Report

Hydrogeological assessment of the Christmas Creek life of mine water management scheme

Technical Services

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Fortescue
The New Force in Iron Ore

	Hydrogeological assessment of the Christmas Creek life of mine water management scheme		**CC-RP-HY-0017**
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EXECUTIVE SUMMARY

Fortescue Metals Group's (Fortescue's) Christmas Creek iron ore mine is within the Pilbara region of Western Australia. The Christmas Creek mine site is located approximately 30 kilometres east of Fortescue's Cloudbreak mine, 50 kilometres south-west of Nullagine and approximately 100 kilometres north of Newman (Figure 1). The Christmas Creek iron ore mine has been operating since 2009, and is currently approved to ship iron ore, via a rail link, from Port Hedland (Figure 1 and Figure 2).

About 70% of iron ore at Christmas Creek is below the watertable, and mine dewatering is undertaken to minimise water ingress into mining pits. Below watertable mining commenced in November 2011, current mine dewatering and associated water management activities are approved under an Assessment on Proponent Information (API) approval (Ministerial Statement 871) granted in 2011. As the API approval covers a limited time period (5 years), this life of mine (LoM) assessment presents results for the period 2014 to 2028 (including a revision of the final two years of the API assessment). In order to ensure that this assessment accurately represents predicted groundwater level change and volumes, operational data for abstraction and water level have been used to provide the initial starting conditions.

Dewatering will be achieved through advance dewatering methods and operational dewatering methods. Dewatering may significantly exceed mine water use requirements, and any surplus (the difference between abstraction water and mine water use) may be transferred to Cloudbreak if required or will be returned to compatible aquifers through injection to preserve water resources and to minimise environmental impacts (groundwater level drawdown/mounding). This process of groundwater abstraction and injection is referred to as the Christmas Creek water management strategy.

The hydrological setting of the project area is characterised by three broad hydrological regimes; a topographic driven flow regime; a density driven flow regime; and the Fortescue Marsh regime which cycles between a recharge and discharge feature in accordance with flooding and drying cycles. Detailed understanding of these flow regimes and the interaction between the flow regimes has been developed based on nearly 10 years of investigations and operations in the region.

Empirical evidence, in particular the demonstrated ability of *T. indica subsp. bidens* to tolerate drought and other stressors, and numerical simulation of soil water dynamics and plant water uptake by samphire vegetation on the fringe of the Fortescue Marsh (HYDRUS) suggest that the ecological water requirements of the fringing samphire communities are wholly or predominantly met by surface inputs (Equinox Environmental, 2012).

A density-driven flow and transport numerical groundwater model was developed and calibrated in the FEFLOW modelling platform for the purpose of conceptual design of the dewatering and injection system and predicting groundwater level conditions. The results of the numerical modelling, including sensitivity and uncertainty analysis has shown;

- The average annual dewatering volume is predicted to be up to 58 GL/a over the LoM period.
- The peak annual dewatering volume is predicted to be up to 110 GL/a.
- Maximum watertable drawdown along the Fortescue Marsh edge[1] is predicted to be up to 2.3 m. Mounding as a result of injection is not predicted to be a long term impact.
- Injection of surplus water into suitable aquifers minimises the long term impacts of drawdown at the watertable.
- With the cessation of dewatering, groundwater level drawdown in the mining area decreases from over 35 m at the end of mining (2028) to about 5 m, after ten years (2038), and to about 3 m after 20 years (2048).

An eco-hydrological study (Equinox Environmental, 2012) has provided confidence that prolonged dry conditions and drawdown, of up to 3 m, will not significantly affect samphire survival and health. Other potential groundwater system impacts associated with the Christmas Creek Project water management strategy, such as disruption to the surface flow regime, water table mounding (due to injection) and water quality changes, are also not predicted to be significant.

Modelling results suggest that the Christmas Creek water management scheme can operate independently. However, the adaptive management strategy of Christmas Creek would be strongly enhanced (enable greater flexibility to distribute injection) by adopting an integrated water management approach with Cloudbreak.

[1] Watertable measurements and predictions at the fringe of the Fortescue Marsh relate to monitoring locations CCFMM01)s to CCFMM05_s.

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1. INTRODUCTION

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1.1 Scope of Works

This report presents the detailed hydrogeological assessment for the proposed LOM groundwater abstraction and injection strategy. Specifically this document includes a description of;

- Site-specific hydrogeological data and its incorporation into the conceptual model of the groundwater and surface water hydrology.
- The development of a predictive numerical model.
- The groundwater abstraction and injection management strategy.
- The results of dewatering and injection simulations, including volumes and water level changes.
- The method and results of sensitivity and uncertainty analysis.

1.2 Previous Studies at Christmas Creek

Hydrogeological assessments undertaken both pre and post commencement of dewatering and injection operations at Christmas Creek are outlined in Table 1. These assessments have been used, in conjunction with those from adjacent sites (principally Cloudbreak) and regional knowledge (Section 1.3), to inform the conceptual hydrogeological understanding for this assessment.

Table 1: Previous groundwater investigations at Christmas Creek

Project/Reference	Scope	Outcomes
Hydrogeology report (Aquaterra, 2004)	• Drilling (four 150mm ND test production bores). • Pumping tests (24 to 48 hour duration). • Develop a numerical model (based on steady-state calibration and hydraulic properties from other Pilbara sites).	• Marra Mamba Formation (MMF) hydraulic conductivity of 0.5 m/day. • Saline gradient toward Fortescue Marsh identified. • Dewatering requirement 1.15 GL/a for 60 metre deep pits. • Remote water supply needed to meet 11.4 GL/a demand. • No impact on vegetation or Fortescue Marsh groundwater anticipated. • Salinity increase through up-coning or ingression not anticipated.
Hydrogeology assessment (FMG, 2009)	• Drilling (14 production bores, three multi-level monitoring bores). • Pump test assessments.	• Improved regional-scale and mine-scale stratigraphic data. • Mineralised MMF hydraulic conductivities in the order of 10 to 200 m/day, therefore greater dewatering rates. • The Oakover Formation's presence and aquifer properties identified. • Cloudbreak-style water management solutions proposed.
Bore Completion report (FMG, 2010)	• Drilling (10 test production bores, 12 multi-level monitoring bores). • Test-pumping (up to seven days duration). • SkyTEM geophysical survey. • Geochemical aquifer characterisation. • Numerical model development.	• Mineralised MMF hydraulic conductivities up to 311 m/day. • Oakover Formation hydraulic conductivities of similar magnitude to Mineralised MMF. • Variable connection between the Oakover Formation and Mineralised MMF; connection between these two units appears to be stronger than that at Cloudbreak. • Saline interface further defined from SkyTEM data; discrete saline pathways identified. • Cloudbreak-style water management solutions proposed.
Hydrogeological assessment in support of Fortescue's API submission (FMG, 2010a)	• FEFLOW modelling. • Ongoing drilling and testing data.	• Natural watertable fluctuation at the fringe of Fortescue Marsh predicted to be up to 3m following large rainfall events. • Abstraction up 50 GL/a required to deliver the mine plan presented. • Watertable change due to mining was predicted to be in the order of 1 m.
FY11 Dewatering and injection program. (FMG, 2013a)	• Groundwater abstraction, injection and monitoring. • Hydrogeological assessment of data. • A compliance assessment against the regulatory commitments.	• 29 production bores and 4 injection bores were constructed during the reporting period. • 0.9 GL abstraction during reporting period. • No injection during the reporting period. • No Class 2 trigger exceedances (environmental significant) were recorded.
Hydrogeological assessment in support of Fortescue's API submission (FMG, 2012)	• FEFLOW modelling. • Ongoing drilling and testing data. • Updated mine plan and project expansion.	• Natural watertable fluctuation at the fringe of Fortescue Marsh predicted to be up to 3m following large rainfall events. • Abstraction up 95 GL/a required to deliver the mine plan presented. • Watertable change due to mining was predicted to be in the order of 1.5 m.
FY12 Dewatering and injection program. (FMG, 2013a)	• Groundwater abstraction, injection and monitoring. • Hydrogeological assessment of data. • A compliance assessment against the regulatory	• 65 production bores and 15 injection bores where constructed during the reporting period. • 10.2 GL abstraction during reporting period. • 1.3 GL injection during the reporting period. • No Class 2 trigger exceedances (environmental significant) were recorded.

Project/Reference	Scope	Outcomes
	commitments.	
Vegetation dependence on shallow groundwater study. (Equinox Environmental, 2012)	Investigation into the impact of drawdown upon groundwater dependent vegetation.	Groundwater drawdown up to 3m, for prolonged periods of time, does not adversely impact the ability for samphire vegetation to acquire water.
April 2013 Quarterly groundwater monitoring summary (FMG, 2013)	Christmas Creek groundwater monitoring review for quarter (Feb 2013 to April 2013)	• 64 production bores and 21 injection bores were operational during the reporting period. • 9.5 GL abstraction during reporting period. • 4.6 GL injection during the reporting period. • No Class 2 trigger exceedances (environmental significant) were recorded.
FY13 Dewatering and injection program (FMG, 2013a)	• Groundwater abstraction, injection and monitoring. • Hydrogeological assessment of data. • A compliance assessment against the regulatory commitments.	• 73 production bores and 29 injection bores were constructed during the reporting period. • 34.4 GL abstraction during reporting period. • 17.4 GL injection during the reporting period. • No Class 2 trigger exceedances (environmental significant) were recorded.

1.3 Previous Studies at Adjacent Sites

The conceptual understanding of the Christmas Creek hydrogeological setting has also been supported by extensive hydrogeological work undertaken at Fortescue's adjacent mine site, Cloudbreak, and other relevant regional studies. Table 2 summarises the works that have contributed to the regional geological and hydrogeological understanding of Christmas Creek, and hydrological functioning of the Fortescue Marsh.

Table 2: Previous groundwater investigations at Cloudbreak and other adjacent sites

Project/Reference	Scope	Outcomes
(Aquaterra, 2005)	• 2 test production bores. • Groundwater model developed. • Dewatering assessment conducted.	• Conceptual model and numerical model utilising 'average' Pilbara hydraulic parameters. • Predicted dewatering requirements of up to 12 GL/a over life of mine.
Hydrogeology assessment (FMG, 2009)	• To support change to Ministerial Statement. • Increase dewatering to 25 GL/a and injection to 18 GL/a. • Review of short term dewatering and injection requirements. • Hydrological Impact assessment.	• Updated conceptual hydrogeology and short term dewatering requirements. • Key updates include significant increase of hydraulic conductivity parameters and inclusion of density coupling in groundwater flow modelling.
Geochemical Assessment (FMG, 2007)	• Measurement of groundwater quality parameters and sampling of groundwater from proposed mine dewatering borefield. • Chemical analysis of groundwater samples. • Assessment of likely changes to the groundwater composition and mineral precipitation due to	• Information on the borefield and aquifer geochemistry. • Precipitation of secondary minerals in the injection bore and the receiving aquifer is unlikely to be significant: calcite and dolomite were already oversaturated in the receiving aquifer. Si is unchanged. Gypsum was and remains after mixing with the injected water, under-saturated in the aquifer. • The potential for bio-fouling to occur is low, due to

Project/Reference	Scope	Outcomes
	mixing of water types, using aqueous geochemical modelling software PHREEQC. • Documentation of methodologies, results, conclusions and recommendations.	the presence of iron-precipitating bacteria, oxygen and ferrous iron.
Geochemical Assessment (MWH, 2009)	• Predicted geochemical interactions for re-injection of saline abstraction water into the saline Oakover Formation and in surface storage facilities. • Assessment of the potential for mineral precipitation with the PHREEQC geochemical model using 3 different scenarios.	• The degrees of saturation with respect to potential mineral precipitates are approximately the same for both the abstraction and injection zone groundwater. • The most likely mineral precipitates for the South Transfer Pond are Ca-Mg carbonates, amorphous silica, and ferric oxyhydroxide according to geochemical modelling results. • Geochemical model calculations for three scenarios predict that mixing of abstraction water with injection zone water (except brackish water) generally reduces the potential for precipitation of most carbonate, sulphate, and silica minerals (except Mn and Fe oxyhydroxides) and therefore limits potential for geochemical fouling.
Saline Injection Trial (FMG, 2010b)	• Assessment of a 6-month saline injection trial. • Summary of the operations, groundwater levels, water quality data, and vegetation monitoring. • Hydrogeological assessment of these data, hydrogeological characterisation of the saline injection area, numerical model assessment. • Commitments assessment. • Compliance assessment.	• Proof of concept has been achieved. • Environmental impact consistent with predictions. • Injection of saline water has not impacted the upper, brackish aquifers except in isolated sites thought to relate to bore construction. • Telemetry system control being developed. • Hydrogeological characterisation of the saline injection area and validation of the model in this area were limited due to limited aquifer response. • Progress in the assessment of clogging potential of saline reinjection.
Cloudbreak Triennial Aquifer Review (FMG, 2010c)	• Three year summary of groundwater abstraction, injection and monitoring. • Hydrogeological assessment of data. • A compliance assessment against the regulatory commitments.	• Presentation of monitoring data and assessment to verify the conceptual hydrogeological model for the Cloudbreak site.
FY11 Dewatering and injection program (FMG, 2013b)	• Groundwater abstraction, injection and monitoring. • Hydrogeological assessment of data. • A compliance assessment against the regulatory commitments.	• 98 production bores and 51 injection bores were active during the reporting period. • 24.9 GL abstraction during reporting period. • 14.2 GL injection during the reporting period. • No Class 2 trigger exceedances (environmental significant) were recorded.
Saline Injection Trial – Stage 2 Close Out Report (FMG, 2012a)	• Updated report to cover full length of saline injection trial and early operation. • Summary of the operations, groundwater levels, water quality data, and vegetation monitoring. • Hydrogeological assessment of these data, hydrogeological characterisation of the saline injection area, numerical model	• Injection has been demonstrated to be a feasible strategy for managing excess water. • Groundwater monitoring indicated a limited hydrogeological response to injection. • Operations will cause minimal impact (drawdown/mounding) to groundwater levels in the shallow aquifer at the Fortescue Marsh, predicted to be within the maximum permissible impact of <1m as set out in the PER document (FMG, 2010d). • Injected saline water has not impacted the upper, brackish watertable aquifers.

Project/Reference	Scope	Outcomes
	assessment. • Commitments assessment. • Compliance assessment.	• The primary clogging mechanism for injection bore has been identified as physical clogging by introduced sediment and debris.
FY12 Dewatering and injection program (FMG, 2013b)	• Groundwater abstraction, injection and monitoring. • Hydrogeological assessment of data. • A compliance assessment against the regulatory commitments.	• 159 production bores and 53 injection bores were active during the reporting period. • 31.7 GL abstraction during reporting period. • 20.3 GL injection during the reporting period. • No Class 2 trigger exceedances (environmental significant) were recorded.
Cloudbreak Triennial Aquifer Review (FMG, 2013b)	• Three year summary of groundwater abstraction, injection and monitoring. • Hydrogeological assessment of data. • A compliance assessment against the regulatory commitments.	• Presentation of monitoring data and assessment to verify the conceptual hydrogeological model for the Cloudbreak site.
Aquifer reviews	• As part of licencing conditions for the Cloudbreak 5C licence. Frequency FMG have produced a series of monitoring summaries and aquifer reviews: • Annual during the mine-construction phase (the 2006 and 2007 licence periods); • Quarterly and annual since dewatering operations commenced in mid-2008.	• Descriptions of volumetric data (abstraction, injection, mine water use), groundwater level data and groundwater quality data.
FY13 Dewatering and injection program (FMG, 2013b)	• Groundwater abstraction, injection and monitoring. • Hydrogeological assessment of data. • A compliance assessment against the regulatory commitments.	• 151 production bores and 48 injection bores were active during the reporting period. • 59.4 GL abstraction during reporting period. • 45.7 GL injection during the reporting period. • No Class 2 trigger exceedances (environmental significant) were recorded.
University of Western Australia (UWA). Ongoing research and investigation into the Fortescue Marsh.	Research projects, investigation works and publications into the dynamics and processes within and adjacent to the Fortescue Marsh, (Skrypek G., 2013).	• Fortescue Marsh is currently recharged by occasional floodwater. • Salt in the Marsh is concentrated by evaporation of rainfall. • Brackish waters reflect modern recharge. • Saline water reflects mixing between modern and old waters. • Deep saline groundwater beneath Fortescue Marsh developed under different climatic regime and accumulated over the last 40,000 to 700,000-years.
Revised hydrogeology modelling as assessment for Cloudbreak Project (FMG, 2013e)	• FEFLOW modelling. • Ongoing drilling and testing data. • Updated mine plan and project expansion.	• Natural watertable fluctuation at the fringe of Fortescue Marsh predicted to be up to 3m following large rainfall events. • Abstraction up 150 GL/a required to deliver the mine plan presented. • Watertable change due to mining was predicted to be in the order of 1.5 m.

2. EXISTING ENVIRONMENT

2.1 Location

The Christmas Creek project area is located in the eastern Chichester Range within an escarpment that gently slopes down to the Fortescue Marsh to the south (Figure 1). The Christmas Creek mine site is located approximately 30 kilometres east of Fortescue's Cloudbreak mine, 50 kilometres south-west of Nullagine and 100 kilometres north of Newman (Figure 1).

2.2 Topography

The regional topography is dominated by the Chichester Range and Hamersley Range to the south. These features are separated by the Fortescue Marsh, which forms the terminating point for the Upper Fortescue River catchment. The Upper Fortescue River flow northwards from Ethel Creek Station and then north-west past Roy Hill Station, before entering into Fortescue Marsh on its eastern margin.

The topography of Christmas Creek is gently sloping from north to south, with a relief ranging from 500 to 600 m AHD in the Chichester Ranges and 400 to 450 m AHD in the Fortescue Valley. The Chichester Range and the major drainage system of the Upper Fortescue catchment both trend west-north-west to east-south-east.

2.3 Climate

The climate of the Pilbara region is classed as subtropical to dry being characterised by very low rainfall, high-daytime temperatures in summer, and low winter minima (Gentilli, 1972). The region is defined by two distinct seasons; a dry winter season and a wet summer season. Rainfall during summer is typically associated with tropical cyclones and local thunderstorms. Winter rains are infrequent, with typically one or two falls of 20 to 30 mm per year. The average annual rainfall is around 320 mm per year. Annual pan evaporation is about 3500 mm (Bureau of Meteorology, 1977).

Monthly average temperature, rainfall and evaporation data for the region are presented in Table 3. Rainfall data and interpreted marsh water level for BoM site at Newman is presented in Figure 4. For the Bureau of Meteorology (BoM) site at Roy Hill (Site 005023), average annual rainfall is 261 mm (Figure 4 and Table 3). Normal maximum temperature ranges are 35 to 40 degrees Celsius (°C) in summer and 24 to 28°C in winter. Most summer rainfall is from scattered thunderstorms and occasional tropical cyclones.

For the period 1907 to 2012, the mean annual rainfall recorded at Bonney Downs (Site 004006) was 310 mm, compared to 406 mm over the last 10 years (2002 to 2012). Five of the last ten years have recorded annual rainfall in excess of 400 mm, with only two years recording less than 200 mm.

Table 3: Average monthly temperature, evaporation and rainfall

Month	Mean temperature (ºC)[1]		Average rainfall (mm/month)		Cloudbreak rainfall (mm/month)[2]		Pan evaporation (mm/month)[3]
	Daily max	Daily min	Roy Hill[4]	Bonney Downs[5]	2011	2012	
Jan	39.5	25	45	57.2	95.7	409.1	390
Feb	37	23.9	58	77	178	13	310
Mar	35	21.5	45	40.7	44	42.5	290
Apr	31.7	17.3	22	19.6	29	1.4	205
May	27.3	11.6	19	18.1	17	0	138
Jun	23.1	6.8	18	14.2	17.5	0	100
Jul	23	5.9	11	14.9	22.9	0	110
Aug	25.8	7.5	6	7.7	0	0	165
Sep	30.5	11.8	2	3.4	0	0	230
Oct	35	17.2	5	4.9	0	9	315
Nov	37.4	20.6	8	10.5	55.2	82.75	380
Dec	38.9	23.6	24	37.4	13	0	405
Annual:	32	16.1	261	310	472.3	557.75	3038

2.4 Hydrology

2.4.1 Regional Hydrology

The Chichester operations are located in the vicinity of the Fortescue Marsh in the upper Fortescue River catchment. In common with other areas in the Pilbara Region, the Fortescue Valley is subjected to localised thunderstorm and cyclonic rainfall events. Typically these events occur during the period between December to April and can produce very large runoff events. The period between July to November typically has relatively low rainfall, although significant runoff events during this time can occur.

The Goodiadarrie Hills, about 60 km east from the town of Wittenoom, effectively cut the Fortescue River into two separate river systems. West from the Goodiadarrie Hills, the Lower Fortescue River Catchment drains to the coast, whereas east from the hills the Fortescue Marsh receives drainage from the upper Fortescue River catchment. The alluvial outwash fan from the

[1] Bureau of Meteorology, Newman Station, 1971-2010
[2] Cloudbreak rainfall data, recorded on site by Fortescue
[3] Interpolated from Bureau of Meteorology 1961-1990 spatial evapotranspiration dataset
[4] Bureau of Meteorology, Roy Hill Station 0050523, 1961-1990
[5] Bureau of Meteorology, Bonney Downs Station 004006, 1907-2012

Weeli Wolli Creek system abutting the Goodiadarrie Hills is believed to be partially responsible for obstructing the Fortescue River and forming the Fortescue Marsh.

The Fortescue Marsh forms an extensive intermittent wetland (located on the floor of the Fortescue Valley) occupying an area around 100 km long by typically 10 km wide. The Fortescue Marsh is listed in the directory of Important Wetlands (Env, 2001) and is listed by the Department of Environment and Regulation (DER) as a Priority 1 Priority Ecological Community. The Fortescue Marsh has an elevation of around 400 m AHD. To the north, the Chichester Plateau rises to over 500 m AHD, whereas to the south the Hamersley Range rises to over 1,000 m AHD. Following significant rainfall events, runoff from the upper Fortescue River catchment (approximately 31,000 km^2) drains to the Fortescue Marsh. For the smaller runoff events, isolated pools form on the Marshes at the main drainage inlets, whereas for the larger events the whole marsh area may flood.

On the southern and northern flanks of the Fortescue Valley, numerous creeks discharge to the Fortescue Marsh. Rainfall runoff from the valley sides initially drains downgradient as overland flow before concentrating in defined flow channels. In this process, surface detention, vegetation, infiltration and other mechanisms absorb water from the runoff stream. In steep areas, the runoff processes are rapid with relatively low losses, and defined drainage channels are typically in close proximity. In the lower slope areas, the runoff processes are slow with relatively higher losses and greater distances between defined drainage channels.

Where defined drainage channels from the steeper slopes enter the lower slope areas, the channels typically have a reduced discharge capacity and in many instances become less defined, braided, or may even completely disperse in flat areas. In these reducing slope channels, runoff tends to overspill the main channel flow zones and spread over a wider front. In some of the lower slope areas, vegetation communities (scrub and Mulga woodlands) have developed. These are dependent on seepage water provided by the overland flow process. In these areas, the overland flow process has been termed sheet-flow. Conversely, the Fortescue River, Weeli Wolli Creek, and other main channels entering the Marshes typically support Eucalyptus woodlands on their banks and floodplains.

Surface water runoff to the Fortescue Marsh is of low salinity and turbidity, though the runoff turbidity significantly increases during peak periods of flooding. Following a significant event that floods the whole marsh area, the ponded water may be over 4 m deep in the lower elevation marsh areas. Water stored on the Fortescue Marsh slowly dissipates through the processes of seepage and evaporation. During the evaporation process, the water salinity levels increase and as the ponded areas recede, traces of surface salt can be seen. During the seepage process, as the ponds evaporate, increasingly more saline water is believed to seep into the valley floor alluvial deposits.

2.4.2 Localised/Site Hydrology

Surface water flows at the Chichester Operations have previously been characterised as one of several modes, summarised as follows:

- Hillslope Runoff. Hillslope runoff zones are located in the portion of catchments where the majority of runoff is contained within small creeks, broad swales or gullies. Naturally, flows are generally convergent which concentrate flows, increases velocities, promotes scour and enhances channel formation. Catchment sizes are usually small but can be larger in cases where the terrain is flat and velocities are insufficient to maintain well defined channels
- Channel Flow. Channel Flow zones are located in the portion of catchments with large channels and adjacent floodplains. These zones are associated with large catchments that predominantly drain the steep areas of the Chichester Range rather than the low relief terrain closer to the Fortescue Marsh. Large convergent flows, high velocities and large, well defined channels are typical of these creeks. Smaller, more frequent flows are mostly confined to the channel while larger and less frequent flood flows break out onto the adjacent floodplain. These zones can be identified using topographic information and vegetation patterns in aerial photos. Channels are usually devoid of vegetation due to bed load movement during flood events. Vegetation on the adjacent floodplains is maintained either by periodic inundation or has rooting depths sufficient to access the superficial fresh aquifer replenished by more frequent smaller flows.
- Diverging Flow. Diverging flow zones are located in the portion of catchments where channel flow has become dispersed, leading to a loss of channel form. The transition from channel flow to diverging flow normally occurs on the low relief terrain after large rivers have discharged from the Chichester Ranges. The distance that the channel form is maintained is proportional to the slope of terrain and the size of the flows generated by a catchment (i.e. the greater the flow, the more well defined the channel is further downstream). Banded grove-intergrove vegetation patterns typical of sheet flow areas are not normally found downstream of areas where diverging flows intersect with sheet flow zones. Sheet flow zones form in ‘fan’ like terrain.
- Sheet flow. Sheet flow zones form in areas where overland flow moves down slope while maintaining a broad shallow front. This is the initial hillslope response to infiltration excess prior to channel initiation. Channel initiation is dependent on a threshold level of stream power, controlled in part by the extent of flow convergence and gradient. There are many examples in the study area where the terrain has been formed by remnant alluvial fans. These areas do not promote convergence of flows and are relatively flat, causing sheet flow zones to be maintained over large areas. The banded Mulga (Acacia aneura) formations common throughout the study area, are part of an ecological response to the sheet flow patterns.

Some areas, including those closer to the shore of the Marsh, may exhibit one or more of these characteristics. The Christmas Creek mining footprint is located across all zones except for the sheet flow zone, with most operations located in the Hillslope runoff or channel zone.

2.4.3 Fortescue Marsh surface water balance

In June 2012 Worley Parsons prepared the Fortescue Marsh Catchment Water Balance Study (Worley Parsons, 2012). As part of this study a water balance model was constructed to assess:

- Rainfall directly on the water surface of the Fortescue Marsh
- Runoff inflows to the Fortescue Marsh
- Evaporation losses from the water surface of the Fortescue Marsh.

A daily rainfall runoff model was established and used to estimated surface runoff into the Marsh. There are four stream flow gauging stations within Weeli Wolli Creek and one stream flow gauging station on the Fortescue River. A rainfall runoff model was established and calibrated for each of these catchments. These gauging stations are all located to the south of the Fortescue Marsh in hilly terrain. The calibrated model parameters were found to be similar for each of these gauging stations.

Median parameters from these gauged catchments were applied to the ungauged catchments draining the Chichester Ranges and East Hamersley's, which were considered to have similar terrain and hydrologic properties. These computed flows were input to the water balance model. The gauged flows for Weeli Wolli Creek (measured at Waterloo Bore) were also entered into the water balance model. (Note that Waterloo is located approximately 30 km south of the Marsh and Weeli Wolli Creek traverses an alluvial fan between Waterloo and the Marsh incurring significant transmission losses during low flows. However, during major inflow events it was considered that transmission losses would be minor.)

The gauging station on the Fortescue River is located at Newman, just upstream of Opthalmia Dam which was constructed in 1981. Opthalmia Dam has a storage capacity of 32 GL, and has only overflowed 3 times since construction. There is no stream flow gauge downstream of Opthalmia Dam and so flows downstream of the dam were estimated by use of the Source Catchments model. This model utilized observed stream flows at Newman and then simulated the storage behaviour of the dam to compute the spills which were then entered into the water balance model.

The water balance model was run for the period from 1/12/1984 to 30/04/2011 for the natural pre-development scenario with no mines at Cloudbreak, Christmas Creek or Roy Hill and with the remainder of the catchment in current conditions in place. Figure 54 shows the annual volume of water entering the Fortescue Marsh for this scenario. Total annual flows into the Fortescue Marsh have been predicted to range between <50 GL/a to 1400 GL/a depending on climatic variation, (Worley Parsons, 2012).

2.4.4 Cultural significance

Semi-permanent water bodies along the shores of the Fortescue Marsh are culturally significant areas. These water bodies, known as Yintas (Goode, 2009), are located at low points in the surface topography of the marsh. Each Yinta is associated with local catchments that drain from the Chichester Range.

Aboriginal heritage surveys associated with the Chichester Range operations (Chichester Range operations refer to mining activities at both the Cloudbreak and Christmas Creek mine sites) have been undertaken since late 2003.

2.5 Geology

The main iron ores of the Hamersley province are hosted with in the Archean to Palaeoproterozoic volcanic and sedimentary sequence of the Mount Bruce Supergroup (MBS). The MBS spans a time interval of over 400 million years (Ma), from greater than 2770 Ma to near 2350 Ma. The MBS rests unconformably on 3.50 to 2.80 billion year old (Ga) granitoids and greenstones that occupy the northern half of the Pilbara Craton. The MBS comprises late Archean metasediments and metavolcanics of the Fortescue Group, unconformably overlain by early Proterozoic metasediments of the Hamersley Group, which in turn are conformably overlain by siliclastics, carbonates and basalts of the Turee Creek Group.

This section describes the geology of the north-eastern margin of the basin, which is directly relatable to the Christmas Creek mine.

2.5.1 Stratigraphy, structure and mineralisation

The local geology is dominated by the Fortescue Group, lower part of the Hamersley Group, and Marra Mamba Formation (MMF). The mineralisation of the Chichester Range is confined to the Nammuldi Member, the lowermost unit of the MMF, overlying the black shales of the Jeerinah Formation at the top of the Fortescue Group. Beneath the Fortescue Valley, the MMF is conformably overlain by the Wittenoom Formation of the Hamersley Group.

The MMF (and Wittenoom Formation where present beneath the Fortescue Valley) is unconformably overlain by younger Tertiary to Quaternary deposits. The Oakover Formation comprises a sequence of lacustrine carbonate, silcrete and mudstone rocks that have been deposited in the palaeodrainage of the Fortescue Valley. The Fortescue Valley is covered by a thick (up to 50 m) blanket of Tertiary colluvial scree slopes (close to the range) and floodplain alluvial sediments. A summary of the generalised stratigraphy is presented in Table 4.

Table 4: Christmas Creek Generalised stratigraphy

Age	Group/Formation/Member			Stratigraphy Code[6]	Stratigraphy Description	Geological Description
Cenozoic	Tertiary alluvium			Ta	Tertiary alluvium	Variable clast composition
	Tertiary detritals / colluvium			Tdi	Tertiary detrital	Immature
				Tds		Semi-mature
				Tdm		Mature
	Tertiary Clay			Te	Tertiary clay	Layer forms semi aquitard above the Oakover Formation
	Oakover Formation			To	Oakover	Calcrete, silcrete and calcareous sediments
Unconformity						
Archaean	Hamersley Group	Hardcap		Hc	Hardcap	Commonly vuggy hard 'ore' with moderate GGM or VGH)
		Wittenoom Formation		WD	Dolomite	Varies between fresh to fractured and/or weathered
		Marra Mamba Formation	Nammuldi Member	MuX	Ore Body	Bedded iron mineralisation, Goethitic & hematitic shales, chert and BIF. Ore body aquifer
	Fortescue Group	Jeerinah Formation	Roy Hill Shale	Jr	Roy Hill Shale	Commonly leached kaolonitic or black shale when fresh
				Fj	Jeerinah Formation	Dolomites, volcanics, sandstones, conglomerates

Regionally, the Chichester Range has gentle dips, usually less than 5°S, marking the onlap of the Hamersley Basin onto the Pilbara Craton. However, the gentle regional southerly dip of the Nammuldi Member at Christmas Creek has been offset by north-south to north-east–south-east trending faults. This is further overprinted by low amplitude (<20 m), long wavelength (200 to 800 m), north-south to north-east–south-west trending and south-south-west plunging folds. This folding is interpreted to be the result of waning phases of deformation in the underlying Pilbara Craton (Hannon, 2005) and (Thorne, 2008).

Small amplitude folds developed at Christmas Creek, and elsewhere along the Chichester Range, have influenced both the development and preservation of mineralisation. The formation of high-grade ore is controlled by north-east–south-east trending faults and folds. Synclines appear to have focused supergene fluids resulting in their preferential mineralisation compared to adjacent anticlines. Subsequent erosion, controlled in part by the same structures, led to the broad stripping of anticlines and also the local removal of synclines along drainage channels.

[6] Stratigraphy codes defined in Table 4 represent Fortescue's interpretation and nomenclature.

The majority of mineralisation developed in the Chichester Range occurs as a sub-horizontal sheet of typical supergene martite-goethite and martite-ocherous goethite enrichment, overprinting hypogene microplaty hematite, which locally persists below the martite-goethite sheet. Hypogene enriched microplaty hematite mineralisation is structurally controlled, while supergene enriched mineralisation is very extensively developed as a sheet continuing for kilometres under recent cover. The majority of the mineralisation is typically a mixture of goethite, martite and hematite in varying amounts, similar to other Marra Mamba ores in the Hamersley Basin.

2.6 Hydrogeology

Groundwater dynamics in the Christmas Creek area are strongly controlled by stratigraphy, topography, mineralisation, structure and density (related to groundwater salinity). This section provides a description of the hydrogeology with consideration for hydraulic characteristics, groundwater recharge, throughflow, storage, discharge, quality and density. A conceptual hydrogeological cross section is provided in Figure 3.

2.6.1 Hydrostratigraphy

The main hydrostratigraphic units and their characteristics are described below and are summarised in Table 5.

Jeerinah Formation (Roy Hill Shale)

The Roy Hill Shale is generally considered to have low transmissivity; however, permeability can be enhanced along the interface with the overlying Marra Mamba formation (MMF) and predominantly north-east to south-west-orientated fault zones. Additionally, a number of stratigraphic horizons within the Roy Hill Shale (located north of the MMF outcrop) have been found to have moderate permeability associated with bedded cherts which have undergone brittle deformation. Groundwater quality in the Roy Hill Shale, beneath the ore body, is generally saline.

Marra Mamba Formation

The distribution of permeability and storage in the MMF is influenced by lithological characteristics, faulting and secondary geochemical processes. In the upper part of the Nammuldi Member, supergene mineralisation processes have formed a broad sub-horizontal aquifer with high permeability and storage characteristics. Although this alteration has developed over a large lateral extent of the Chichester Ranges, later erosion of the anticlines and in some places synclines (by drainage features) has resulted in lateral discontinuity of the aquifer. The supergene zone diminishes to the south, which also results in lower permeability and storage.

The lower part of the Nammuldi Member is chert dominated and has not undergone the same alteration to form an extensive aquifer. Zones of high permeability are associated with fracture zones, which based on regional structural interpretation, are dominantly developed in a north-east to south-west orientation. Permeability is expected to persist more extensively to the north and south along these features than the aquifer in the upper part of the Nammuldi Member. Structural features that have been the focus of sub-vertical hypogene mineralisation can display higher permeability.

Groundwater quality is generally brackish in the upper part of the Nammuldi Member and becomes more saline within the lower part.

Wittenoom Formation

The Wittenoom Formation conformably overlies the MMF in the area of the Fortescue Valley. It comprises calcitic dolomite, with minor interbedded chert and shale and volcaniclastic sandstone. Lithological logging suggests that where fresh, it is crystalline, massive in nature, and has low intergranular permeability. Local permeable zones may be developed along fault zones.

Tertiary Calcrete and Silcrete (Oakover Formation)

The Oakover Formation is approximately 20 m thick and continuously developed beneath the Tertiary clay at about 50 metres below ground level (m bgl). The Oakover Formation onlaps with the MMF at its northern extent and extends beneath the Fortescue Marsh to the south, where it overlies the Wittenoom Formation.

Within the project area the Oakover Formation consists of calcretised and silicified carbonate formation, which typically has karstic characteristics that result in secondary permeability and enhanced storage properties. It is poorly developed or absent to the east, towards the Roy Hill deposit.

Regionally the Oakover Formation is described as a sequence of Tertiary lacustrine carbonate, silcrete and mudstone rocks deposited in the palaeodrainage of the Fortescue River Valley (Clout, 2011). Fortescue's definition for the Oakover Formation may only comprise a section of the larger formation identified within the Fortescue Valley.

Tertiary Clay

Beneath the mixed Tertiary detritals and alluvial sedimentary sequence within the Fortescue Valley, there is a clay dominated layer. The homogeneous nature of the clay suggests deposition within a lacustrine environment. It is typically 10 to 20 metres thick and continuous across the Christmas Creek and Cloudbreak project areas. At its northern limit, the Tertiary clay overlies the MMF (Figure 18). The clay is considered an aquitard that results in confining conditions for the Oakover Formation.

Evidence of significant clay layers has been identified from drilling completed within and to the south of the Fortescue Marsh by Rio Tinto Iron Ore, UWA and others (Skrypek G., 2013).

Tertiary Detrital and Alluvial Sediments

Detrital and alluvial deposits cover the Tertiary clay, MMF and Fortescue Valley. Hydraulic characteristics are often variable due to the nature of deposition in alluvial fans and flood plains. Areas of low to moderate yield and storage are associated with chert and reworked MMF gravels that have been deposited proximal to source. More distal deposits comprise clayey (variable) magnetite pisolitic gravels that have lower permeability. Recent work, (Equinox Environmental, 2012), has shown the importance of varying conditions of the detritals and alluvium deposits in controlling near surface and groundwater processes, in particular, at the Marsh fringe.

- Tertiary alluvium and colluvium – variable hydraulic conductivity and storativity as influenced by depositional heterogeneity, substrate geology and particle size distribution. Aquifers within the Tertiary depositional sequence are semi-confined to unconfined. Fortescue bore records show that the watertable at the edge of the marsh fluctuate in the order of 2 to 3 m under natural conditions, and are responsive to significant rainfall events. However, the response of shallow watertable to rainfall rapidly diminish moving further north from the marsh boundary.

- Tertiary Detritals (clay) - thick, low permeability clay layers are prominent in the deeper profile near the Fortescue Marsh. These overlie the Oakover Formation, and at their northern extent onlap the Marra Mamba Formation. These layers are believed to impede vertical water transfer between the surficial and deeper groundwater systems.

Table 5: Summary of geological and hydro-stratigraphic framework

Fortescue Stratigraphy Code	Stratigraphy Description[7]	Hydrogeological Characteristics
Ta	Tertiary alluvium	Detrital and alluvial sediments, ranging from proximal cobble to pebble, alluvial fans to distal silty and clayey flood plain deposits. Basal layers can have well-rounded hematite and magnetite pisoliths in clay matrix.
Tdi	Tertiary detrital	
Tds		
Tdm		
Te	Tertiary clay	Consolidated red-brown clay, highly plastic, cohesive. Forms an aquitard overlying Oakover Formation
To	Oakover Formation	Zones of re-precipitated calcium carbonate and silica developed within Fortescue Valley. Can be karstic creating zones of high permeability. Confined aquifer conditions developed beneath Tertiary clay.
WD	Wittenoom Formation	Generally massive dolomite, localised permeability associated with fault zones. Upper zone generally weathered and clay-dominant. Conformably overlies the

[7] Refer to Table 4

Fortescue Stratigraphy Code	Stratigraphy Description[7]	Hydrogeological Characteristics
		MMF, only present to the south of the mineralised MMF
Hc	Hardcap	Cherty shale and ferruginous chert, intrusive hypogene hematite deposits and post-depositional supergene geochemical alteration and iron enrichment zones. Noticeably vuggy and porous, high porosity and permeability. Generally thin and discontinuous unit.
MuX	MMF	– Hematite zones; massive, friable, foliated, intrusion and precipitation of iron rich fluids along fault zones. Interpreted to have high porosity (micro-scale), but tends to have low to moderate permeability.
	Mineralised MMF	Goethite, martite and hematite zones; secondary alteration and mineralisation. Complex overprinting of primary deposits by secondary processes. Geochemical alteration (iron mineralogy transformations) resulting in iron enrichment zone, related to hydration and dehydration. Enhanced 'secondary' porosity and moderate to high permeability. Very high permeability zones generally only semi-continuous.
	MMF lower (non-mineralised)	Ferruginous bedded chert and iron formation, generally very low storage and low permeability with higher permeability associated with NE – SW fault zones
Jr	Royhill shale	Upper weathered zones can have moderate permeability. Lower, unweathered zones represent a thick unit with generally low permeability. Enhanced permeability zones associated with cross cutting fractures and cherty interbeds.

2.6.2 Hydraulic properties

The results of hydraulic testing from previous field programs are summarised in Table 6 and Table 7. Table 7 provides individual bore or borefield data and Table 6 provides a summary of the range of values for Christmas Creek's hydrostratigraphic units. These data are derived from ongoing operations being referenced in Fortescue (FMG, 2010), (FMG, 2010c), (FMG, 2010d), (FMG, 2010a) and (FMG, 2013a).

Table 6: Aquifer test results (by aquifer)

Aquifer	T[1]		K[2]		S[3]		No. of Tests
	Range	Avg.	Range	Avg.	Range	Avg.	
Tertiary Detrital	59–210	135	4.2–5.3	4.8	$1.3 \times 10^{-3} – 4.2 \times 10^{-4}$	8.6×10^{-4}	2
Oakover Fmn.	3460–5505	4483	115–167	141	$3.3 \times 10^{-3} – 4.4 \times 10^{-4}$	7.87×10^{-3}	8
Mineralised MMF	1520–7069	4046	11- 311	226	$3.3 \times 10^{-5} – 7.9 \times 10^{-3}$	5.01×10^{-3}	9
Non-mineralised MMF	18–773	287	1.7–32	13	-	1.7×10^{-3}	3
MMF. (all[4])	222–8054	2358	11–386	100	$1.4 \times 10^{-4} – 7.7 \times 10^{-3}$	2.03×10^{-3}	67

1 Transmissivity (m^2/day)

2 Hydraulic Conductivity (m/day)

3 Aquifer storativity (dimensionless) (not assessed where no monitoring bore data are available)

4 All includes both the mineralised and un-mineralised MMF. However, the bore may not screen the entire non-mineralised sequence.

Table 7: Hydraulic assessment results

Bore	Assessment results						
	Q[1]	Sw[2]	b[3]	T[5]	K[6]	S[7]	Main aquifer
Flinders Pit 1-4[10]	32.9	12.2	25	3877	168	6.6×10^{-2}	MMF (all[4])
Flinders Pit 5-8[10]	37.9	10	35	8054	236.4	1.3×10^{-3}	
Windich Pit 30-32[10]	40	17	37	1646	44.5	7.9×10^{-4}	
Spinifex Pigeon[10]	33.6	9	30	7069	226.8	3.7×10^{-3}	Mineralised MMF
Saline Injection[10]	31.6	2	30	4483	141	7.87×10^{-3}	Oakover Formation
Hillside East Extension[10]	18.75	13.9	23	296	15.5	2.5×10^{-3}	MMF (all[4])
CCP10_S[9]	1.5	5.53	14	59	4.2	1.3×10^{-3}	Detrital
CCE14_S	6.5	30.61	40	210	5.3	4.2×10^{-4}	Detrital/Oakover
CCE10	32.4	1.38	33	5505	167	4.4×10^{-4}	Oakover/Mineralised MMF
CCE02[8]	31	2.57	30	3460	115	3.3×10^{-3}	Oakover/Non-mineralised MMF
CCE12	31.7	1.33	40	3278	81.9	1.5×10^{-3}	MMF (all[4])
CCP08[9]	15.7	9.39	20	222	11	1.8×10^{-3}	
CCE13	10	12.06	38	734	19.3	1.6×10^{-4}	
CCP16[9]	25.7	6.1	24	501	20.9	1.4×10^{-3}	
CCP07[9]	20.7	4.14	25	576	23	-	
CCE14_D	35	4.3	40	1350	33.8	1.5×10^{-3}	
CCE16	15	10.215	18	923	51.3	1.4×10^{-4}	
CCE18	35	0.85	47	4005	85.2	-	
CCCP02[9]	21.6	1.03	21	1897	90.3	-	
CCP24[9]	27.6	5.245	30	2910	97	-	
CCP09[9]	26.6	0.5	22	2803	127	-	
CCP10[9]	27.5	0.94	24	3659	152	7.7×10^{-3}	
CCP22[9]	26.1	1.845	20	4585	229	-	
CCCP01[9]	22	0.51	15	5797	386	-	
CCE01	31	6.575	18	1520	84.4	7.9×10^{-3}	Mineralised MMF
CCP10_I[9]	13.9	7.53	12	3663	305	7.1×10^{-3}	
CCE05_I	28	5.965	24	6955	290	3.3×10^{-5}	
CCE05_D	10.2	37.4	11	18	1.65	-	Non-mineralised MMF
CCP08_D[9]	14.7	13.96	18	70	3.9	1.7×10^{-3}	
CCP23[9]	25.6	8.67	24	773	32.2	-	

1 Pumping rate (L/s)
2 Total drawdown (m)
3 Aquifer thickness (m)
4 All includes both the mineralised and un-mineralised MMF. However, the bore may not screen the entire non-mineralised sequence.
5 Transmissivity (m^2/day)
6 Hydraulic Conductivity (m/day)
7 Aquifer storativity (dimensionless) (not assessed where no monitoring bore data are available)
8 Parameters defined from reinjection test data
9 2008 test results
10 Average test results from all bores

2.6.3 Hydrostratigraphic connectivity

Knowledge of connectivity between hydrostratigraphic units is of particular importance, the significance and interpreted nature of the connectivity between the hydrostratigraphic units is described below:

Tertiary Detrital (alluvium and detrital) and Oakover Formation

The presence of the thick clay layer (Tertiary clay) between the Oakover Formation and the upper Tertiary alluvium is observed[8] to limit fluxes between these aquifer systems. This is significant as the Oakover Formation will be subject to pressurisation and depressurisation at different stages during the LOM, and the low connectivity due to the presence of the clay layer will inhibit manifestation of pressure changes in overlying and shallow aquifer zones.

Tertiary Detrital (alluvium and detrital) and Mineralised MMF

Tertiary detritals/alluvium overlying the MMF are saturated and therefore require dewatering where the mine plan requires access to the orebody. They also represent a store of water in water supply areas. The Tertiary detritals/alluvium has low hydraulic conductivity making it inefficient to abstract groundwater directly from the aquifer; as such, there is a reliance on leakage being induced by abstracting from the underlying MMF.

Dewatering operations, at both Christmas Creek and Cloudbreak, has shown that leakage from the Tertiary detritals/alluvium occurs in response to lowering the piezometric head in the MMF.

Oakover Formation and Mineralised MMF

The connectivity between the mineralised MMF and Oakover Formation is an important factor in determining the flux of high salinity groundwater to the mine pits and abstraction borefields. The connectivity between these aquifers may be direct, in areas where the Oakover Formation overlies the mineralised MMF; or indirect via NE-SW orientated fracture zones through the Wittenoom Formation and unmineralised MMF. The connectivity, as assessed by investigations and piezometric response to dewatering, is variable with the possibility of indirect pathways being the more prevalent means of connection.

Roy Hill Shale and MMF

The degree of hydraulic connection between the Roy Hill Shale and the MMF is important to understand with respect to geotechnical issues and the potential for up-welling of saline water. Observations from operations and investigations at Christmas Creek have shown that abstraction from the MMF does induce depressurisation of the Roy Hill Shale during the latter stages of the dewatering program. It is conceivable that decreasing the overlying pressure in

[8] Injection of saline water into the Oakover Formation has pressurised the Oakover aquifer. This has resulted in an increase in monitoring bore water level in the Oakover Formation. This rise in water level has not been observed in monitoring bores screened within the Tertiary alluvium at coincidental locations.

the Roy Hill Shale by dewatering and mining may result in the opening of fine fractures and facilitate greater vertical leakage of water. The Roy Hill Shale has a typically low storage and contributing only a small volume of groundwater though upward leakage.

2.6.4 Groundwater levels and flow

Baseline[9] (March 2010) groundwater levels in the Tertiary detrital and the MMF[10] measured in both hydraulic head[11] and freshwater equivalent head[12] are shown in Figure 5 to Figure 8. Groundwater gradients are relatively shallow from the mining area to the Fortescue Marsh in both the Tertiary detrital and MMF. This gradient steepens to the east (south of Roy Hill mine), with a change in geology. Further information regarding long-term groundwater trends is developed from the modelled groundwater levels under various climatic conditions (Section 5.6).

Seasonal fluctuations in water levels are observed to vary across the site and in different hydrostratigraphic units. Figure 9 shows ponding of water observed across the Fortescue Marsh, following a significant rainfall event in late February 2009[13], and the locations of reference monitoring bores from the Cloudbreak monitoring network and two University of Western Australia research sites[14]. Interpretation of this data and operational monitoring provides the following conclusions:

- Christmas Creek and Cloudbreak monitoring bore data, for all hydrostratigraphic units, display a general groundwater level recession between 2006 and 2010, related to below-average rainfall.
- Groundwater recession between 2006 and 2007 was approximately 1 m and approximately 0.5 to 1 m from 2007 to early 2010, within the Tertiary detrital/alluvium. The recession trend was punctuated by a rainfall event in early 2009 and subsequent groundwater recharge.
- Since 2010, a number of large rainfall events resulted in variable Tertiary detrital/alluvium water levels across Christmas Creek and Cloudbreak. Since 2010, Tertiary detrital/alluvium groundwater levels adjacent to the Fortescue Marsh have shown annually fluctuations of up to 2 m.

Ponding on the Fortescue Marsh, related to high intensity rainfall, is directly related to Tertiary detrital/alluvium groundwater level responses observed within and at the fringe of the Fortescue

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[9] Baseline data taken prior to dewatering activities commenced in September 2011.
[10] The Oakover Formation and MMF are considered as a single unit for the purpose of generating contours shown in Figure 5 to Figure 8.
[11] A combined measure of the elevation and the water pressure at a point in an aquifer which represents the total energy of the water
[12] Hydraulic head is dependent on density (salinity) of water. To compare one or more hydraulic heads they need to be standardised to a constant density. This is usually to their fresh water head, i.e. the hydraulic head if all water bodies had a salinity and hence density of fresh water.
[13] Interpreted from Landsat imagery (Appendix 1).
[14] Data is available for the Cloudbreak and UWA monitoring bores, shown on Figure 9, from 2006 onwards.

Marsh. The control exerted, on groundwater levels, by ponding within the Marsh is reduced with distance from the Marsh. These trends are supported by the following observations:

- Significant rainfall and flooding of the Fortescue Marsh between January and March 2006 (380 mm rainfall recorded at Newman) resulted in the cessation of the long-term Tertiary detrital/alluvium groundwater level recession.
- Subsequent smaller rainfall events resulted in a groundwater level rise (130 mm) between March and April 2007. Notably, Tertiary detrital/alluvium groundwater level increases were only observed in monitoring bores located adjacent to the Fortescue Marsh.
- Tertiary detrital/alluvium groundwater level increases in the order of 0.5 m, adjacent to the Fortescue Marsh, were observed in response to a rainfall event (105 mm in one day) in early 2009. This rainfall event caused significant ponding on the Fortescue Marsh[15] which is clearly visible from Landsat imagery and was recorded at two UWA research sites within the margin of the Fortescue Marsh (see Figure 9).
    - The westernmost site (Site B) recorded ponding of approximately 0.5 m above ground level (406.8 m AHD)
    - The easternmost site (Site A) recorded ponding of approximately 0.2 m above ground level (405.8 m AHD).
- Tertiary detrital/alluvium groundwater level increases, at the fringe of the Marsh, were observed following Cyclone Heidi (Jan 2012) at both Christmas Creek and Cloudbreak. The increase observed varied spatially along the Marsh and was directly related to proximity and localised/regional ponding.
    - Christmas Creek bores[16] showed a rapid increase in groundwater level (0.5-1.5 m) in the month following Cyclone Heidi. Water level fluctuation was most pronounced at CCFMM03, adjacent to a creek line, with a relatively subdued response to the east and west.
    - Cloudbreak bores, being located further from the Marsh, showed a delayed and smaller increase in groundwater level (0.3 – 1 m), in comparison to the Christmas Creek. Most pronounced variations were observed closest to the Marsh and adjacent to areas of previous ponding (Historical Landsat data, Appendix 1).

2.6.5 Groundwater quality

Groundwater in the Christmas Creek region ranges from marginal/brackish (<1,500 milligrams per litre [mg/L] Total Dissolved Solids [TDS]) in shallow recharge areas to hypersaline at depth and close to the Fortescue Valley (>150,000 mg/L TDS). Hypersaline groundwater has evolved through evapoconcentration beneath the Fortescue Marsh, over prolonged periods of time and

[15] This ponding event was localised and appears to be related to discharge from discrete catchments in the Chichester Range.
[16] Monitoring bores CCFMM01 – CCFMM05.

potentially under different climatic regimes over periods of up to 700,000 years (Skrypek G., 2013).

The distribution of brackish and saline water within the Christmas Creek area is shown schematically in Figure 3. Baseline salinity levels in the Tertiary detrital and the MMF are shown in Figure 12 and Figure 13. Baseline salinity in both the Tertiary detrital and MMF increases with proximity to Fortescue Marsh and are generally aligned with the alignment of the Marsh fringe. Salinity concentrations in Tertiary detrital and MMF vary between 25,000 µs/cm (south of the active mining area) to 150,000 µs/cm (at the Marsh fringe).

