

Dwg No: 464-0/16/02-App II-5

COMPARISON BETWEEN MEASURED AND MODEL-CALCULATED WATER LEVELS IN OBSERVATION BORES HCL1, HCL2 & HCL3

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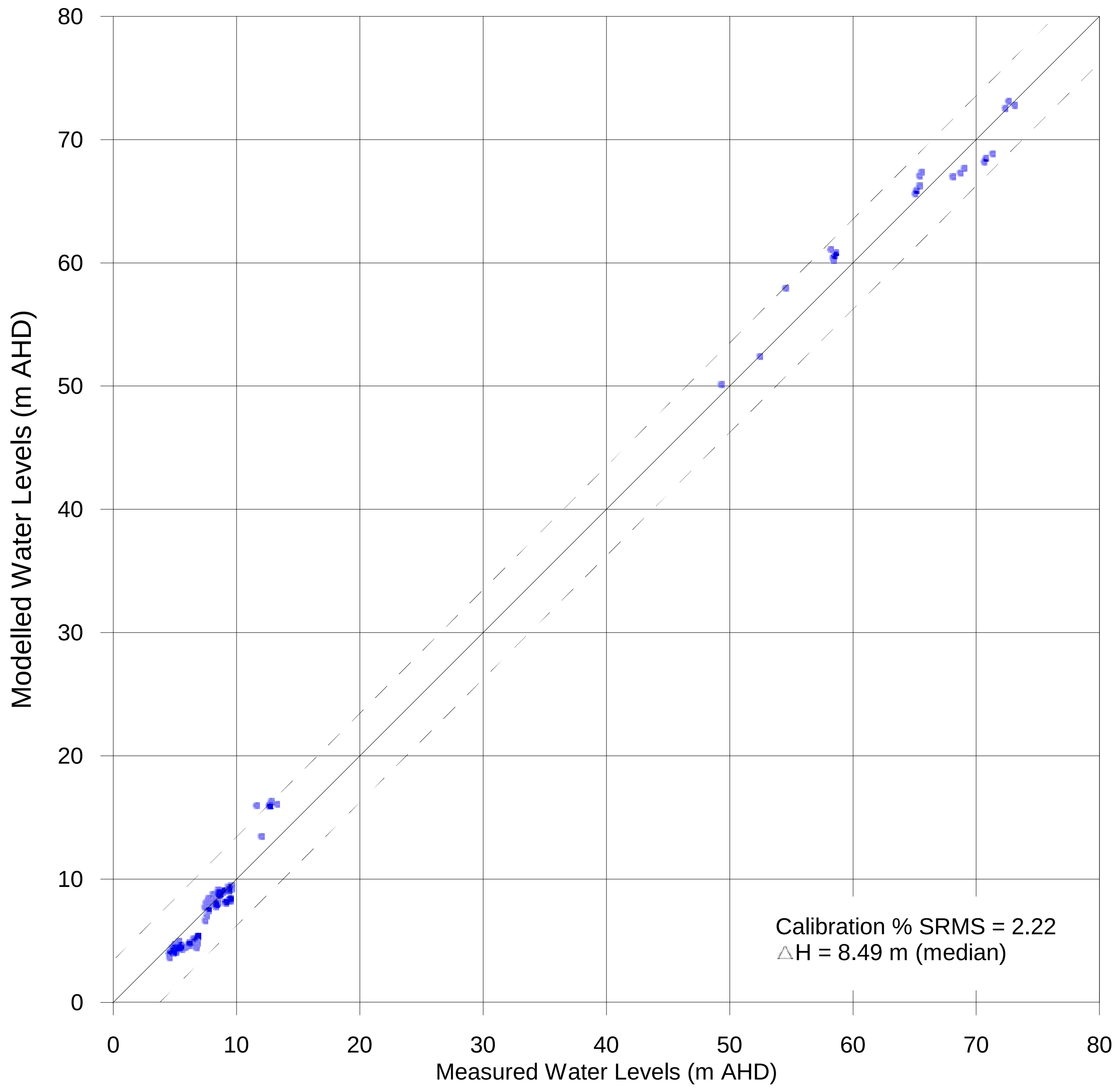
Appendix II-5



368-0//Grapher/App IV/Measured vs Modelled.grf

CLIENT: Cardno/Shire of Broome

PROJECT: Broome Coastal Vulnerability Study

DATE: May 2014

Dwg No: 353-1/13/01- App II-7

MEASURED VS MODELLED
WATER LEVEL SCATTER PLOT

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