Groundwater chemistry analysis (Figure 10 and Figure 11) in the MMF indicates Type 5 to Type 9 waters (Expanded Durov analysis). Type 5 waters have a low concentration of total dissolved solids (TDS) and are generally associated with recharge areas to the north of Christmas Creek. Type 9 waters have high proportions of sodium and chloride, and are considered to be end-point waters with regards to evaporation. Therefore, the MMF includes an evolution from recharge to end-point characteristics.

Groundwater in the Tertiary detrital and alluvium (Figure 1- and Figure 11) show a wide range in compositions with variable TDS and major ion concentrations suggesting spatial variation in groundwater flow and age. Whereas, groundwater in the Oakover Formation (Figure 10 and Figure 11) has high proportions of sodium and chloride ions with groundwater salinity ranging from 10,000 mg/L to over 100,000 mg/L.

The spatial distribution of groundwater salinity was assessed via a SkyTEM[17] airborne electromagnetic survey. Data-inversion was carried out using the Laterally-Constrained Inversion (LCI) method. Field data was filtered and then modelled against a subsurface layer structure constrained laterally on a number of chosen model parameters (including layer conductivity and layer thickness). The 3D inversion data were provided as slices through specific hydrogeological surfaces, including 5 m below the watertable (Figure 14) and the top of the ore zone (Figure 14). This approach has assisted in mapping the position of the salt interface and developing the following concepts:

- The heterogeneity of the saltwater interface, in particular associations with structural lineaments and other preferential flow paths.
- Brackish water forms a lens in the MMF and Tertiary detritals/alluvium overlying saline groundwater near the Chichester Ranges.
- Salinity increases towards the Marsh in all hydrostratigraphic units, and

[17] SkyTEM is a helicopter-mounted, time domain electromagnetic (TDEM) system. The SkyTEM survey was conducted by Geoforce Pty Ltd over an eight-day field program in September 2009. The surveyed area extended from the Fortescue Marsh boundary to the Chichester Range, from Christmas Creek in the East to Cloudbreak in the West.

- Saline zones beneath the ore zone may be disconnected from principal flow mechanisms ('fossil' groundwater).

2.6.6 Density driven flow

Density gradients due to salinity difference are an important driving force of groundwater flow. Density contrast between saline groundwater beneath and adjacent to the Fortescue Marsh, and fresher groundwater along the flanks of the Chichester Ranges has resulted in a saline transition zone. Stratigraphy, structure, hydraulic head and salinity concentration influence the extent and nature of the saline transition zone. The saline interface may, naturally, move seasonally owing to changes in hydraulic head conditions.

The piezometric head[11] measured in a saline aquifer must be converted to a fresh water equivalent head to account for the pressure exerted by the overlying column of saline water. The measured piezometric heads can be converted to equivalent freshwater head via the following density-conversion equation[18]:

$$equivalent\ head = measured\ head\ \times \frac{(0.0007723 \times S) + 997.31}{1000}$$

When measured piezometric head in the hypersaline Oakover Formation are converted to fresh water equivalent head, a pressure gradient can be observed in the opposing direction to the topographical-driven gradient from the Chichester Ranges into the Fortescue Valley (Figure 3).

2.6.7 Groundwater recharge

Primary mechanisms for groundwater recharge are:

- Infiltration recharge from direct rainfall and local streamflow on MMF outcrop and Tertiary detritals/alluvium.
- Infiltration recharge associated with ponding on the Fortescue Marsh.
- Inflow from basement aquifers to the north of the project area.

Direct rainfall recharge to the Tertiary detritals/alluvium and MMF is considered to be low in the Christmas Creek area, reflecting the low rainfall and high evaporation of the region (see Section 2.3).

Recharge is enhanced in creeks and areas of streamflow. Areas of outcrop and subcrop with drainage incisions can have direct connection between surface water and underlying permeable lithologies.

[18] Where S is salinity (mg/l) as adapted from (Bear, 1972)

2.6.8 Groundwater discharge

Based on the evolution of groundwater within the upper Fortescue Valley, the groundwater system beneath the Fortescue Marsh is considered a closed system with limited outflow to the west beneath the Goodardarie Hills. Discharge is therefore interpreted to only occur through evaporation and evapotranspiration processes beneath and fringing the Marsh. Discharge would be greatest when water levels are high, following recharge events and lowest after a prolonged dry period when the extinction zone for evaporation or evapotranspiration (from the watertable) is reached.

2.6.9 Hydrogeological setting comparison

Table 8 provides a comparison of the hydrogeological setting at Christmas Creek with respect to that of the nearby Cloudbreak and Roy Hill projects in order to provide a regional context.

Table 8: Hydrogeological setting comparison

Aspect	Christmas Creek	Cloudbreak	Roy Hill (Hancock , 2009)
Drawdown Footprint			
Operational Dewatering strike length	~30 km	~30 km	~35 km
Distance from the Fortescue Marsh boundary	7 - 9 km	4 - 6 km	5 - 10 km
Ore body Parameters			
Mineralised Marra Mamba Formation	30 to 100 m/day	30 to 100 m/day	7.5 m/day
Oakover Formation	200 m/day	50 to 300 m/day	Up to 5 m/day
Regional hydraulic connection	Regional connection between MMF and Oakover Fm.	Discrete zones of connection between MMF and Oakover Fm.	Oakover Fm. not present to the south of Roy Hill.
Numerical Modelling			
Estimated annual abstraction rate	Up to 110 GL/a (dewatering)	Up to 100[19] GL/a (dewatering)	22 GL/a (dewatering)
Basis for assessment	Pumping tests and calibration against over 18 months of operational data	Pumping tests and calibration against over 36 months of operational data	10 pump tests of up to 4 days duration.
Modelling approach	FEFLOW density-coupled model; 11 model layers, BASD (moving mesh) saturated flow parameters	FEFLOW density-coupled model; 11 model layers, BASD (moving mesh) saturated flow parameters	MODFLOW Finite difference model; 6 model layers. Further details (e.g. density coupling) unknown
Water excess management approach	Reinjection to compatible aquifers (all excess water)	Reinjection to compatible aquifers (all excess water)	Evaporation pond(s); salt encapsulation.

[19] 100GL as defined within the 2011 PER submission. The latest assessment predicts abstraction at Cloudbreak up to 160GL.

2.7 Flora and Fauna

2.7.1 Flora and Vegetation

ENV Australia (ENV, 2013) was commissioned by Fortescue Metals Group Limited, to undertake an assessment of the flora and vegetation of the Life of Mine area at Christmas Creek. This assessment consisted of a compilation and analysis of the results of previous surveys, and additional surveys conducted in 2011, 2012 and 2013.

In total, 541 taxa, including 14 Priority Flora and 20 weed species have been recorded from the survey area. No species listed by the *Environment Protection and Biodiversity Conservation Act 1999*, or gazetted as Declared Rare Flora (DRF) pursuant to the *Wildlife Conservation Act 1950* were recorded (ENV, 2013).

A desktop assessment (Department of Parks and Wildlife (DPAW) database searches and previous surveys) identified known records for 46 Priority listed flora in the vicinity of Christmas Creek (ENV, 2013). The most recent surveys recorded 13 species of Priority flora at low densities. Two additional species have been recorded in previous surveys and five species have been recorded in close proximity to Christmas Creek during previous surveys.

2.7.2 Fauna

A total of 275 vertebrate fauna species (five amphibians, 84 reptiles, 149 birds and 37 mammals) could potentially occur at Christmas Creek, based on literature reviews and database searches. The most recent survey, undertaken by (ENV, 2012) recorded a total of 120 vertebrate species: four frog species, 45 reptile species, 11 mammal species and 60 birds.

Desktop analysis determined 25 conservation significant species have been recorded or are known to occur within the vicinity of the Proposal area. Of these, four were recorded during the current survey (ENV, 2012) and four have been recorded during previous surveys. In addition, ENV undertook a targeted survey of the Proposal area to verify the presence or absence of the Northern Quoll, Pilbara Olive Python and the Western Pebble-mound Mouse (ENV, 2012). The survey found no Northern Quoll or Pilbara Olive Python; however, the Western Pebble-mound Mouse was recorded.

A Short Range Endemic (SRE) invertebrate fauna survey of the Disturbance Envelope was undertaken by Subterranean Ecology (2012). The survey found 26 target SRE taxa from six invertebrate orders of which no specimens are considered 'confirmed SRE' species (Subterranean Ecology, 2012). Four taxa are considered 'potential SRE', pending further resolution of their identification and SRE status.

A subterranean fauna assessment was undertaken by Bennelongia Environmental Consultants (Bennelongia, 2008 and 2012). The surveys recorded 29 troglofauna species of 13 Orders, and 68 stygofauna species belonging to 13 higher taxonomic groups. It is considered that this represents a moderately rich troglofauna community and a rich stygofauna community for the Pilbara region.

2.7.3 Fortescue Marsh

Work recently completed by Equinox Environmental (Equinox Environmental, 2012) provides a consolidated summary of knowledge gained from studies relating to ecohydrology of the Fortescue Marsh. (Equinox Environmental, 2012) also describes a conceptual ecohydrological model of the Fortescue Marsh fringe and discusses potential indirect impacts to the Fortescue Marsh and fringing areas.

Supported by empirical evidence from multiple studies, the Fortescue Marsh conceptual ecohydrological model indicates that the water balance dynamics of the marsh are principally controlled by surface water inflows from the greater marsh catchment, as dictated by episodic flooding events. The flood events replenish a shallow aquifer system in the Tertiary sediments beneath the marsh, which is gradually depleted by direct surface evaporation and evapotranspiration by the fringing vegetation communities. In periods of prolonged drought, the shallow watertable reaches a pseudo-steady state set by the evaporation extinction depth in the lowest parts of the marsh basin. The fringing vegetation is dominated by samphire communities which exhibit zonal species distribution patterns influenced by soil water and salinity dynamics, depth to watertable and flooding frequency (Equinox Environmental, 2012).

A vertical 2-dimensional variably-saturated model (HYDRUS) was used to simulate soil water dynamics and plant water uptake by samphire vegetation on the fringe of the Fortescue Marsh (Equinox Environmental, 2012). In combination with empirical observations, in particular the demonstrated ability of *T. indica* subsp. *bidens* to tolerate drought and other stressors, the findings of the modelling study suggest that the ecological water requirements of the fringing samphire communities are wholly or predominantly met by surface inputs. The findings also provide confidence that drawdown, of up to 3 m, will not significantly affect samphire survival and health. Other potential groundwater system impacts associated with the Christmas Creek Project water management strategy, such as injection mounding and water quality changes, are also not predicted to be significant.

Mining and infrastructure development associated with the Christmas Creek Project will disturb the surface flow regime north of the Fortescue Marsh, within a zone of relatively stable channel systems occasionally separated by sheetflow areas. The divergent channel drainage network downstream from these areas will remain largely unaffected by mining disturbances. Assuming effective implementation of the Fortescue Chichester Operations Surface Water Management Plan (FMG, 2009a), minimal disruption to the downstream flow regime at the marsh fringe is expected. Where changes to the flow regimes of individual drainage outlets occur, these are predicted to be modest and will not significantly affect the ecological water requirements of the Fortescue Marsh samphire communities.

2.8 Aboriginal heritage

There is a long history of Aboriginal habitation in the vicinity of Fortescue Marsh. A number of ethno-archaeological sites (mainly stone artefact scatters) have been identified in the course of exploration and mine development activities associated with the Chichester Operations. Aboriginal heritage surveys associated with the Christmas Creek mine commenced in late 2003.

Two Yinta areas in the Christmas Creek project area (near the edge of the Fortescue Marsh) were visited and recorded as possible Aboriginal Sites under the *Aboriginal Heritage Act 1972*. These Yinta sites are shown in Figure 2.

2.9 Pastoral bore use

The Christmas Creek project is located on Hillside, Bonney Downs, Wandanya and Roy Hill pastoral leases (Figure 2). These pastoral stations operate beef cattle production enterprises. Station infrastructure is minimal but includes multiple stock watering points with shallow bores. Known operational pastoral bores for the greater project area are summarised in Table 9.

Table 9: Pastoral groundwater bores

Station Bore Name	Easting (GDA94, Zone 50)	Northing (GDA94, Zone 50)	Pastoral Station
22 Mile Bore	781,847	7,517,729	Roy Hill
Ricks Bore	786,167	7,515,181	
Christmas Creek Bore	792,653	7,510,810	
Gorge Bore	794,476	7,518,193	

3. CHRISTMAS CREEK OPERATIONS

3.1 Groundwater Management Strategy

The groundwater management strategy has been in operation at Christmas Creek since 2011 and is consistent with the strategy developed for the Cloudbreak mine. The strategy has been developed to meet requirements of the mine and Fortescue Marsh Management objectives (EPA, 2013). A summary of objectives and management strategies is presented in Table 10 and briefly described below.

- Advance dewatering and operational dewatering methods for multiple water quality streams.
- Brackish injection.
- Saline injection.

The Groundwater management strategy has been enhanced with the connectivity of the Cloudbreak and Christmas Creek systems, which has created flexibility to redistribute water across a 90 km distance, and offers a high level of flexibility to manage groundwater level responses.

Table 10: Water management objectives and strategies

Objectives	Strategies
Christmas Creek • Prevention of disruption to mining due to water. • Conservation of groundwater resource. • Completion of water management operations in a cost-effective manner.	• Inclusion of water management as a key parameter in the mine planning process. • Adoption of Managed Aquifer Recharge (MAR) as the principal excess water management method.
Fortescue Marsh Management Objectives • Minimisation of impacts associated with discharge of excess water to the environment. • Minimisation of Groundwater Dependent Ecosystem (GDE) impact due to operational groundwater level change. • Prevention of aquifer contamination. • Sustainable use of groundwater resource. • carbon-efficient construction and operation. • Minimisation of ground clearing requirement. • Minimisation of closure legacy.	• Operation of separate water management conveyance systems for brackish and saline water. • Banking (storing) brackish groundwater for future recovery. • Targeted injection of excess water to reduce drawdown footprint. • Injection of saline groundwater into compatible saline quality aquifer(s). • Adoption of a flexible water conveyance system that enables the redistribution of water as required to manage potential impacts. • Adoption of mine site surface water diversion strategies to minimise disruptions to volume of surface water flow from the Chichester Range to the Fortescue Marsh.
Social • Minimisation of impact to cultural values. • Minimisation of impact to other stakeholders.	• Continued pursuit of process-improvement strategies for water management. • Continued development and implementation of Fortescue's groundwater management framework.

3.2 Operations management

The following regulation applies to abstraction and injection operations:

- Groundwater abstraction is regulated under Section 5C of the *Rights in Water and Irrigation Act 1914* (RIWI Act) by the Department of Water (DoW). The groundwater license GWL167593 has an abstraction entitlement of 48 GL/a. Operational commitments applicable to the licence, including monitoring and reporting commitments are documented in the *Christmas Creek Groundwater Operating Strategy* (FMG, 2012b).
- Groundwater injection is regulated under Part V of the *Environmental Protection Act 1986* (EP Act), by the Department of Environment Regulation (DER). The applicable licence is L8454/2010/1 with operational commitments including monitoring and reporting commitments being documented in the *Christmas Creek Water Management Scheme* (FMG, 2013c).

Reporting to the DoW, is undertaken quarterly to demonstrate compliance with the operating strategy and to inform of groundwater impacts. The most recent quarterly monitoring summary covers the period from 1 February 2013 to 30 April 2013 (FMG, 2013). A triennial review summarising data up to July 2013 was submitted in September 2013 (FMG, 2013a).

Groundwater monitoring is undertaken by a dedicated Christmas Creek Monitoring and Compliance team. Groundwater levels, salinities and abstraction volumes are measured monthly (or at more frequent intervals).

A brief summary of performance against Fortescue Marsh management objectives and the Christmas Creek Operating strategy is outlined below.

3.3 Operations performance summary

Fortescue has been compliant with all requirements of the Operating Strategy (FMG, 2012b) and Water Management Scheme (FMG, 2013c). No significant impacts have been recorded and adaptive management solutions have been implemented to ensure continuing success of operations (FMG, 2013a).

Mining below watertable has progressed in two mine pits (Flinders and Windich) spanning approximately 8 km of the mineralised Marra Mamba Formation (MMF). Water quality permitting, this groundwater is used for ore processing and dust suppression; excess brackish water has been injected to the east and west of the below water table mining area (but within the same aquifer) and saline groundwater has been injected to the Oakover Formation located to the south of the below watertable mining area (and north of the Fortescue Marsh). In the period August 2010 to July 2013, brackish groundwater was abstracted from injection areas to supplement brackish supply for the mine site.

A total of 0.9 GL, 10.2 GL, and 34.4 GL were abstracted for the 2010/2011, 2011/2012 and 2012/2013 licence periods respectively. Of the total abstraction, mine site water use and injection comprised 100% and 0% respectively for 2010/2011; 72% and 28% for 2011/2012; and 40% and 60% for 2012/2013.

Water level changes due to dewatering and injection activities have followed the expected trends, being summarised as;

- The piezometric level has been lowered in the MMF aquifer and overlying Tertiary detrital/alluvial aquifer in the below watertable mining (and dewatering) area.
- The piezometric level has risen and subsequently started to recede in the MMF aquifer and overlying Tertiary detrital/alluvial aquifer in the brackish injection area to the east and west of the below watertable mining area.
- Piezometric levels have risen in the Oakover Formation in the saline injection area and to a lesser extent in the near marsh area.
- Piezometric levels in the Tertiary detrital/alluvial aquifer (overlying the Oakover Formation) in the saline injection area and near marsh areas have displayed cyclical periods of rise and fall in response to climatic induced groundwater recharge events.

The salinity of groundwater abstracted from dewatering operations has increased in response to depletion of the brackish water resource in the dewatering area; salinity has remained relatively constant in the MMF in the brackish injection zones; and salinity has remained relatively stable in the Oakover Formation and overlying alluvial aquifer in the saline injection and near-marsh areas.

4. CONCEPTUAL HYDROGEOLOGICAL MODEL

Extensive hydrological knowledge developed from site and regional investigations, and operations (Sections 1 & 3) have been synthesised to inform the conceptual hydrogeological model for Christmas Creek. The conceptual model forms the basis of the numerical modelling. The hydrogeological setting can be classified based on the dominant flow processes into three regimes:

- Topographic driven groundwater flow system of the Chichester Range.
- Density driven groundwater flow system of the Upper Fortescue Valley.
- Surface water driven Fortescue Marsh and peripheral shallow groundwater system.

Characteristics of each of these systems and the relationship between the flow systems are described below and in Figure 3. Elements of the conceptual model which are represented in the numerical modelling study are summarised in Table 11.

4.1 Topographic driven groundwater flow system of the Chichester Range

Rainfall and streamflow on the upper and lower slopes of the Chichester Ranges infiltrate the soil and recharge the MMF directly or through Tertiary detritals/alluvium. The mineralised MMF is the main aquifer in this part of the flow system. The mineralised MMF is bounded below by the lower MMF and Jeerinah Formation and overlain by saturated Tertiary detritals/alluvium.

Groundwater flow is generally in a south to south-westerly direction towards the Fortescue Marsh. The hydraulic gradient is very low due to the opposing density driven flow system and a small amount of discharge for limited periods is expected to occur by evapotranspiration at the Fortescue Marsh.

Seasonal groundwater trends are generally subdued due to the low infiltration rate, high storage of Tertiary detritals/alluvium and low rate of discharge from the system.

4.2 Density driven groundwater flow system of the Upper Fortescue Valley

The hypersaline environment of the Upper Fortescue Valley groundwater system creates a density driven flow system that directly opposes the topographic driven flow system. Evidence suggests that hypersaline conditions developed due to a constriction of the regional groundwater flow system at the Goodardarie Hills, as well as a long period of evapo-concentration of flood waters on the Fortescue Marsh.

The Oakover Formation is the main aquifer in this part of the flow system. The Oakover Formation is bounded below by the Wittenoom Formation and overlain by a homogeneous clay layer which in turn is overlain by saturated Tertiary detritals/alluvium.

The opposing density driven and topographic driven flow systems result in the formation of a dynamic saline interface, which extends over many kilometres between the Fortescue Marsh and the lower slopes of the Chichester Ranges, and is present throughout the flow system. Changing pressure conditions within each part of the system create a dynamic interface, the distribution of which reflects hydrostratigraphic connectivity and dispersion characteristics of the aquifer system.

Direct connectivity between the mineralised MMF and the Oakover Formation is variable and indirect connectivity is locally enhanced through north-east–south-west fault zones in the underlying MMF and Wittenoom Formation.

4.3 The Fortescue Marsh and peripheral shallow groundwater system

The upper groundwater system of the Upper Fortescue Valley is associated with the Fortescue Marsh, which is the discharge point for the Upper Fortescue surface water catchment. The Upper Fortescue catchment covers an area of 30,000 km^2. Runoff following major rainfall events in the catchment result in significant flooding on the Fortescue Marsh.

The extreme variability of hydrological dynamics that occur between flood and prolonged dry periods can be described by three dynamic phases and are illustrated in Figure 16:

4.3.1 Flood phase

Following major rainfall events catchment runoff enters the Fortescue Marsh and forms a lake or series of lakes. Lake volumes in excess of 300 GL have been calculated. Under this condition, the surface water and shallow groundwater become connected as surface water infiltrates and raises the groundwater level to the surface. The capacity of the groundwater system beneath the Fortescue Marsh to receive water is generally low as the watertable is normally around 1 or 2 m below ground surface. The fresh surface water infiltrating the unsaturated zone is quickly salinized due to abundance of salts in the soil profile (Skrypek G., 2013). The elevated head associated with the lake creates a hydraulic gradient away from the Fortescue Marsh and groundwater flows into the adjacent alluvium.

Flooding within the Fortescue Marsh has been observed to have an influence on shallow groundwater (Tertiary detrital/alluvium) levels up to 2 km from the fringe of the Marsh (Figure 9).

4.3.2 Inter-flood phase

Between flooding events, referred to as the inter-flood period (Figure 16), rainfall and catchment runoff is generally low and evaporation exceeds the direct rainfall on the Fortescue Marsh. The lake is reduced over time through evaporation. At this stage, hydraulic gradients developed by the interplay of the topographic and density driven flow systems resumes, and evaporative discharge through and fringing the lake continues to lower the watertable.

4.3.3 Prolonged dry phase

Following an extended period of low rainfall, the Fortescue Marsh may reach the 'prolonged dry' condition (Figure 16). If the dry period progresses for a prolonged period the watertable level will fall below the evaporative extinction depth and discharge will diminish.

Table 11: Conceptual model summary

Element	Description
Model Framework	
Domain	The model domain covers an area of approximately 941 km^2.
Hydrogeological units	See Section 2.6.1
Hydraulic properties	See Section 2.6.2
Salinity	Groundwater salinity ranges between fresh (<500 mg/L) and hypersaline (up to 150,000 mg/L)
Model boundaries	Northern boundary. Though the MMF is truncated where it outcrops in the Chichester Range, this does not represent the northern boundary of the hydrogeological system. Groundwater occurrence within the underlying Jeerinah Formation (Roy Hill Shale) is connected with the MMF. Although connection between MMF & Roy Hill Shale is constrained to discrete fracture zones, the northern boundary has been selected to represent an interpreted surface water and groundwater divide within the Jeerinah Formation. The southern boundary is located along the Fortescue Marsh centreline. The eastern boundary is beyond the eastern extent of the operation, and groundwater flow is considered to be parallel to this boundary. The western boundary is beyond the western extent of the operation, and groundwater flow is considered to be parallel to this boundary. The model base is at a selected level below the groundwater flow system. The model top represents the watertable. During ponding events on the Fortescue Marsh, this will be expressed above the surface.
Groundwater Recharge	
Chichester Range recharge	Recharge due to infiltration of rainfall is estimated to range between 0.2 to 3% of rainfall (approximately 0.5 GL/a).
Fortescue Marsh recharge	After a prolonged dry period in which water levels below the Fortescue Marsh decline to 3 m below the surface, the occurrence of a significant ponding event (over 600 km^2) could recharge the groundwater system by approximately 30 GL of water. Groundwater recharge related to flooding can be predicted based on correlation between observed flooding and rainfall records.
Groundwater Discharge	
Evaporation and evapotranspiration	Evaporation and evapotranspiration principally occur in the Fortescue Marsh area, where the depth to watertable is shallowest. Potential evapotranspiration rates in the region are as high as 3,000 mm/year. This rate is expected to exponentially decline as depth to watertable increases (to a maximum depth of 3 metres).
Groundwater Flow	

Element	Description
Hydraulic gradient and through flow (topographic-driven flow)	Groundwater flow through the Chichester Range aquifer system is considered to be equivalent to catchment recharge. Chichester Range groundwater through flow is low compared to the Fortescue Marsh's recharge and evapotranspiration fluxes, as it is constrained by the presence of dense water beneath the Fortescue Marsh. Topographic driven flow from the Chichester Ranges tends to flow through shallow stratigraphy towards the watertable beneath the Fortescue Marsh
Salinity and density gradients (density-driven flow)	High salinity water has a higher density than fresh water, and resultant density gradients have an important influence on groundwater flow. The density value at 150,000 mg/L is 1.117kg/L.
Anthropogenic	
Pastoral bores	Several pastoral bores and bores are located in the project area. The drawdown from these bores and bores is very low and is drawn from the watertable.
Christmas Creek dewatering	Mining pits are located at areas with mineralised MMF.
Christmas Creek injection	The injection of brackish groundwater will occur laterally into MMF; the injection of saline groundwater will be to the south into the Oakover Formation aquifer.
Cloudbreak operations	Cloudbreak mining operations are located to the west of Christmas Creek and some dewatering and injection activities at Cloudbreak require consideration by Christmas Creek.

4.4 Water Balance

A conceptual water balance for each of the Fortescue Marsh phases is presented in Table 12. The water balance is for illustrative purposes and represents broad average recharge conditions, whereas recharge (especially related to the Fortescue Marsh) is event based.

- On an annual basis recharge to the groundwater system beneath the upper and lower slopes of the Chichester Ranges is estimated to be approximately 0.5 GL/a based on average rainfall conditions, an estimated 3% of rainfall recharging the aquifer system and the aerial extent of the Christmas Creek domain.
- Under flooded conditions, the groundwater system is being recharged. The lake, or open water, formed on the Fortescue Marsh following significant rainfall (average lake volume of around 300 GL) results in around 30 GL of water entering the shallow groundwater system.
- Under interflood conditions, the groundwater system is still receiving around 0.5 GL of recharge from the Chichester Ranges; however, discharge (evaporative) through and fringing the Fortescue Marsh is dominant.
- Under the prolonged dry condition, the system is effectively static (not receiving recharge or discharging).

Table 12: Simplified analytical water balance

	Recharge (GL/a)	Discharge (GL/a)
Flooded Condition		
Chichester Ranges	6	0
Fortescue Marsh (groundwater system)	30	0
Net	**36**	
Interflood Condition		
Chichester Ranges	0.5	0
Fortescue Marsh (groundwater system)	0	30
Net	**29.5**	
Prolonged Dry Condition		
Chichester Ranges	0	6
Fortescue Marsh (groundwater system)	0	0
Net	**-6**	

5. GROUNDWATER MODELLING ASSESSMENT

5.1 Modelling objectives and scope

A computer-based, numerical groundwater flow and transport model has been developed for the Christmas Creek project area for the purpose of predicting groundwater level conditions and conceptual design of the dewatering and injection system.

This section describes the following key components of this assessment:

- Construction of a numerical groundwater flow and transport model.
- Calibration.
- Simulation of dewatering and injection and prediction of water level change.
- Uncertainty analysis.
- Model limitations.

5.2 Numerical model construction

5.2.1 Numerical model complexity

Within the context of the Australian Groundwater Modelling Guidelines (SKM & NGRT, 2012), the numerical model is considered to be of moderate complexity as an Impact Assessment model. Within this approach, where understanding or data is lacking, it is possible to design the associated model aspects to be conservative with respect to their intended use.

5.2.2 Model software selection and code settings

To select suitable modelling software, several criteria were used:

- The software should have the function of simulating density driven flow and transport, since density-driven flow and salt transport is a major feature of the aquifer system.
- The model domain, which is very large (941 km^2) to achieve the goal of assessing environmental impacts, has to be discretised efficiently with the total number of elements (largely determining computer running time) being at a reasonable level.
- The software should industry recognised and technically well supported.

FEFLOW software (version 6.0) was determined to rate highly against the criteria and was selected as the preferred modelling code.

The following solver and code settings were adopted:

- Default iterative non-symmetrical equation solver ‘preconditioned Lanczos-type BICGSTAPB’.
- Default convergent form transport equations.
- Non-Fickian dispersion law.
- Extended Boussinesq approximation to density dependence.
- Neglect fluid viscosity effects on conductivity.
- The predictor-corrector, automatic, time-stepping system utilising the Forward Adams-Bashford/backward trapezoid rule.
- Default Euclidean L2 integral Root Mean Square (RMS) error norm with a convergence criteria of 0.0005.
- ‘Full upwinding’ techniques were applied to dampen oscillations.

5.2.3 Numerical mesh and numerical layers design

Model domain

The model domain (Figure 17) covers the Fortescue Marsh and mining area, as well as has been extended in all directions to locations where no flow boundary conditions are valid assumptions. The total model area is about 941 km^2.

Model layer structure

The hydrogeological stratigraphic units represented in the model are listed in Table 13 and shown graphically in Figure 18. An additional numerical layer (Layer 1) is used in the model to represent open water in Fortescue Marsh. This layer has a porosity of 1 and a large conductivity of 8640 m/day to simulate surface water ponding that may occur after significant rainfall events.

Spatial discretisation

Each numerical layer within the FEFLOW model is discretised into triangles with variable element sizes throughout the model domain. The finite element mesh was refined in and around the proposed mining area (Figure 17) with elemental side length down to 50 m.

Discretisation parameters were selected on the basis of the ability of the mesh to represent the curvature in the groundwater table and corresponding groundwater heads at depth. The gradation in element size from small to large radiating out from the mining regions is considered appropriate. Figure 18, shows the distribution of hydrogeological units in a vertical cross section of the model.

Table 13: Model layers

Numerical Model Layer Number	Description
1	Fortescue Marsh Open Water
2	Tertiary Detrital
3	Tertiary Clay
4	Oakover Formation
5	Wittenoom Formation
6	Hardcap: Depleted Marra Mamba Formation (MMB)
7	Mineralised MMB: above the Economical Ore Base
8	Mineralised MMB: below the Economical Ore Base
9	Fractured MMB
10	Un-mineralised MMB
11	Jeerinah Formation (Roy Hill Shale)

5.2.4 Model parameters

Hydraulic properties

The values and distribution of model hydraulic properties have been developed from field based aquifer testing (see Section 2.6.2) and model calibration (undertaken for borefield planning and design purposes) at both Christmas Creek and Cloudbreak. Initial hydraulic parameter values used in the model are presented in Table 14.

Model calibration undertaken as the operation has progressed has assisted in constraining hydraulic parameters determined from aquifer tests, particularly vertical conductivity and specific yield parameters, which are inherently difficult to determine from relatively short duration tests.

Table 14: Initial model hydraulic parameters

Hydrostratigraphic unit	Hydraulic conductivity			Specific yield	Specific storage coefficient
	K_h (m/s)	K_h (m/day)	K_h/K_z		
Marsh water body	1.0×10^{-1}	8640.0	1	1.0	10^{-5}
Tertiary Detrital	2.48×10^{-5}	2.15	50	0.04	10^{-4}
Alluvial clay	1.16×10^{-7}	0.01	10	0.01	10^{-4}
Oakover Formation	2.31×10^{-3}	200.0	10	0.04	10^{-4}
Wittenoom Formation	1.16×10^{-5}	1.0	10	0.005	10^{-5}
Hardcap	1.16×10^{-6}	0.1	10	0.03	10^{-5}
Mineralised Marra Mamba Formation	6.94×10^{-4}	60.0	50	0.03	10^{-5}
Fractured Marra Mamba Formation	5.78×10^{-5}	5.0	10	0.03	10^{-5}
Un-mineralised Marra Mamba Formation	5.78×10^{-6}	0.5	50	0.01	10^{-5}
Roy Hill Shale	1.16×10^{-7}	0.01	10	0.001	10^{-5}

5.2.5 Boundary conditions for groundwater flow

Boundary conditions used in the numerical model are summarised in Table 15.

Table 15: Numerical model boundary conditions

Boundary	Boundary Type	Description of hydrogeological representation
Western	No flow Boundary	For simplicity, the western and eastern boundaries are represented as no flow boundaries. • Under natural flow conditions, the assumption of a no flow boundary is considered appropriate as natural groundwater flow is roughly parallel to these boundaries. • Under mining conditions, no flow boundary conditions are also considered appropriate as they are located significant distances from active areas of mining (over 6 km to the western boundary and over 10 km from the eastern boundary).
Eastern	No flow Boundary	

Boundary	Boundary Type	Description of hydrogeological representation
		If any significant drawdown is predicted along these boundaries, it would represent the worst case scenario that might occur as long as no significant drawdown is caused by the neighbouring mining activity.
Northern	No flow boundary	The northern boundary is aligned with the surface water catchment divide within the Chichester Ranges. Groundwater flow is expected to closely follow topography and therefore the selected alignment represents a natural groundwater divide. Drawdown impacts are not expected to extrapolate to this boundary thereby not influencing the natural groundwater flow regime.
Southern	No flow Boundary	The southern model boundary lies in the foot hills of the Hamersley Plateau (to the south of the Marsh). The hydrogeological stratigraphy at this boundary is dominated by the Brockman Formation which is generally of low flow potential. Tertiary sequences in filling major drainages (Weeli Wolli CID) have the potential to transmit larger groundwater fluxes. The groundwater gradient is towards the Fortescue Marsh. Inflow through this southern boundary is represented by applying areal recharge (Table 16 and Figure 17).

5.2.6 Recharge

Recharge is the component of direct rainfall or surface water flowing across the land surface that infiltrates to the watertable. The model area was divided into seven recharge zones as described in Table 16 and presented in Figure 17.

Table 16: Numerical model recharge zones

Recharge zone	Description	Flux
1	Northern recharge zone	Infiltration from rainfall and stream flow applied as areal flux.
2	Rainfall recharge to the south of the Fortescue Marsh	Infiltration from rainfall (also accounts for inflow from Brockman Formation Domain) applied as areal flux.
3	Rainfall recharge and 'lake[20] recharge in the Fortescue Marsh	Infiltration from rainfall and more significantly infiltration from 'lakes' applied as areal flux to artificial layer above ground surface.

[20] Term used for surface water ponding on Fortescue Marsh following significant rainfall in the catchment and subsequent runoff.

Fortescue Marsh recharge

The recharge over the Fortescue Marsh is calculated as:

Equation 1 $$Recharge = POW \times Repot$$

Equation 2 $$Repot = F \times Raflood - Epan$$

Equation 3 $$POW = \begin{cases} 0 & HMSE > 407 \\ \frac{(407 - HMSE)}{2} & 405 \leq HMSE \leq 407 \\ 1 & HMSE < 405 \end{cases}$$

Where;

- POW is the depth of Potential Open Water.
- Repot is the potential net recharge.
- F is the coefficient to be calibrated and is related to stream flow entering Fortescue Marsh from the greater catchment region in flooding events.
- Raflood is the moving average (over 3 months) of measured monthly rainfall events that are greater than 90 mm/month.
- Epan is the average monthly rate of pan evaporation (mm/month).
- HMSE is the land surface elevation (m AHD).

From Equation 3, the following conclusions can be drawn.

- Low ground areas receive more recharge than high ground areas in the Fortescue Marsh.
- The actual recharge rate is equal to the potential net recharge rate in areas where the land surface elevation is less than 405 m AHD and decreases with increasing land surface elevation.
- In areas with ground surface elevations greater than 407 m AHD, the actual recharge equals zero.

5.2.7 Evapotranspiration

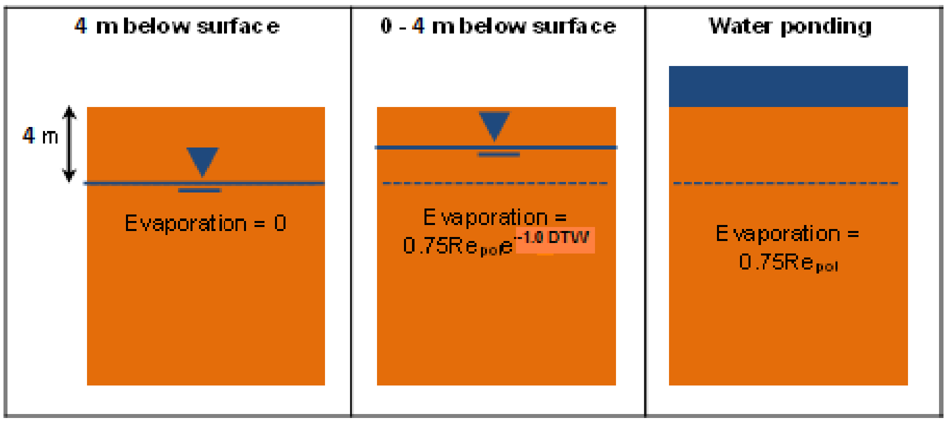
Evaporation is the sum of evaporation and plant transpiration direct from the watertable or surface water feature. Evapotranspiration is not significant over the upper and lower slopes of the Chichester Ranges owing to the depth to the watertable and nature of plant assemblages, which dominantly draw moisture from the soil profile. Evapotranspiration is a dominant process occurring within the Fortescue Marsh (Recharge Zone 3).

Evaporation is the discharge mechanism for open water occurring on the Fortescue Marsh and shallow groundwater beneath the Marsh. The application of evapotranspiration to the Fortescue Marsh is described below.

Fortescue Marsh evapotranspiration

In the model, evaporation over Fortescue Marsh is applied using the principles and formulas outlined in Table 17.

Table 17: Fortescue Marsh evaporation algorithm



5.2.8 Solute transport and density couple flow modelling

Solute transport processes

Solute transport occurs in two ways, advection and hydrodynamic dispersion (Bear, 1972).

- Advection is the process by which a volume of water is transported through porous media, carrying with its own concentration of solutes (dissolved mass).
- Hydrodynamic dispersion consists of diffusion and mechanical dispersion.
    - Diffusion is a process whereby spatial variations in concentration lead to movement of solutes, even when the water itself is motionless.
    - Mechanical dispersion is caused by spatial variations in velocity at various scales as a result of the tortuosity of porous media and heterogeneity of hydraulic conductivity.

Dissolved salts at low concentrations have little effect on flow processes. However, it has been shown that a concentration difference as small as several thousand mg/L may cause enough density effect that significantly affects groundwater flow, especially in situations where hydraulic gradients are small. In the Christmas Creek area, the hydraulic gradient is only 0.1 to 0.2% (head differences of 1 or 2 m over a horizontal distance of 10 km). In such circumstances, small density differences may cause density-driven groundwater flow. Given that the salinity gradient at Christmas Creek is large, density-driven flow may be a dominating process in some areas of the model domain.

Solute transport and density driven flow have been included in the numerical model, key solute transport parameters are listed in Table 18.

Table 18: Solute transport parameters

Parameter	Value
Reference concentration (C_o)	0 mg/L
Maximum concentration (C_s)	150,000 mg/L
Density coefficient ( )	0.12 (Specific Gravity = 1.12 [in the relationship ($[i_o)$ = 1 + = $1_o)/(C_s–C_o)$, hence S.G. at 150,000 mg/L is 1.11])
Molecular diffusion coefficient	10^{-9} m^2/s
Longitudinal dispersivity ($_L$)	500 m
Transverse dispersivity ($_T$)	50 m
Effective Porosity	Sy (used to calculate pore velocity in the solute transport equation)

Boundary conditions for solute transport

For solving the transport equation, boundary conditions need to be specified (Table 19). Zero-solute fluxes were applied to all lateral boundaries since they are all no-flow boundaries. As the salt concentration of rain water is small compared to groundwater salinity, the top boundary with rainfall recharge was assumed to be zero solute flux boundary. Salt concentrations of groundwater underneath the Fortescue Marsh are very high, up to 150,000 mg/L, and are not likely to change significantly over the model simulation period. As a result, a constant concentration boundary condition (internal boundary condition) was applied to all nodes underneath the Fortescue Marsh.

Table 19: Solute transport boundary conditions

Boundary Condition	Rationale
Zero solute flux on all lateral boundaries	These boundaries are no flow boundaries
Zero solute flux on top of the model	Rain water salinity is close to 0 mg/L
The concentration at nodes underlying the Fortescue Marsh is constant at 150,000 mg/L.	The hypersaline groundwater body has been formed over geological time periods. Groundwater salinity is unlikely to change significantly over the simulation time period (20 years).

5.3 Model calibration

5.3.1 Initial conditions and steady state calibration

The initial head and salinity distributions were derived from a long-term (4500 year) simulation. This long term simulation modelled the evolution of an initially brackish aquifer system by applying a constant salinity boundary condition set at 150,000 mg/L at the Fortescue Marsh surface to represent evapo-concentration processes. The actual historical evolution of the current salinity distribution is currently hypothesised to be due to similar processes but may have taken place over 10,000 to 100,000's of years, with various inter-waning periods (Skrypek et al., 2013). The process applied enables the derivation of a reasonable and stable spatial distribution of salinity to be used as the initial condition for the calibration model.

The simulated initial conditions for head and salinity distributions for 1 April 2010 are shown in Figure 19 and Figure 20. A comparison of the observed (freshwater equivalent) and simulated heads on 1 April 2010 is shown in Figure 21. The average absolute error is 1.07 m, which indicates that the simulated groundwater heads are within 1.1 m of measured heads. The normalised RMS is 8%, which is within the range of 5% to 10% recommended by (SKM & NGRT, 2012) for moderately complex systems.

5.3.2 Transient calibration

Transient calibration was conducted by using monitoring bore records and Fortescue Marsh flooding records (interpreted from Landsat images) in the period from 1/01/1997 to 31/12/2012 (16 years). The period is divided into two stages, i.e., the pre-dewatering stage (from 1/01/1997 to 30/06/2011) and dewatering stage (from 1/07/2011 to 31/12/2012).

The evaluation criteria for the model included:

- Residuals between observed and simulated heads at monitoring bores.
- Correlation between simulated and measured hydrographs of head (representing groundwater hydraulic dynamics at selected monitoring bores).
- Consistency between modelled water balance and estimated water balance in the model conceptualisation stage.
- Correlation between simulated and observed salinity distribution in the model area.

Calibration results for the two stages are presented separately in the following sections.

Pre-dewatering calibration stage

By adjusting key model parameters and boundary conditions described, the best overall agreement between simulated and measured heads was achieved by using:

- Model parameter values shown in Table 20. Calibrated parameters are consistent with calculated parameters in Table 14. The largest parameter change was the K_h for the Fractured Marra Mamba Formation (0.5 m/day to 5 m/day).
- Fortescue Marsh catchment runoff and evapotranspiration are 311 and 317 GL/a (see Table 21), respectively. The runoff of 311 GL/a equals 5% of effective rainfall over the whole Fortescue catchment (30,000 km^2).
- Average Fortescue catchment rainfall recharge rate is 1.4% of total rainfall, or 2.5% of the effective rainfall (sum of rainfall in all months with rainfall over 90 mm).

Table 20: Calibrated model hydraulic parameters

Hydro-stratigraphic unit	Hydraulic conductivity			Specific yield	Specific storage coefficient (1/m)
	K_h (m/s)	K_h (m/day)	K_h/K_z		
Marsh water body	1.0×10^{-1}	8640.0	1	1.0	10^{-5}
Tertiary Detrital	0.25×10^{-4}	2.15	50	0.04	10^{-4}
Tertiary Clay	1.16×10^{-8}	0.001	10	0.04	10^{-4}
Oakover Formation	23.1×10^{-4}	200	10	0.04	10^{-4}
Wittenoom Formation	0.35×10^{-4}	3	10	0.005	10^{-5}
Hardcap	1.16×10^{-6}	0.1	10	0.03	10^{-5}
Mineralised Marra Mamba Formation	6.94×10^{-4}	60	50	0.01	10^{-5}
Fractured Marra Mamba Formation	0.6×10^{-4}	5.0	100	0.03	10^{-5}
Un-mineralised Marra Mamba Formation	0.06×10^{-4}	0.5	50	0.01	10^{-5}
Roy Hill Shale	1.16×10^{-7}	0.01	10	0.001	10^{-5}

Simulated heads are compared with measured levels in Figure 23. The error between observed and simulated groundwater levels is in the range of -4.52 to 4.67m. The average absolute error is 0.92 m, which is about 4.5% of the maximum difference in observed groundwater levels. Typically, an error less than 5% is indicative of an acceptable calibration, since it means that the error is only a small part of natural groundwater level variations. The normalised Root Mean Squared error of the calibration is 5.9%, which is smaller than the value of 10% recommended by (SKM & NGRT, 2012).

Calibration of the model to the record of flooding for the Fortescue Marsh was undertaken for the period 1st January 1997 to 1st June 2011. The available rainfall data from Newman rainfall station was used as the primary time-varying model parameter for the Fortescue Marsh recharge formulation. The Fortescue Marsh runoff was adjusted to reproduce the observed Fortescue Marsh flood water levels (as shown in Figure 23).

The water balance of the calibrated model is shown in Table 21. Catchment rainfall recharge which refers to groundwater recharge is approximately 8.4 GL/a.

The water balance is dominated by surface water fluxes (311 GL/a) and evapotranspiration (311.4 GL/a) from the surface of the Fortescue Marsh. Water levels in the zone immediately beneath the marsh surface only fluctuate by 1 to 4 m in response to cycles of flooding and evapotranspiration and the related groundwater storage change is small when compared to the surface water storage change. The small increase in groundwater storage change (8 GL/a) suggests that groundwater levels are slightly higher at the end than at the beginning of the model calibration period. This groundwater level increase is due to a simulated large recharge event at the end of the calibration period.

Table 21: Model water balance in the calibration period

Model Input		Model Output	Aquifer Storage Change (GL/a)
Catchment Recharge (GL/a)	Fortescue Marsh Recharge (GL/a)	ET[1] (GL/a)	
8.4	311	311.4	8

Dewatering calibration stage

Recorded monthly pumping and injection rates were used as model inputs. Model parameters and recharge coefficients obtained from the pre-dewatering stage calibrations were used as initial parameters. In the dewatering stage calibration hydraulic parameters were adjusted to achieve reasonable fit with water levels, abstraction rates and injection rates. A scattergram for observed versus simulated water levels is presented in Figure 53. The results of the dewatering stage calibration are summarised as follows:

- Simulated abstraction was equivalent to 95% of actual abstraction.
- The error between observed and simulated groundwater levels is in the range of -10.14 m to 12.5 m. The average absolute error is 2.49 m.

- The ratio of the average absolute error to the maximum observed groundwater level difference (42.51 m) is 4.7%.
- The normalised Root Mean Squared error of the calibration is 5.9%, which is the same as that achieved in the pre-dewatering calibration.

As expected both the error range and the average absolute error are larger than those achieved in the pre-dewatering calibration, as groundwater levels are more dynamic under dewatering conditions. However, the ratio of the average absolute error to the maximum observed groundwater level difference is still small. All other calibration indicators are considered appropriate.

5.3.3 Calibration Summary

Hydrographs showing simulated and observed groundwater levels for both the pre-dewatering and dewatering stage calibrations are presented in Appendix 5. The correlation between measured and simulated hydrographs at key locations is consistent, implying that the calibrated model has included the major processes and is representative of the groundwater system.

A major finding of the dewatering stage calibrations is that the hydraulic conductivity of the ore body in some areas may be much higher than the average value calibrated in the pre dewatering calibration. Therefore, it is important to investigate the sensitivity of dewatering volumes to ore body conductivity when simulating mining operations.

5.4 Water management simulations

5.4.1 Mine plan and water management strategy

The basis of predictive simulations for this assessment was the *Christmas Creek mine plan LoM 8.4, July 2011* (Internal Reference Number CC_i8.4b_55Mtpa_LOM_Sequence). This plan is based on a mining rate of up to 55 Mtpa (ROM), and is shown in Figure 24 in yearly time steps.

The proposed mining sequence commences proximal to the proposed Ore Processing Facility (OPF) site, and then extends both towards the east and west. Mining sequencing includes a combination of above watertable and below watertable ore deposits.

The simulated abstraction and injection program is in line with the Water Management Strategy outlined in Section 4.1, as such, the following key elements are represented in the model:

- Dewatering of below watertable resource areas in accordance with the mine sequence outlined in the mine plan.
- Provision of brackish water for mine water use requirements.

- The remaining dewatered groundwater is mainly saline water and thus injected to the Oakover Formation aquifer located to the south of the mining area.

Dewatering and injection is simulated in the following manner:

Dewatering

- Dewatering is simulated by applying seepage nodes to the bottom of mine pits.
- Mining pits are assumed to be mined over a period of one year followed by a 6 month backfilling period; therefore pit dewatering is maintained for a period of 18 months.
- Mine site water use (supplied from the dewatering operation) is assumed to be 12 GL/a in the period from 2016 to 2024, decreasing to 6 GL/a in 2025 to 2027 and zero in the last mining year (2028) due to the expected reduction in the available amount of brackish water.

Injection

- Yearly injection volumes were calculated by subtracting mine water usage from predicted dewatering volumes.
- The reinjection of saline water was modelled by injection through conceptual bores as defined in Figure 25.

5.4.2 Setup of numerical simulations

Non-dewatering scenario

A non-dewatering simulation is conducted in order to provide a baseline from which change can be estimated. This simulation is run for the whole LoM period but without any dewatering or injection. This simulation therefore provides a prediction of the natural fluctuation and dynamics of the hydrogeological system without mining. Figure 26, Figure 27 and Figure 28 show the fluctuation of the watertable at key monitoring locations adjacent to Fortescue Marsh for the base, dry and wet rainfall simulations respectively.

Dewatering and injection scenario

An initial dewatering only simulation (without injection) is conducted to provide an initial abstraction volume from which injection rates are estimated (abstraction less mine water use).

This injection volume is then applied in the second iteration of the scenario. Injection results in an increased in the abstraction rate due to recirculation of injected water to the abstraction point. The results of this simulation are used to revise the injection rate for the next simulation. This process is continued until abstraction is equivalent to the sum of mine water use and injection. Groundwater injection is adjusted spatially during this process to minimise water level impacts in areas sensitive to water level fall or rise.

The number and location of injection bores in the model are conceptual only. In practice, bore location and number of bores required will be determined by actual bore injection capacity.

Post-mining recovery

Following cessation of mining in 2028, the numerical model was run without further dewatering and injection to simulate the rebound of groundwater levels. Further information is provided in Section 6.5 and Appendix 7.

5.4.3 Generation of synthetic rainfall sequences

To enable consideration of climate variation on the water level predictions, rainfall data from the Newman rainfall station dating back to 1971 were used to create three rainfall sequences representing average, wet and dry climate scenarios, respectively.

An average rainfall sequence was generated using 1973, 1984, 2001, 2006, and 2008 as base years. These five years have annual precipitation closest to the long-term average rainfall (of 338 mm/year). An eighteen year time series was randomly generated using the five year data. The result is a sequence of 2008, 1973, 2001, 2006, 2006, 2008, 2008, 2006, 1984, 2006, 1984, 1984, 2001, 1973, 2008, 2001, 1973, and 2001. Using 90 mm/month as the threshold value for Fortescue Marsh flooding, there are 11 flooding events in the 18 years prediction period (Table 22).

A stochastic method from the Stochastic Climate Library (SCL) (http://www.toolkit.net.au/scl) was used to generate 1000 realisations of rainfall data for the 38 year Newman rainfall record. Stochastic climate data are random numbers that are modified so that they have the same statistical characteristics (in terms of mean, variance, skew, long-term persistency, and etcetera) as the historical data from which they are based. Each stochastic replicate (sequence) has different characteristics compared to the historical data, but the average of each characteristic from all the stochastic replicates is the same as the historical data.

The 1000 realisations were ranked from the driest realisation to the wettest realisation based on the total rainfall over the period. The realisation at 5% ranking was used to generate the dry scenario. The driest continuous 14 years in the 5% ranking realisation was used for the dry scenario, which had five flood events (monthly rainfall >90 mm) in the prediction period (Table 22). The realisation at 95% ranking was used to generate the wet scenario. The wettest continuous 14 year period in this realisation was used for the wet scenario, which has 25 flood events (monthly rainfall > 90 mm) (Table 22).

Table 22: Model generated monthly rainfall data used for groundwater model predictions

Average Scenario			Dry Scenario			Wet Scenario		
Year	Month	Rainfall^	Year	Month	Rainfall^	Year	Month	Rainfall[21]
1	3	122.8	1	2	94.6	1	2	142.5
3	2	282.2	3	4	101.6	1	12	197.6
6	3	122.8	7	2	92.5	2	1	172.1
7	3	122.8	12	2	278.9	2	2	179.0
9	2	124.5	16	2	102.9	2	12	249.5
11	2	124.5				3	2	325.4
12	2	124.5				4	1	294.1
13	2	282.2				4	3	135.8
15	3	122.8				5	1	228.1
16	2	282.2				6	2	260.1
18	2	282.2				8	2	338.2
						9	1	229.4
						9	3	106.0
						10	1	160.7
						10	2	123.8
						10	4	95.6
						12	1	164.6
						12	2	171.2
						12	12	199.2
						13	2	286.7
						15	1	142.4
						15	2	148.1
						15	12	211.1
						16	3	123.1
						17	3	121.6

[21] Only rainfall events >=90mm/month are shown

5.5 Model limitations

All numerical groundwater models are representations of the natural groundwater system. As a result of assumptions used in model conceptualisation and numerical model construction, groundwater models are subject to various limitations when applied to make predictions. The following limitations of the Christmas Creek model are noted.

5.5.1 Heterogeneity of hydraulic parameters

The hydraulic conductivity of the MMF and Oakover Formation aquifers is spatial-variability; as such, their representation in the model as homogeneous aquifers is a simplification of hydrogeological complexity. Groundwater levels at some localised areas may be either over-predicted or under-predicted. Numerical scenarios employing a broad parameter range for key hydraulic units have been conducted to assess the regional water level impact of these uncertainties. Monitoring and in some cases incorporation of additional detail to models through operations will be employed to manage local scale responses.

5.5.2 Duration of dataset

The groundwater monitoring bore dataset used for Christmas Creek model calibrations covers the period from 2007 to 2012. This is sufficient for a robust characterisation of the aquifer system under natural conditions. The calibration of the model under the mine dewatering condition was limited to the Flinders pits area, where pits were active during July 2011 to December 2012 (calibration stage 2 period).

The fluctuation of Fortescue Marsh water levels were verified by using Landsat-derived data, and direct measurements from Cyclone Heidi. The model will need to be further calibrated against additional direct measured Marsh water levels; as such data become available in the future.

5.5.3 Fortescue Marsh data

The monitoring bore network extends to the Fortescue Marsh fringe but not onto the Fortescue Marsh surface at Christmas Creek. The Marsh's response to flooding and evaporation has been simulated using inference to marsh surface monitoring data at Cloudbreak and other datasets such as historical Landsat records. This is a limitation as it is not based on directly measurement of groundwater responses within the Christmas Creek project area.

5.5.4 Limited resolution in salinity distribution

Simulation of salinity distribution has been undertaken to provide a broad representation of the density-driven flow mechanism. Salinity was not modelled with sufficient spatial resolution to accurately predict salinity distribution in the vertical direction. Therefore, the salinity in the shallow aquifer may be over predicted owing to numerical dispersion in the vertical direction.

A 2-D numerical modelling investigation for the Chichester Range (FMG, 2010e) demonstrated that groundwater salinity in the shallow aquifer, at the fringe of the Marsh, is little affected by mine dewatering and saline water injection. Initial operational data confirms this finding and will be updated with continued observation and monitoring data.

5.5.5 The effect of pit back filling on pit dewatering volumes

A simulation considering the change in hydraulic properties was conducted to investigate the likely effect of a change in hydraulic properties after mining. The results are presented in Appendix 8, and the approach and justification is outline in Section 5.4.2.

The permeability of the backfill materials may be higher than the original overburden material (Tertiary Detrital), but lower than the original ore. The specific yield is likely to be higher than original overburden materials, since backfill materials are unlikely to retain their original density following backfilling.

Sensitivity analysis of the hydraulic properties of backfill material found that neither drawdown nor dewatering volumes were significantly different. Not considering the change in hydraulic properties of backfill materials does not introduce any significant errors in model predictions.

6. GROUNDWATER MODELLING RESULTS

6.1 Predicted Results - Base Scenario

The base scenario has been simulated using average climatic conditions. An initial simulation without dewatering and injection was completed followed by simulation incorporating dewatering and injection, again with the average climate conditions. Comparison of the two simulations enables assessment of mining impacts. Results of this assessment are presented below.

6.1.1 Predicted natural groundwater regime

Hydrographs[22] at five key locations along the Fortescue Marsh edge are shown in Figure 26 to Figure 28 together with rainfall data used in our model predictions. These figures show:

- Groundwater levels on the margin of the Fortescue Marsh only respond following rainfall events of 90 mm/month or more. This is directly related to flooding and ponding of water on the surface of Fortescue Marsh.
- Groundwater levels on the margin of the Fortescue Marsh may naturally vary between surface and 5 m bgl at various times and locations.
- The expected natural change in water level at locations on the edge of the Fortescue Marsh for the LoM period will depend on the rainfall sequence. The groundwater level may recede by up to 4 m after a long dry period; whilst a major rainfall event may result in groundwater level rise of up to 4 m.

These predictions are consistent with observed watertable responses and predicted watertable responses from the calibrated model.

The rate of groundwater evapotranspiration decreases with depth to watertable. Evapotranspiration (of groundwater) is therefore greatest when water levels are closest to ground surface without ponding of water on the surface of Fortescue Marsh, i.e. immediately following flooding events.

6.1.2 Predicted dewatering and injection volumes

Model predicted dewatering and injection volumes for the base scenario are presented in Table 23. The predicted average annual dewatering volume (no injection) over the period 2014 to 2028 is 30.4 GL/a, which increases to 40.5 GL/a as surplus water is injected back into the aquifer system.

[22] Hydrographs presented in Figure 26 to Figure 28 do not include abstraction or injection and represent the predicted natural groundwater levels without mining.

Injection results in an annual average increase in dewatering volumes of approximately 29.3% and up to 49% in an individual year at peak recirculation (Table 23).

Table 23: Model results – Base scenario

Year ending	Mine water use (GL/a)	Dewatering volume (GL/a)			Injection volume (GL/a)
		Without injection	With injection	Increase due to Recirculation	
June 2014	12	38.1	50	15%	38
June 2015	12	55.9	73.5	15%	61.5
June 2016	12	29.2	32.2	10%	20.2
June 2017	12	28.9	35.5	23%	23.9
June 2018	12	31.3	39.3	26%	27.3
June 2019	12	34.8	44.2	27%	32.8
June 2020	12	48.1	69.0	43%	57.4
June 2021	12	28.9	45.7	58%	34.3
June 2022	12	29.8	44.4	49%	33.4
June 2023	12	38.3	56.6	48%	45.0
June 2024	12	33.3	44.6	34%	32.7
June 2025	6	19.7	24.6	25%	18.9
June 2026	6	16.3	19.5	20%	13.8
June 2027	6	14.6	17.8	22%	11.8
June 2028	0[23]	8.8	10.9	24%	11.1
Av. Annual (GL/a)	**9.7**	**30.4**	**40.5**	**29.3%**	**30.8**
Total (GL)	**150**	**456**	**608**		**462**

6.1.3 Predicted groundwater drawdown/mounding distribution

For the base scenario, the predicted drawdown and mounding impact (difference between simulated water levels under natural conditions and water levels under dewatering and injection conditions) at the end of each mining year is presented in Figure 29 to Figure 43. These figures also include the depth to watertable contours (m bgl).

Time series of drawdown and mounding at five key monitoring bore locations along the Fortescue Marsh edge are plotted in Figure 44. The locations of the key monitoring bores are shown in Figure 2 and their coordinates presented in Table 24.

[23] Mine water use is reduced in the final years of operation as a result of scaled down operations, requirement to inject water and likelihood that an external water source will be required by this point.

Table 24: Co-ordinates of the five key near-marsh monitoring locations

Site name	Location (MGA, Zone 50)	
	Easting	Northing
CCFMM01	764,370	7,519,827
CCFMM02	770,239	7,517,777
CCFMM03	776,985	7,514,952
CCFMM04	785,617	7,510,150
CCFMM05	794,760	7,503,874

The drawdown and mounding predictions illustrate the impact mining related dewatering and injection has on the watertable. Predicted drawdown and mounding shown in Figure 29 to Figure 43 and Figure 44 indicate that:

- Watertable drawdown due to mine dewatering is restricted to the mining area. Small drawdown may extend towards the Fortescue Marsh.
- The maximum watertable drawdown at the key monitoring locations (Table 24) is predicted to be about 1.9 m, along the western edge of the Fortescue Marsh in 2028 (CCFMM04).
- Watertable mounding is limited to small areas and is not considered a long term impact of operations. Maximum watertable mounding is predicted to be about 1.5 m, along the edge of the Fortescue Marsh in 2015 (CCFMM01). The Oakover Formation is highly permeable and its storage capacity is much larger than the volume of injected water. The presence of the Tertiary clay also serves to mitigate pressure transmission to the watertable.
- Saline water injection is an essential component for mitigating groundwater drawdown and impacts to the Fortescue Marsh. Modelling suggests that groundwater drawdown would be much larger without injection into the Oakover Formation.

6.1.4 Predicted water demand and supply strategies

The assessment assumes mine water use (Table 23) will be met by the volume of brackish groundwater abstracted during mine dewatering. Based on an estimated brackish resource of 200 GL and LOM water requirement of 150 GL, this is plausible. However, long term water quality is difficult to predict and in certain years (Table 23) abstraction volumes are close to the predicted water demand. The following approach to mitigating brackish water shortfalls from dewatering operations is recommended:

1. Reduce brackish water demand where possible (water saving options are currently being assessed).
2. Transfer water between Cloudbreak and Christmas Creek to balance brackish water demand (such transfers are currently being undertaken).
3. Abstract ‘banked’ brackish groundwater previously injected.
4. Assess water transfer options such as other proximal mine sites.

5. Assess other brackish water supply options such as reverse osmosis (RO) treatment of abstracted water and/or supply from a remote borefield.

6.2 Numerical Model Sensitivity and uncertainty analysis

Sensitivity analysis has been undertaken to examine the model response to extreme values of the primary impact-determining parameters (SKM & NGRT, 2012). Five key parameters were selected to undertake the sensitivity study:

1. Rainfall sequence;
2. Hydraulic conductivity of the Oakover Formation;
3. Hydraulic conductivity of the ore body (mineralised Marra Mamba Formation);
4. Specific yield of the ore body; and
5. Specific storage coefficient of the Oakover Formation.

For each parameter, two simulations were conducted by varying the parameter value used in the base scenario to an upper value and a lower value, respectively. The upper and lower values of each parameter are listed in Table 26. These values were chosen based on field data from both Christmas Creek and Cloudbreak, representing the end member values that may be reasonably expected.

6.2.1 Sensitivity analysis of dewatering volumes

Predicted dewatering volumes for all sensitivity simulations are summarised and compared to the base scenario results in Table 26 and summarised below;

The highest uncertainty in average and peak annual dewatering rates is associated with the hydraulic conductivity of the ore body.

- The average annual dewatering volume increased by 42% in the simulation with the upper conductivity value, but decreased by 30% in the simulation with the lower conductivity value.
- The peak annual dewatering volume increased by 37% for the high conductivity simulation and decreased by 31% for the low conductivity simulation.

The second most sensitive parameter is the conductivity of the Oakover Formation.

- With an upper conductivity value, both the average and the peak annual dewatering volumes increased by 22%. When the lower value was used, the average and peak annual dewatering volumes decreased by 18% and 22%, respectively.

Predicted dewatering volumes are slightly sensitive to climate condition.

- Under the wet climate condition average and peak annual dewatering volumes increased by 7% and 5%, respectively.
- Under the dry climate condition, both the average and the peak annual dewatering volumes decreased by 2%.

Dewatering volumes are not sensitive to specific yield of the ore body or the specific storage coefficient of the Oakover Formation, since both average and peak annual dewatering volumes changed by less than 2%.

6.2.2 Sensitivity analysis of drawdown/mounding

Hydrographs at selected key locations for dry and wet scenarios are shown and compared to those for the base scenario in Figure 48 to Figure 52. Groundwater levels under both natural and mining conditions are significantly affected by climate with watertable increase of >3 m following large rainfall events. Hydrographs showing the water level for each of the parameter sensitivity scenarios are presented in Appendix 5 and discussed below.

Maximum drawdown and deviations of maximum drawdown, over the whole mining period at key locations for all sensitivity simulations are summarised and compared to those from the Base scenario in Table 27. These results suggest that maximum drawdown at the selected key locations is significantly sensitive to climate (rainfall) data and hydraulic conductivities of both the ore body and the Oakover Formation, but not sensitive to specific yield of the ore body or the storage coefficient of the Oakover Formation.

The largest drawdown of all sensitivity simulations (2.29 m) occurs at the key location CCFMM01 in the simulation with upper end value of ore body conductivity, which is larger than the maximum drawdown of 1.92 m in the base scenario.

6.2.3 Maximum drawdown and deviations of maximum drawdown, over the whole mining period at key locations for climatic sensitivity simulations are summarised and compared to those from the Base scenario in Table 28.Sensitivity to the ratio of brackish abstraction

The numerical scenarios assume that all surplus water is injected to the Oakover Formation aquifer based on a ratio of brackish to saline water (all brackish water abstracted is used by the mine). Should there be more brackish water, then any surplus would be injected in injection borefields located along strike of the MMF (such as the Hillside East borefield). A sensitivity scenario was designed to assess the potential impacts arising from this additional injection. This simulation assumed that 10 GL/a of surplus brackish water would be injected into the ore body aquifer. The results are presented in Appendix 8 and described below.

It was found that the dewatering volumes in the period with brackish water injection are less than the Base Scenario simulation. The difference in drawdown between the two simulations is spatially limited to the mining area and temporally to short periods of time. Up to 3.5 m groundwater mounding may occur at the brackish injection borefield in the years with brackish water injection. Depth to watertable is maintained at greater than 2 m and the mounding declines quickly after the termination of brackish injection.

6.3 Water balance analysis

The water balance of the simulated base scenario is summarised in Table 25 as average annual volumes over the life of mine (LoM). The results highlight:

- Inputs are dominated by the Fortescue Marsh runoff (89%). Catchment recharge and water injection are only 1% and 10% of the total input, respectively.
- Under natural conditions (no mine dewatering), evapotranspiration is the only output. Under mine dewatering, output is still dominated by surface water evpaotranspiration (86%) with mine dewatering accounting for 14% of the total output.
- The net mine water use (the difference between dewatering and injection volumes) is 9.7 GL/a during the life of mine.
- The storage reduction is less than the net mine use for both the dry and base simulations but greater in the dry simulation.

Table 25: Model water balance – Base, Dry & Wet scenarios

Scenario	Water Management Option	Model inputs (GL/a)[24]			Model outputs (GL/a)		Change in storage (GL/a)
		Catchment Recharge	Fortescue Marsh Runoff	Water Injection	ET[25]	Mine Dewatering	
Base	No dewatering[26]	2.6	242.1	0.0	237.7	0.0	-7.0
	Dewatering[27]	2.6	242.1	27.9	232.4	37.2	-3.0
Dry	No dewatering	0.8	72.2	0.0	87.0	0.0	-14.0
	Dewatering	0.8	72.2	27.9	82.5	36.4	-18.0
Wet	No dewatering	5.0	439.1	0.0	449.5	0.0	-5.4
	Dewatering	5.0	439.1	30.7	443.8	40.0	-9.0

[24] Average annual volume (GL/a)
[25] Evapotranspiration
[26] Natural conditions (with no mine dewatering)
[27] Water management, as outlined in Section 5.4

Table 26: Model results (abstraction volumes) from sensitivity study

Sensitivity case	Hydraulic parameter				Average dewatering rate		Peak dewatering rate		Sensitivity ranking
	Oakover Formation		MMF						
	Kh (m/d)	Ss (1/m)	Kh (m/d)	Sy	GL/a	Change from base case	GL/a	Change from base Case	
Base Case	***200***	***1.00E-04***	***60***	***0.03***	**40.5**	**-**	**73.5**	**-**	
Wet	200	1.00E-04	60	0.03	43.3	7%	77.2	5%	3
Dry	200	1.00E-04	60	0.03	39.7	-2%	72.1	-2%	
High Oakover K	*400*	1.00E-04	60	0.03	49.4	22%	60.2	22%	2
Low Oakover K	*100*	1.00E-04	60	0.03	34.3	-18%	60.2	-22%	
High Ore Body K	200	1.00E-04	*120*	0.03	57.5	42%	108.8	37%	1
Low Ore Body K	200	1.00E-04	*30*	0.03	31.2	-30%	56.1	-31%	
High Ore Body S_y	200	1.00E-04	60	*0.045*	40.9	1%	73.5	0%	4
Low Ore Body S_y	200	1.00E-04	60	*0.015*	40.1	-1%	72.1	-2%	
High Oakover S_s	200	*5.00E-04*	60	0.03	40.9	1%	73.5	0%	5
Low Oakover S_s	200	*2.00E-05*	60	0.03	37.3	0%	73.5	0%	

Table 27: Model results (drawdown change) from sensitivity study

Sensitivity case	Hydraulic parameter				Maximum Drawdown at Key Locations (m)					Deviation of Maximum Drawdown from the Base Scenario (m)				
	Oakover Formation		MMF											
	Kh (m/d)	Ss (1/m)	Kh (m/d)	Sy	CCFM01	CCFM02	CCFM03	CCFM04	CCFM05	CCFM01	CCFM02	CCFM03	CCFM04	CCFM05
Base Case	***200***	***1.00E-04***	***60***	***0.03***	1.68	1.29	1.44	1.92	0.28	-	-	-	-	-
Wet	200	1.00E-04	60	0.03	1.63	1.97	0.98	1.62	0.344	-0.05	0.68	-0.46	-0.3	0.064
Dry	200	1.00E-04	60	0.03	2.21	**2.05**	**1.93**	**2.13**	0.37	0.53	0.76	0.49	0.21	0.09
High Oakover K	***400***	1.00E-04	60	0.03	1.47	1.05	1.27	1.56	0.29	-0.21	-0.24	-0.17	-0.36	0.01
Low Oakover K	***100***	1.00E-04	60	0.03	1.93	1.5	1.63	2.2	0.31	0.25	0.21	0.19	0.28	0.03
High Ore Body K	200	1.00E-04	***120***	0.03	**2.29**	1.84	1.66	2.13	**0.47**	0.61	0.55	0.22	0.21	0.19
Low Ore Body K	200	1.00E-04	***30***	0.03	1.44	1.02	1.43	1.95	0.28	-0.24	-0.27	-0.01	0.03	0
High Ore Body S_y	200	1.00E-04	60	***0.045***	1.68	1.35	1.5	2.02	0.29	0	0.06	0.06	0.1	0.01
Low Ore Body S_y	200	1.00E-04	60	***0.015***	1.68	1.28	1.36	1.82	0.29	0	-0.01	-0.08	-0.1	0.01
High Oakover S_s	200	***5.00E-04***	60	0.03	1.63	1.3	1.41	1.92	0.29	-0.05	0.01	-0.03	0	0.01
Low Oakover S_s	200	***2.00E-05***	60	0.03	1.65	1.33	1.42	1.89	0.35	-0.03	0.04	-0.02	-0.03	0.07

Table 28: Model results (mounding change) from sensitivity study

Sensitivity case	Hydraulic parameter				Maximum Mounding at Key Locations (m)					Deviation of Maximum Mounding from the Base Scenario (m)				
	Oakover Formation		MMF											
	Kh (m/d)	Ss (1/m)	Kh (m/d)	Sy	CCFM01	CCFM02	CCFM03	CCFM04	CCFM05	CCFM01	CCFM02	CCFM03	CCFM04	CCFM05
Base Case	***200***	***1.00E-04***	***60***	***0.03***	1.53	0.46	0.64	0.85	0.05	-	-	-	-	-
Wet	200	1.00E-04	60	0.03	1.53	0.48	0.6	0.85	0.04	0	0.02	-0.04	0	-0.01
Dry	200	1.00E-04	60	0.03	1.53	**0.41**	**0.65**	**0.86**	0.03	0	-0.05	0.01	0.01	-0.02

6.4 Cumulative impacts

The predicted drawdown and mounding at the end of LOM are shown in Figure 44 to Figure 46. This has considered and included predicted drawdowns associated with the Cloudbreak Operations, and other publicly-available drawdown predictions of water level impacts in the region, as detailed in:

- The Hancock Prospecting PER document (Hancock , 2009) for the proposed Roy Hill project, which lies to the east of the Christmas Creek project.
- The Brockman Resources PER (Aquaterra, 2010) document for the proposed Marillana project, which lies on the southern side of the Fortescue Marsh.

6.4.1 Marillana project

The predicted groundwater drawdown from the proposed Marillana project is distant and remote to the Christmas Creek project. Based on modelling by Aquaterra (2010) and the project's position on the other side of the Fortescue Marsh, it is considered that drawdown at Marillana will not interact with Christmas Creek operations.

6.4.2 Roy Hill project

The Roy Hill project, developed by Roy Hill Iron Ore Pty Ltd (RHIO), lies immediately east of the Christmas Creek project. The dewatering impact from the Christmas Creek Operation is predicted to overlap with those at Roy Hill (Figure 47).

Dewatering activities at both Roy Hill and Christmas Creek are designed to achieve the required lowering of groundwater level, as opposed to maintaining a specified abstraction rate. Therefore, overlap of the drawdown is mutually beneficial to meeting the objectives of both Roy Hill and Christmas Creek operations.

Injection at Christmas Creek, undertaken near the RHIO project, in the initial years of mining is predicted to result in about 7 L/s additional dewatering for the Roy Hill project.

Fortescue and RHIO have developed a Stakeholder Consultation Reinjection Management Plan (SRMP) to address potential water management interactions between RHIO and Fortescue. The SRMP was approved by the Office of the Environment Protection Authority on 25 November 2011.

6.4.3 Cloudbreak project

The modelling results presented in Section 6.5.3 include proposed injection in the Hillside East injection area by the Cloudbreak operation. Fortescue have adopted an integrated Chichester Range approach to water management to support Fortescue Marsh management objectives.

6.5 Simulation of post-mining groundwater level recovery

Groundwater level recovery after mine closure was simulated over a range of time frames. In the mine area, drawdown is predicted to recover from a maximum of around 35 m to around 5 m after 10 years and 3 m after 20 years.

The drawdown distribution for time increments following mine closure is shown in Appendix 7 and key changes are summarised below;

- One year after mining (2029) – Within the mining area drawdown has reduced significantly following 12 months on non-abstraction form over 20 m in 2028, Figure 43, to approximately 8 m in 2029. At the fringe of Fortescue Marsh there is little observed change between 2028 and 2029.
- Five years after mining (2033) – Drawdown within the mining area continues to reduce although less pronounced that within the initial 12 months following mining. At the fringe of Fortescue Marsh, drawdown has reduced to 1 m or less at all key monitoring locations.
- 10 years after mining (2038) – Drawdown across all areas has reduced. Within the mining area drawdown is 5 m or less and at Fortescue Marsh is less than 1 m.
- 20 years after mining (2048) – Drawdown within the area of mining has reduced further, to less than 3 m, and there is no impact to monitoring locations at the fringe of Fortescue Marsh.
- 50 years after mining (2078) – Drawdown across all areas is less than 2 m with no impact at key monitoring locations at the fringe of Fortescue Marsh.

Following mining activities and the cessation of abstraction and dewatering, the recovery of water levels will be highly dependent on rainfall.

7. CONCLUSIONS

Hydrogeological characteristics of the stratigraphy in the project area include:

- The project area is underlain by the Jeerinah Formation the upper-most formation of the Fortescue Group. The lithology is shale dominated creating low permeability conditions. Regional NE-SW fault systems and lithological variation can create zones of enhanced permeability.
- The Nammuldi Member of the Marra Mamba Formation (MMF) conformably overlies the Jeerinah Formation. This formation outcrops in the Chichester Ranges and dips gently southward beneath a blanket of recent cover. A broad blanket of supergene mineralisation (mineralised MMF) in the upper part of the Nammuldi Member has formed a laterally extensive and high permeability and storage aquifer along the strike of the Chichester Ranges. The aquifer is unsaturated to the north and the mineralisation and aquifer properties diminish to the south at around 4 to 8 km from the Fortescue Marsh. The lower part of the Nammuldi member is characteristically cherty and unaltered. Permeability is more constrained to sub vertical NE-SW trending fracture zones.
- The Wittenoom Formation overlays the MMF in areas south of where mineralisation occurs and is characteristically massive with low hydraulic conductivity. Regional NE-SW fault zones may have associated higher permeability.
- The mineralised MMF and Wittenoom Formation are unconformably overlain by a sequence of Tertiary detrital and alluvial sediments that thicken towards the south. The Tertiary sequence is characterised by; a lower calcrete and silcrete unit (Oakover Formation) with high permeability and storage; a clay aquitard, which overlays the Oakover Formation; and silts, sands and gravels (Tertiary Detritals) with generally low permeability. The shallow Tertiary Detrital layer is not a major aquifer due to its low permeability, but it is potentially environmentally important as it may be a source of water supply for vegetation uptake in areas fringing the Fortescue Marsh.
- Groundwater salinity distribution in the mining area is brackish in the Tertiary detritals and mineralised MMF; saline in the lower fracture dominated MMF; and becoming hypersaline in the Jeerinah Formation. Laterally towards the Fortescue Marsh, the saline interface occurs higher in the hydrostratigraphy with groundwater in portions of the Tertiary Detritals and Oakover Formation being hypersaline near the Fortescue Marsh. The origins of saline water are associated with evapoconcentration and hydrological function within the closed basin.

The key regional groundwater and surface water hydrological regimes include:

- Topographic driven groundwater regime; in which rainfall and streamflow infiltration on the upper and lower slopes of the Chichester Ranges flows in a southward direction through the Tertiary Detritals, mineralised MMF and Oakover Formation.
- Density driven groundwater regime; in which high salinity groundwater beneath the Fortescue Valley results in a pressure gradient that directly opposes the topographic driven regime. The interface of these two systems creates a saltwater interface that extends over many kilometres and is gradational throughout the flow system.

- The Fortescue Marsh regime; cycles periodically from a surface water dominated recharge system under flood conditions that recharges the shallow groundwater system, to a discharge regime where evapotranspiration is dominant.

A density-driven flow and transport numerical groundwater model was developed and calibrated in the FEFLOW modelling platform for the Christmas Creek project area. Calibration of steady state pre-mining conditions, short term aquifer tests and longer term operational conditions have validated the numerical model. The calibrated numerical model was used to predict groundwater dynamics in the LoM period by using various rainfall sequences (that is, Base [an average-probability rainfall sequence], Dry [5% probability extreme-dry rainfall sequence] and Wet [5% probability extreme-wet rainfall sequence] scenarios) that were generated based on historical rainfall records in the area.

Incorporating the baseline climatic conditions into a non-mining scenario, the model has simulated water levels in the shallow Tertiary Detritals adjacent to the Fortescue Marsh consistent with historical observed water level rise and fall in response to cycles of flooding evapotranspiration on the Marsh.

The proposed mine water management strategy for Christmas Creek is consistent with the strategy employed at Cloudbreak, and is designed to meet the mining requirements and Fortescue Marsh Management objectives. A cornerstone of the strategy is managed aquifer recharge.

Dewatering will be achieved through advance dewatering methods and operational dewatering methods. Dewatering may significantly exceed mine water use requirements, and any surplus (the difference between abstraction water and mine water use) will be returned to compatible aquifers through injection to preserve water resources and to minimise environmental impacts (groundwater level drawdown/mounding).

Excess brackish water will generally be injected into the along-strike mineralised Marra Mamba Formation aquifer for future use. Excess saline water will be injected into the naturally-saline Oakover Formation aquifer, south of mining areas, to reduce the dewatering drawdown footprint.

Groundwater dewatering volumes and drawdown/mounding have been predicted by using the calibrated model and the LoM plan (CC 55 Mtpa LoM Sequence iteration 8.4b) as the basis for the dewatering and injection plan. Prediction results for the base case show that:

- The average annual dewatering volume is about 40.5 GL/a over the LoM period.
- The peak annual dewatering volume is about 74 GL/a (see statements below regarding dewatering-volume sensitivity).
- Groundwater drawdown along the Fortescue Marsh edge is small (less than 1.5 m) until June 2025 and then increases with mining progress due to cumulative drawdown effects to about 1.9 m drawdown along the Fortescue Marsh edge in the last three years of mining.

The sensitivity of model predictions to climate conditions and key model parameters was investigated through numerical simulations. Results show that:

- Groundwater abstraction rates are most sensitive to conductivities of ore body and Oakover Formation, with average annual dewatering rates increasing by up to 42% (to about 58 GL/a) in the worst scenario (with ore body having the upper end value of conductivity). The equivalent peak (as opposed to average) annual dewatering volume may increase by up to 37% (to about 110 GL/a).
- Groundwater drawdown along the Fortescue Marsh edge is moderately sensitive to climate conditions and conductivities of the ore body and the Oakover Formation. The maximum drawdown (as measured at the five key near-marsh monitoring sites) may slightly increase from 1.9 m in the base scenario to about 2.3 m in the worst scenario with the ore body having the upper end value of conductivity.
- Simulations to assess the effect of backfill materials concluded that neither drawdown nor dewatering volumes are significantly different under various backfill-material permeability values.
- Injection scenarios based on varying proportions of brackish and saline abstraction were explored to determine potential influence on groundwater level drawdown and mounding. These simulations found that a higher ratio of brackish water (and resultant along-strike brackish injection) reduces dewatering volumes slightly, but any changes to drawdown are limited to the mining area and immediately south of mining pits. In the region of brackish injection, up to 3.5 m groundwater mounding may occur in and around the brackish injection borefields. The elevated water level remains below ground level and mounding was shown to decline quickly after the termination of brackish injection.
- The model is sensitive to the degree of connection between the Oakover Formation and MMF orebody aquifers. A high degree of connection is assumed for this modelling assessment; however, poorer connectivity will result in less drawdown and lower dewatering volumes.

To assess potential groundwater-quality impacts from the proposed water management scheme on the near-marsh environment, a 2-D numerical modelling assessment for the Chichester Range was undertaken. This work concluded that the groundwater salinity of the shallow aquifer, adjacent to Fortescue Marsh, is little affected by mine dewatering and saline water injection.

Groundwater level recovery after mine closure was simulated and suggested that groundwater drawdown in the mining area decreases from over 35 m at the end of mining to about 5 m, after ten years, and to about 3 m after 20 years.

Modelling results suggest that the Christmas Creek water management scheme can operate independently. However, opportunities to improve operational efficiencies and control of water levels near the Fortescue Marsh would be realised by adopting an integrated water management approach with Cloudbreak.

Inter-mine transfer has the opportunity to provide contingency options to mitigate potential shortfalls in the brackish water resource and near marsh water level impacts. These contingencies are listed below in order of priority:

- Reduce brackish water demand where possible (water saving options are currently being assessed).
- Transfer water between Cloudbreak and Christmas Creek to balance brackish water demand (such transfers are currently being undertaken).
- Abstract 'banked' brackish groundwater previously injected.
- Assess water transfer options such as other proximal mine sites.
- Assess other brackish water supply options such as reverse osmosis (RO) treatment of abstracted water and/or supply from a remote borefield.

7.1 Future work

Ongoing hydrogeological assessment will assist in conceptual understanding and water management at Christmas Creek. Further investigations that could improve understanding and operational water management are outlined below.

- Ongoing hydrogeological investigations in areas of uncertainty to support ongoing development of the conceptual model, particularly relating to the dynamics beneath the Fortescue Marsh.
- Routine updating of the numerical model with findings of investigations and operational groundwater response to refine the model predictive capability.

Modelling results suggest that the Christmas Creek water management scheme can operate independently. However, opportunities to improve operational efficiencies and control of water levels near the Fortescue Marsh would be realised by adopting an integrated water management approach with Cloudbreak.

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Figure 1: Site Location Plan

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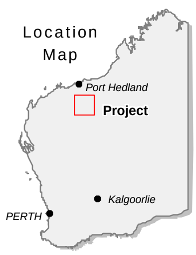

Mine Sites
Towns
FMG Railway
Other Railways
Roads
Major Creek/Drainage

N

0 25 50
kilometres

Fortescue Metals Group Ltd

Site Location

Author: IBdR	Date: 27/05/2010
Drawn By: SH	Revision: 5
Doc No: GE_MP_HY_0005_Fig1	Confidentiality: 1
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Figure 2: Site setting

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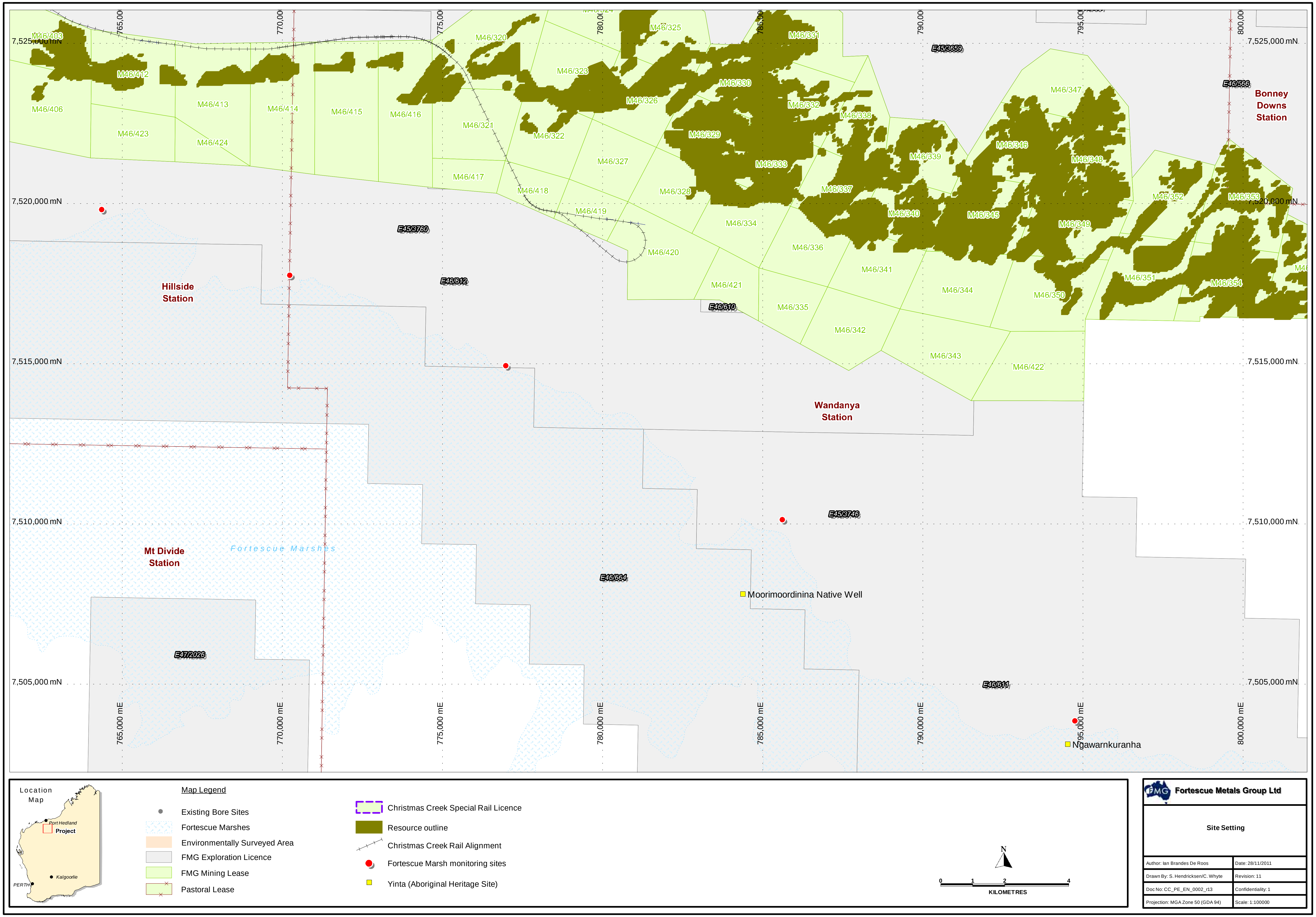

Hillside Station
Wandanya Station
Mt Divide Station
Bonney Downs Station
Fortescue Marshes
Moorimoordinina Native Well
Ngawarnkuranha
E45/3760
E46/612
E46/610
E45/3659
E46/566
E45/3746
E46/664
E47/2026
E46/611
M46/403
M46/406
M46/412
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M46/420
M46/421
M46/422
M46/423
M46/424
M46/320
M46/321
M46/322
M46/323
M46/325
M46/326
M46/327
M46/328
M46/329
M46/330
M46/331
M46/332
M46/333
M46/334
M46/335
M46/336
M46/337
M46/338
M46/339
M46/340
M46/341
M46/342
M46/343
M46/344
M46/345
M46/346
M46/347
M46/348
M46/349
M46/350
M46/351
M46/352
M46/353
M46/354
7,525,000 mN
7,520,000 mN
7,515,000 mN
7,510,000 mN
7,505,000 mN
765,000 mE
770,000 mE
775,000 mE
780,000 mE
785,000 mE
790,000 mE
795,000 mE
800,000 mE
Location Map
Port Hedland
Project
Kalgoorlie
PERTH
Map Legend
Existing Bore Sites
Fortescue Marshes
Environmentally Surveyed Area
FMG Exploration Licence
FMG Mining Lease
Pastoral Lease
Christmas Creek Special Rail Licence
Resource outline
Christmas Creek Rail Alignment
Fortescue Marsh monitoring sites
Yinta (Aboriginal Heritage Site)
N
0 1 2 4
KILOMETRES
Fortescue Metals Group Ltd
Site Setting
Author: Ian Brandes De Roos
Date: 28/11/2011
Drawn By: S. Hendricksen/C. Whyte
Revision: 11
Doc No: CC_PE_EN_0002_r13
Confidentiality: 1
Projection: MGA Zone 50 (GDA 94)
Scale: 1:100000

Figure 3: Conceptual Chichester cross section

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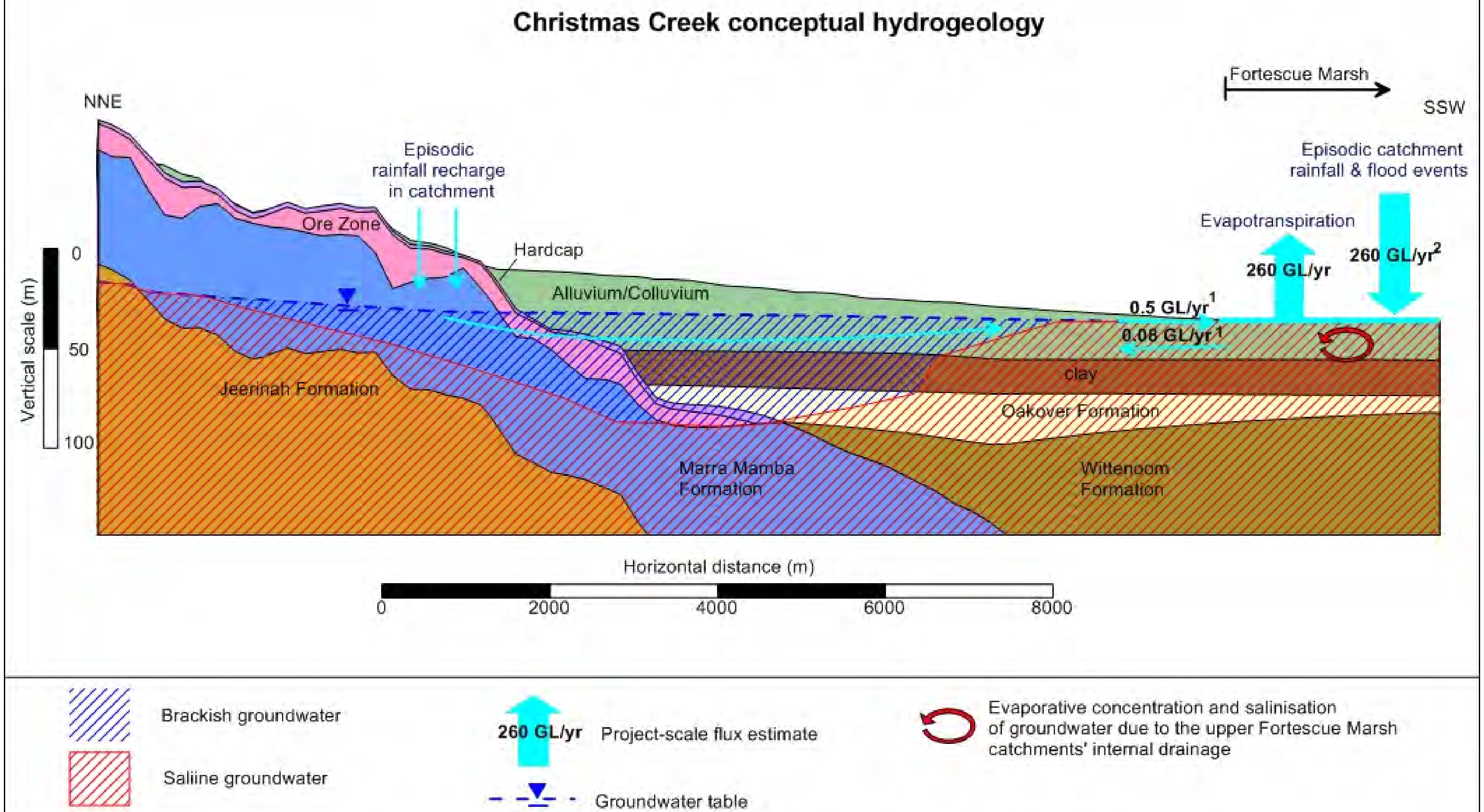

Footnotes:

1 Annual groundwater discharge to the marsh and recharge from marsh flooding (average rates along the marsh edge, south of the Christmas Creek pits [about 36km strike length], calculated from a calibration numerical model with a simulation period from January 2007 to June 2011)

2 Based on Worley Parsons (2012): Christmas Creek Life of Mine Expansion - Fortescue Marsh Catchment Water Balance Study. Average inflow based on a water balance from 1984 to 2011. Other time periods will yield different average inflows.

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Western Australia 6004

Christmas Creek Conceptual Cross Section

Figure 03

29/08/2013

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Figure 4: Historical rainfall

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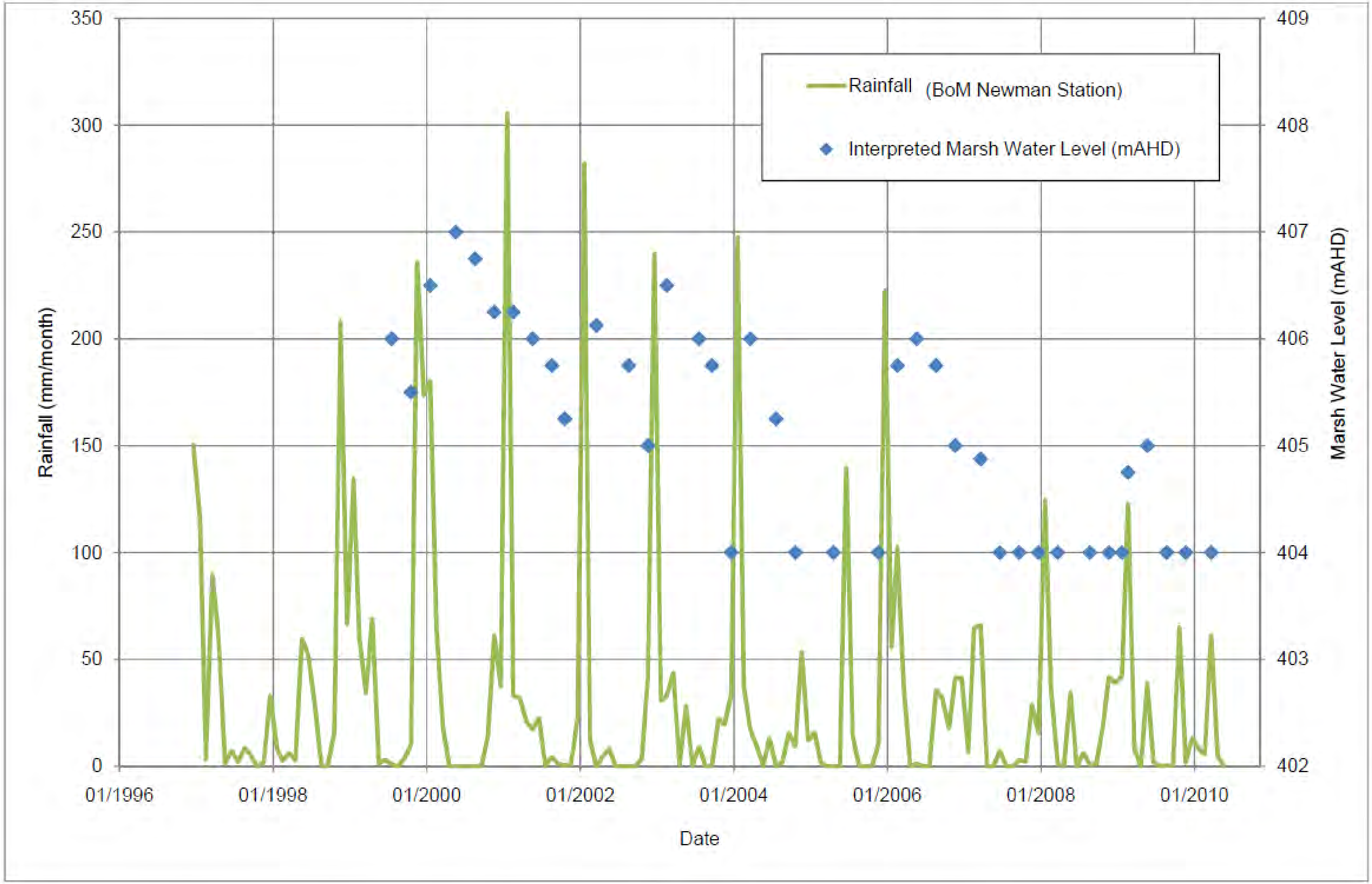

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87 Adelaide Terrace, East Perth
Western Australia 6004

Historical Rainfall and Interpreted Marsh Water Level

Figure 04

29/08/2013

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Figure 5: Baseline groundwater levels – Tertiary Detrital

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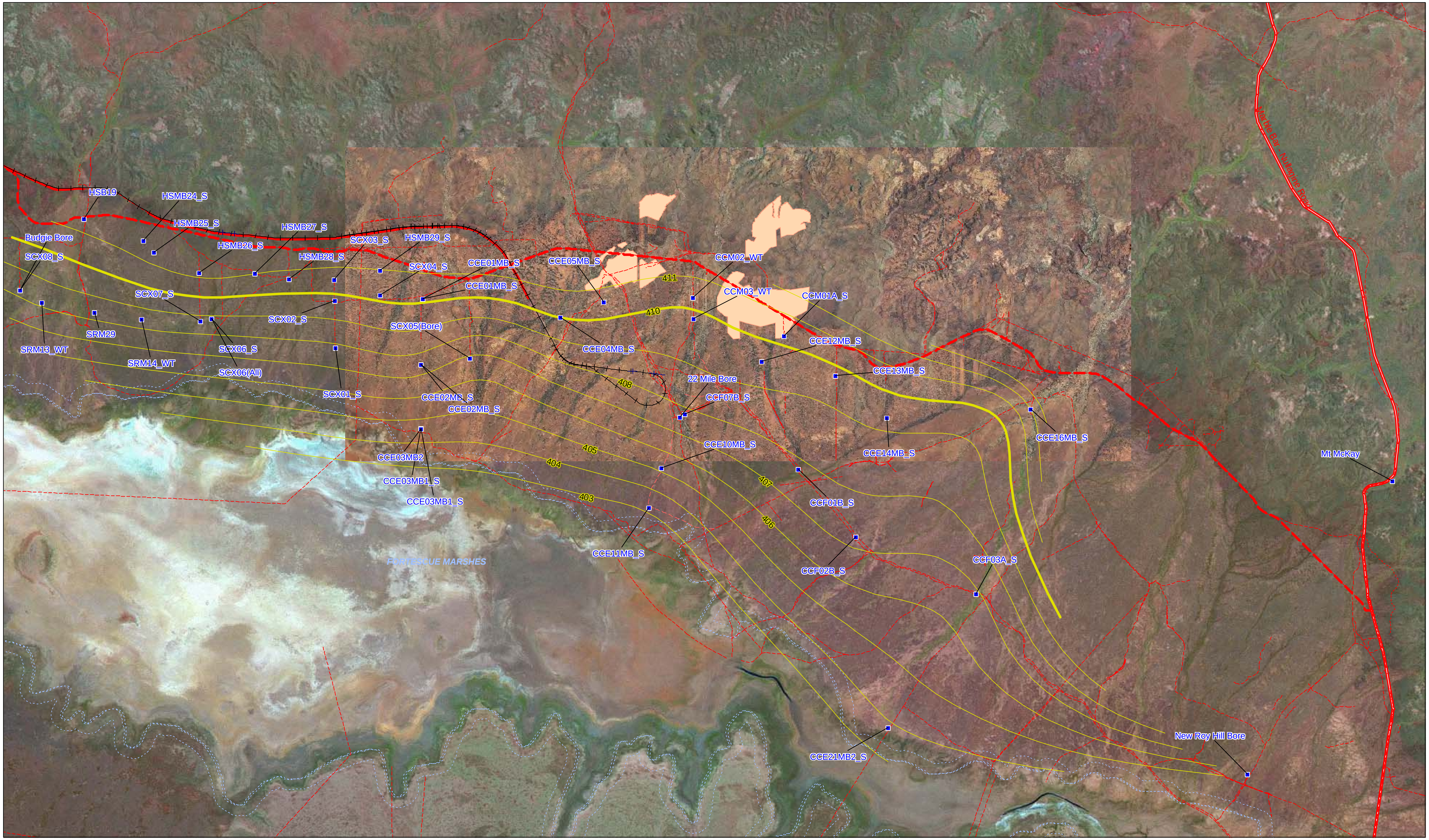

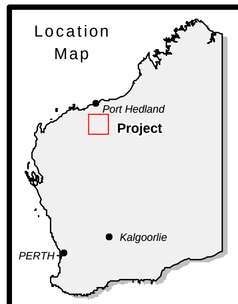

- Proposed Railway
- Existing Tracks
- Mine Plan 2015
- Point Locations
- Contours

N

0 1.25 2.5 5
kilometres

Fortescue Metals Group Ltd

BASELINE GROUNDWATER LEVELS TERTIARY DETRITALS

Author:I. BDR	Date:27/5/2010
Drawn By: S.Hendricksen	Revision: 0
Doc No: CC_MP_HY_0028_R1	Confidentiality: 1
Projection: MGA Zone 50 (GDA 94)	Scale: 1:125000

Figure 6: Baseline groundwater levels (fresh water equivalence) – Tertiary Detrital

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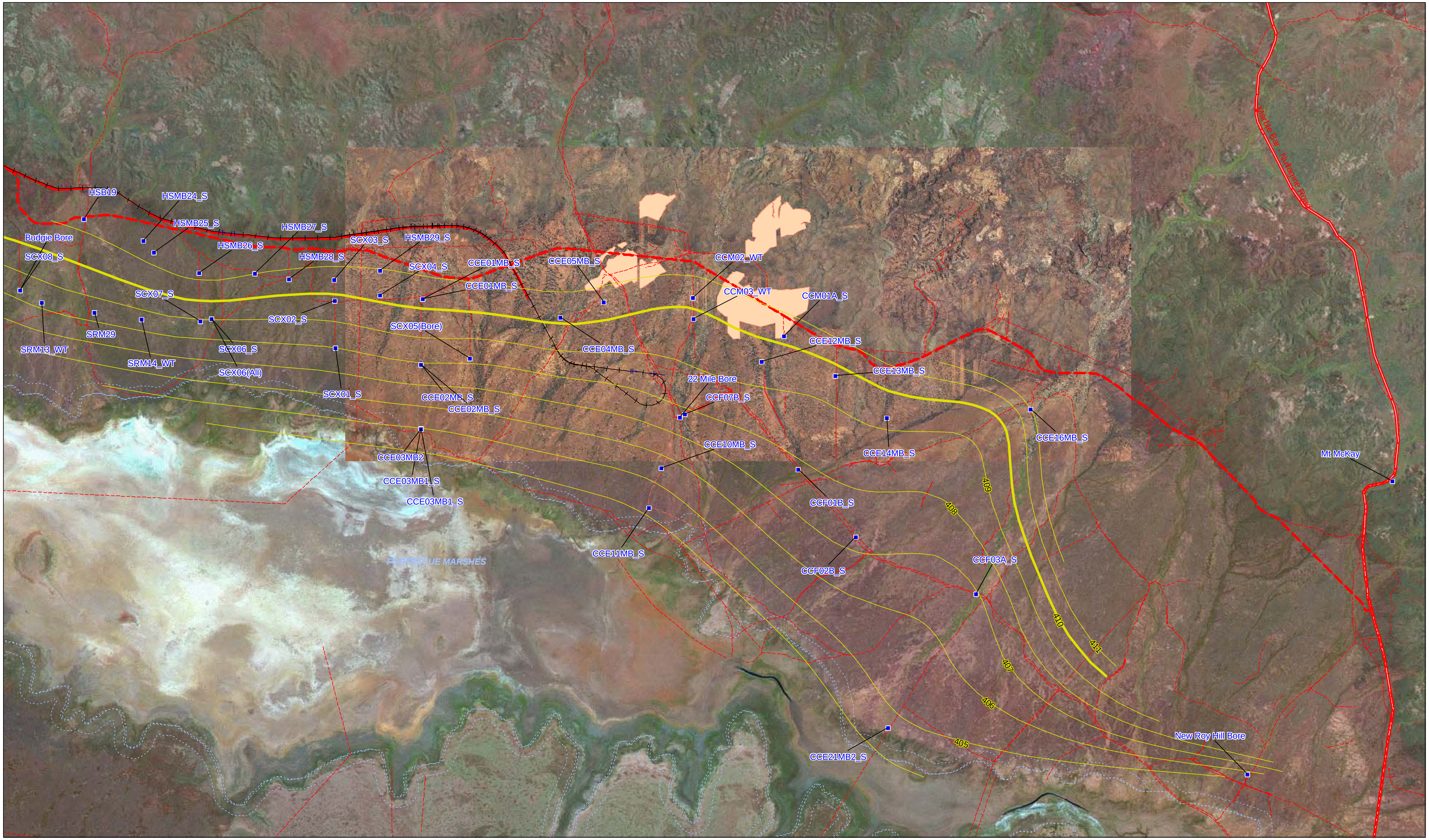

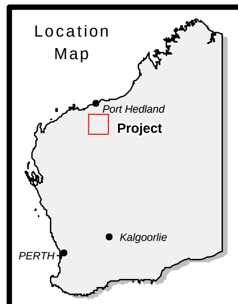

- Proposed Railway
- Existing Tracks
- Mine Plan 2015
- Point Locations
- Contours

N

0 1.25 2.5 5
kilometres

Fortescue Metals Group Ltd

BASELINE GROUNDWATER LEVELS
TERTIARY DETRITALS
EQUIVALENT FRESHWATER HEAD

Author: I. BDR	Date:27/5/2010
Drawn By: S.Hendricksen	Revision: 0
Doc No: CC_MP_HY_0028_R1	Confidentiality: 1
Projection: MGA Zone 50 (GDA 94)	Scale: 1:125000

Figure 7: Baseline groundwater levels – Marra Mamba Formation

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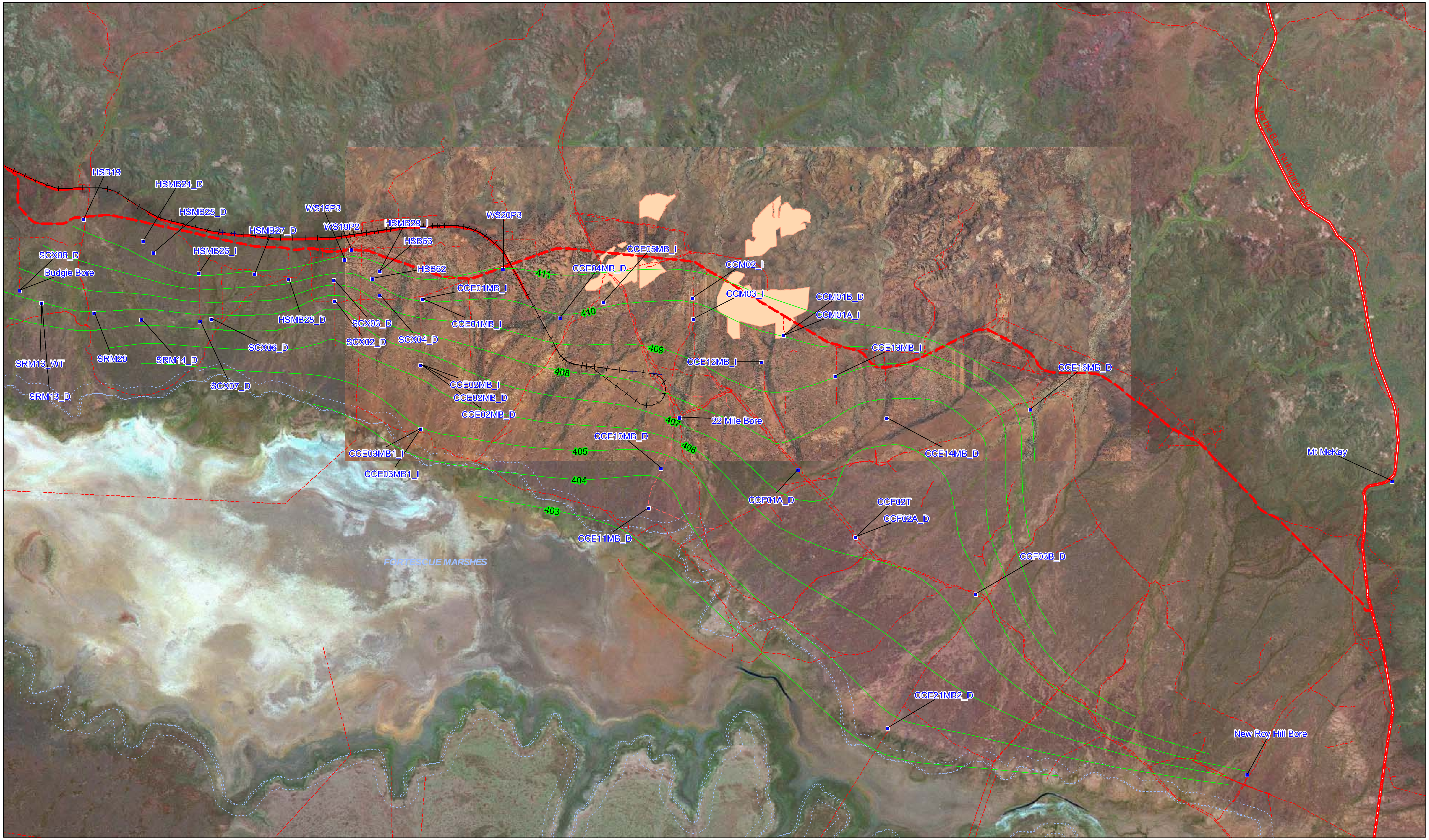

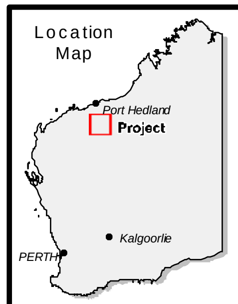

- Proposed Railway
- Existing Tracks
- Mining Pit Outlines
- Point Locations
- Contours

N

0 1.25 2.5 5
kilometres

Fortescue Metals Group Ltd

BASELINE GROUNDWATER LEVELS MARRA MAMBA FORMATION

Author: I. BDR	Date: 27/5/2010
Drawn By: S.Hendricksen	Revision: 0
Doc No: CC_MP_HY_0028_R1	Confidentiality: 1
Projection: MGA Zone 50 (GDA 94)	Scale: 1:125000

Figure 8: Baseline groundwater levels (fresh water equivalence) – Marra Mamba Formation

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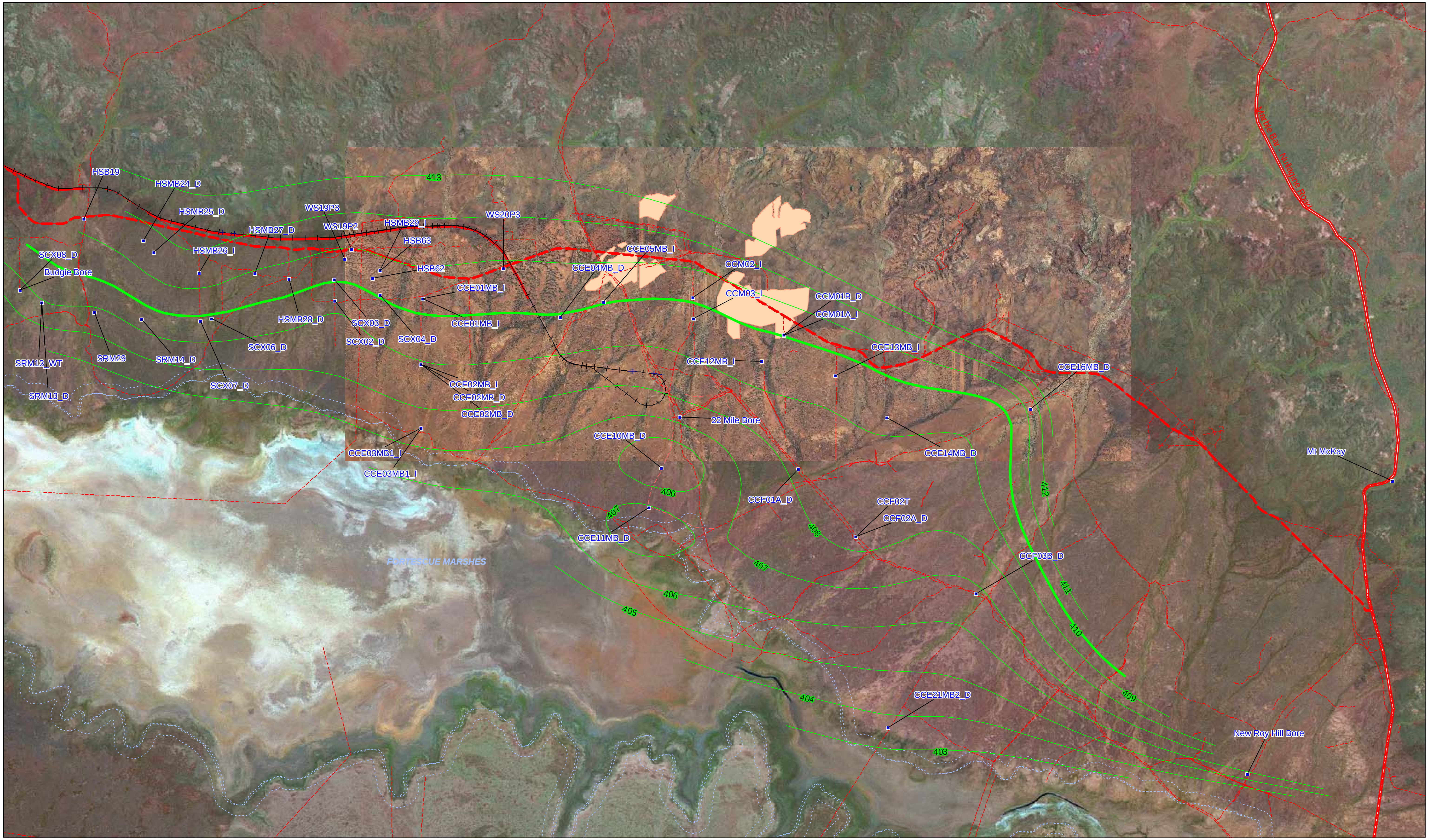

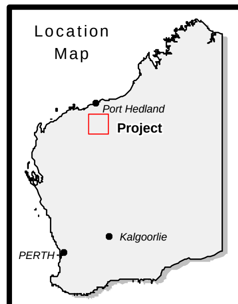

Proposed Railway

Existing Tracks

Mining Pit Outlines

Point Locations

Contours

N

0 1.25 2.5 5

kilometres

Fortescue Metals Group Ltd

BASELINE GROUNDWATER LEVELS
MARRA MAMBA FORMATION
EQUIVALENT FRESHWATER HEAD

Author: I. BDR	Date:28/5/2010
Drawn By: S.Hendricksen	Revision: 0
Doc No: CC_MP_HY_0028_R1	Confidentiality: 1
Projection: MGA Zone 50 (GDA 94)	Scale: 1:125000

Figure 9: Fortescue Marsh ponding event

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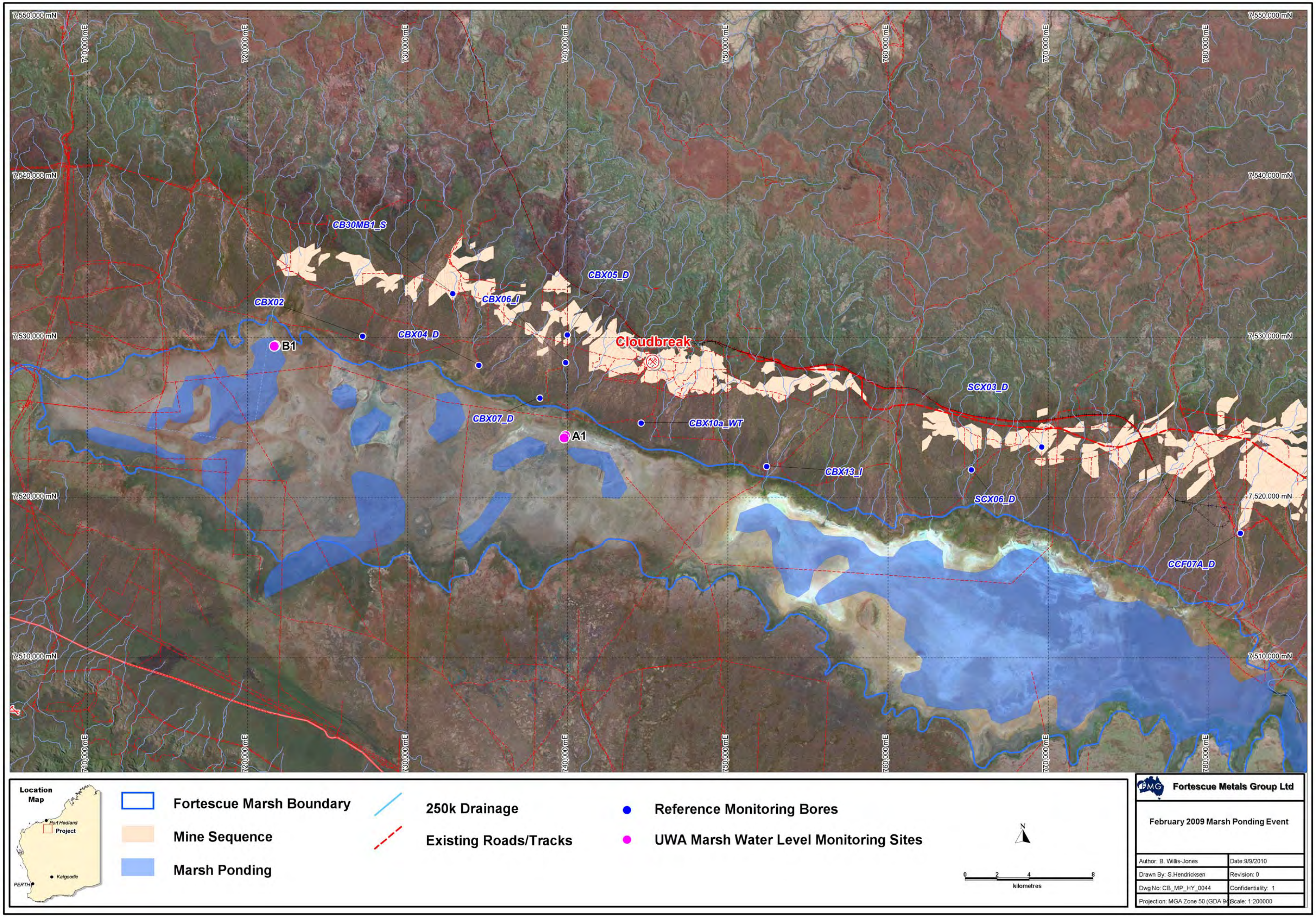

7,550,000 mN
7,540,000 mN
7,530,000 mN
7,520,000 mN
7,510,000 mN
710,000 mE
720,000 mE
730,000 mE
740,000 mE
750,000 mE
760,000 mE
770,000 mE
780,000 mE
CB30MB1_S
CBX05_D
CBX02
CBX06_I
CBX04_D
B1
Cloudbreak
SCX03_D
CBX07_D
CBX10a_WT
A1
CBX13_I
SCX06_D
CCF07A_D
Location Map
Port Hedland
Project
Kalgoorlie
PERTH
Fortescue Marsh Boundary
Mine Sequence
Marsh Ponding
250k Drainage
Existing Roads/Tracks
Reference Monitoring Bores
UWA Marsh Water Level Monitoring Sites
N
0 2 4 8
kilometres
Fortescue Metals Group Ltd
February 2009 Marsh Ponding Event
Author: B. Willis-Jones
Date:9/9/2010
Drawn By: S.Hendricksen
Revision: 0
Dwg No: CB_MP_HY_0044
Confidentiality: 1
Projection: MGA Zone 50 (GDA 94)
Scale: 1:200000

Figure 10: Expanded Durvo diagram – Christmas Creek

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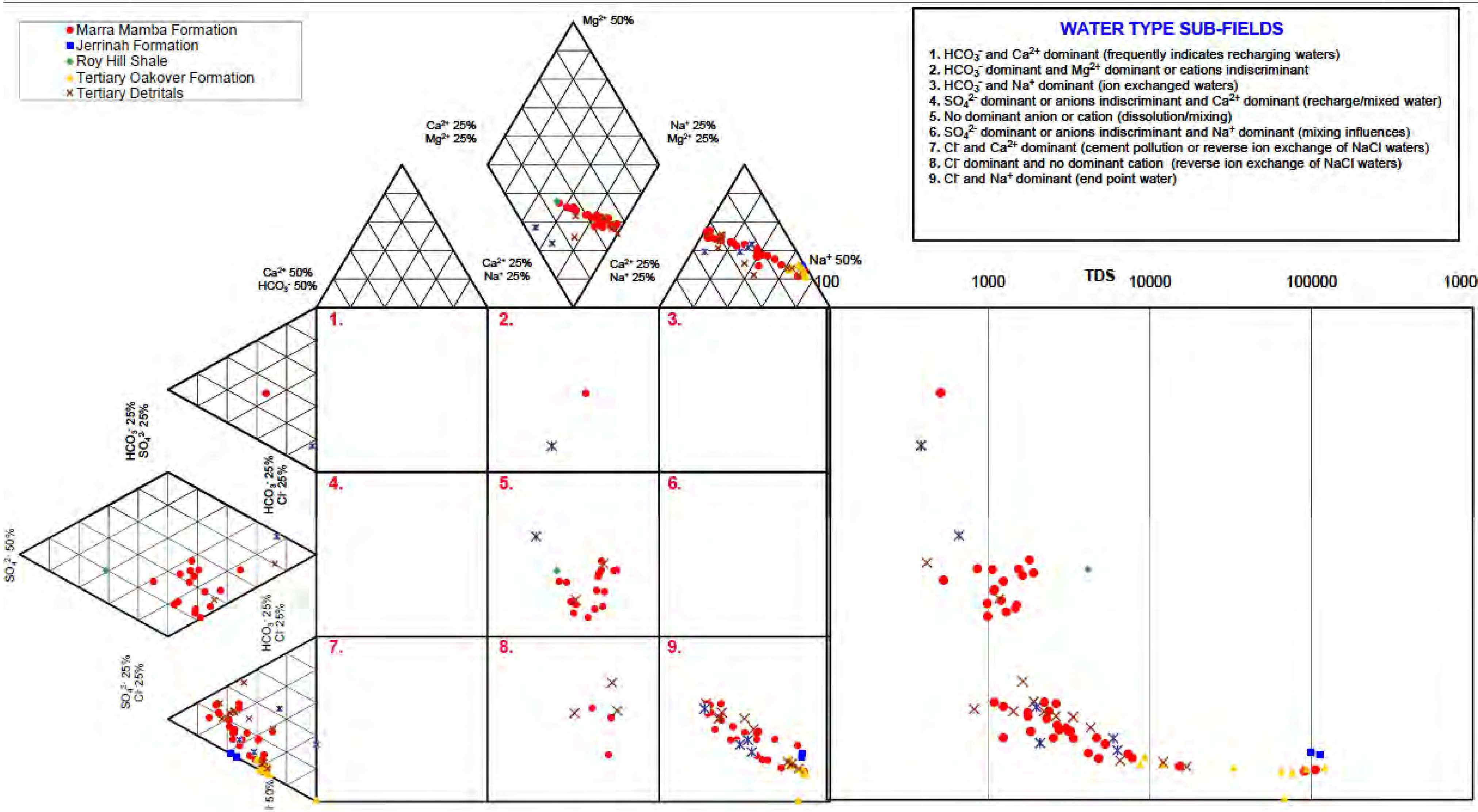

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Western Australia 6004

Expanded Durov Diagram

Figure 10

29/08/2013

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Figure 11: Expanded Durvo diagram - Cloudbreak

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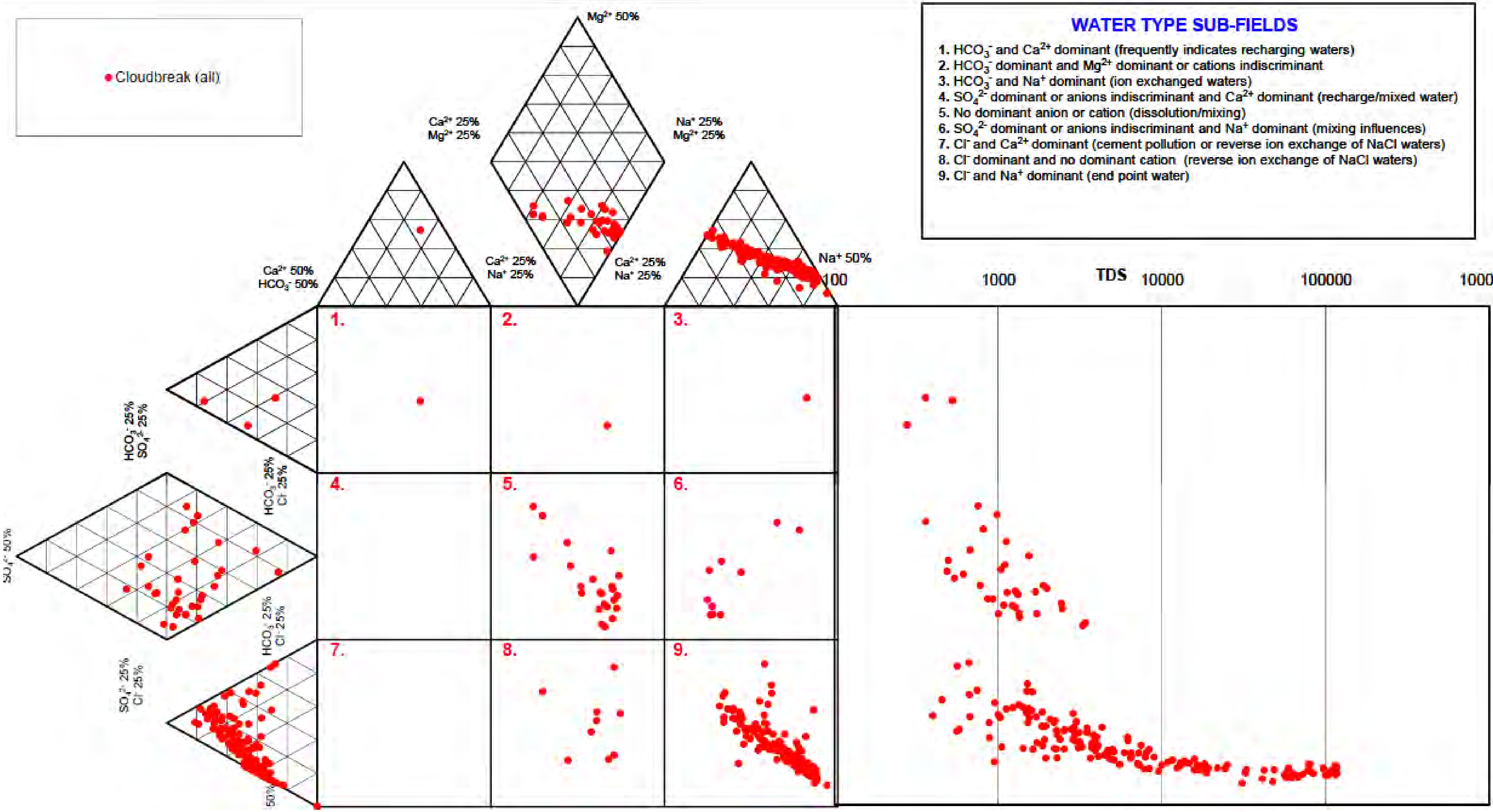

WATER TYPE SUB-FIELDS

1. HCO_3^- and Ca^{2+} dominant (frequently indicates recharging waters)
2. HCO_3^- dominant and Mg^{2+} dominant or cations indiscriminant
3. HCO_3^- and Na^+ dominant (ion exchanged waters)
4. SO_4^{2-} dominant or anions indiscriminant and Ca^{2+} dominant (recharge/mixed water)
5. No dominant anion or cation (dissolution/mixing)
6. SO_4^{2-} dominant or anions indiscriminant and Na^+ dominant (mixing influences)
7. Cl^- and Ca^{2+} dominant (cement pollution or reverse ion exchange of NaCl waters)
8. Cl^- dominant and no dominant cation (reverse ion exchange of NaCl waters)
9. Cl^- and Na^+ dominant (end point water)

FMG Fortescue Metals Group Ltd ACN: 002 594 872 87 Adelaide Terrace, East Perth Western Australia 6004	**Expanded Durov Diagram—Cloudbreak**	**Figure 11**
		29/08/2013

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Figure 12: Baseline E.C. – Tertiary Detritals

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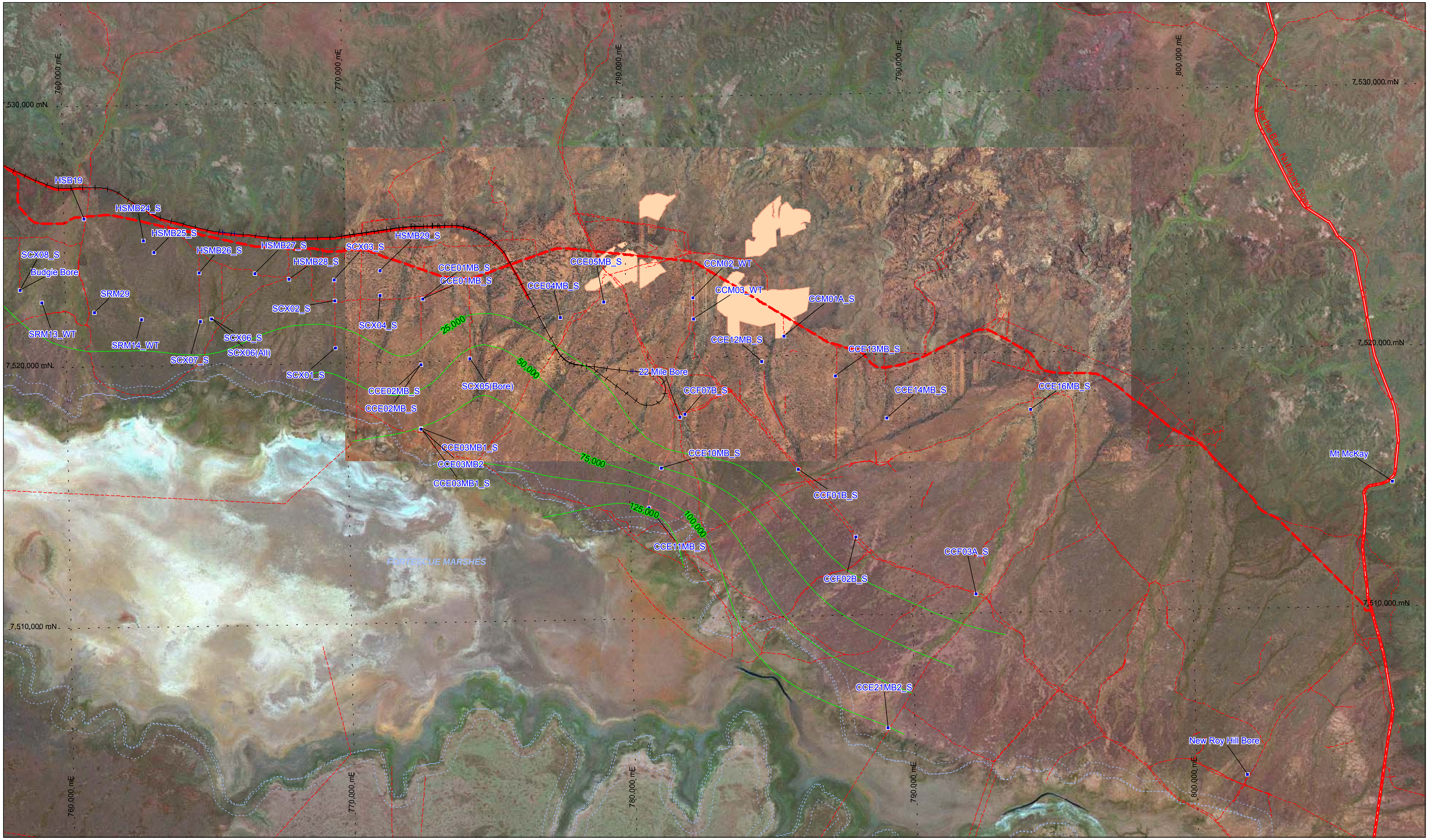

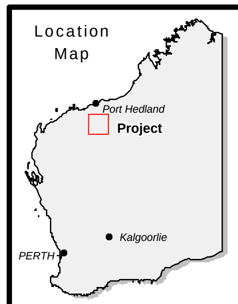

Proposed Railway

Existing Tracks

Mine Plan 2015

Point Locations

EC contour (uS/cm)

N

0 1.25 2.5 5

kilometres

Fortescue Metals Group Ltd

BASELINE EC
TERTIARY DETRITALS

Author: I. DBR	Date:27/5/2010
Drawn By: S. Hendricksen	Revision: 1
Doc No: CC_MP_HY_0028_R1	Confidentiality: 1
Projection: MGA Zone 50 (GDA 94)	Scale: 1:125000

Figure 13: Baseline E.C. – Marra Mamba Formation

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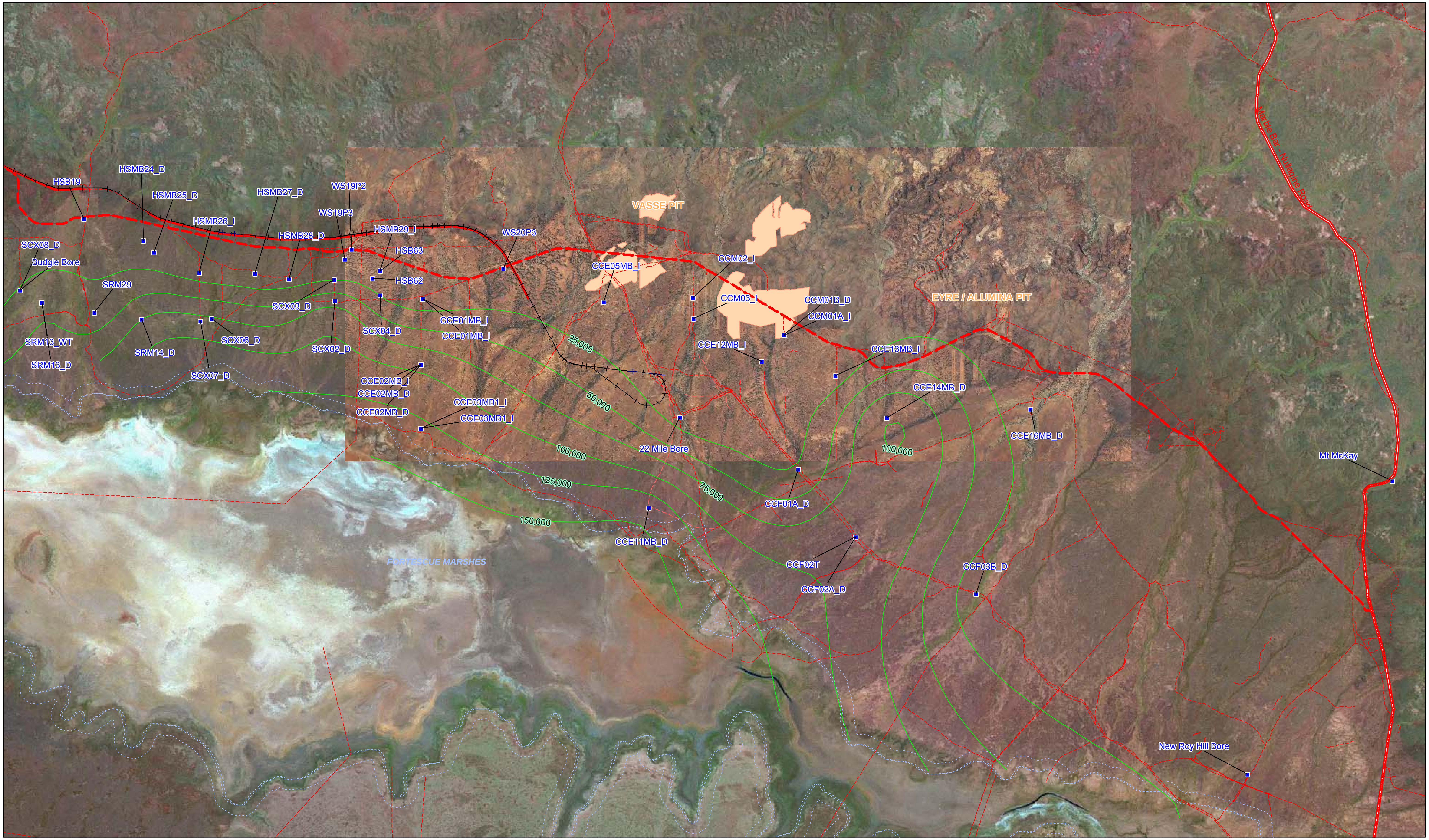

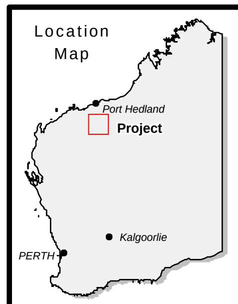

- Proposed Railway
- Existing Tracks
- Mine Plan 2015
- Point Locations
- EC contour uS/cm

N

0 1.25 2.5 5
kilometres

Fortescue Metals Group Ltd

BASELINE EC
MARRA MAMBA FORMATION

Author:I.BDR	Date:27/5/2010
Drawn By:S.Hendricksen	Revision: 0
Doc No: CC_MP_HY_0028_R1	Confidentiality: 1
Projection: MGA Zone 50 (GDA 94)	Scale: 1:125000

Figure 14: Airborne EM conductivity – Marra Mamba Formation

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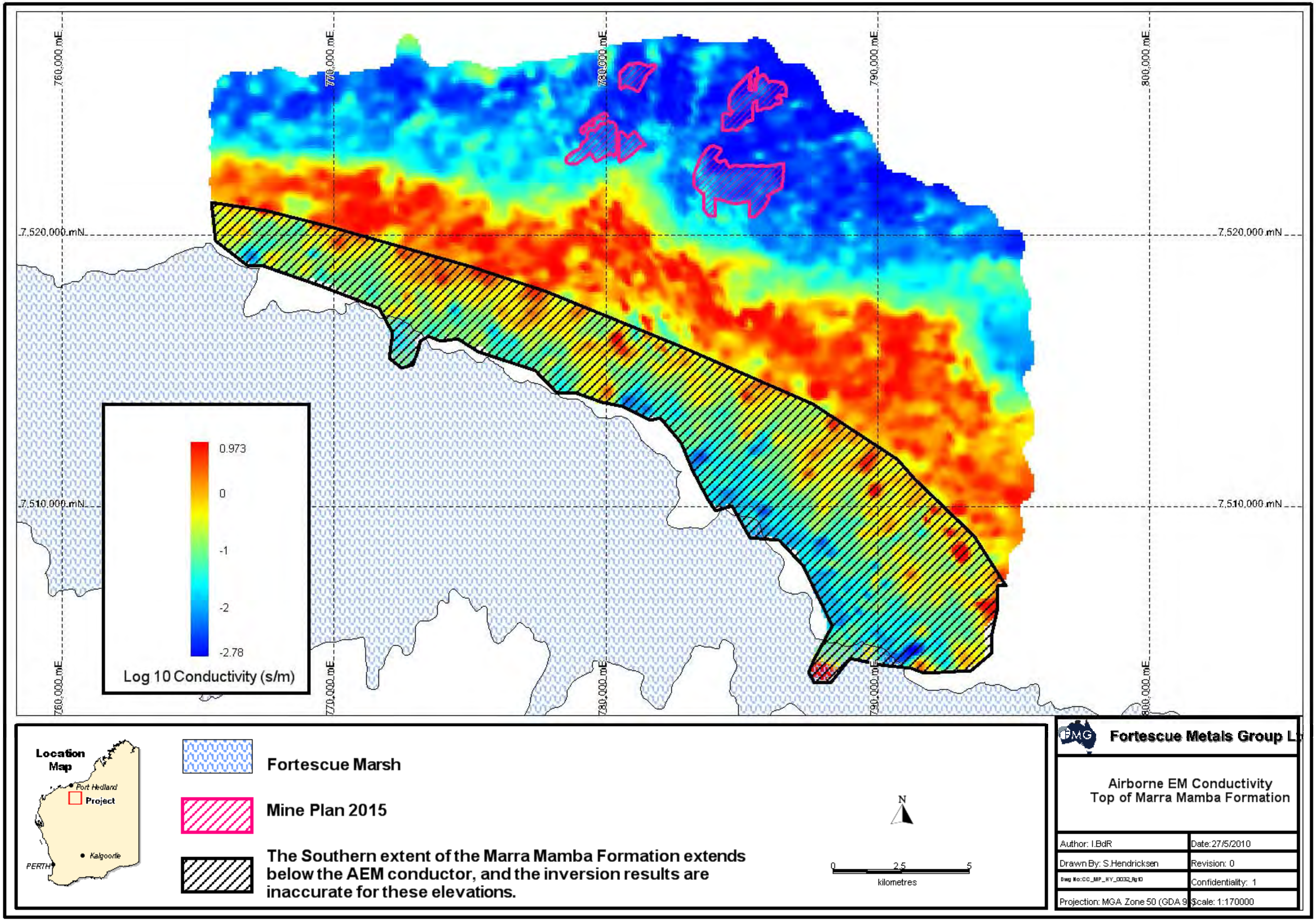

760,000 mE
770,000 mE
780,000 mE
790,000 mE
800,000 mE
7,520,000 mN
7,510,000 mN
0.973
0
-1
-2
-2.78
Log 10 Conductivity (s/m)
Location Map
Port Hedland
Project
Kalgoorlie
PERTH
Fortescue Marsh
Mine Plan 2015
The Southern extent of the Marra Mamba Formation extends below the AEM conductor, and the inversion results are inaccurate for these elevations.
N
0
2.5
5
kilometres
Fortescue Metals Group Lt
Airborne EM Conductivity
Top of Marra Mamba Formation
Author: I.BdR
Date:27/5/2010
Drawn By: S.Hendricksen
Revision: 0
Confidentiality: 1
Projection: MGA Zone 50 (GDA 9
Scale: 1:170000

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Figure 15: Airborne EM conductivity – water table minus five metres

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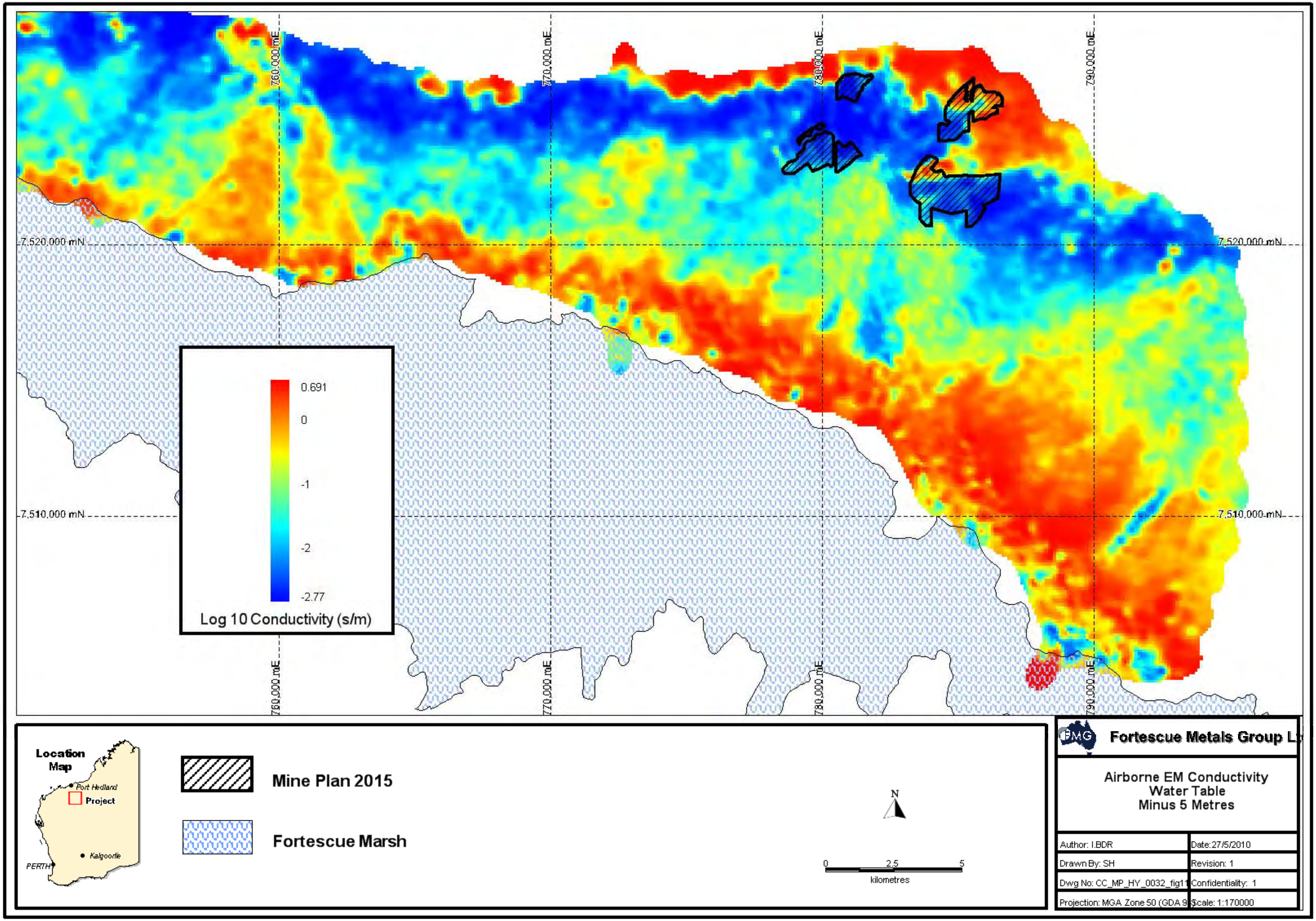
760,000 mE
770,000 mE
780,000 mE
790,000 mE
7,520,000 mN
7,510,000 mN
0.691
0
-1
-2
-2.77
Log 10 Conductivity (s/m)
Location Map
Port Hedland
Project
Kalgoorlie
PERTH
Mine Plan 2015
Fortescue Marsh
N
0
2.5
5
kilometres
Fortescue Metals Group Lt
Airborne EM Conductivity
Water Table
Minus 5 Metres
Author: I.BDR
Date:27/5/2010
Drawn By: SH
Revision: 1
Dwg No: CC_MP_HY_0032_fig11
Confidentiality: 1
Projection: MGA Zone 50 (GDA 9
Scale: 1:170000

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Figure 16: Fortescue Marsh conceptual section

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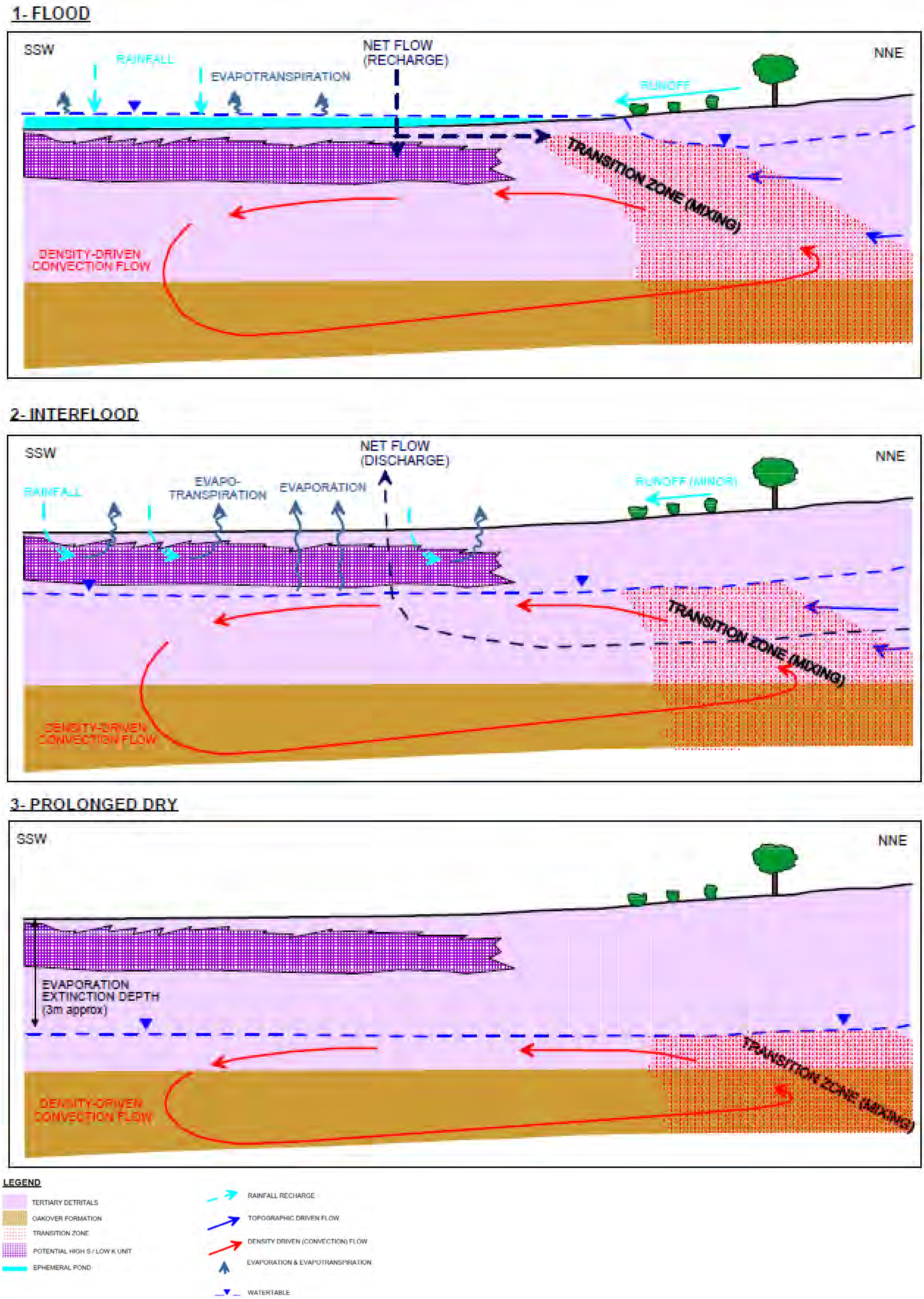

Fortescue Metals Group Ltd ACN: 002 594 872 87 Adelaide Terrace, East Perth Western Australia 6004	**Fortescue Marsh Conceptual Hydrogeology**	**Figure 16**
		29/08/2013

Figure 17: Model domain and boundary conditions

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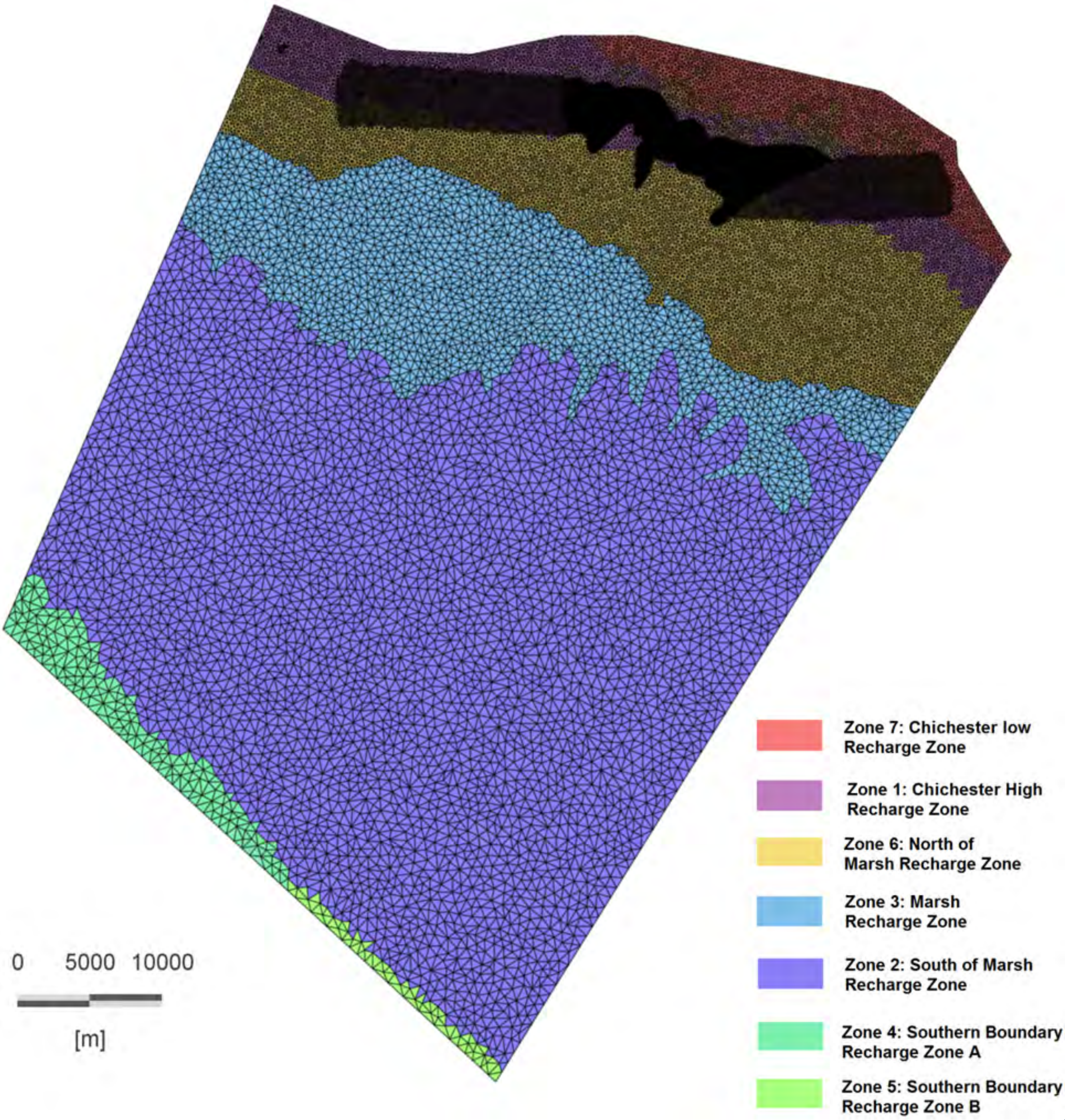

Fortescue Metals Group Ltd ACN: 002 594 872 87 Adelaide Terrace, East Perth Western Australia 6004	**Model Domain, Numerical Mesh and Recharge Zones**	**Figure 17**
		29/08/2013

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Figure 18: Model cross section

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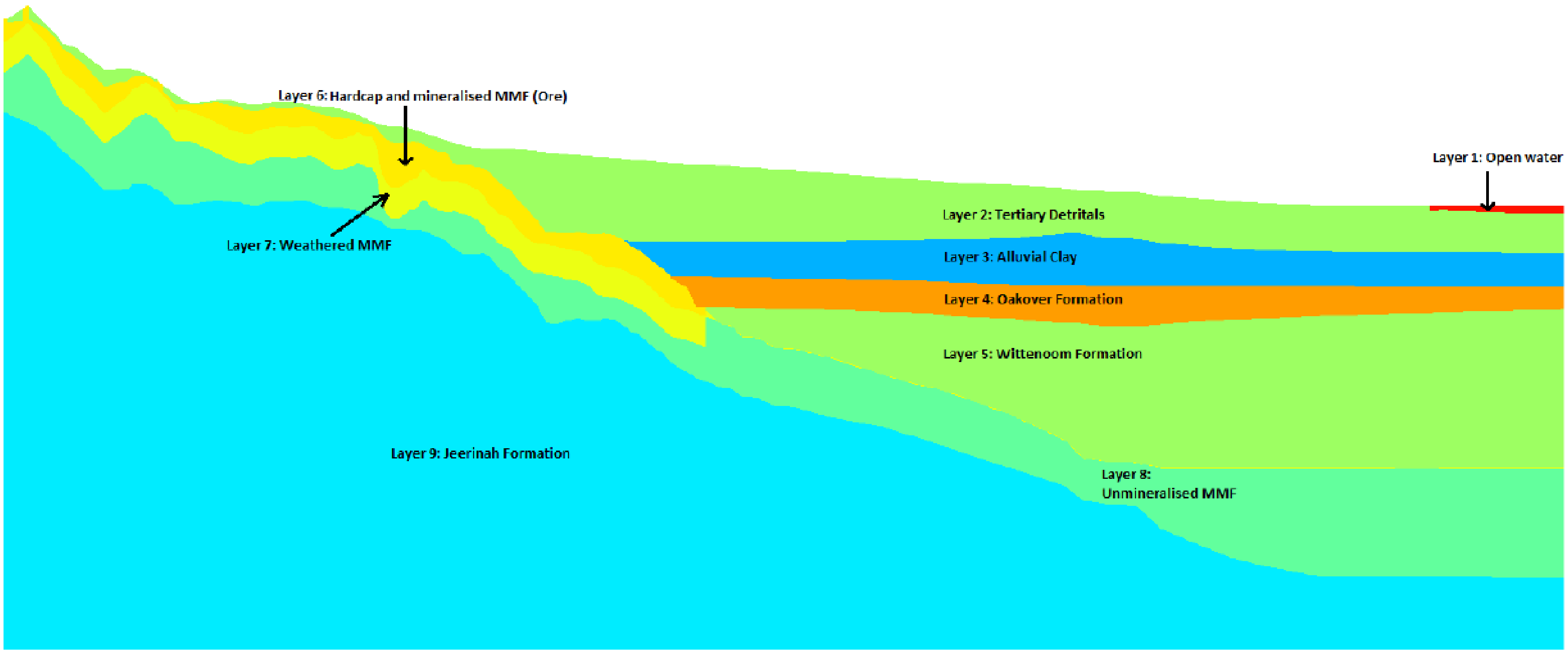

Fortescue Metals Group Ltd ACN: 002 594 872 87 Adelaide Terrace, East Perth Western Australia 6004	**Numerical Model Cross Section**	**Figure 18**
		29/08/2013

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Figure 19: Distribution of initial heads within the numerical model (slice one)

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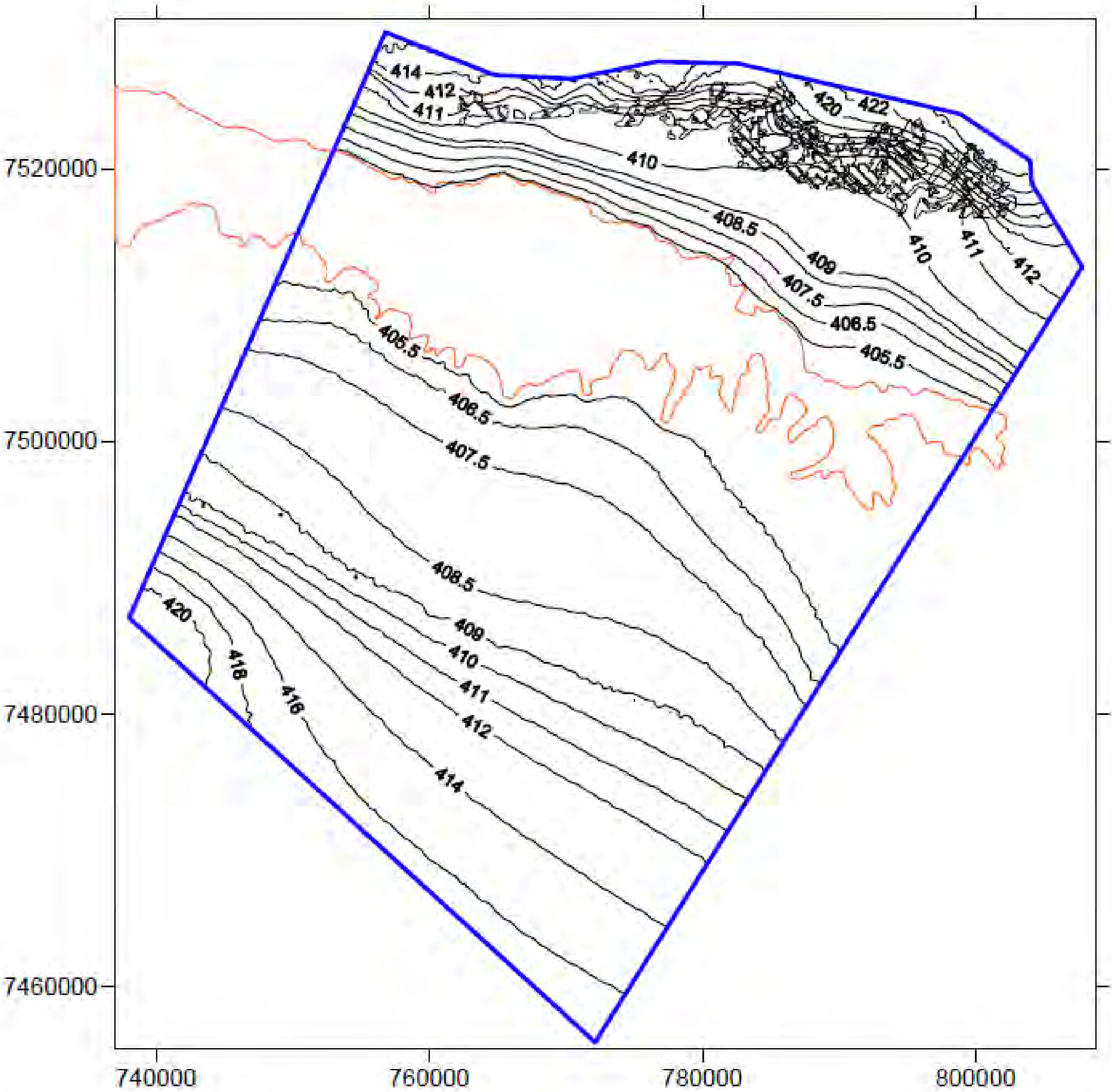

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87 Adelaide Terrace, East Perth
Western Australia 6004

Distribution of Initial Model Heads (Slice 1)	Figure 19
	29/08/2013

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Figure 20: Distribution of initial salinity within the numerical model (slice one)

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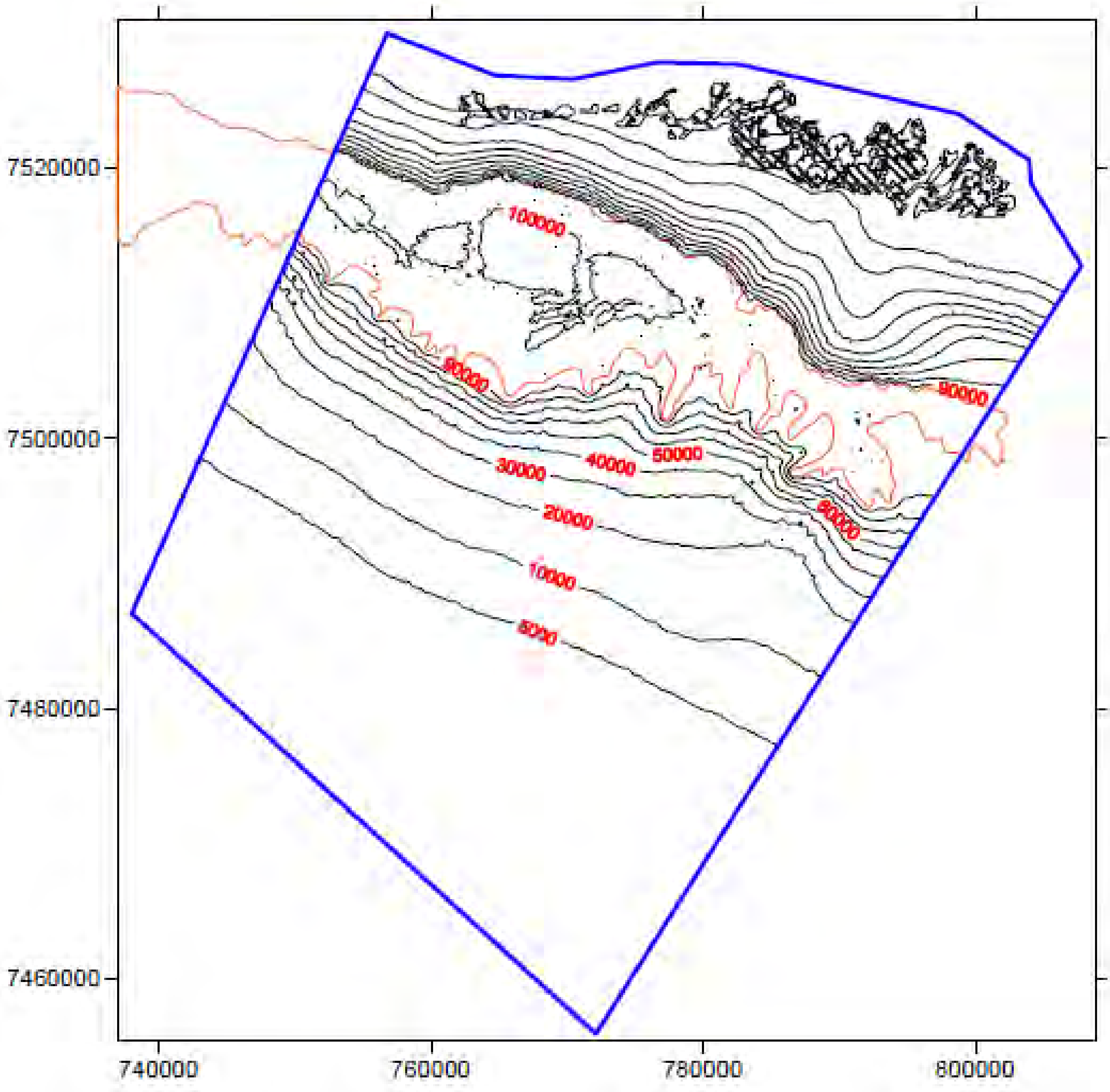

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Western Australia 6004

Distribution of Initial Salinity (Slice 1)

Figure 20

29/08/2013

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Figure 21: Steady state calibration results: Measured v's model predicted groundwater levels

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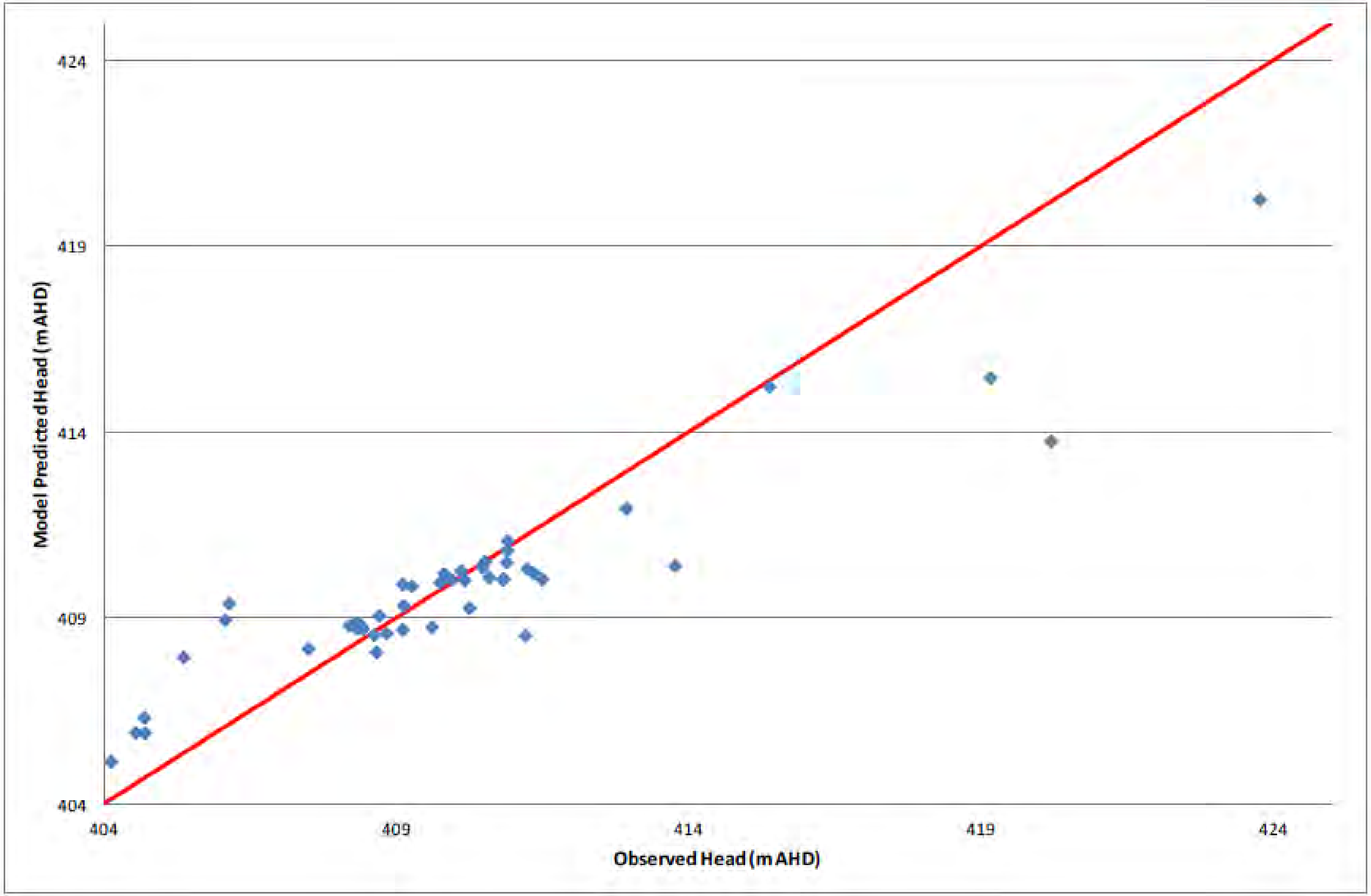

Fortescue Metals Group Ltd ACN: 002 594 872 87 Adelaide Terrace, East Perth Western Australia 6004	**Steady State Calibration Results: Measured v's Model Predicted Groundwater Levels**	**Figure 21**
		29/08/2013

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Figure 22: Transient calibration results: Measured v's model predicted groundwater levels

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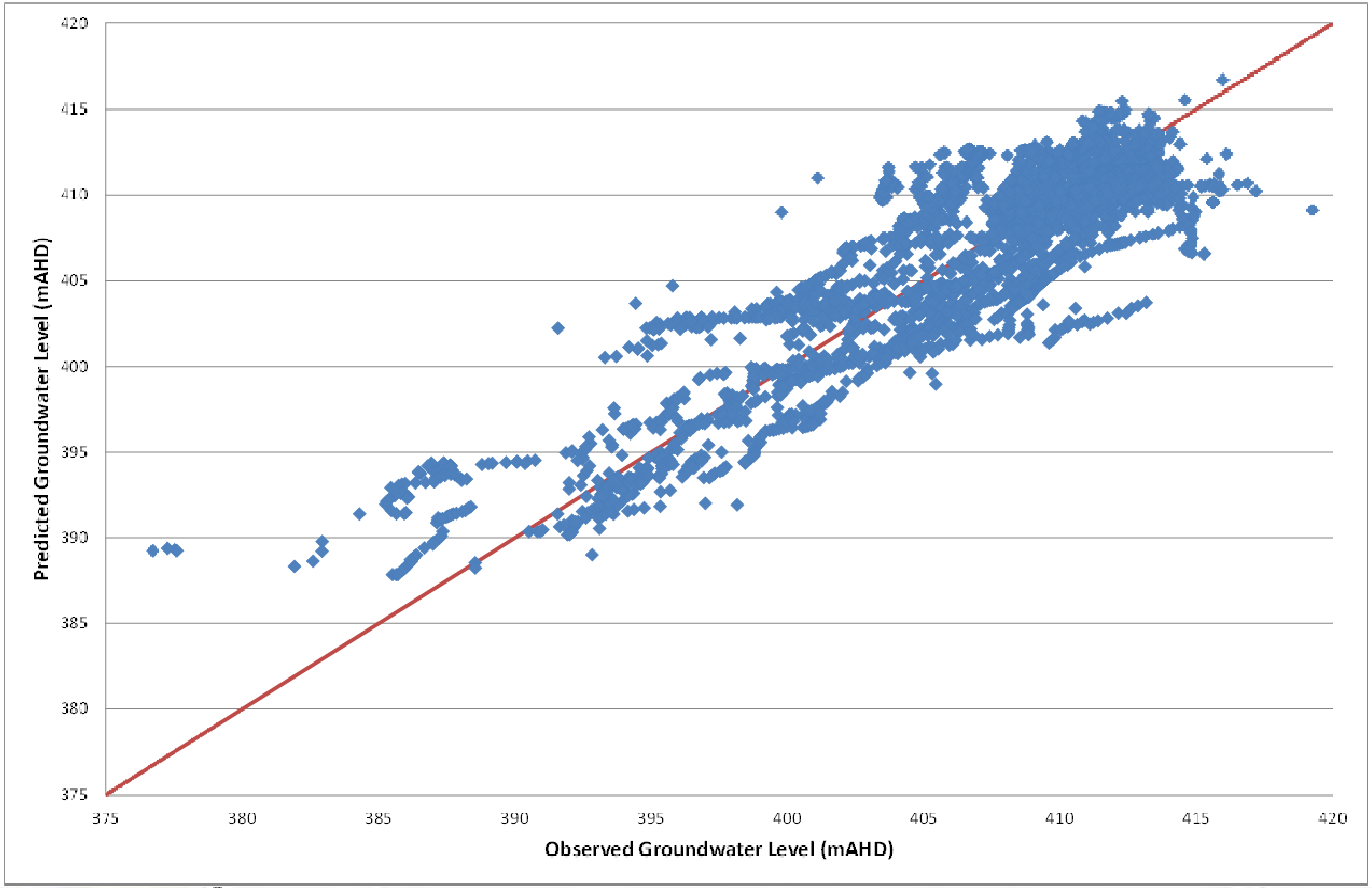

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ACN: 002 594 872
87 Adelaide Terrace, East Perth
Western Australia 6004

Transient Calibration Results:
Measured v's Model Predicted Groundwater Levels

Figure 22

29/08/2013

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Figure 23: Transient calibration results: Comparison between simulated and interpreted Fortescue Marsh water levels

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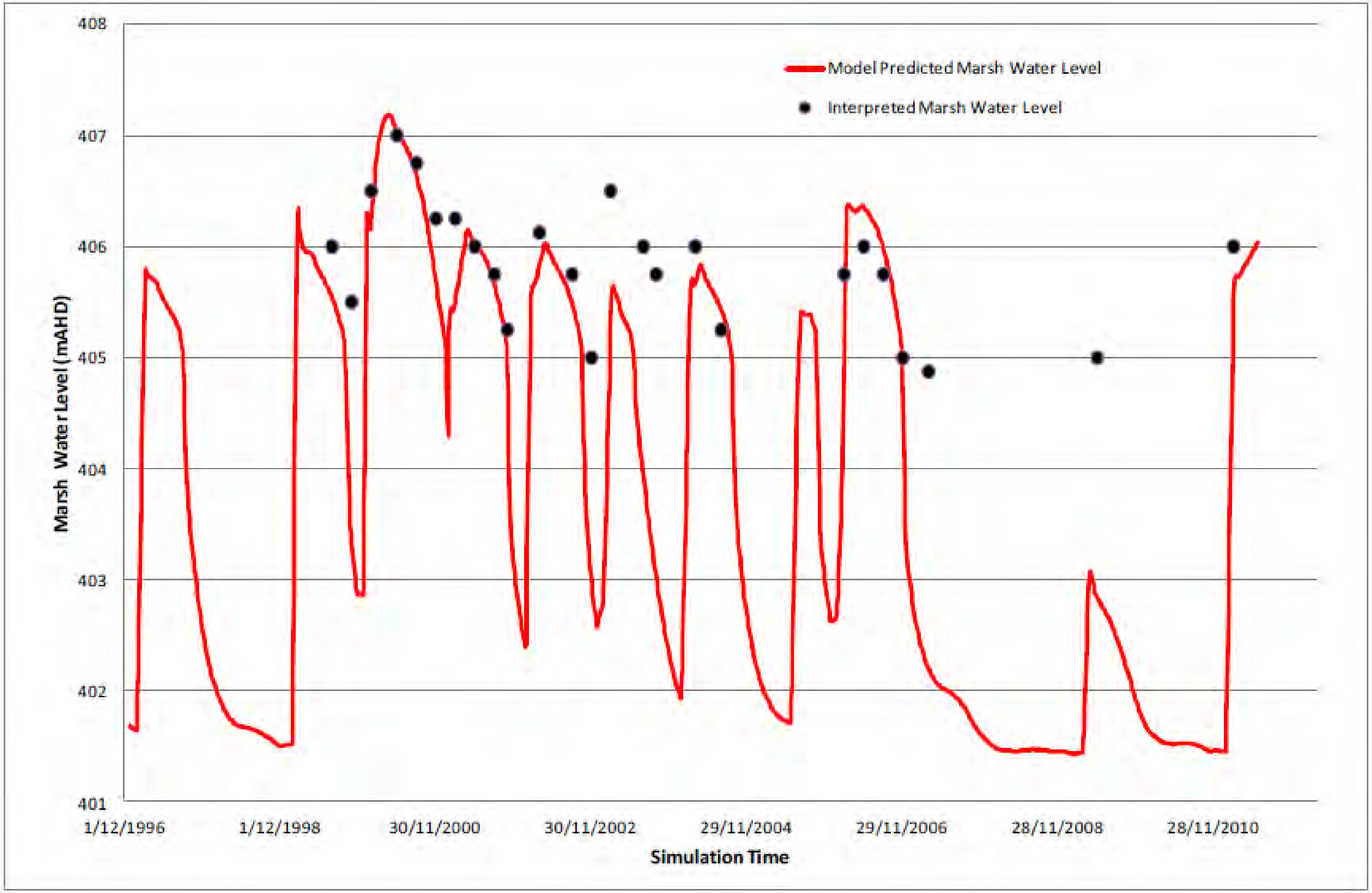

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87 Adelaide Terrace, East Perth
Western Australia 6004

Transient Calibration Results:
Simulated and interpreted Fortescue Marsh Water Levels

Figure 23

29/08/2013

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Figure 24: Christmas Creek life of mine plan 8.4b

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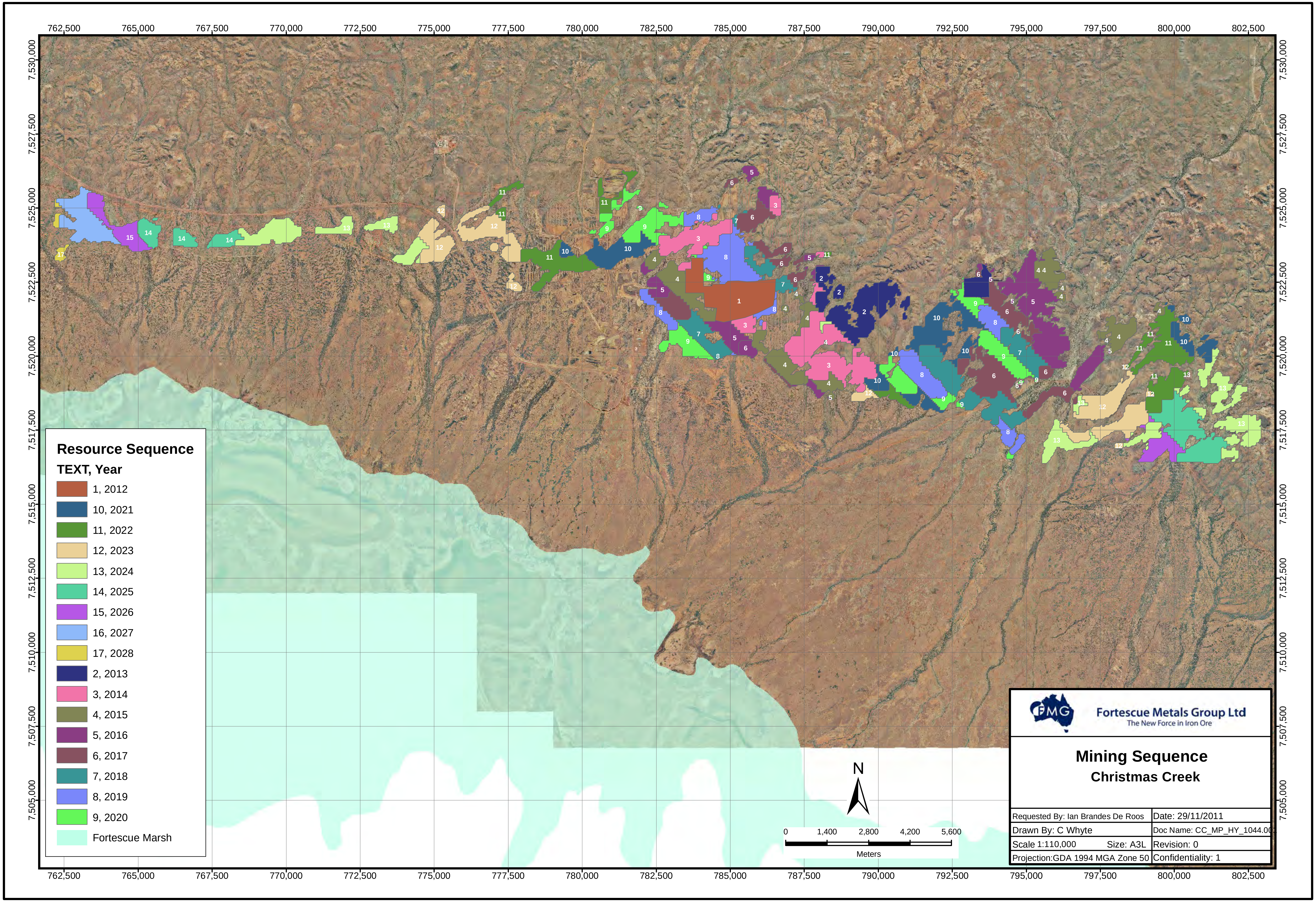
Resource Sequence
TEXT, Year
1, 2012
10, 2021
11, 2022
12, 2023
13, 2024
14, 2025
15, 2026
16, 2027
17, 2028
2, 2013
3, 2014
4, 2015
5, 2016
6, 2017
7, 2018
8, 2019
9, 2020
Fortescue Marsh
N
0 1,400 2,800 4,200 5,600
Meters
Fortescue Metals Group Ltd
The New Force in Iron Ore
Mining Sequence
Christmas Creek
Requested By: Ian Brandes De Roos
Date: 29/11/2011
Drawn By: C Whyte
Doc Name: CC_MP_HY_1044.00
Scale 1:110,000
Size: A3L
Revision: 0
Projection:GDA 1994 MGA Zone 50
Confidentiality: 1
762,500 765,000 767,500 770,000 772,500 775,000 777,500 780,000 782,500 785,000 787,500 790,000 792,500 795,000 797,500 800,000 802,500
7,530,000 7,527,500 7,525,000 7,522,500 7,520,000 7,517,500 7,515,000 7,512,500 7,510,000 7,507,500 7,505,000

Figure 25: Distribution of conceptual saline injection bores used in numerical simulations

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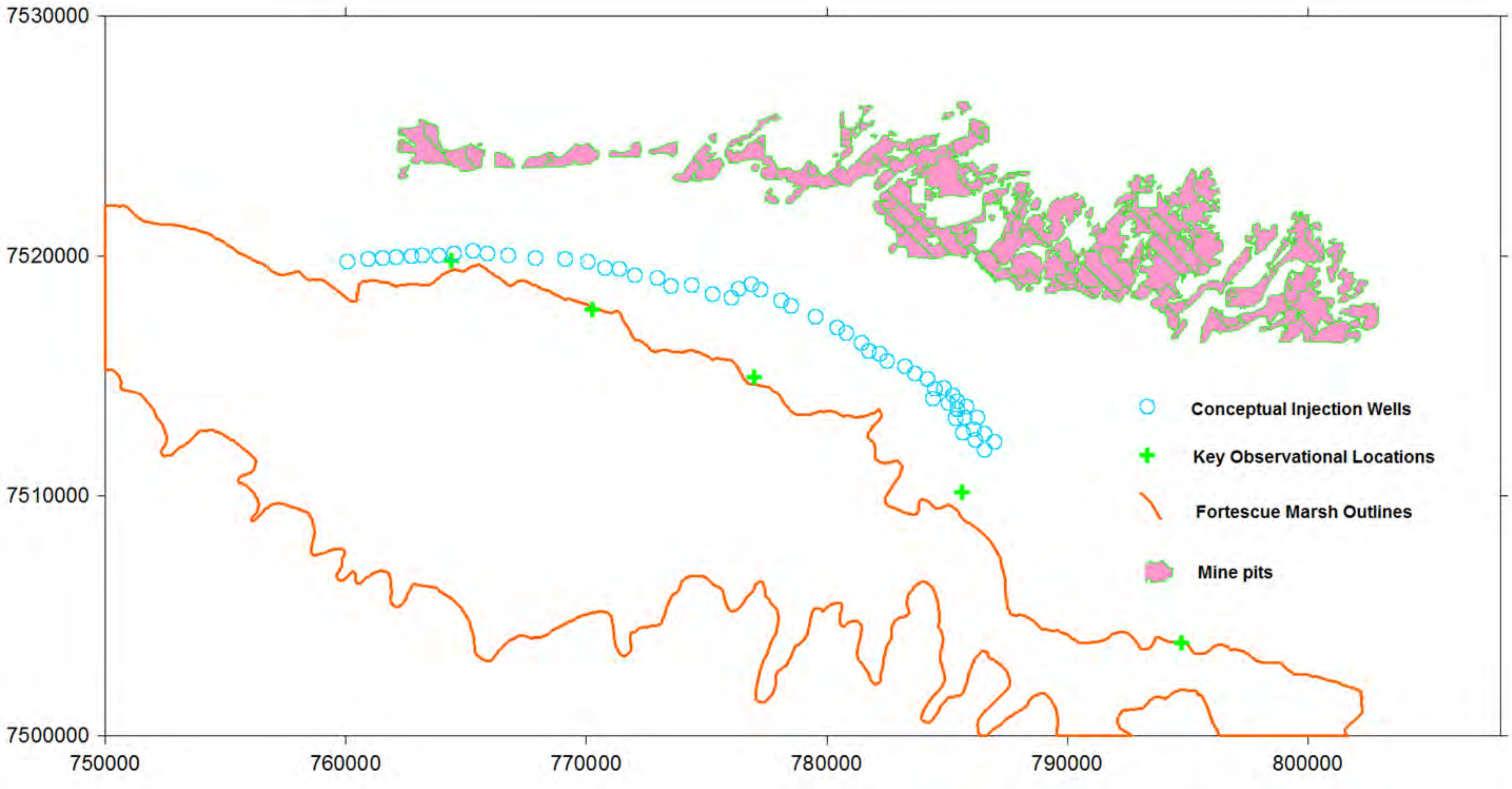

Fortescue Metals Group Ltd
ACN: 002 594 872
87 Adelaide Terrace, East Perth
Western Australia 6004

Distribution of Conceptual Saline Injection Wells

Figure 25

29/08/2013

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Figure 26: Hydrographs at five key locations for the base simulation without mining

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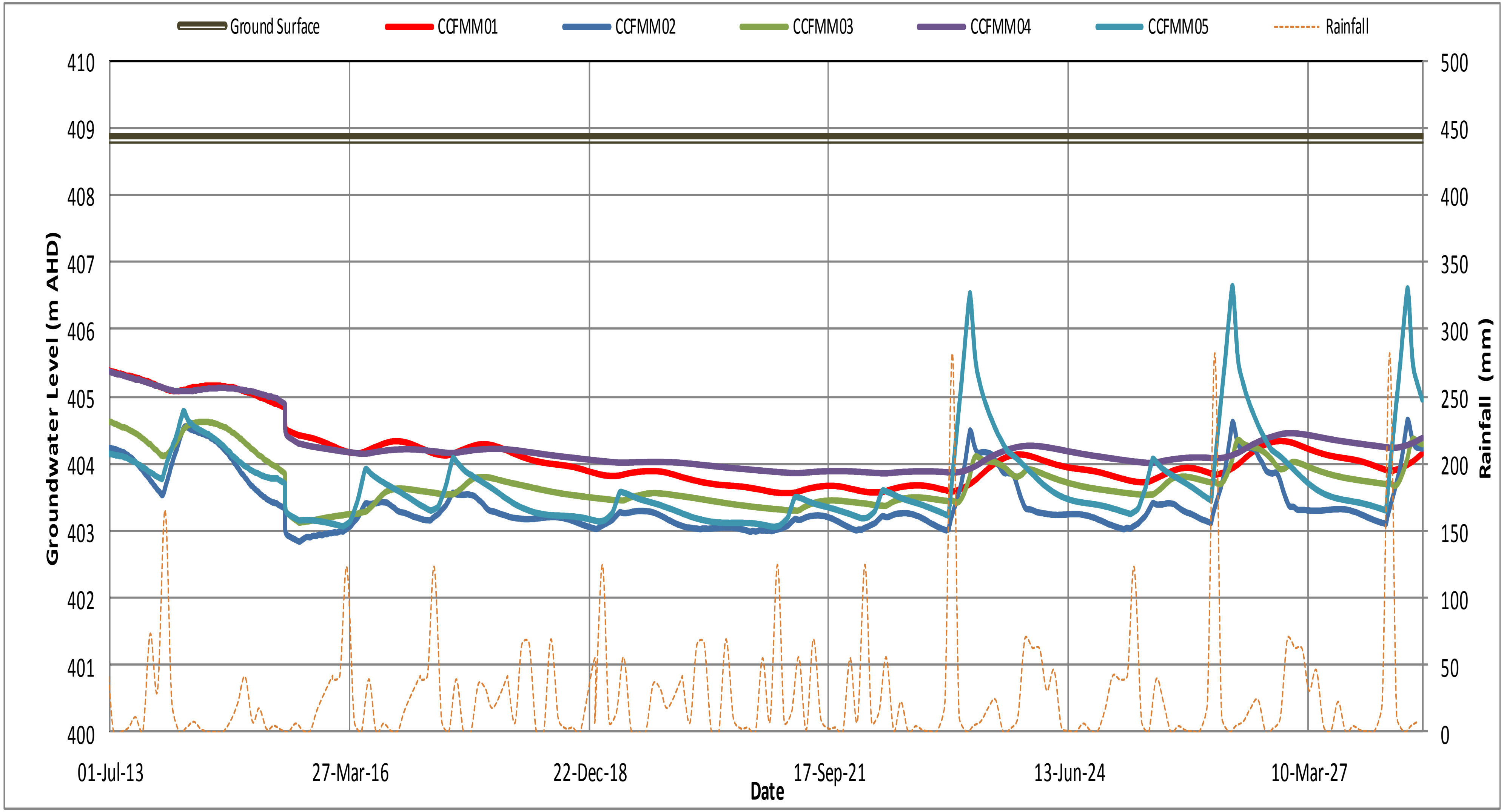

Fortescue Metals Group Ltd ACN: 002 594 872 87 Adelaide Terrace, East Perth Western Australia 6004	**Hydrograph at five selected key locations for the Base scenario without mine dewatering**	**Figure 26**
		29/08/2013

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Figure 27: Hydrographs at five key locations for the dry simulation without mining

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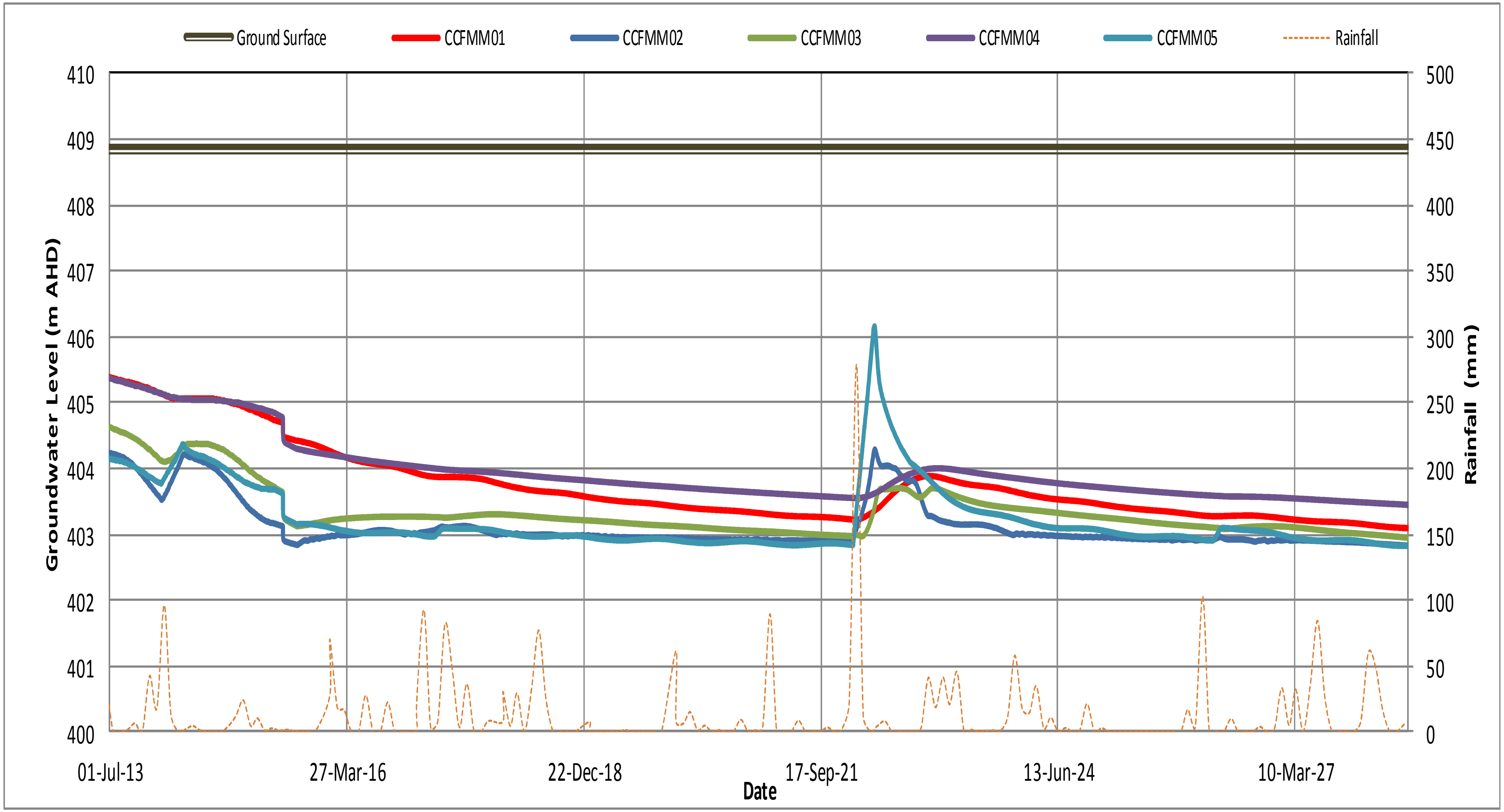

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ACN: 002 594 872
87 Adelaide Terrace, East Perth
Western Australia 6004

Hydrograph at five selected key locations for the Dry scenario without mine dewatering

Figure 27

29/08/2013

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Figure 28: Hydrographs at five key locations for the wet simulation without mining

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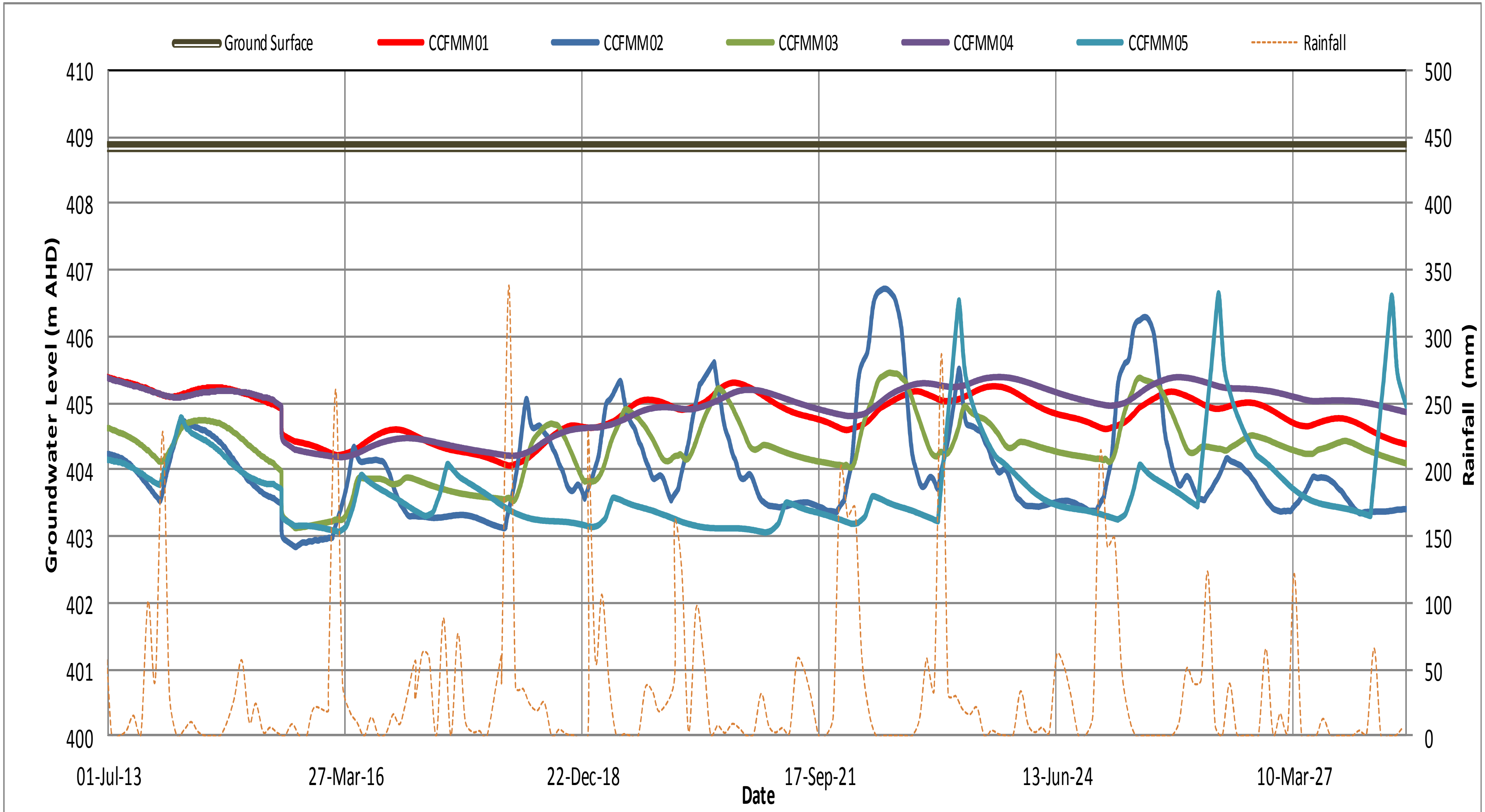

Fortescue Metals Group Ltd ACN: 002 594 872 87 Adelaide Terrace, East Perth Western Australia 6004	**Hydrograph at five selected key locations for the Wet scenario without mine dewatering**	**Figure 28**
		29/08/2013

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Figure 29: Distribution of drawdown/mounding due to mining for the base simulation - 2014

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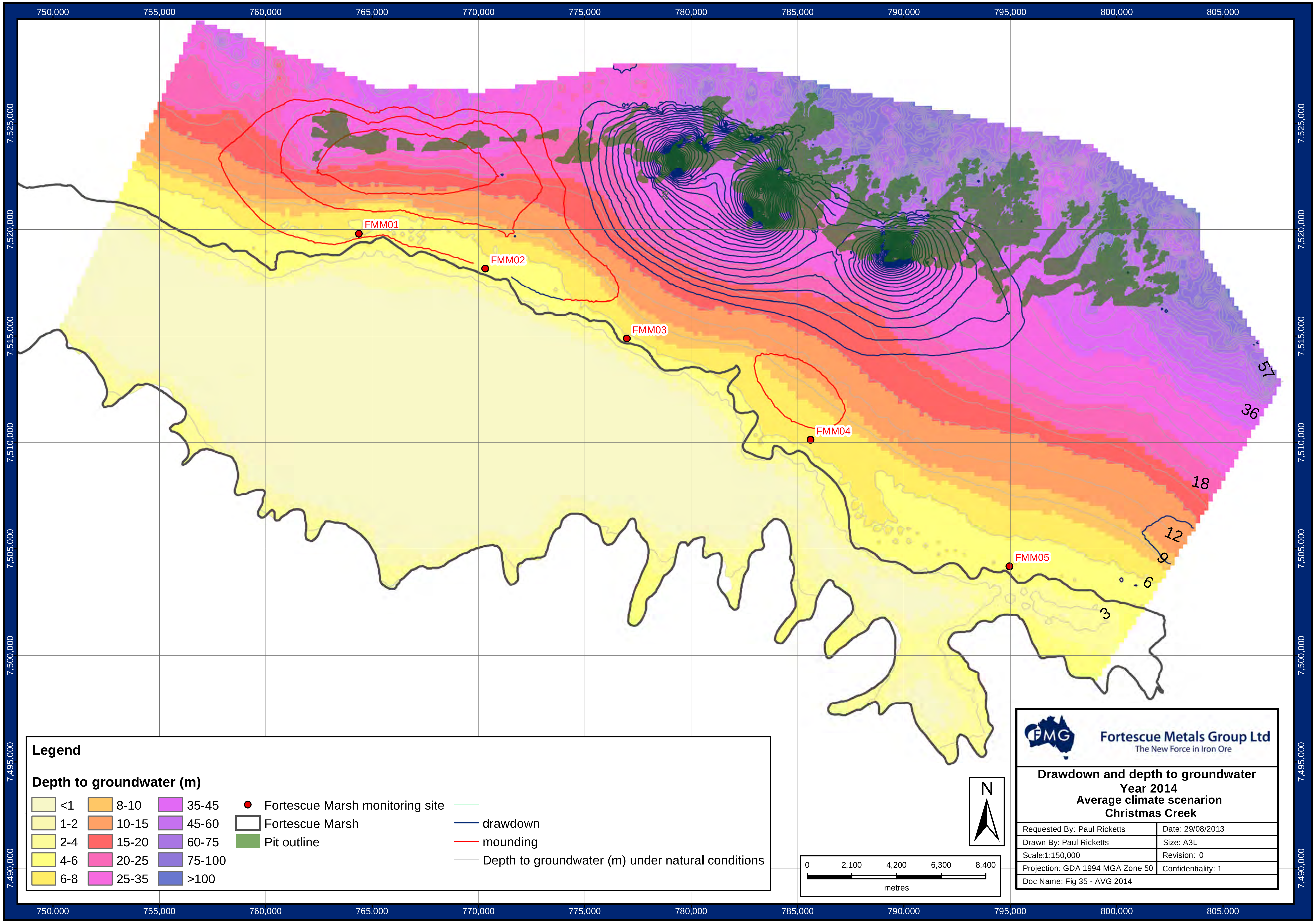

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Legend
Depth to groundwater (m)
<1
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2-4
4-6
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10-15
15-20
20-25
25-35
35-45
45-60
60-75
75-100
>100
Fortescue Marsh monitoring site
Fortescue Marsh
Pit outline
drawdown
mounding
Depth to groundwater (m) under natural conditions
N
0
2,100
4,200
6,300
8,400
metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2014
Average climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 29/08/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 35 - AVG 2014

Figure 30: Distribution of drawdown/mounding due to mining for the base simulation - 2015

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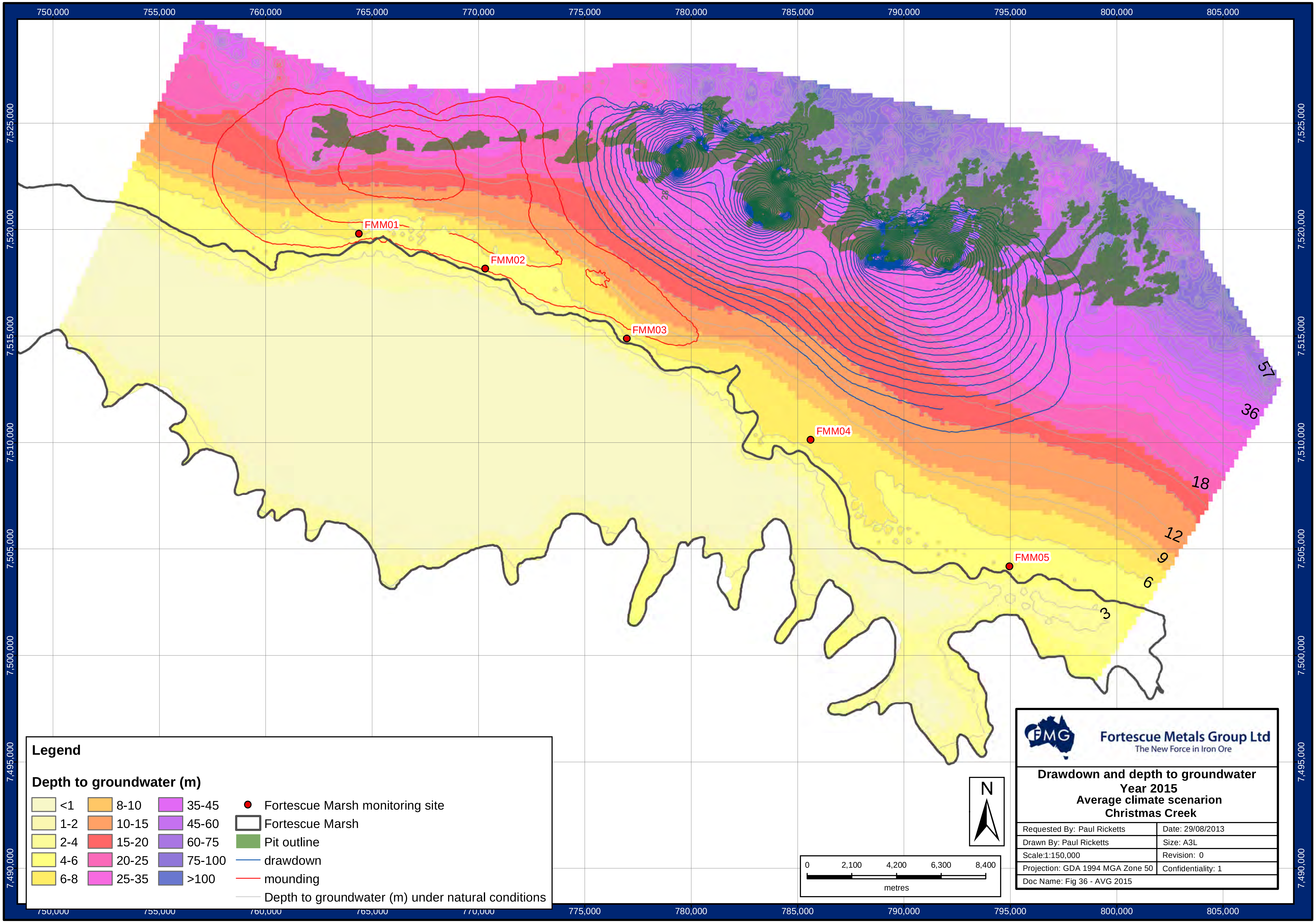
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Legend
Depth to groundwater (m)
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25-35
35-45
45-60
60-75
75-100
>100
Fortescue Marsh monitoring site
Fortescue Marsh
Pit outline
drawdown
mounding
Depth to groundwater (m) under natural conditions
N
0
2,100
4,200
6,300
8,400
metres
FMG
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2015
Average climate scenarion
Christmas Creek
Requested By: Paul Ricketts
Date: 29/08/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 36 - AVG 2015

Figure 31: Distribution of drawdown/mounding due to mining for the base simulation - 2016

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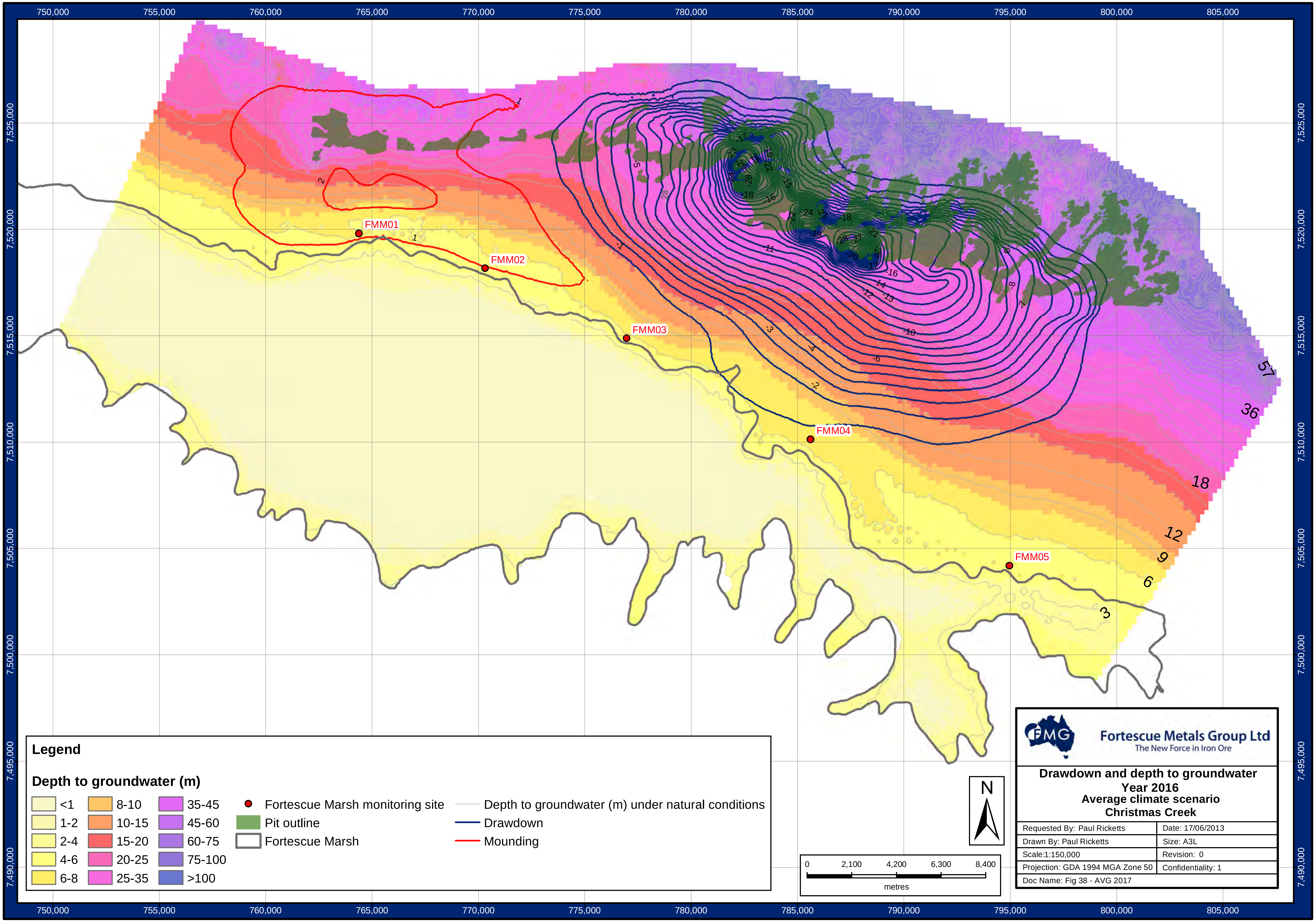

Legend
Depth to groundwater (m)
<1
1-2
2-4
4-6
6-8
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10-15
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25-35
35-45
45-60
60-75
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>100
Fortescue Marsh monitoring site
Pit outline
Fortescue Marsh
Depth to groundwater (m) under natural conditions
Drawdown
Mounding
FMM01
FMM02
FMM03
FMM04
FMM05
N
0
2,100
4,200
6,300
8,400
metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2016
Average climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 17/06/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 38 - AVG 2017
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7,525,000
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Figure 32: Distribution of drawdown/mounding due to mining for the base simulation - 2017

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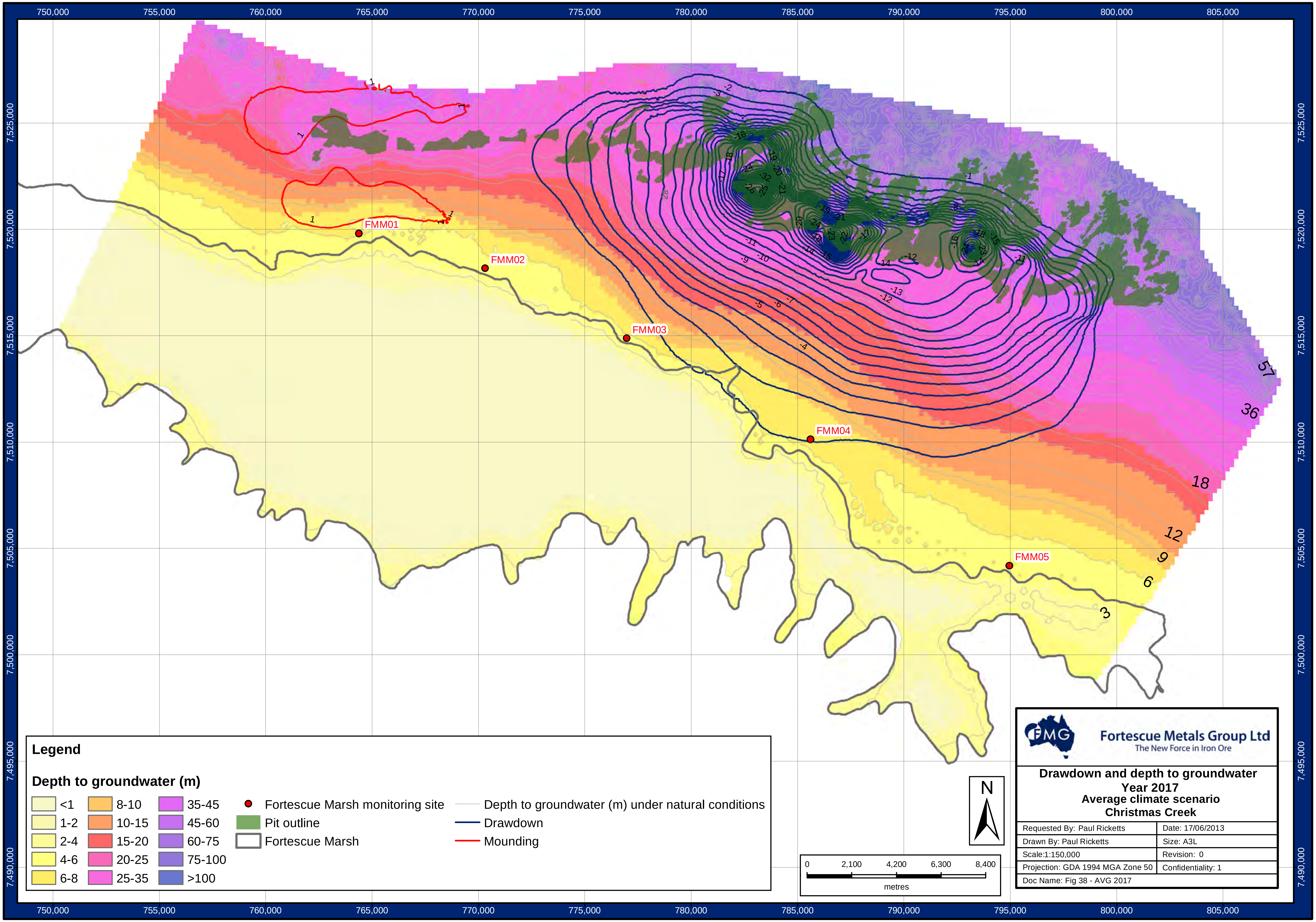

Legend
Depth to groundwater (m)
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1-2
2-4
4-6
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20-25
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45-60
60-75
75-100
>100
Fortescue Marsh monitoring site
Pit outline
Fortescue Marsh
Depth to groundwater (m) under natural conditions
Drawdown
Mounding
FMM01
FMM02
FMM03
FMM04
FMM05
57
36
18
12
9
6
3
N
0
2,100
4,200
6,300
8,400
metres
FMG
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2017
Average climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 17/06/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 38 - AVG 2017
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Figure 33: Distribution of drawdown/mounding due to mining for the base simulation - 2018

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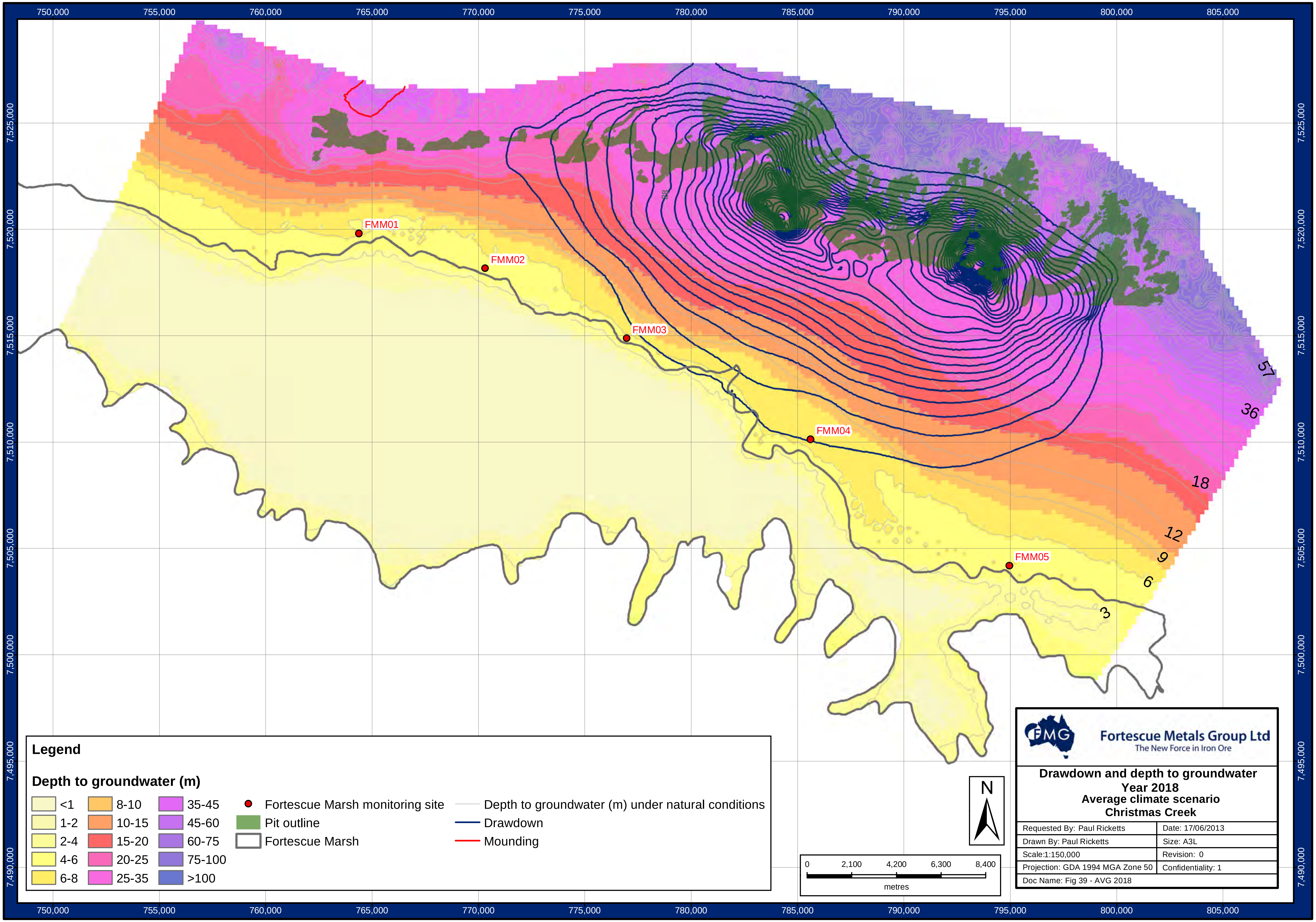

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Legend
Depth to groundwater (m)
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Fortescue Marsh monitoring site
Pit outline
Fortescue Marsh
Depth to groundwater (m) under natural conditions
Drawdown
Mounding
N
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2,100
4,200
6,300
8,400
metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2018
Average climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 17/06/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 39 - AVG 2018

Figure 34: Distribution of drawdown/mounding due to mining for the base simulation - 2019

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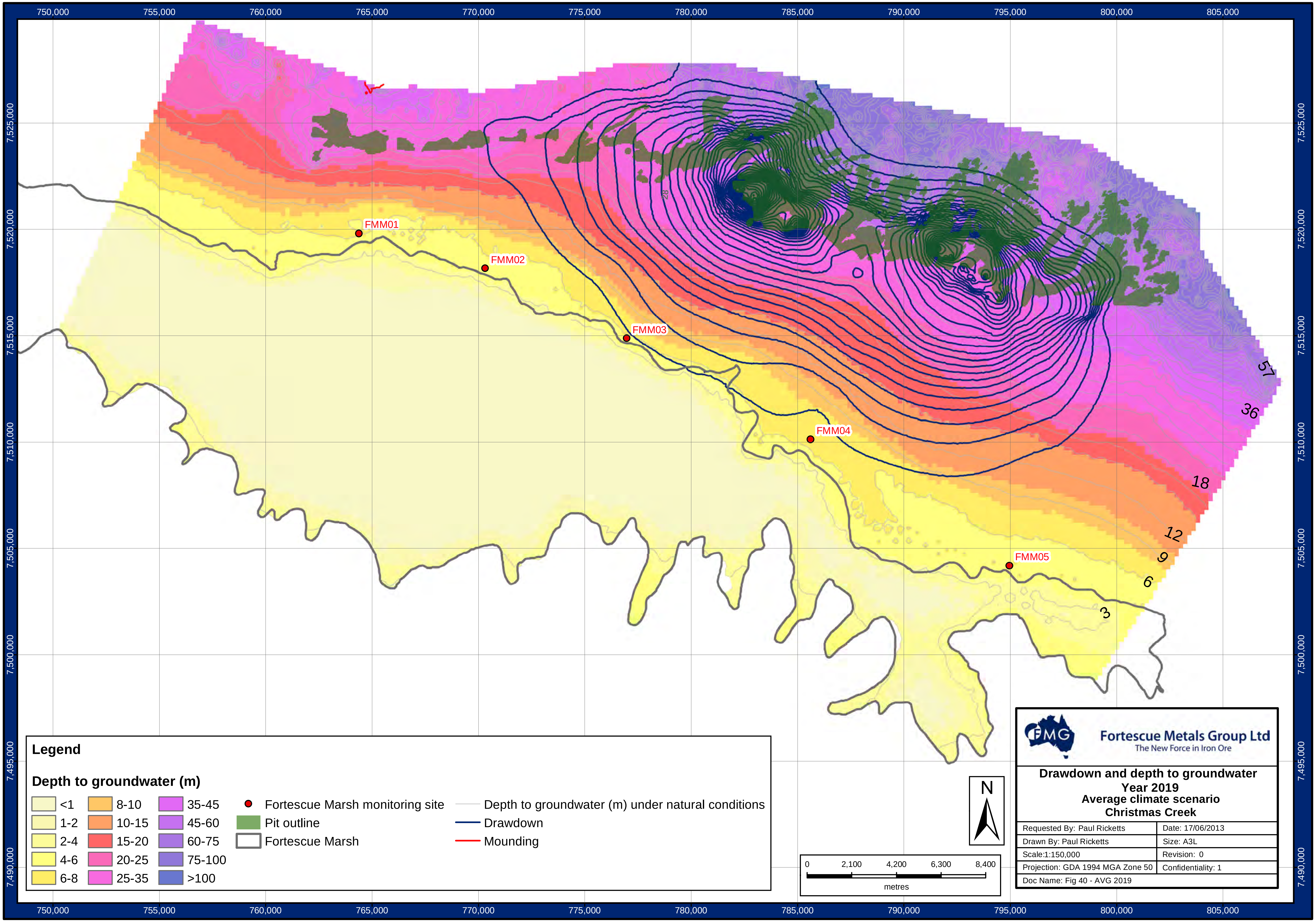

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Legend
Depth to groundwater (m)
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Fortescue Marsh monitoring site
Pit outline
Fortescue Marsh
Depth to groundwater (m) under natural conditions
Drawdown
Mounding
N
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2,100
4,200
6,300
8,400
metres
FMG
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2019
Average climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 17/06/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 40 - AVG 2019

Figure 35: Distribution of drawdown/mounding due to mining for the base simulation - 2020

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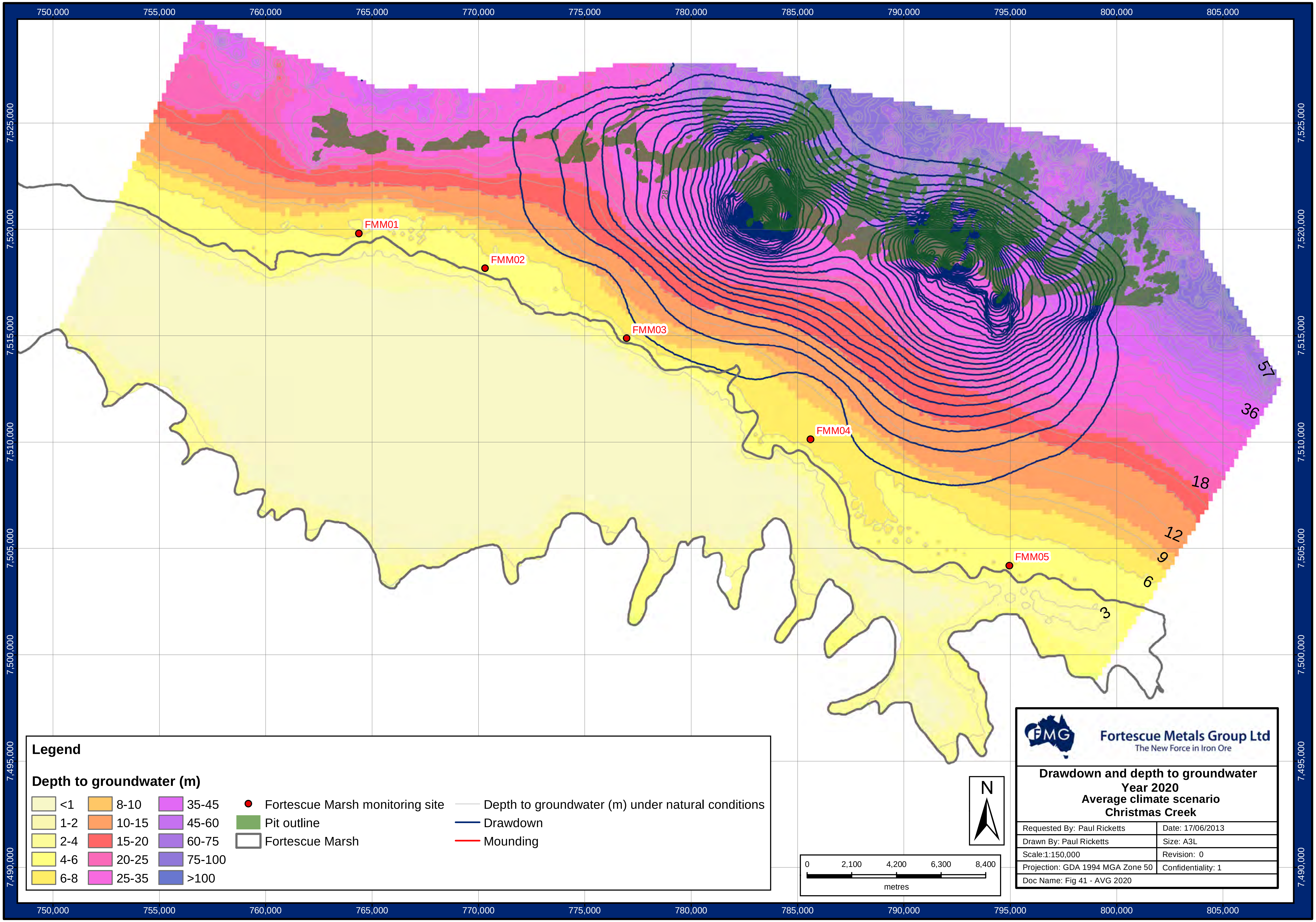

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Depth to groundwater (m)
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Fortescue Marsh monitoring site
Pit outline
Fortescue Marsh
Depth to groundwater (m) under natural conditions
Drawdown
Mounding
N
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2,100
4,200
6,300
8,400
metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2020
Average climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 17/06/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 41 - AVG 2020

Figure 36: Distribution of drawdown/mounding due to mining for the base simulation - 2021

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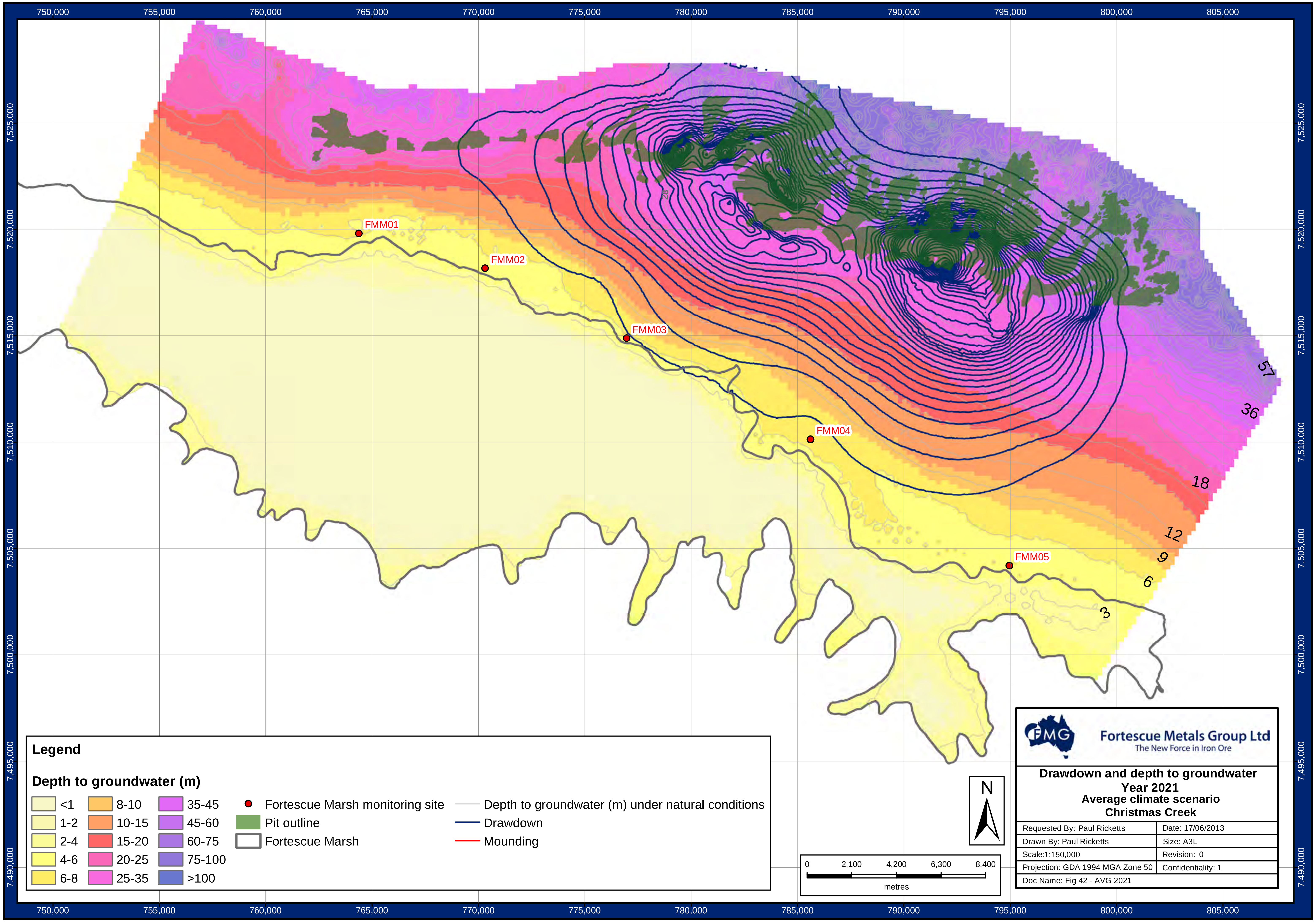
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Legend
Depth to groundwater (m)
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>100
Fortescue Marsh monitoring site
Pit outline
Fortescue Marsh
Depth to groundwater (m) under natural conditions
Drawdown
Mounding
N
0
2,100
4,200
6,300
8,400
metres
FMG
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2021
Average climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 17/06/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 42 - AVG 2021

Figure 37: Distribution of drawdown/mounding due to mining for the base simulation - 2022

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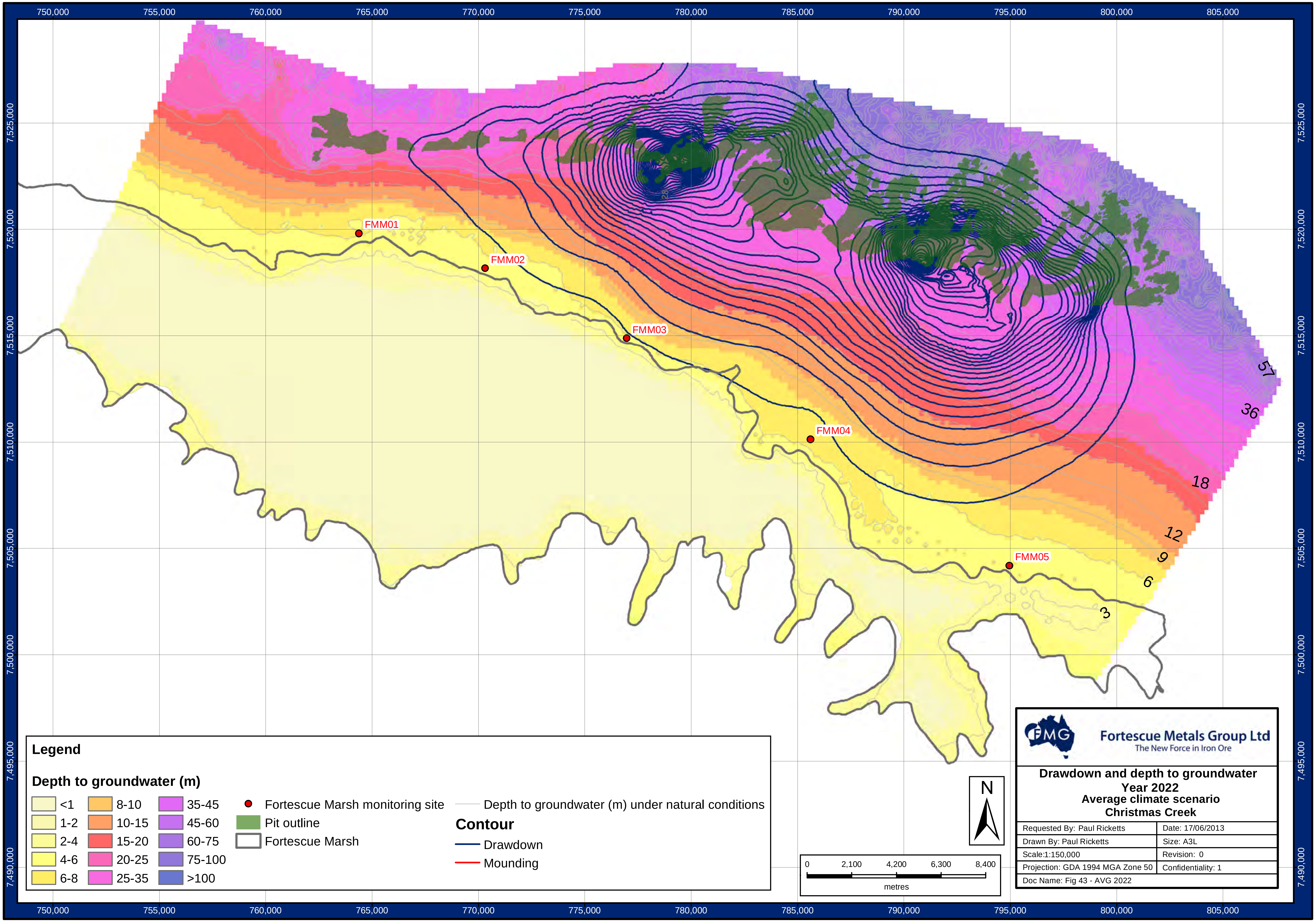
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Legend
Depth to groundwater (m)
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4-6
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15-20
20-25
25-35
35-45
45-60
60-75
75-100
>100
Fortescue Marsh monitoring site
Pit outline
Fortescue Marsh
Depth to groundwater (m) under natural conditions
Contour
Drawdown
Mounding
N
0
2,100
4,200
6,300
8,400
metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2022
Average climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 17/06/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 43 - AVG 2022

Figure 38: Distribution of drawdown/mounding due to mining for the base simulation - 2023

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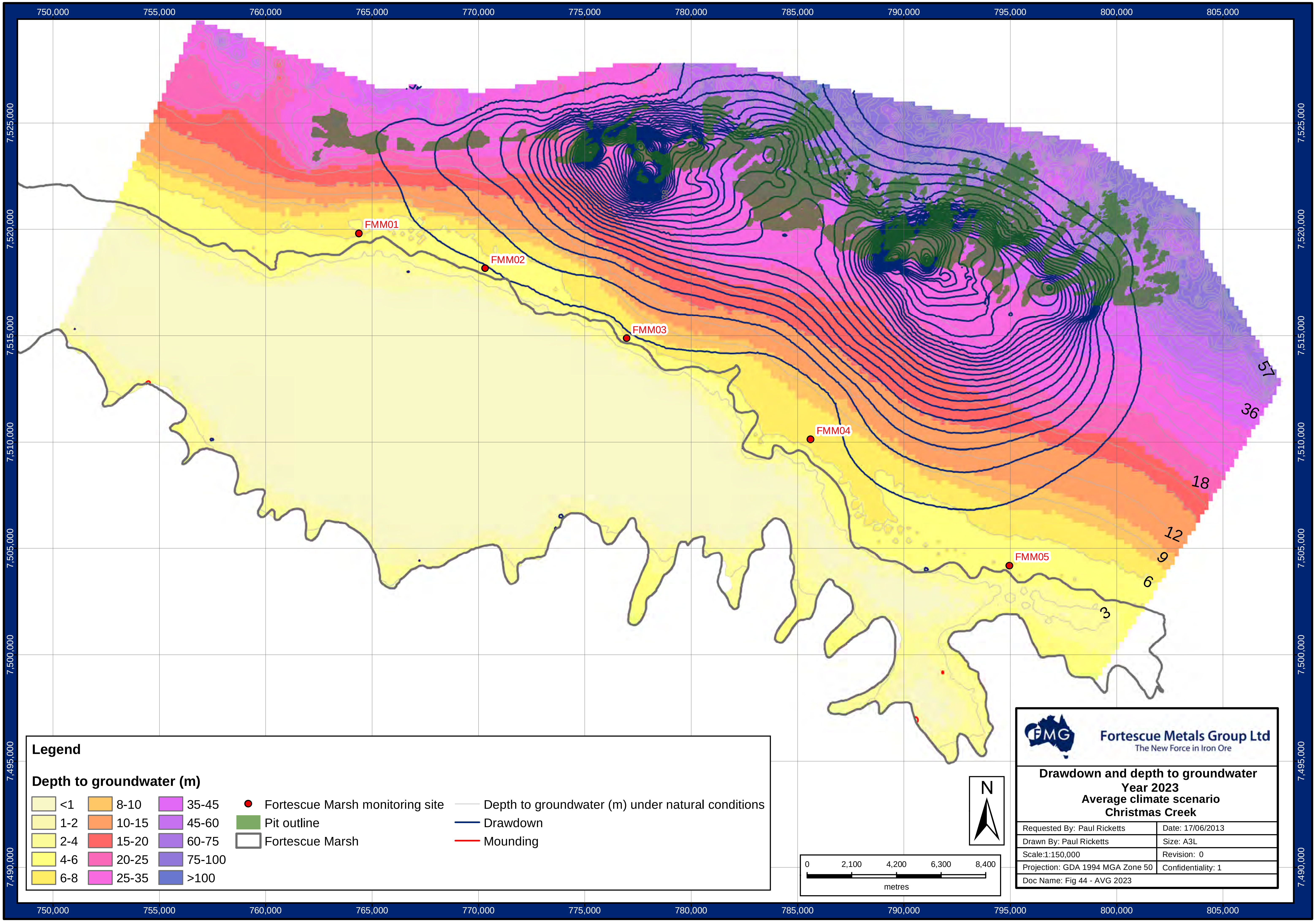

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Legend
Depth to groundwater (m)
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35-45
45-60
60-75
75-100
>100
Fortescue Marsh monitoring site
Pit outline
Fortescue Marsh
Depth to groundwater (m) under natural conditions
Drawdown
Mounding
N
0
2,100
4,200
6,300
8,400
metres
FMG
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2023
Average climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 17/06/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 44 - AVG 2023

Figure 39: Distribution of drawdown/mounding due to mining for the base simulation - 2024

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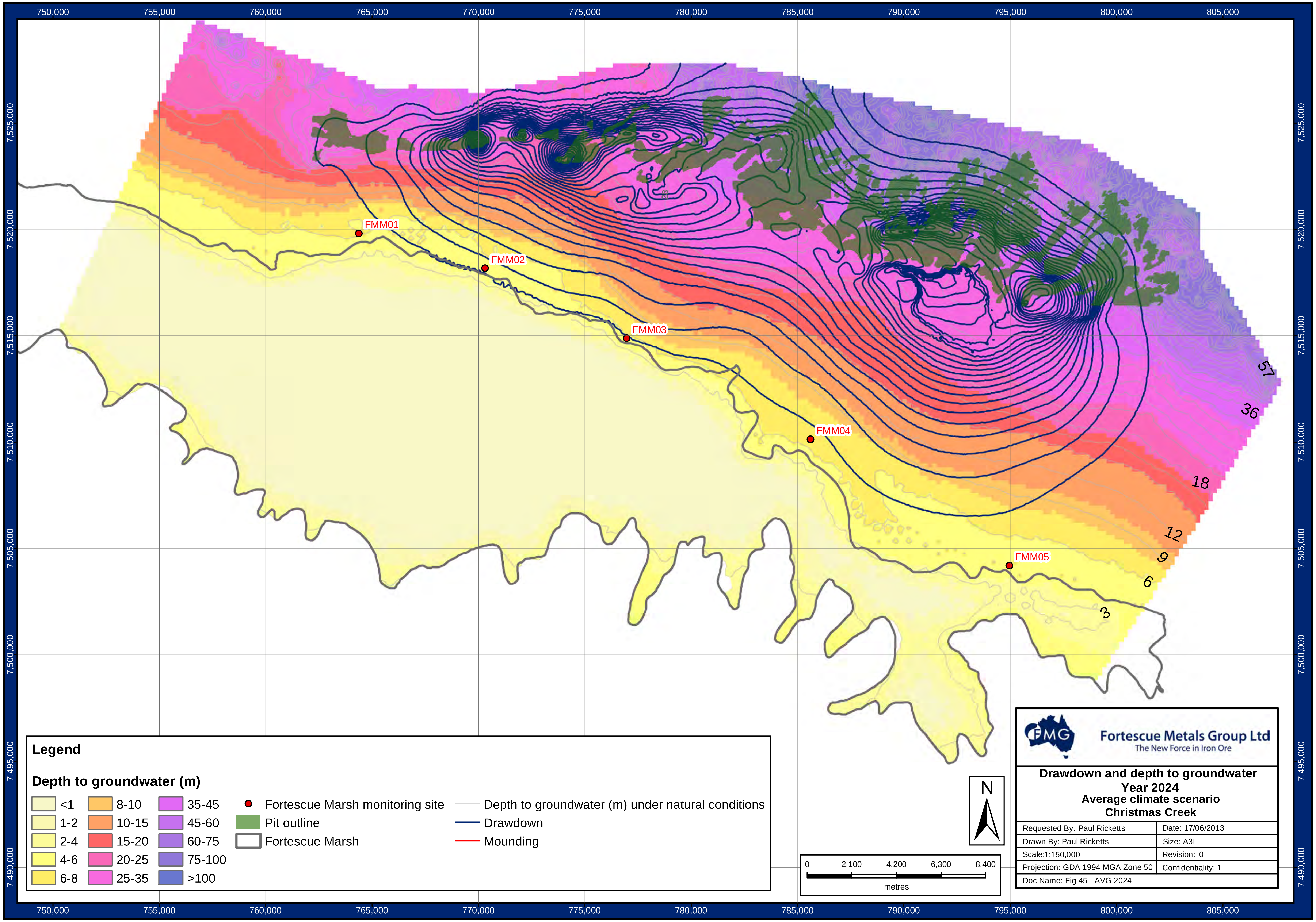

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FMM03
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FMM05
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Legend
Depth to groundwater (m)
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2-4
4-6
6-8
8-10
10-15
15-20
20-25
25-35
35-45
45-60
60-75
75-100
>100
Fortescue Marsh monitoring site
Pit outline
Fortescue Marsh
Depth to groundwater (m) under natural conditions
Drawdown
Mounding
N
0
2,100
4,200
6,300
8,400
metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2024
Average climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 17/06/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 45 - AVG 2024

Figure 40: Distribution of drawdown/mounding due to mining for the base simulation - 2025

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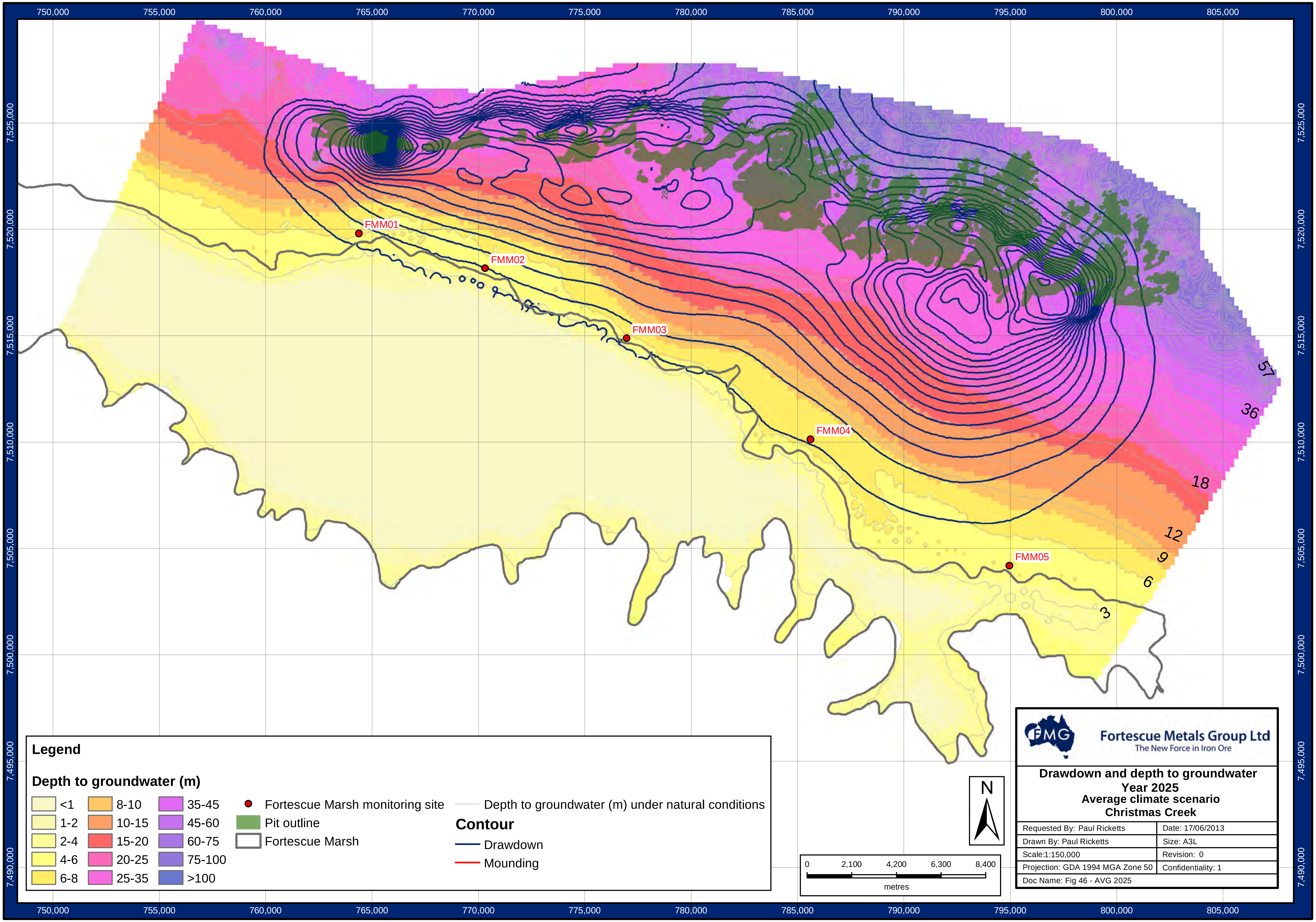

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Legend
Depth to groundwater (m)
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2-4
4-6
6-8
8-10
10-15
15-20
20-25
25-35
35-45
45-60
60-75
75-100
>100
Fortescue Marsh monitoring site
Pit outline
Fortescue Marsh
Depth to groundwater (m) under natural conditions
Contour
Drawdown
Mounding
N
0
2,100
4,200
6,300
8,400
metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2025
Average climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 17/06/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 46 - AVG 2025

Figure 41: Distribution of drawdown/mounding due to mining for the base simulation - 2026

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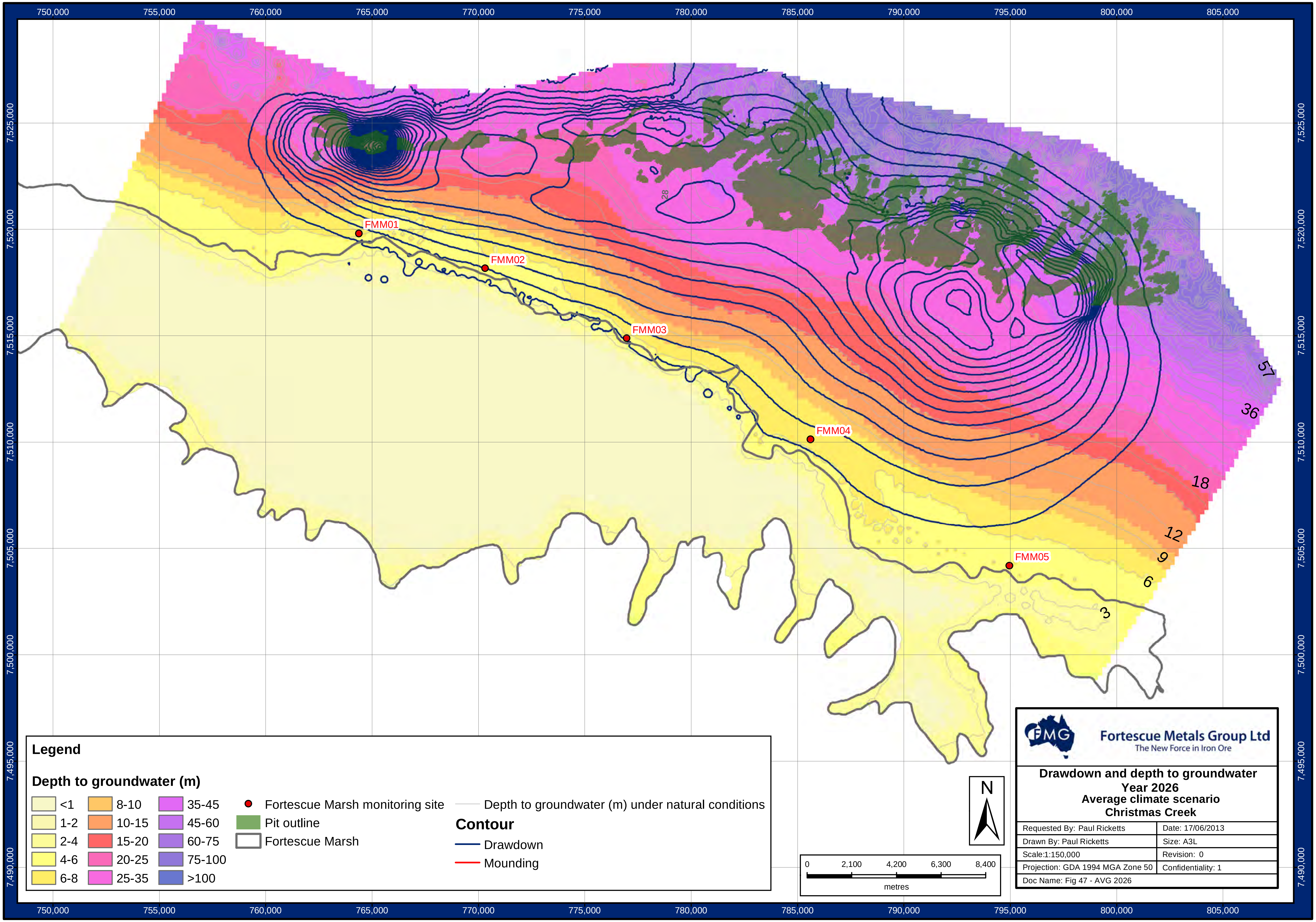

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Legend
Depth to groundwater (m)
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35-45
45-60
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75-100
>100
Fortescue Marsh monitoring site
Pit outline
Fortescue Marsh
Depth to groundwater (m) under natural conditions
Contour
Drawdown
Mounding
N
0
2,100
4,200
6,300
8,400
metres
FMG
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2026
Average climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 17/06/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 47 - AVG 2026

Figure 42: Distribution of drawdown/mounding due to mining for the base simulation - 2027

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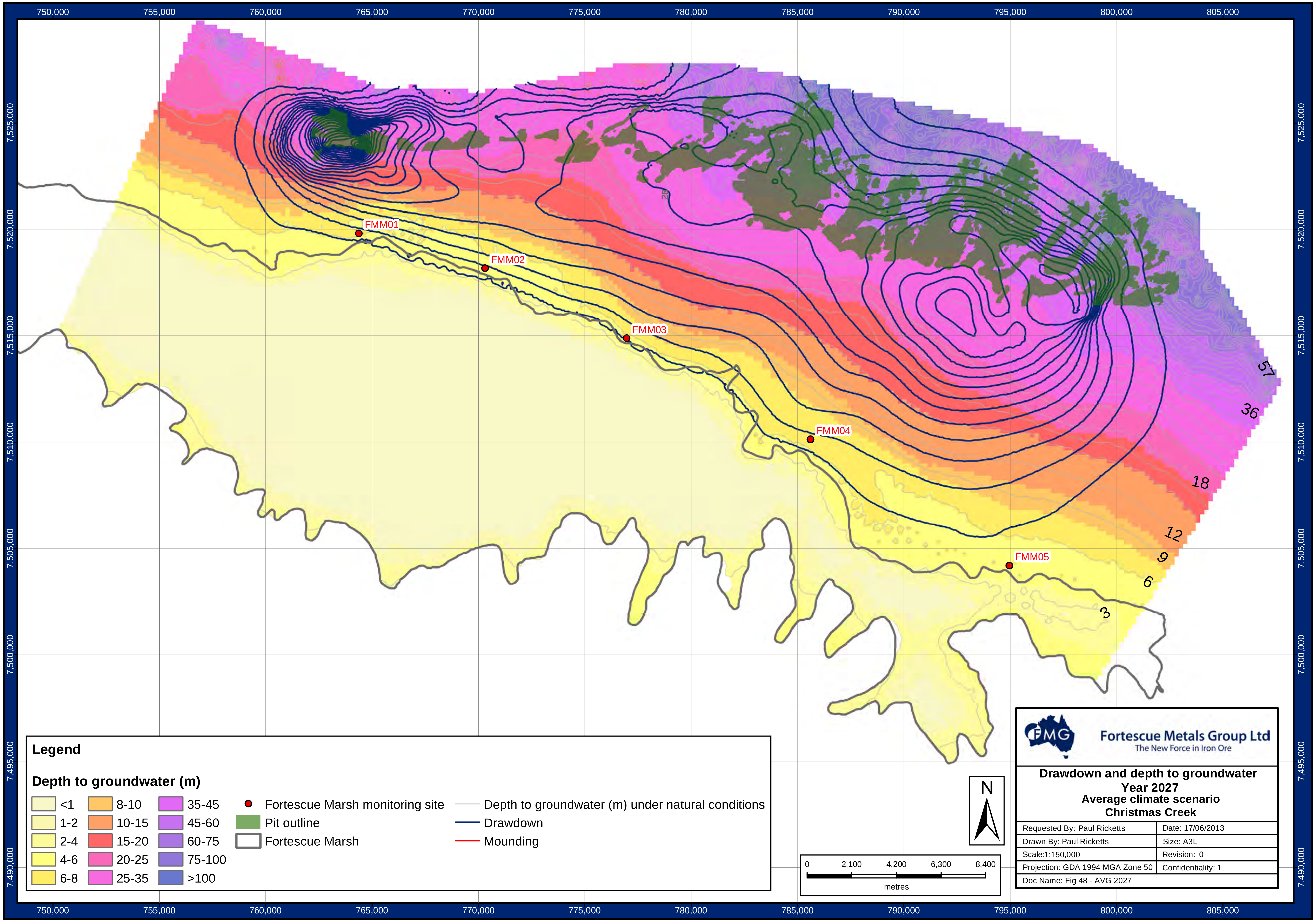

Drawdown and depth to groundwater
Year 2027
Average climate scenario
Christmas Creek

Requested By: Paul Ricketts	Date: 17/06/2013
Drawn By: Paul Ricketts	Size: A3L
Scale:1:150,000	Revision: 0
Projection: GDA 1994 MGA Zone 50	Confidentiality: 1
Doc Name: Fig 48 - AVG 2027	

Figure 43: Distribution of drawdown/mounding due to mining for the base simulation - 2028

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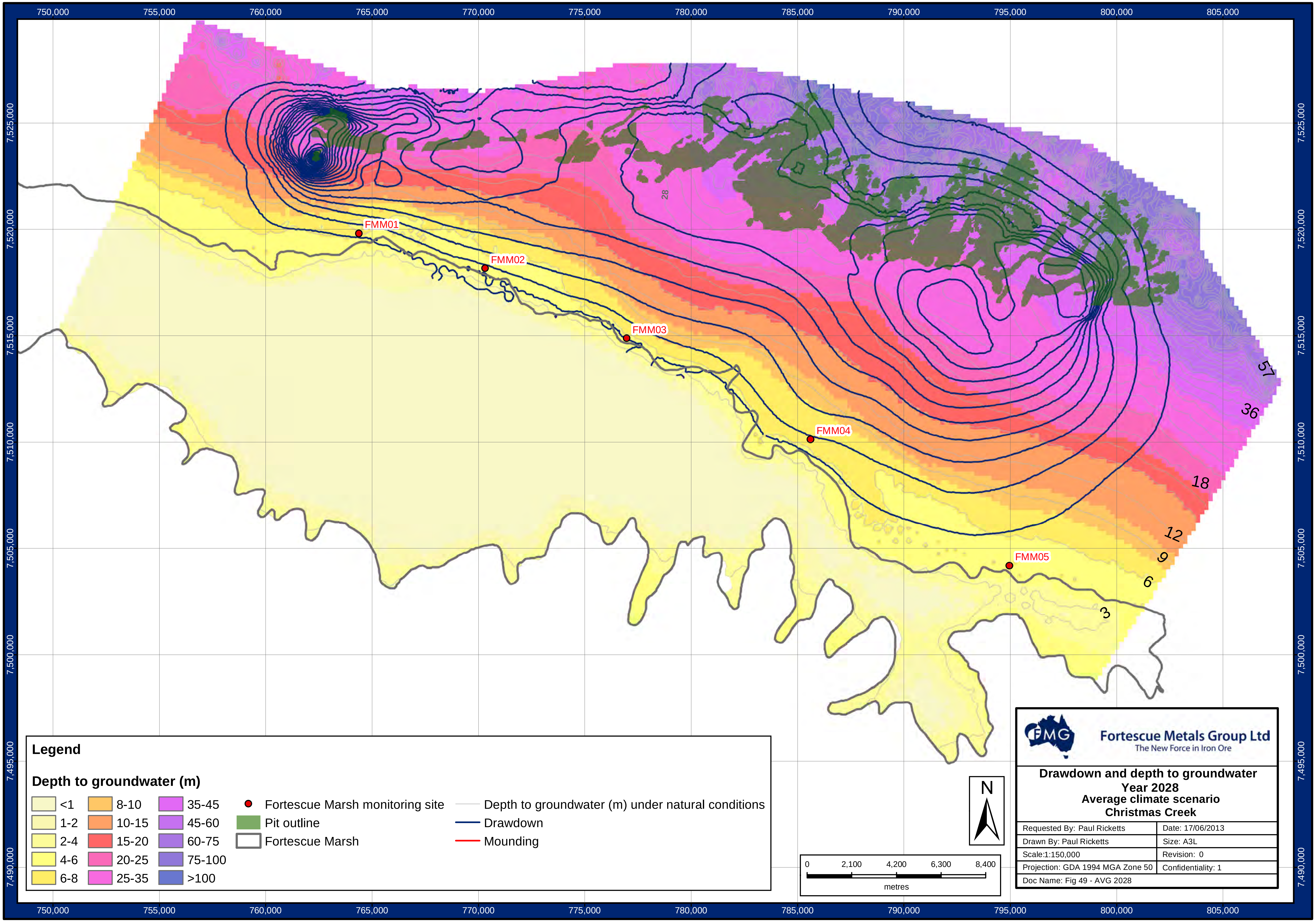

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Legend
Depth to groundwater (m)
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20-25
25-35
35-45
45-60
60-75
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>100
Fortescue Marsh monitoring site
Pit outline
Fortescue Marsh
Depth to groundwater (m) under natural conditions
Drawdown
Mounding
N
0
2,100
4,200
6,300
8,400
metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2028
Average climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 17/06/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: Fig 49 - AVG 2028

Figure 44: Groundwater level change at the five key monitoring locations for the base simulation

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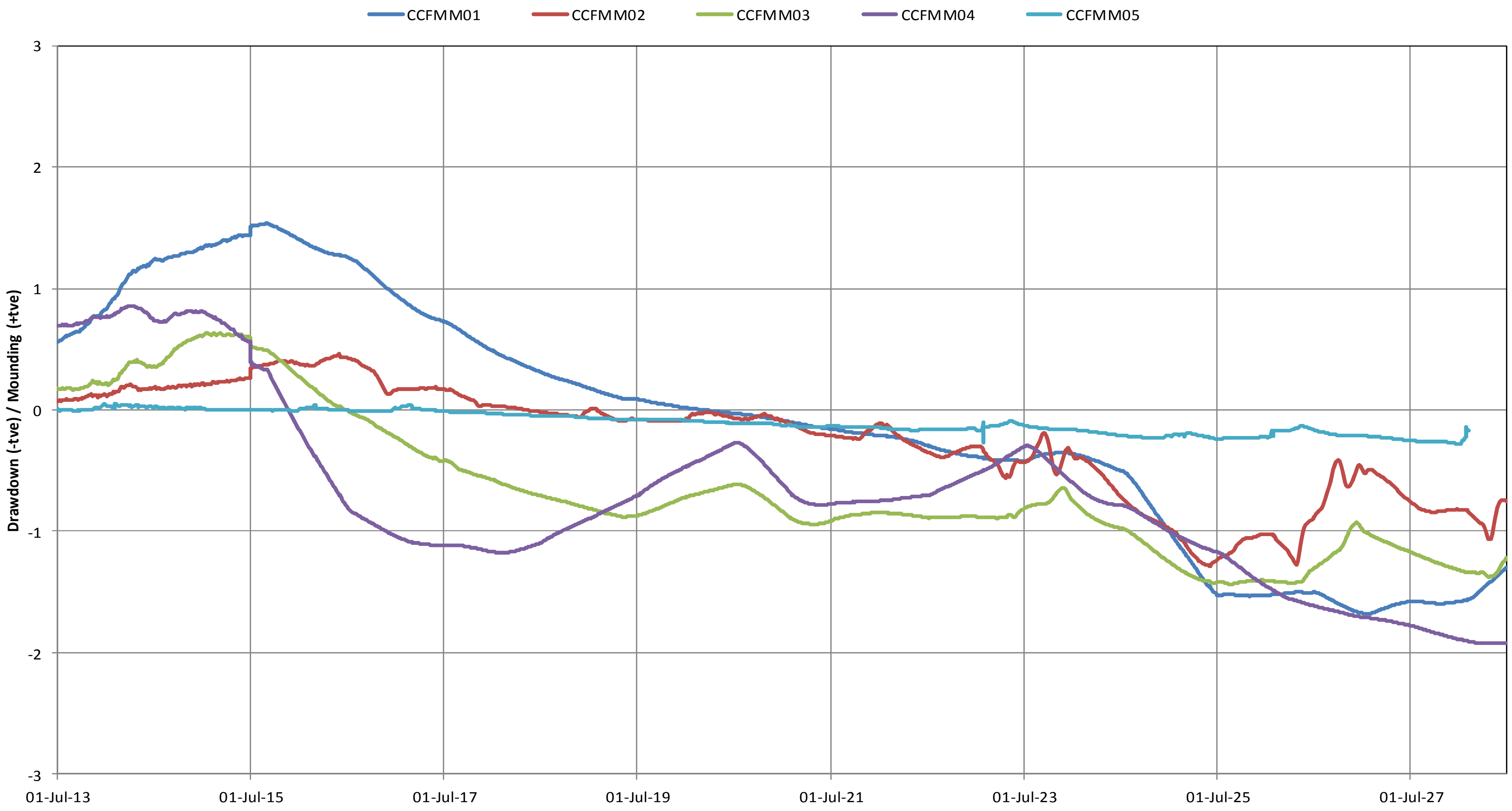

Fortescue Metals Group Ltd ACN: 002 594 872 87 Adelaide Terrace, East Perth Western Australia 6004	**Groundwater level change (drawdown/mounding relative to natural conditions) at five key locations—Base scenario**	**Figure 44**
		29/08/2013

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Figure 45: Groundwater level change at the five key monitoring locations for the dry simulation

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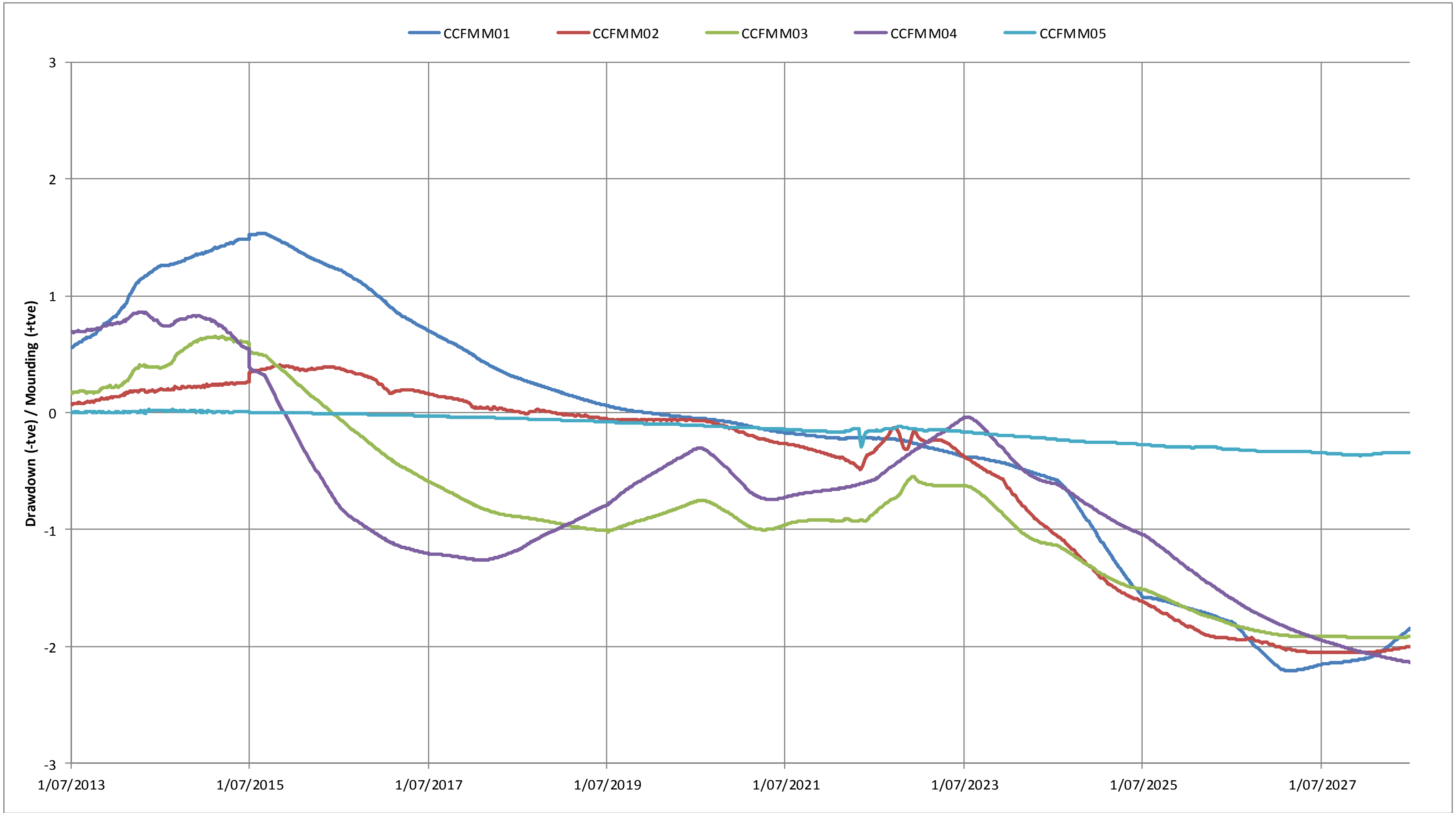

Fortescue Metals Group Ltd
ACN: 002 594 872
87 Adelaide Terrace, East Perth
Western Australia 6004

Groundwater level change (drawdown/mounding relative to natural conditions) at five key locations—Dry scenario

Figure 45

29/08/2013

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Figure 46: Groundwater level change at the five key monitoring locations for the wet simulation

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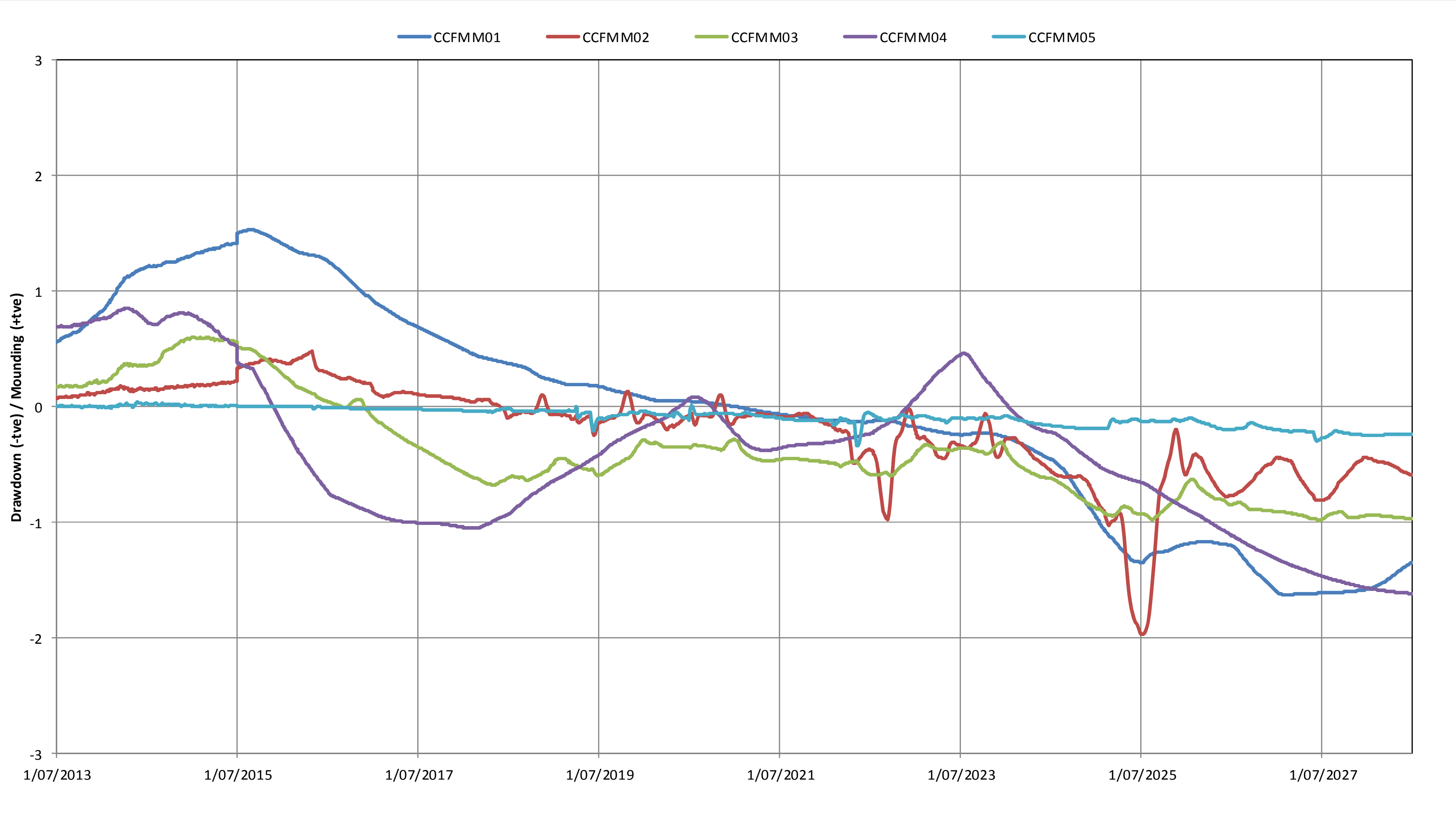

Fortescue Metals Group Ltd ACN: 002 594 872 87 Adelaide Terrace, East Perth Western Australia 6004	**Groundwater level change (drawdown/mounding relative to natural conditions) at five key locations—Wet scenario**	**Figure 46**
		29/08/2013

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Figure 47: Cumulative impact on groundwater levels

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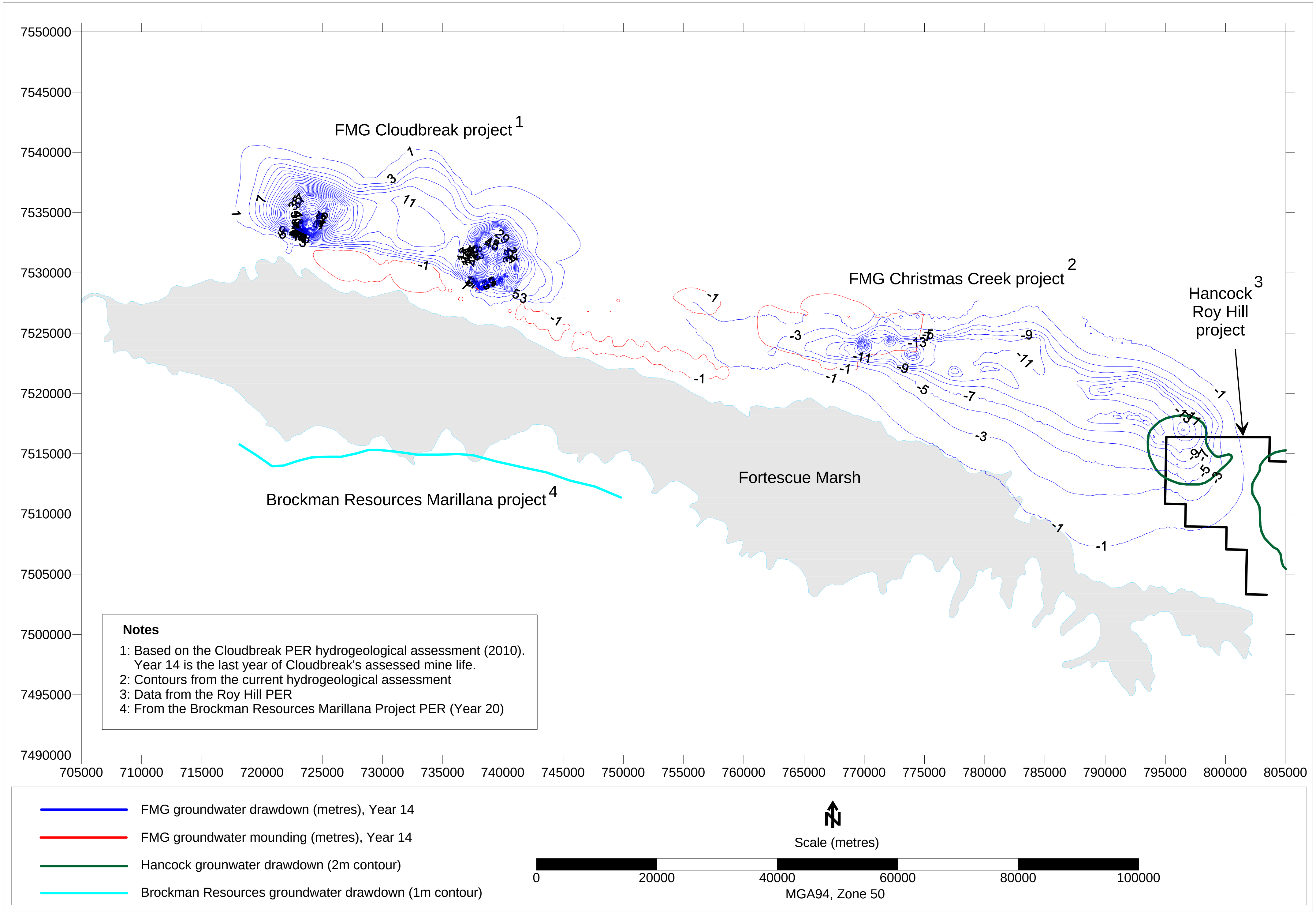

FMG Cloudbreak project 1
FMG Christmas Creek project 2
Hancock Roy Hill project 3
Brockman Resources Marillana project 4
Fortescue Marsh
Notes
1: Based on the Cloudbreak PER hydrogeological assessment (2010). Year 14 is the last year of Cloudbreak's assessed mine life.
2: Contours from the current hydrogeological assessment
3: Data from the Roy Hill PER
4: From the Brockman Resources Marillana Project PER (Year 20)
FMG groundwater drawdown (metres), Year 14
FMG groundwater mounding (metres), Year 14
Hancock grounwater drawdown (2m contour)
Brockman Resources groundwater drawdown (1m contour)
N
Scale (metres)
0
20000
40000
60000
80000
100000
MGA94, Zone 50

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Figure 48: Hydrograph at CCFMM01, under natural and mining conditions for the Base, Dry and Wet simulations

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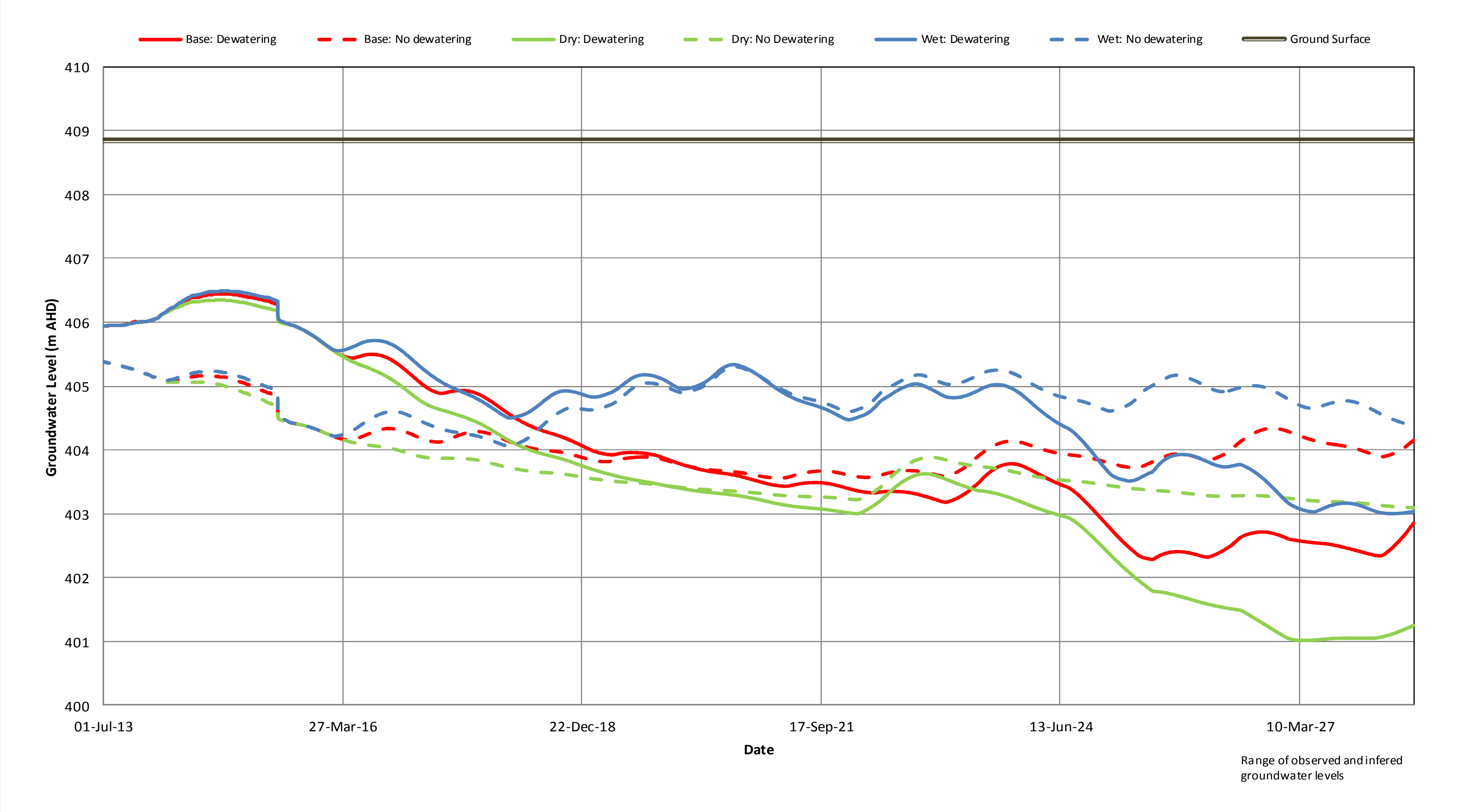

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87 Adelaide Terrace, East Perth
Western Australia 6004

Hydrographs at CCFMM01 under natural (dashed lines) and mining (solid lines) conditions for Base, Dry and Wet scenarios

Figure 48

29/08/2013

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Figure 49: Hydrograph at CCFMM02, under natural and mining conditions for the Base, Dry and Wet simulations

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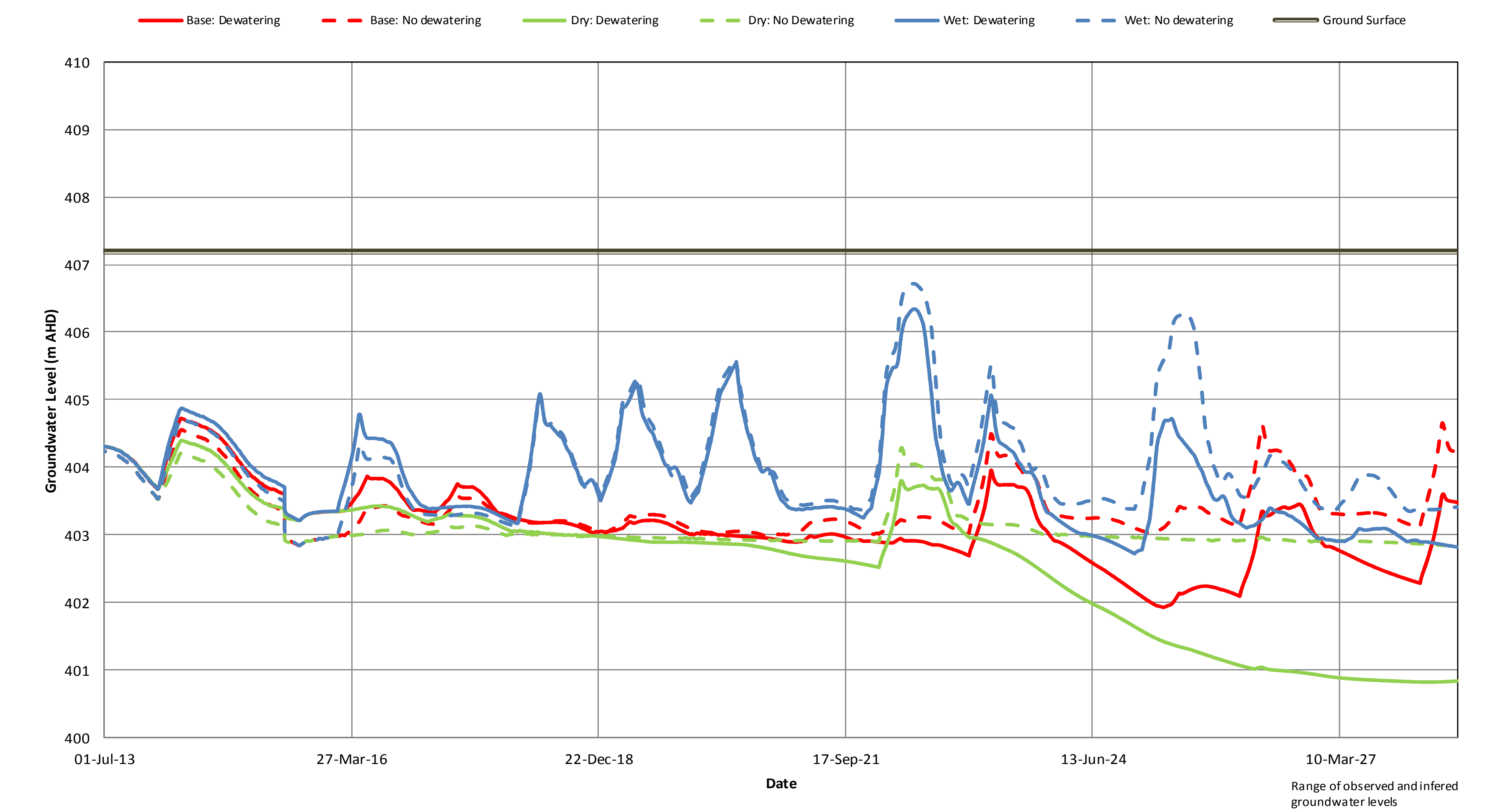

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Western Australia 6004

Hydrographs at CCFMM02 under natural (dashed lines) and mining (solid lines) conditions for Base, Dry and Wet scenarios

Figure 49

29/08/2013

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Figure 50: Hydrograph at CCFMM03, under natural and mining conditions for the Base, Dry and Wet simulations

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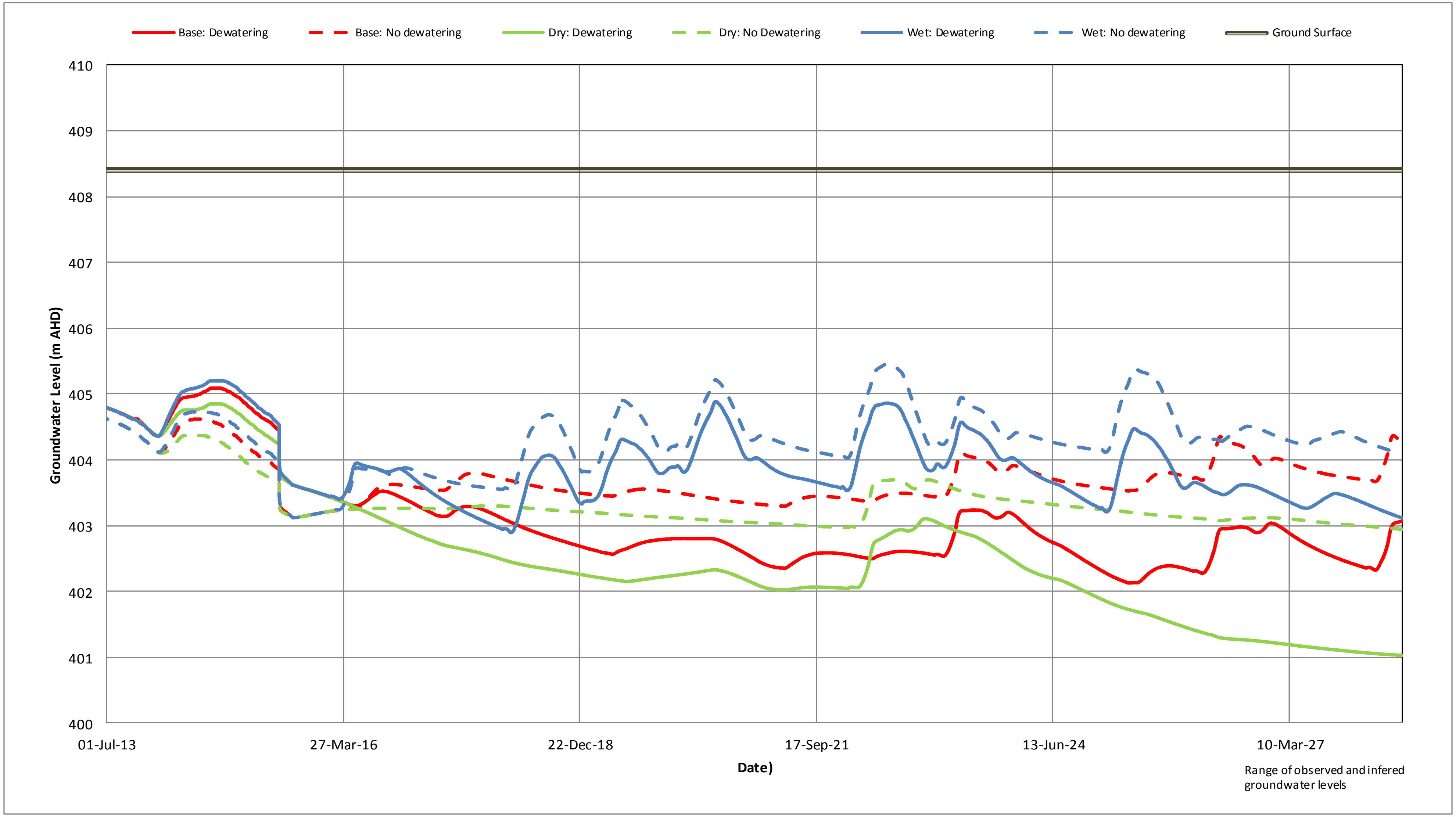

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Western Australia 6004

Hydrographs at CCFMM03 under natural (dashed lines) and mining (solid lines) conditions for Base, Dry and Wet scenarios

Figure 50

29/08/2013

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Figure 51: Hydrograph at CCFMM04, under natural and mining conditions for the Base, Dry and Wet simulations

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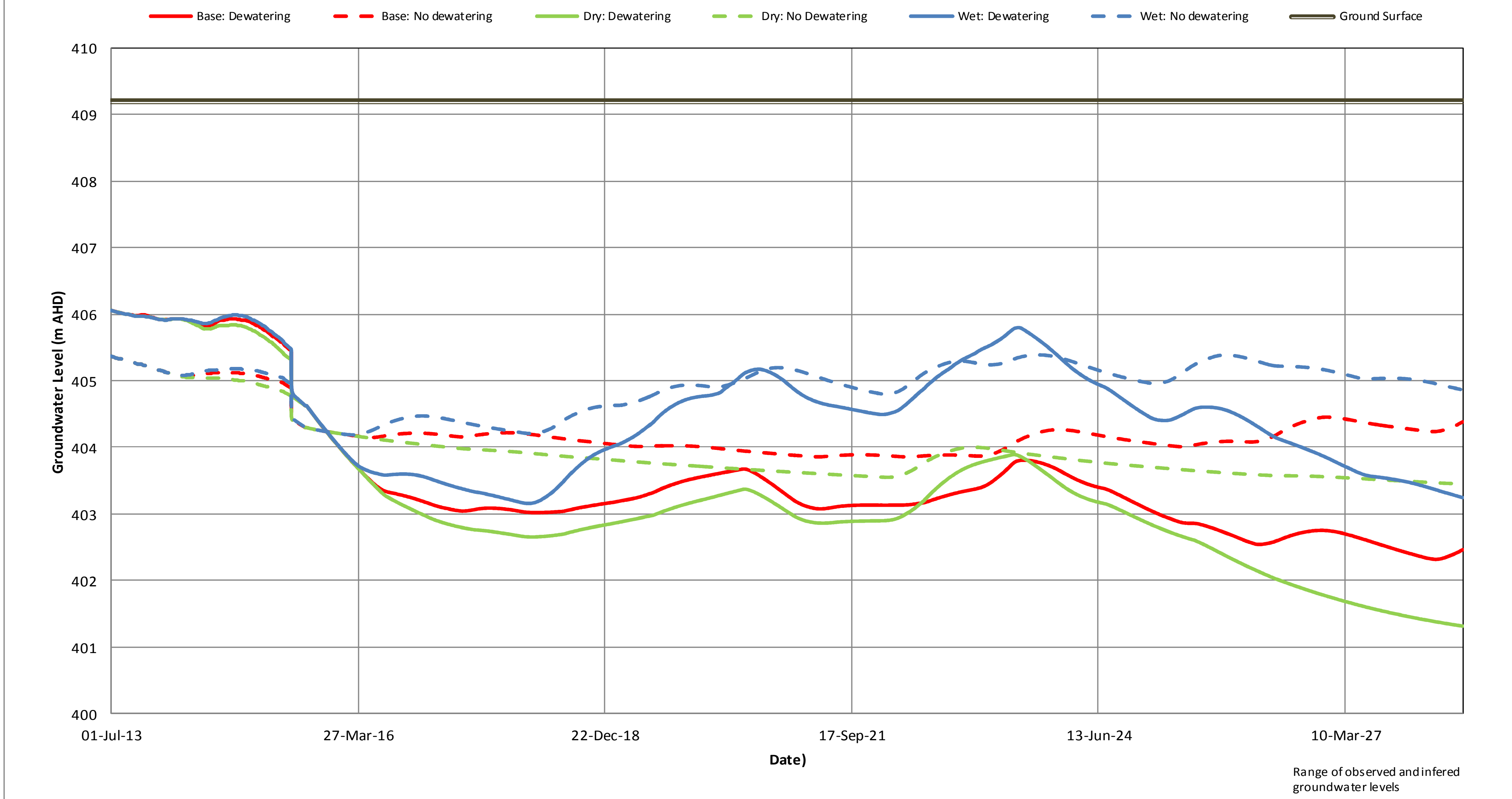

Fortescue Metals Group Ltd ACN: 002 594 872 87 Adelaide Terrace, East Perth Western Australia 6004	**Hydrographs at CCFMM04 under natural (dashed lines) and mining (solid lines) conditions for Base, Dry and Wet scenarios**	**Figure 51**
		29/08/2013

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Figure 52: Hydrograph at CCFMM05, under natural and mining conditions for the Base, Dry and Wet simulations

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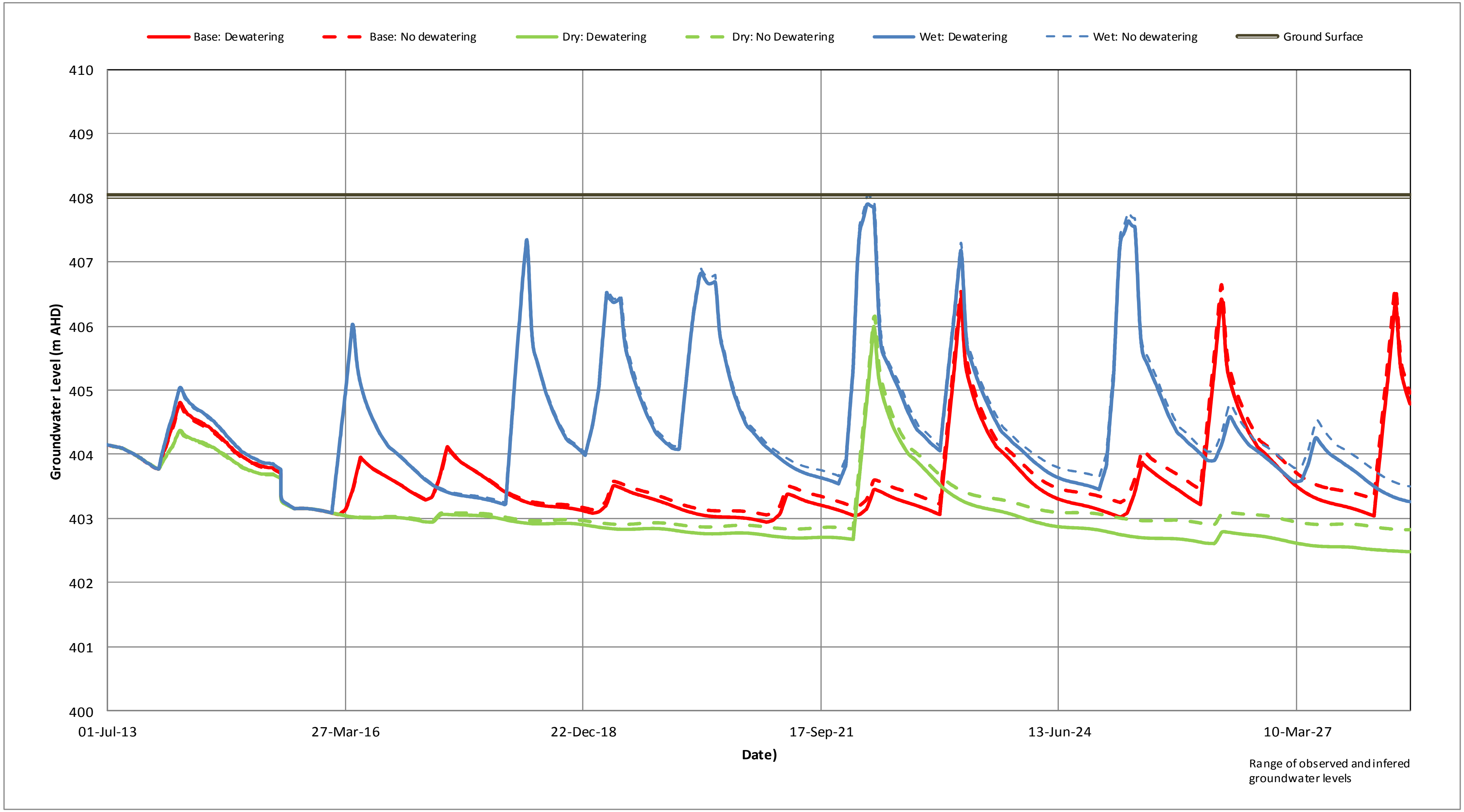

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Western Australia 6004

Hydrographs at CCFMM05 under natural (dashed lines) and mining (solid lines) conditions for Base, Dry and Wet scenarios

Figure 52

29/08/2013

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Figure 53: Transient calibration results (dewatering stage): Scattergram of measured v's model predicted groundwater levels

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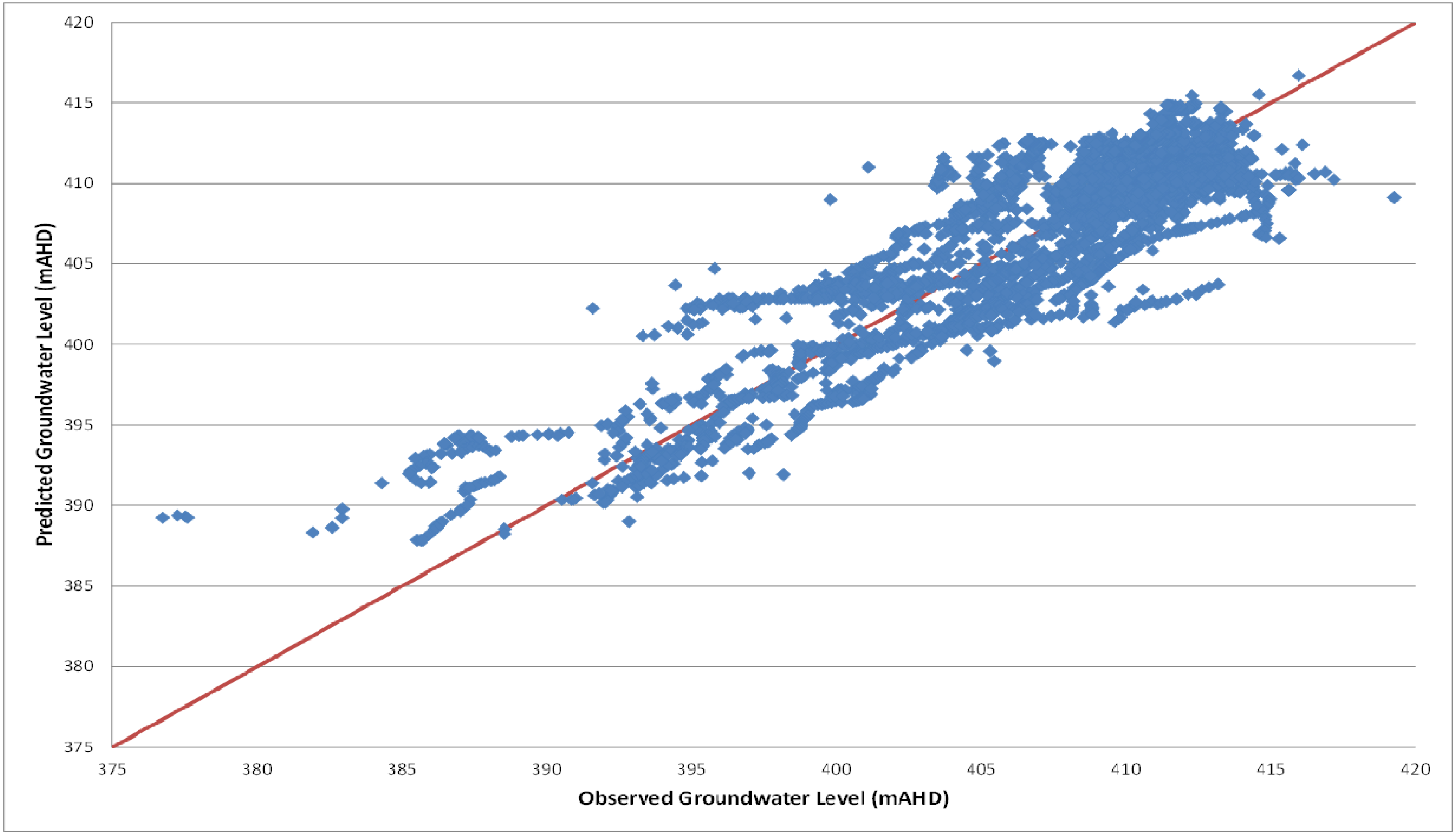

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87 Adelaide Terrace, East Perth
Western Australia 6004

Transient Calibration Results

Figure 53

29/08/2013

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Figure 54: Fortescue Marsh water balance

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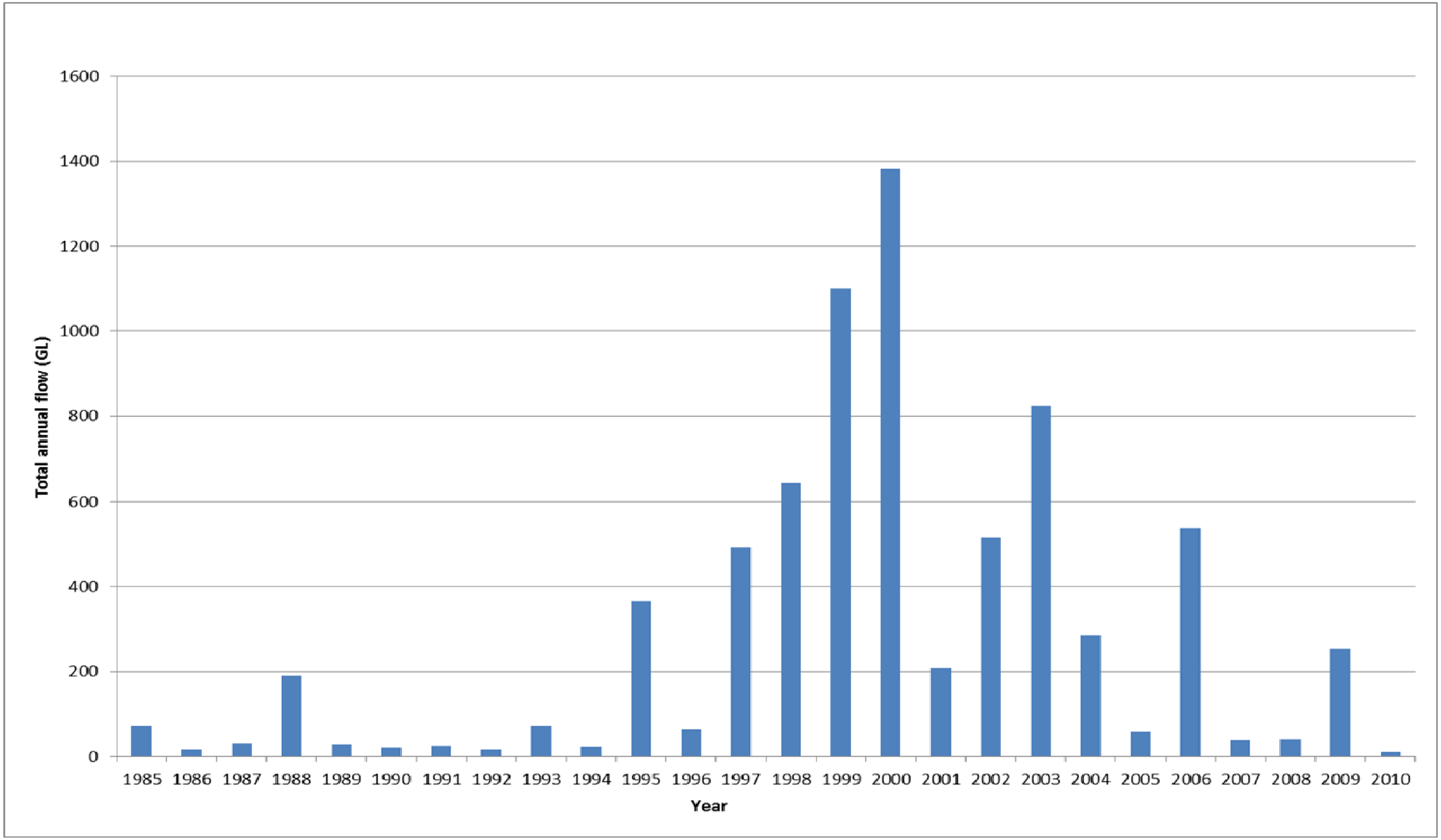

Fortescue Metals Group Ltd ACN: 002 594 872 87 Adelaide Terrace, East Perth Western Australia 6004	**Fortescue Marsh—Water Balance Model results (1985 to 2010)**	**Figure 54**
		13/11/2013

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Appendix 1: Historical Landsat data

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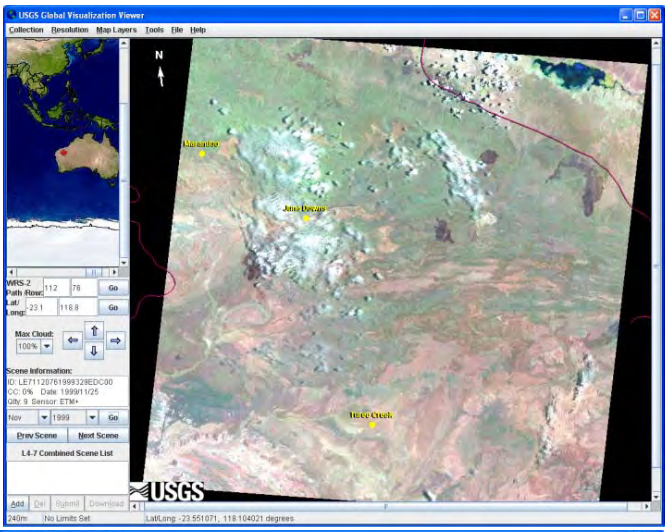
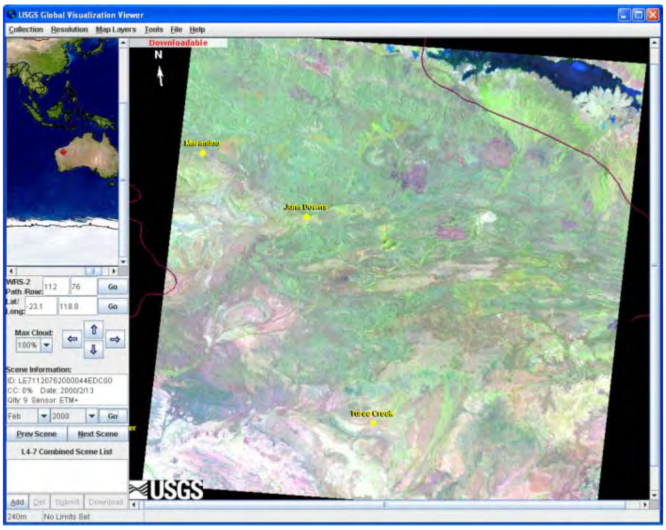
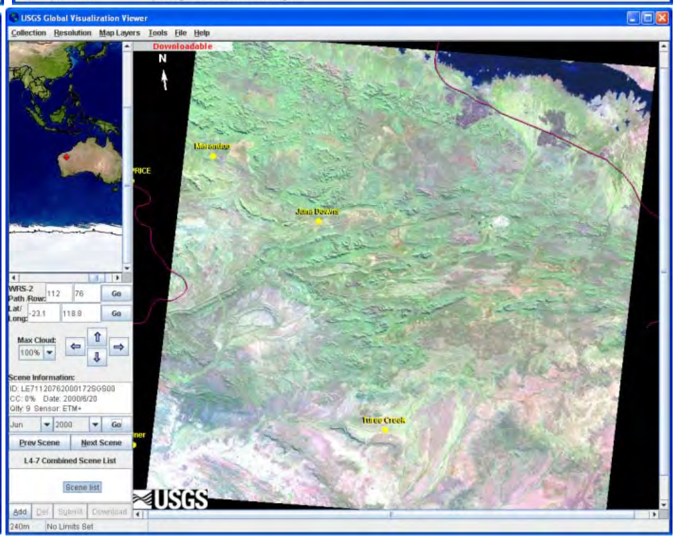
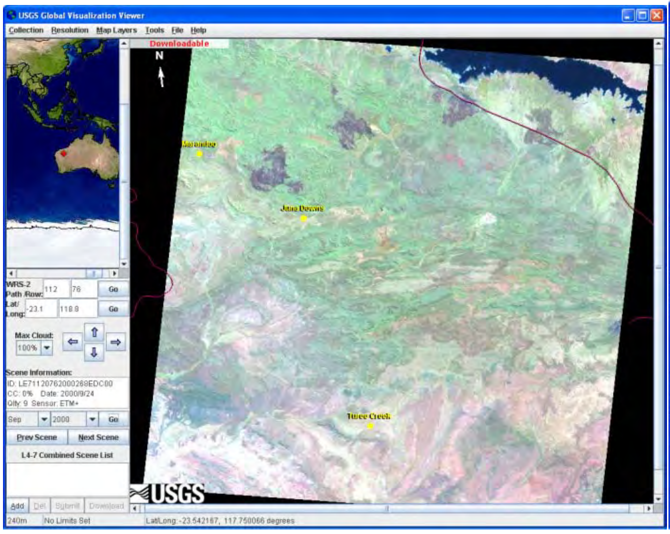
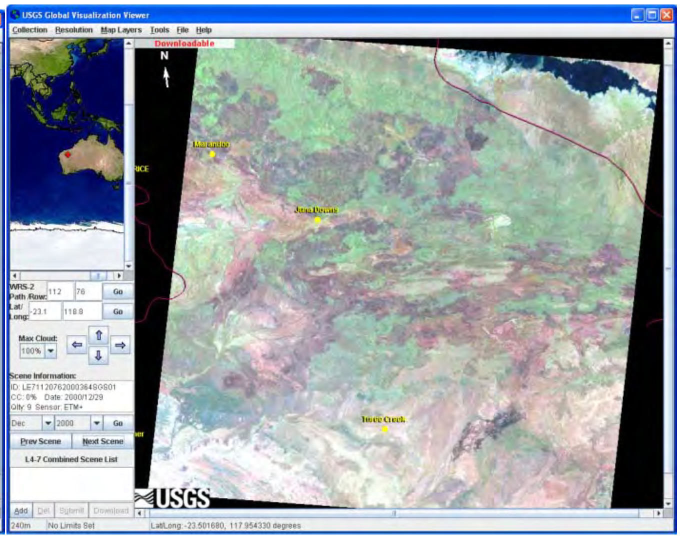
Aug 1999-Dec 2000



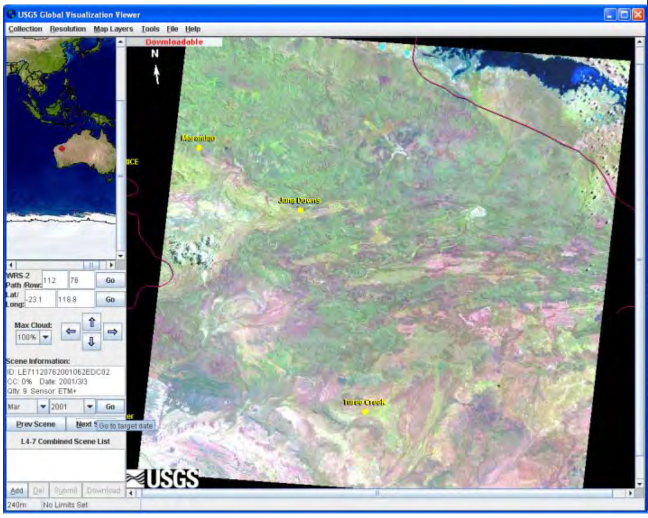


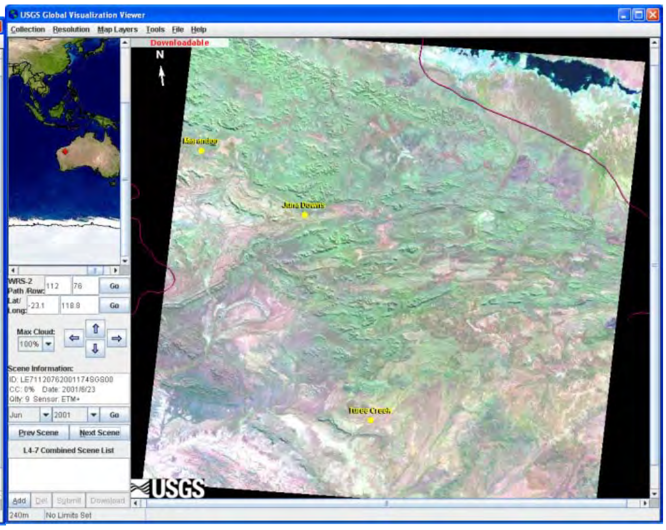


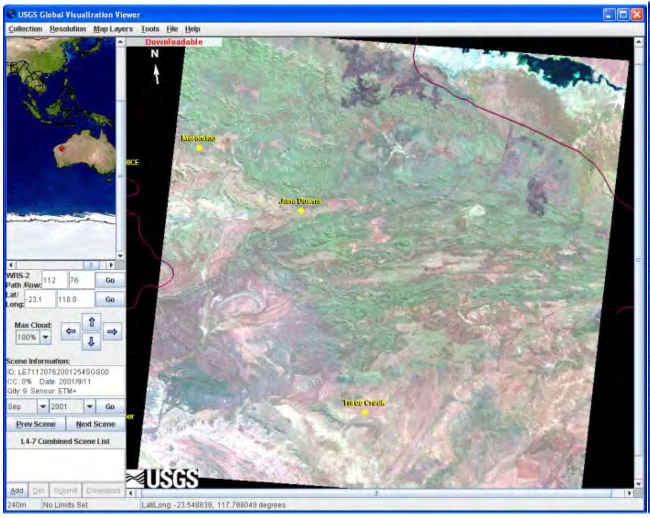


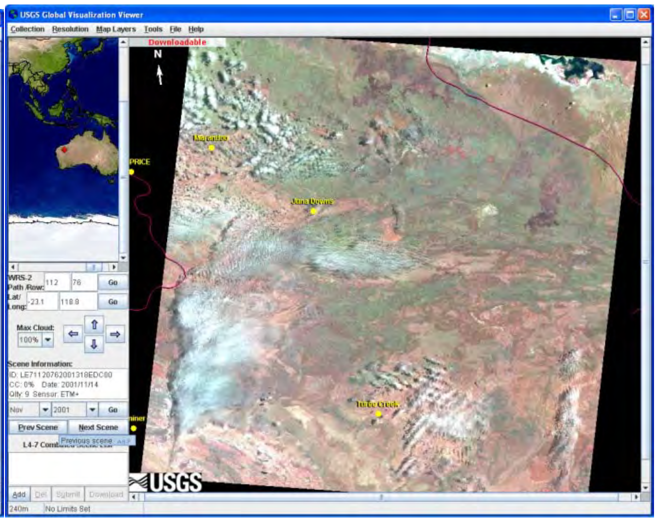


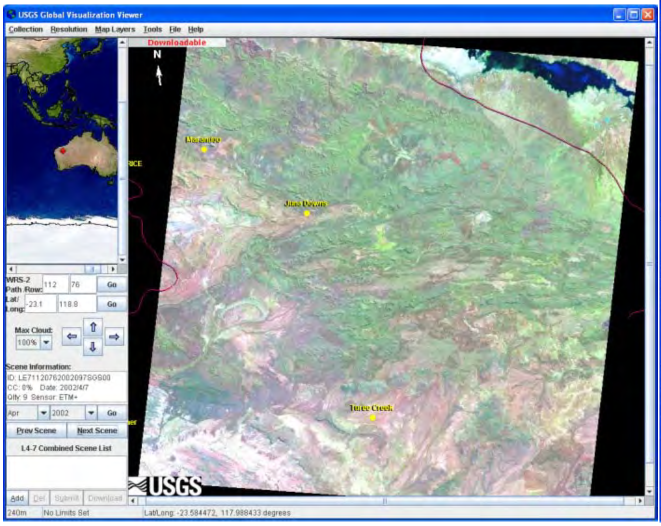
Mar 2001 – Sep 2002

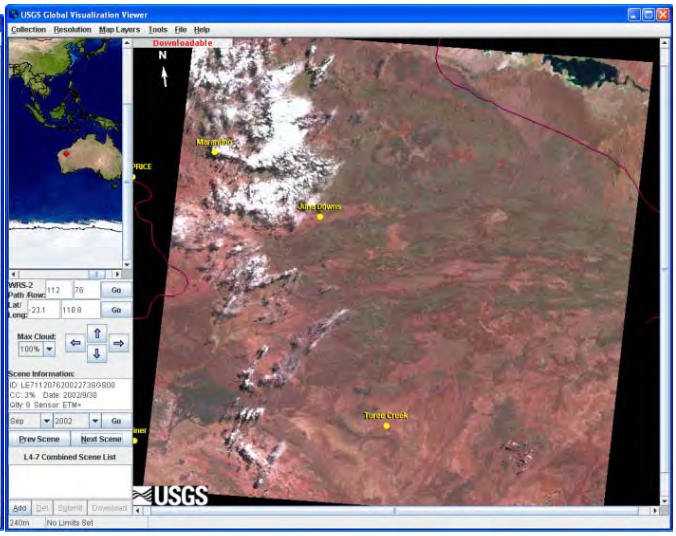




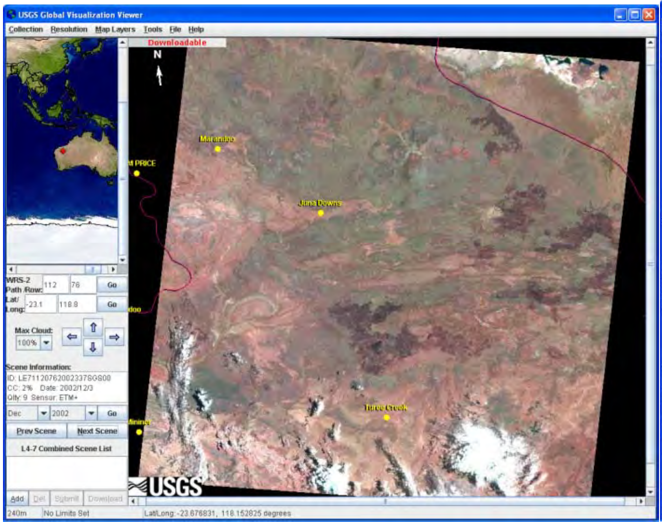


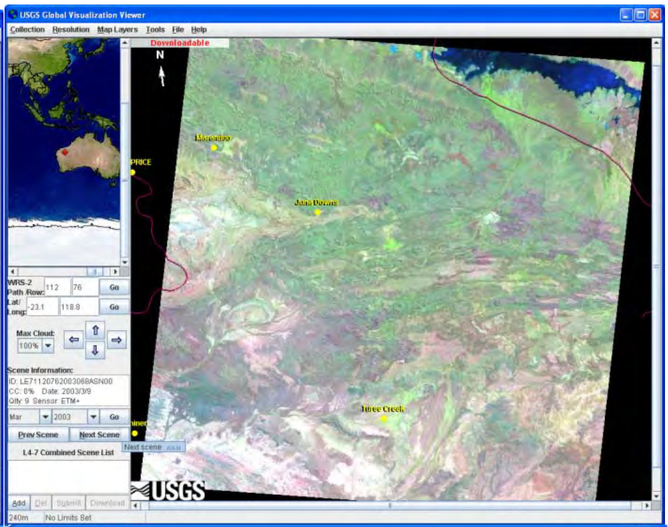


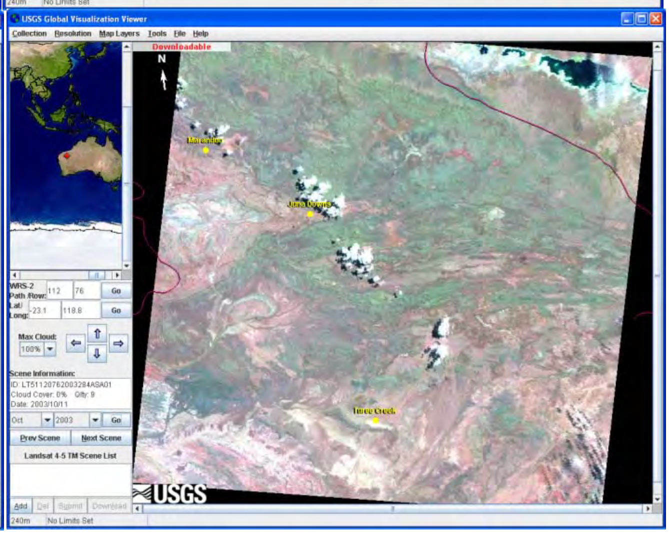


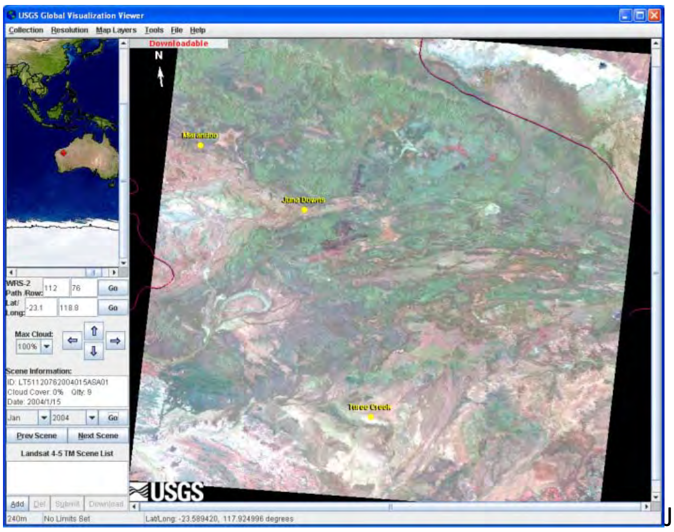


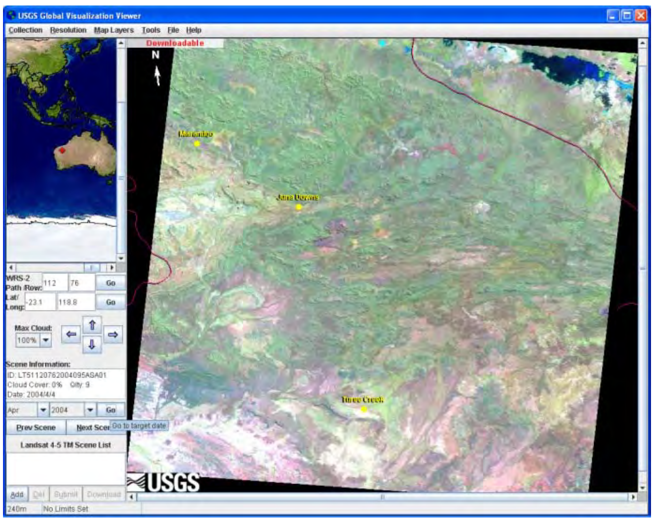
Dec 2002 – April 2004



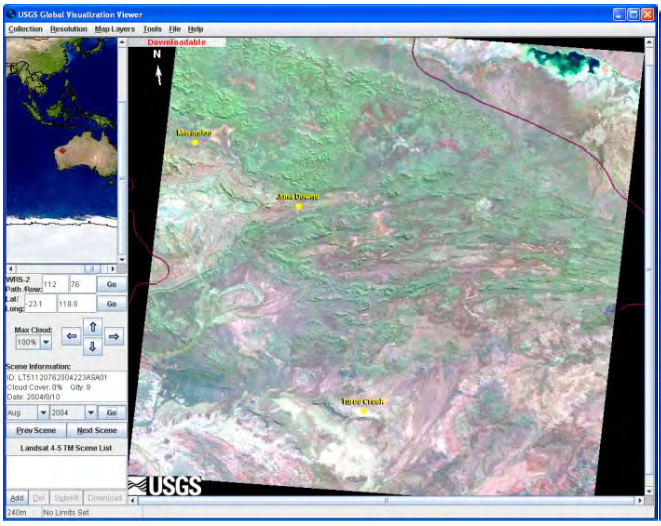


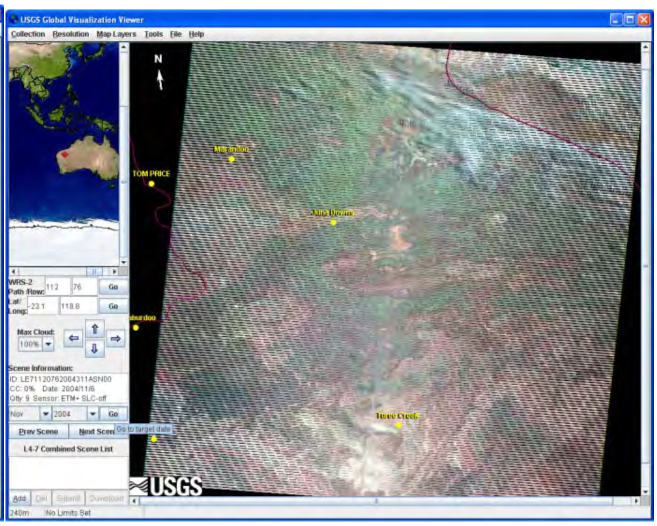


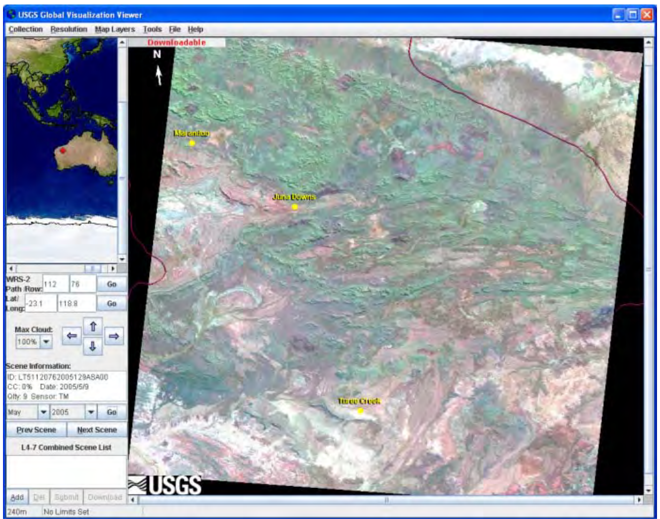


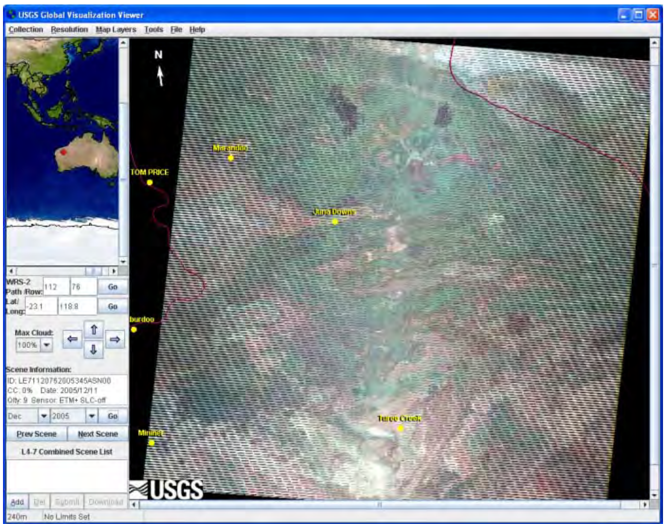


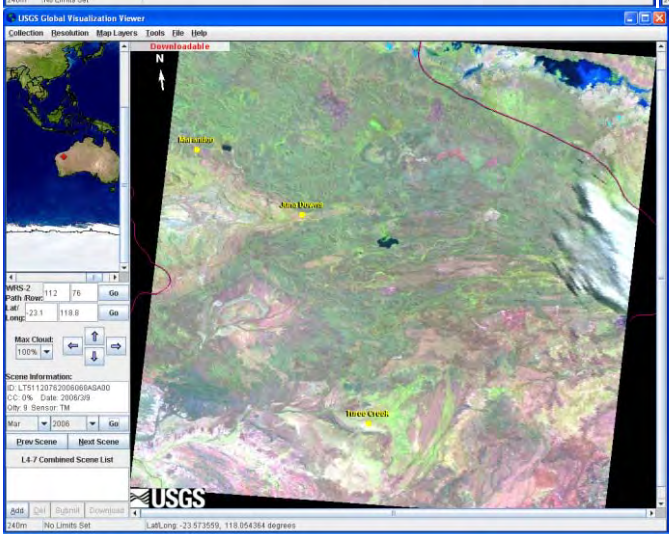
Aug 2004 – June 2006



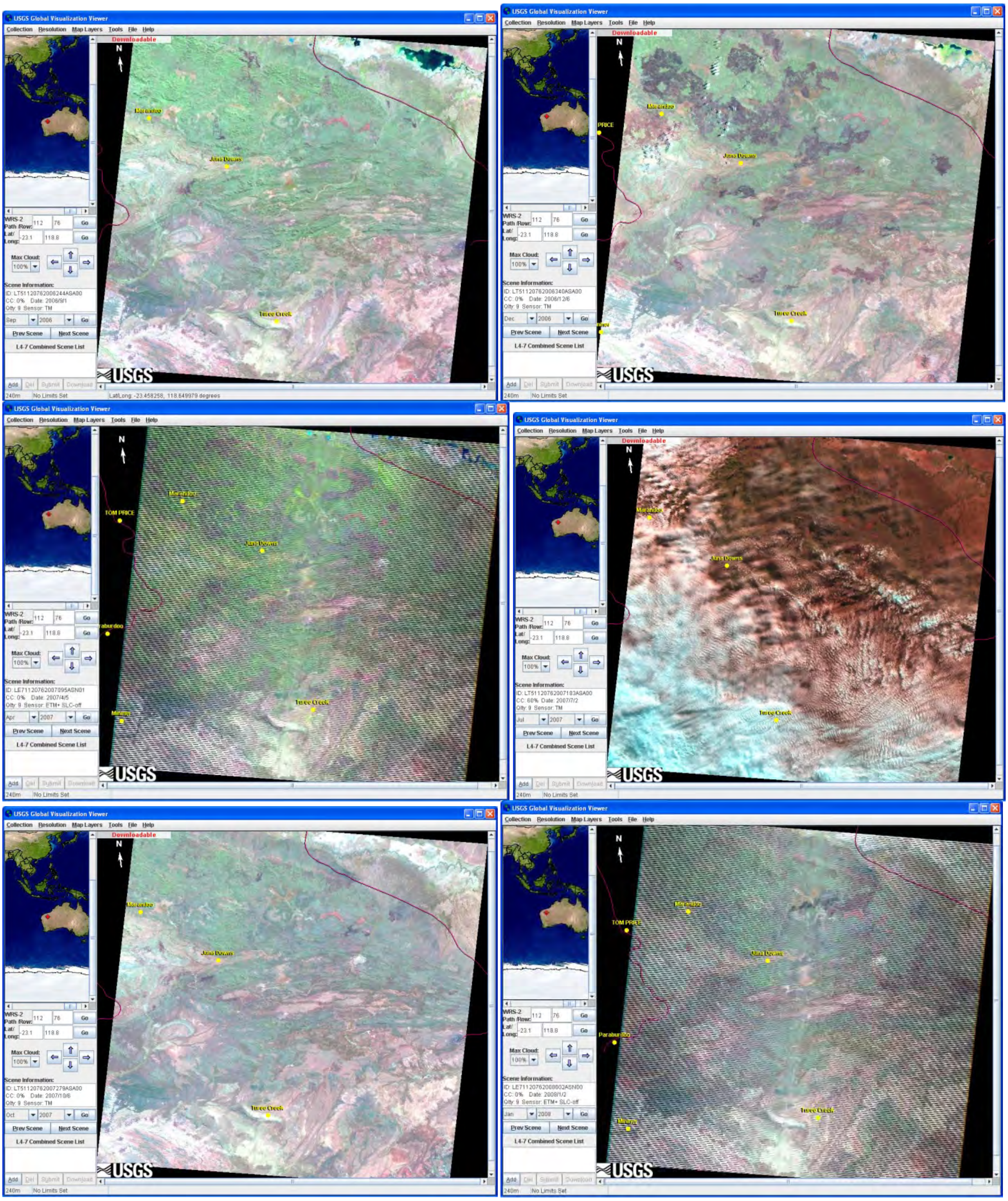




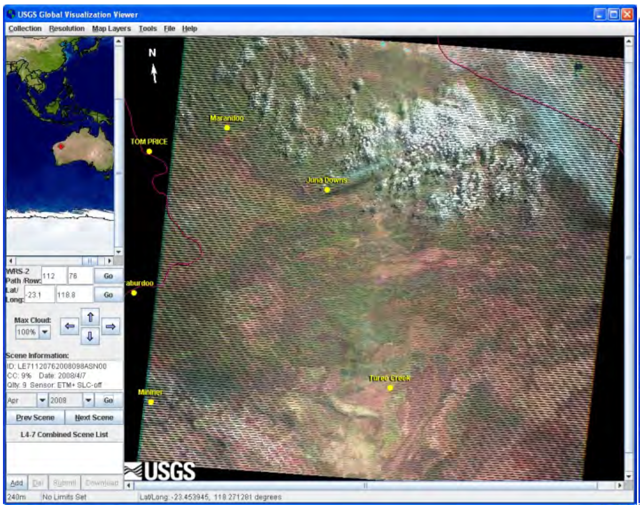


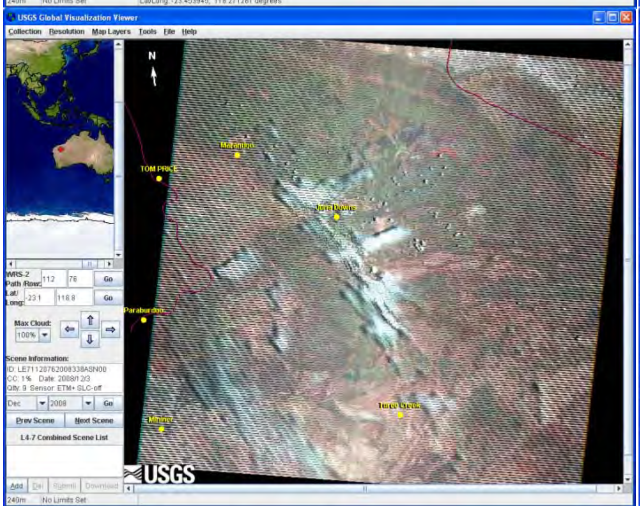


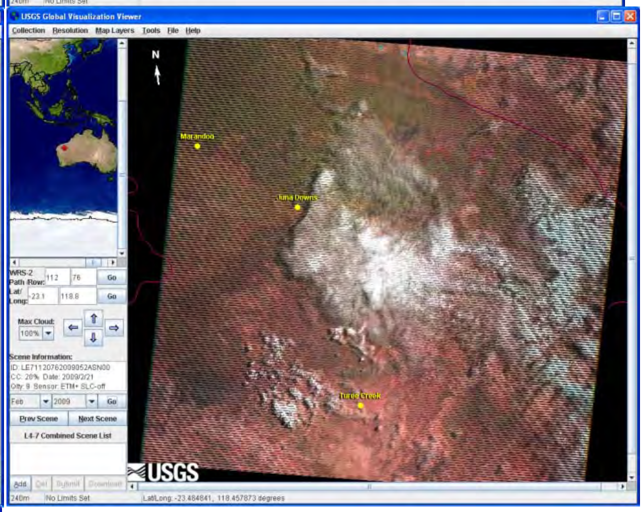
Sep 2006 – Jan 2008

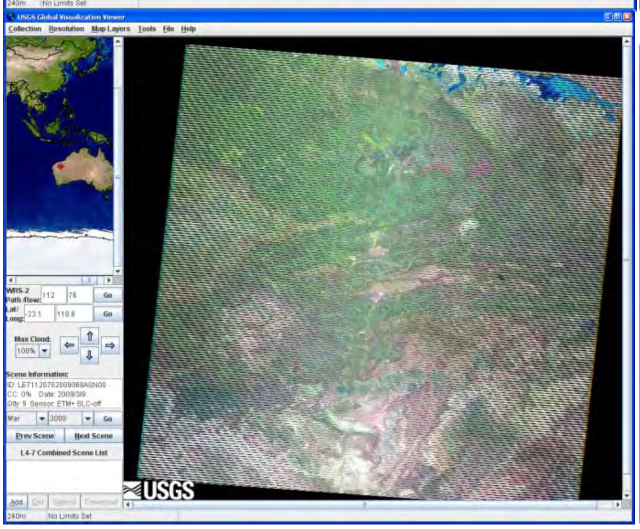


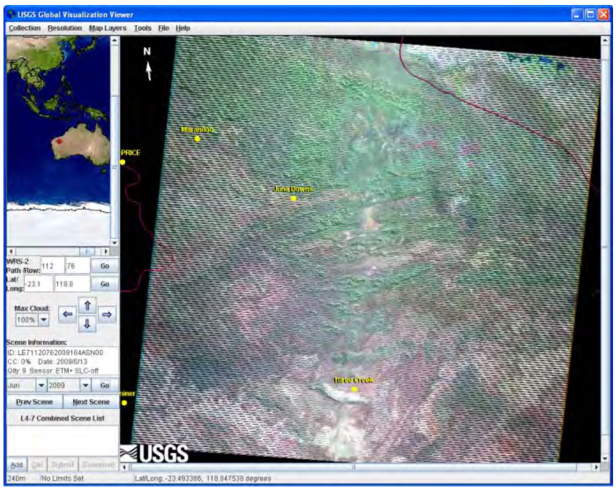
April 2008-June 2009



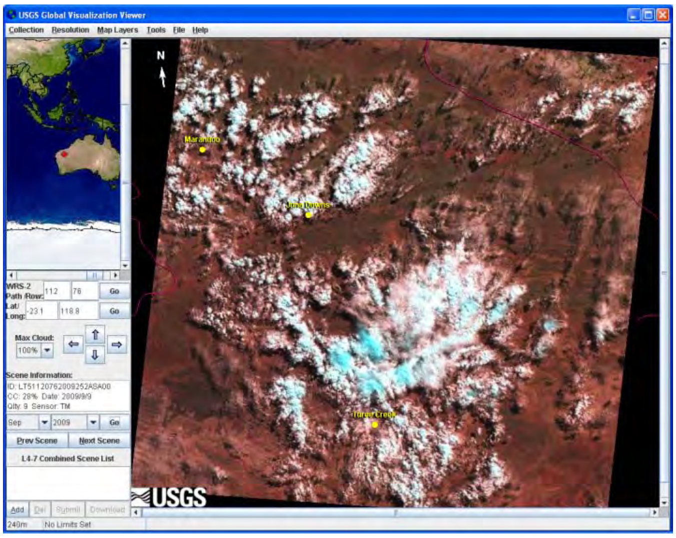


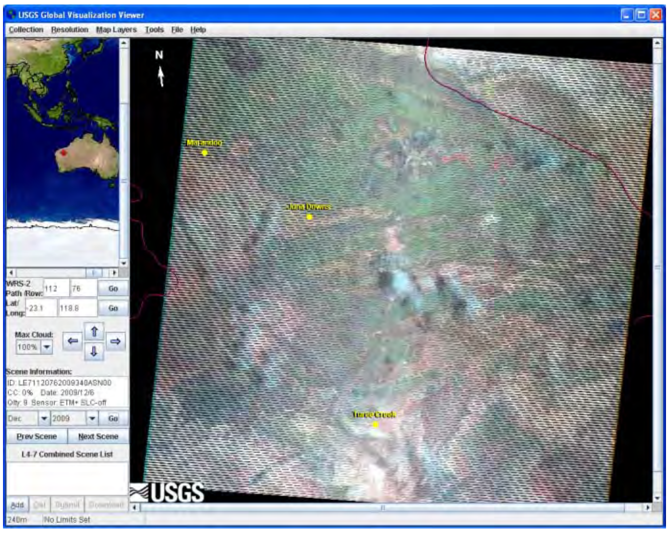


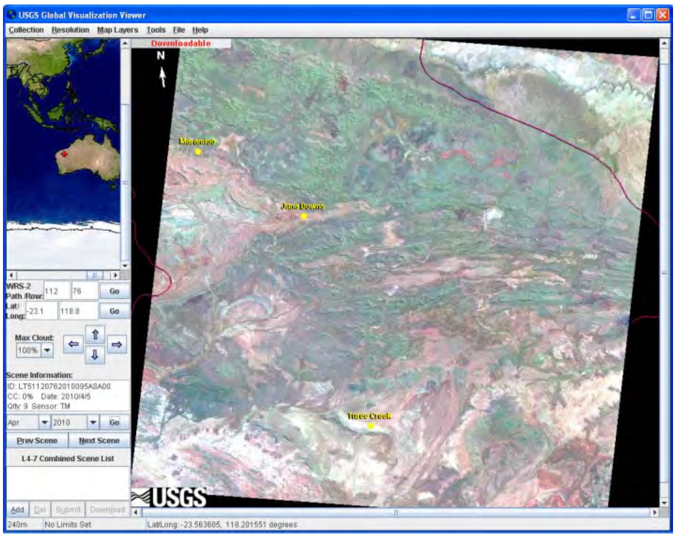




Sep 2009 – April 2010







Appendix 2: Geological cross sections

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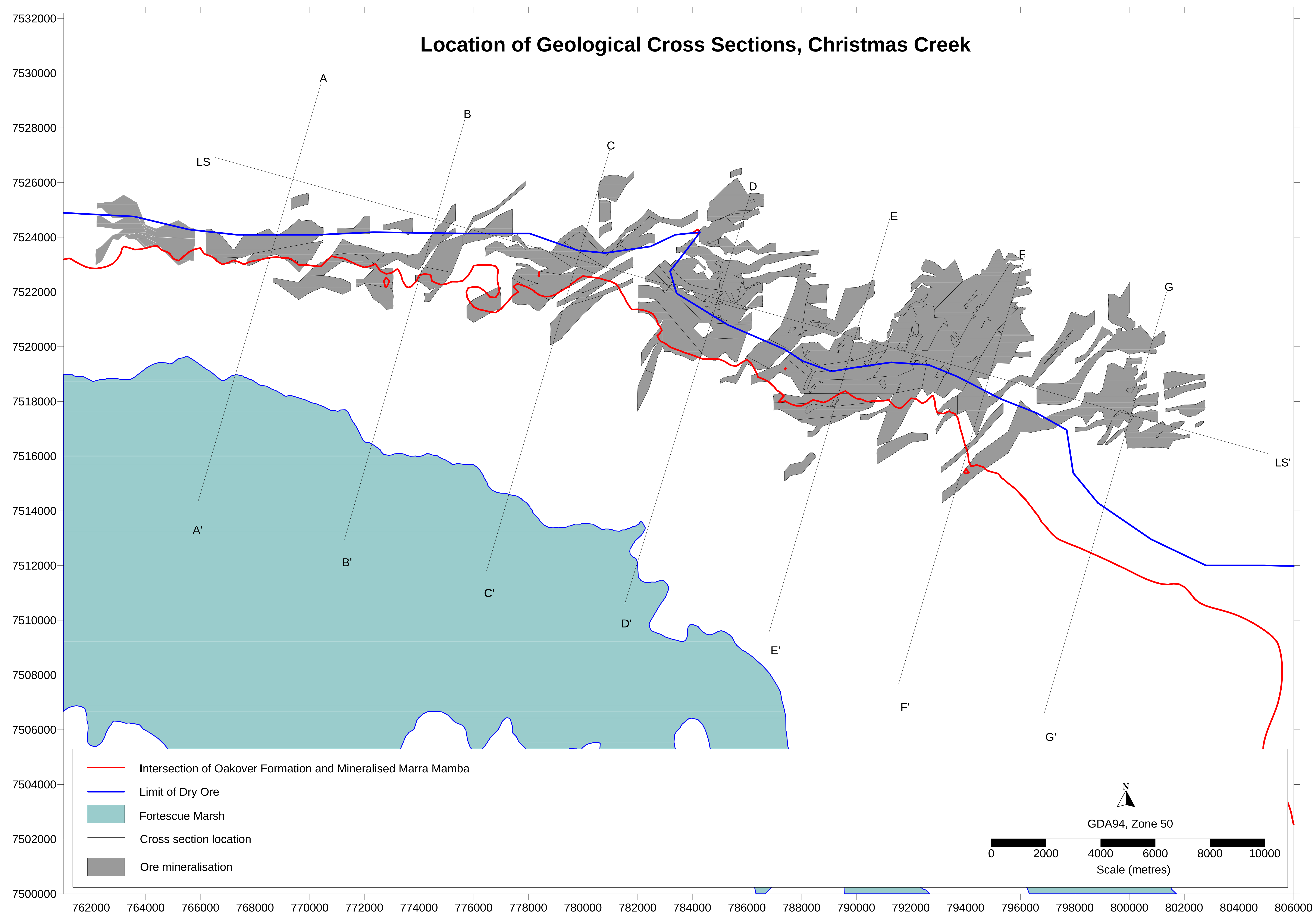
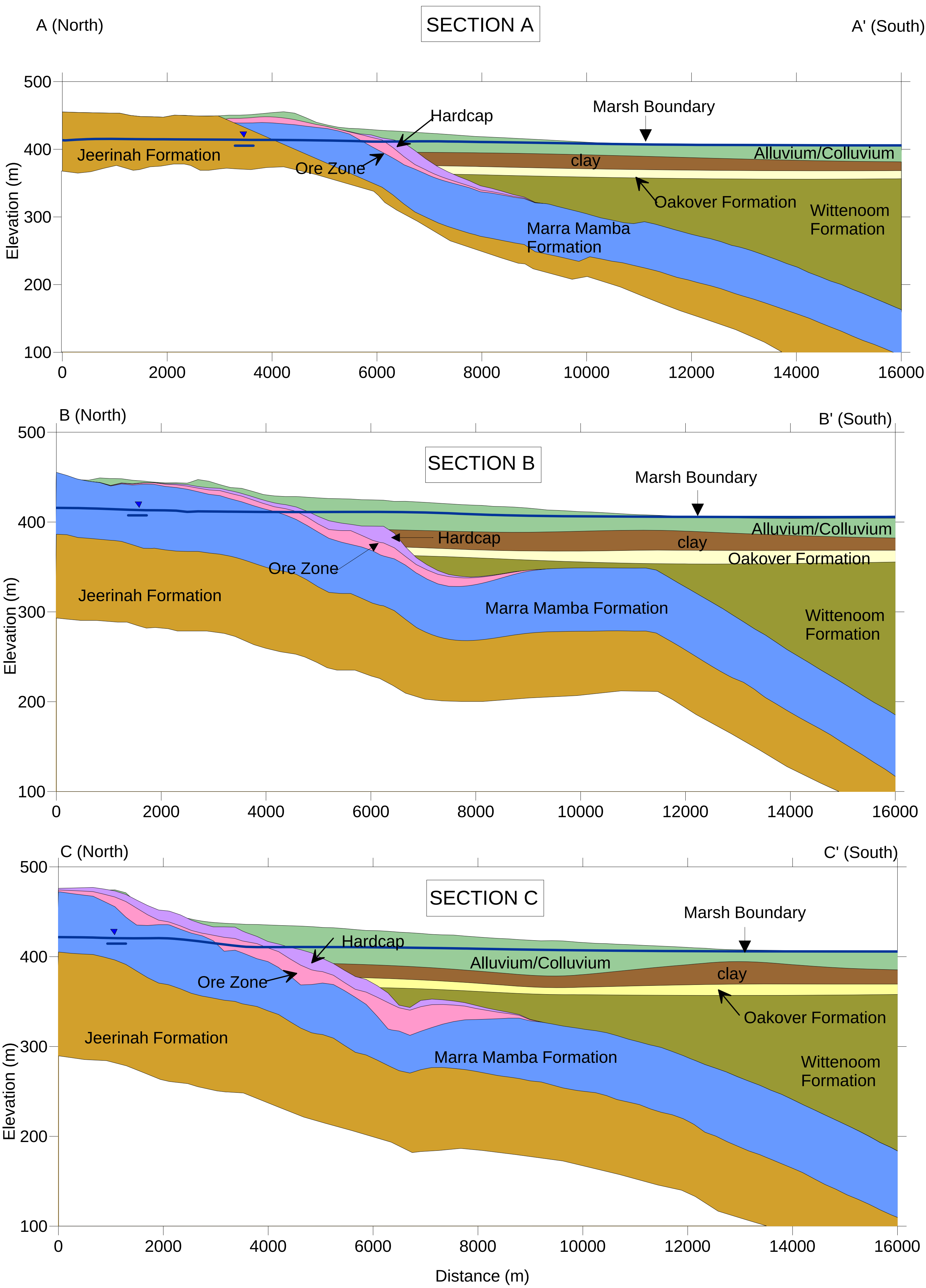


Location of Geological Cross Sections, Christmas Creek
A
A'
B
B'
C
C'
D
D'
E
E'
F
F'
G
G'
LS
LS'
7532000
7530000
7528000
7526000
7524000
7522000
7520000
7518000
7516000
7514000
7512000
7510000
7508000
7506000
7504000
7502000
7500000
762000
764000
766000
768000
770000
772000
774000
776000
778000
780000
782000
784000
786000
788000
790000
792000
794000
796000
798000
800000
802000
804000
806000
Intersection of Oakover Formation and Mineralised Marra Mamba
Limit of Dry Ore
Fortescue Marsh
Cross section location
Ore mineralisation
N
GDA94, Zone 50
0
2000
4000
6000
8000
10000
Scale (metres)



A (North)
SECTION A
A' (South)
Hardcap
Marsh Boundary
Jeerinah Formation
Ore Zone
clay
Alluvium/Colluvium
Oakover Formation
Wittenoom Formation
Marra Mamba Formation
Elevation (m)
500
400
300
200
100
0
2000
4000
6000
8000
10000
12000
14000
16000
B (North)
SECTION B
B' (South)
Marsh Boundary
Alluvium/Colluvium
Hardcap
clay
Oakover Formation
Ore Zone
Jeerinah Formation
Marra Mamba Formation
Wittenoom Formation
C (North)
SECTION C
C' (South)
Marsh Boundary
Hardcap
Alluvium/Colluvium
clay
Ore Zone
Oakover Formation
Jeerinah Formation
Marra Mamba Formation
Wittenoom Formation
Distance (m)

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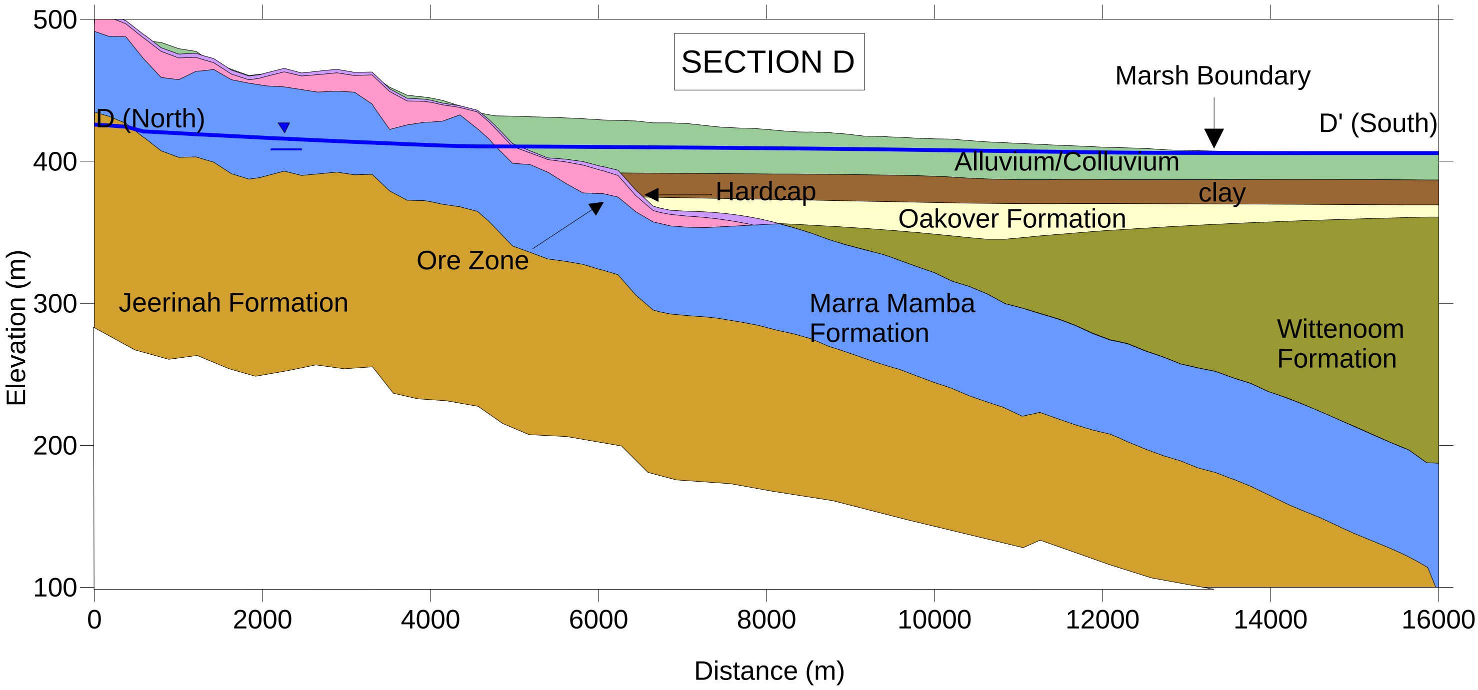
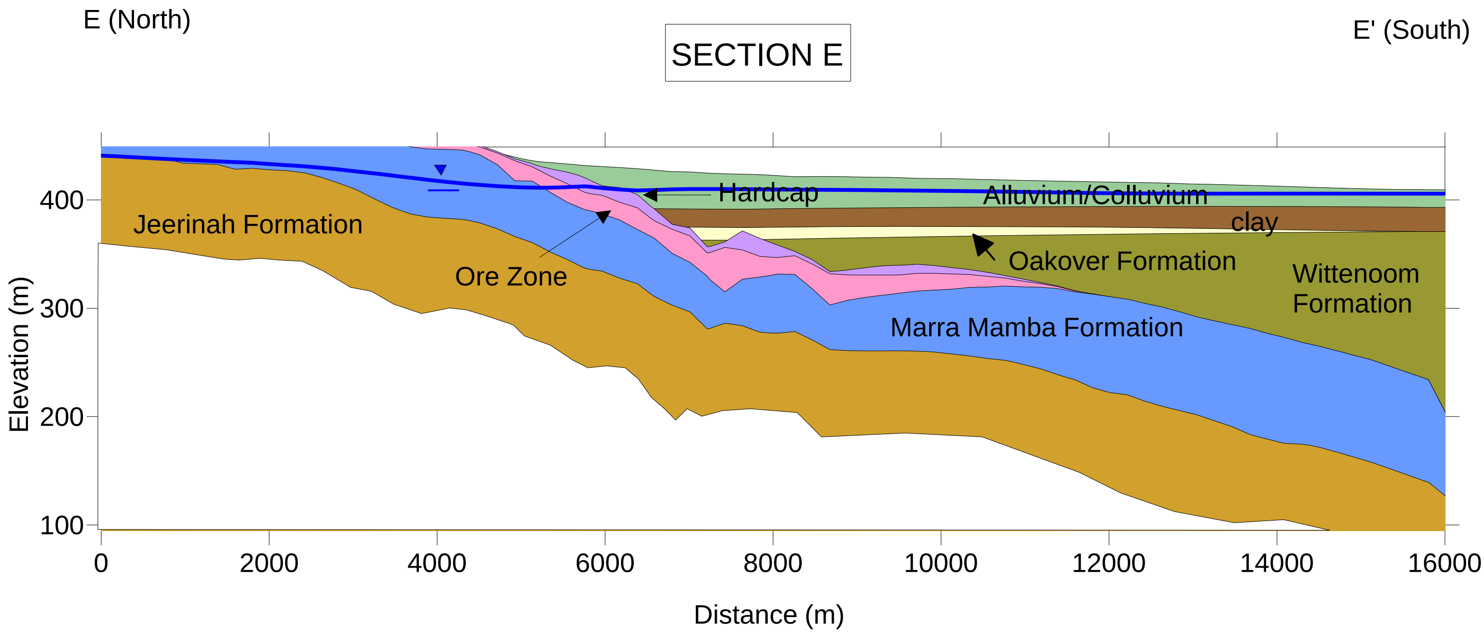
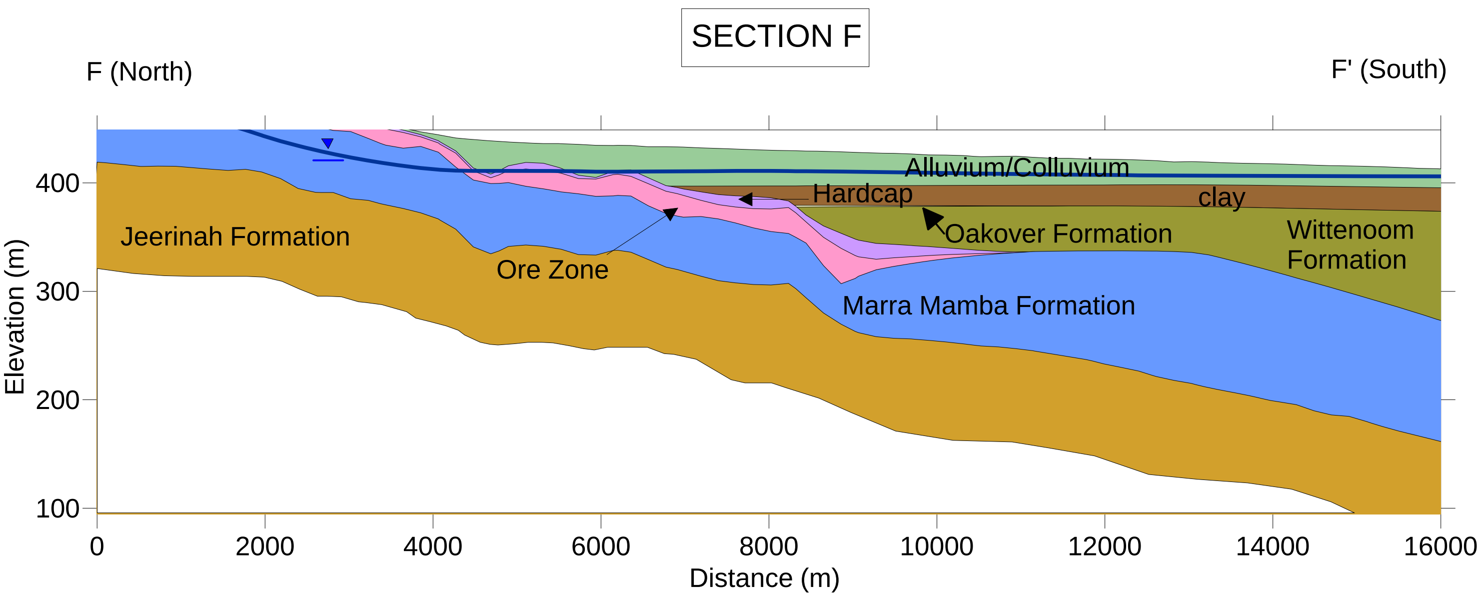

SECTION D
Marsh Boundary
D (North)
D' (South)
Alluvium/Colluvium
Hardcap
clay
Oakover Formation
Ore Zone
Jeerinah Formation
Marra Mamba Formation
Wittenoom Formation
Elevation (m)
Distance (m)
500
400
300
200
100
0
2000
4000
6000
8000
10000
12000
14000
16000


E (North)
E' (South)
SECTION E
Hardcap
Alluvium/Colluvium
clay
Jeerinah Formation
Oakover Formation
Ore Zone
Wittenoom Formation
Marra Mamba Formation
Elevation (m)
Distance (m)
400
300
200
100
0
2000
4000
6000
8000
10000
12000
14000
16000


SECTION F
F (North)
F' (South)
Alluvium/Colluvium
Hardcap
clay
Oakover Formation
Wittenoom Formation
Jeerinah Formation
Ore Zone
Marra Mamba Formation
Elevation (m)
Distance (m)
400
300
200
100
0
2000
4000
6000
8000
10000
12000
14000
16000

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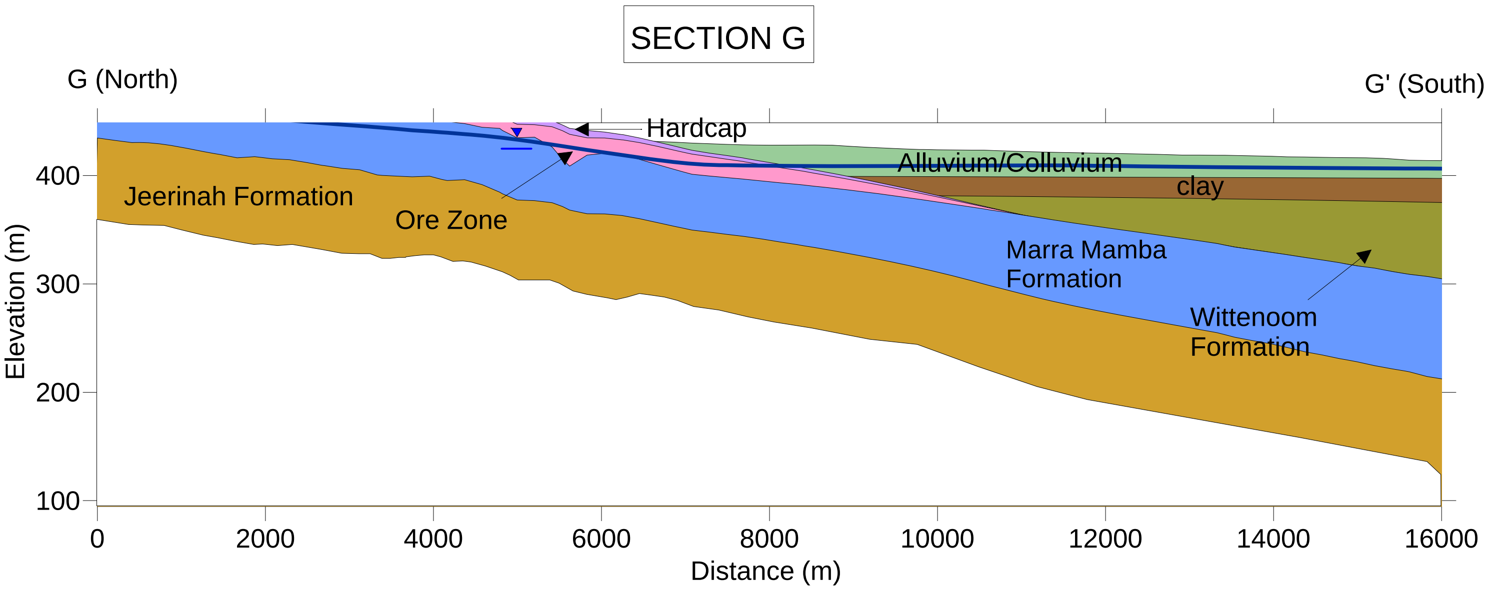
SECTION G
G (North)
G' (South)
Hardcap
Alluvium/Colluvium
clay
Jeerinah Formation
Ore Zone
Marra Mamba Formation
Wittenoom Formation
Elevation (m)
400
300
200
100
0
2000
4000
6000
8000
10000
12000
14000
16000
Distance (m)

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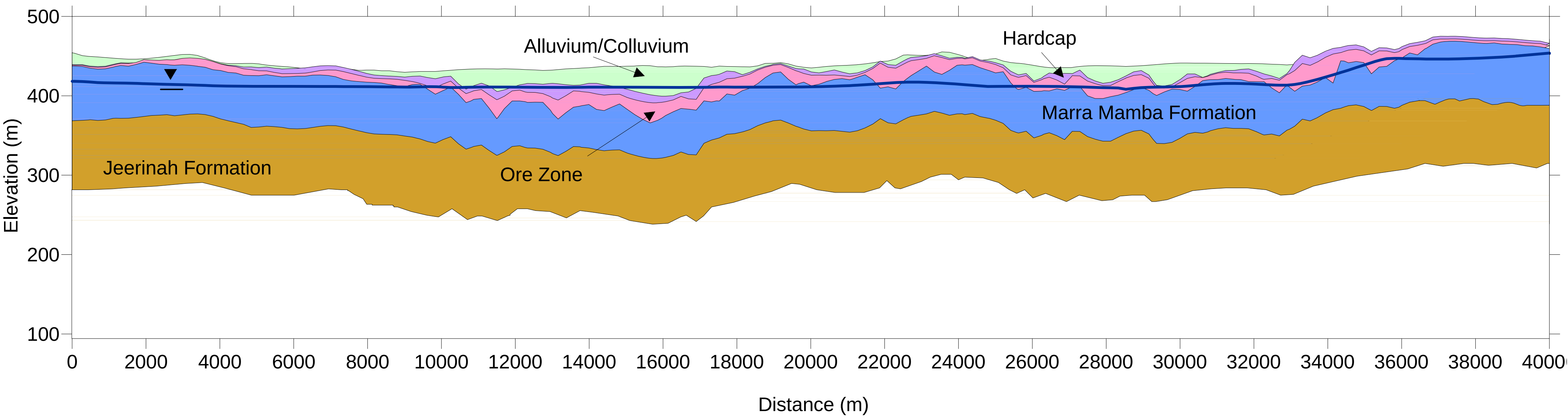
LONG SECTION



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Appendix 3: Numerical model hydraulic property zones and layer thicknesses

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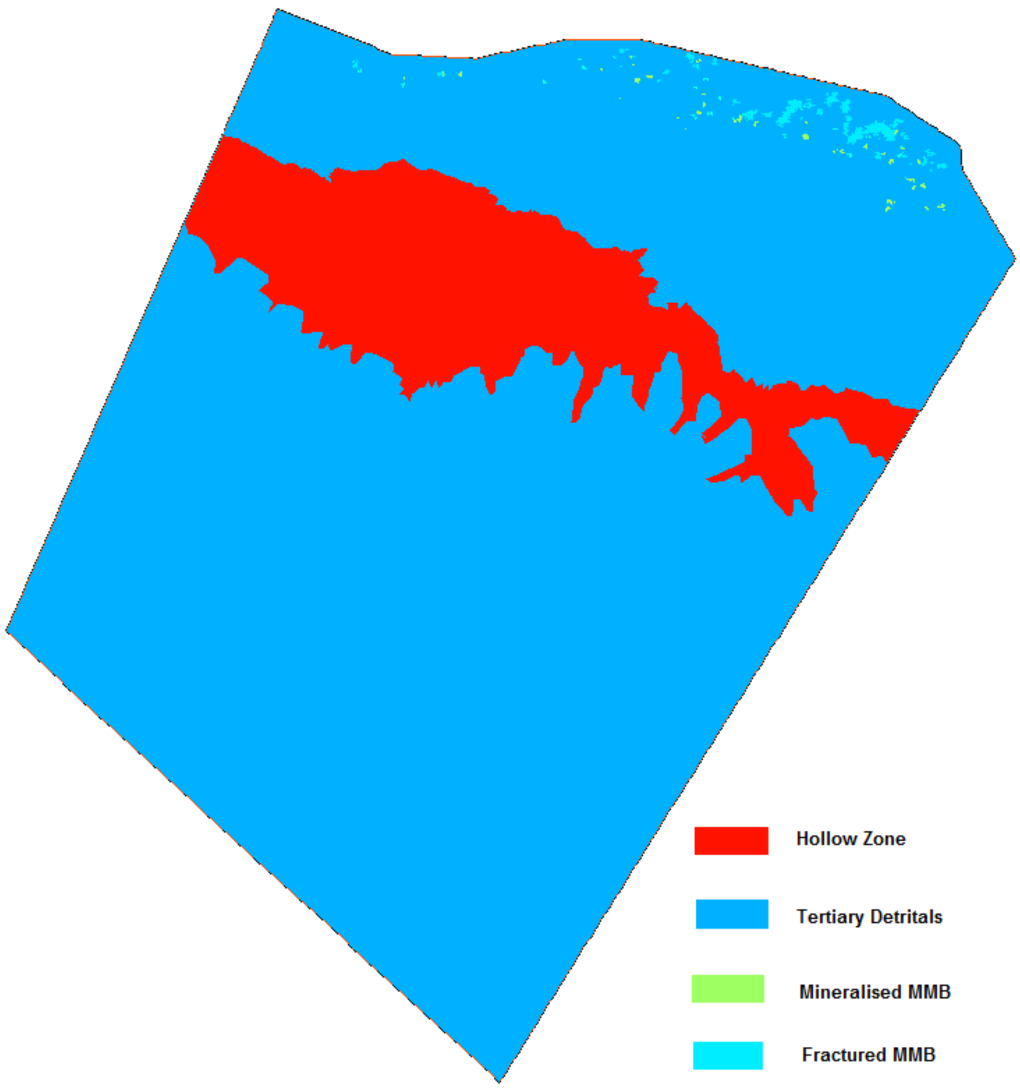
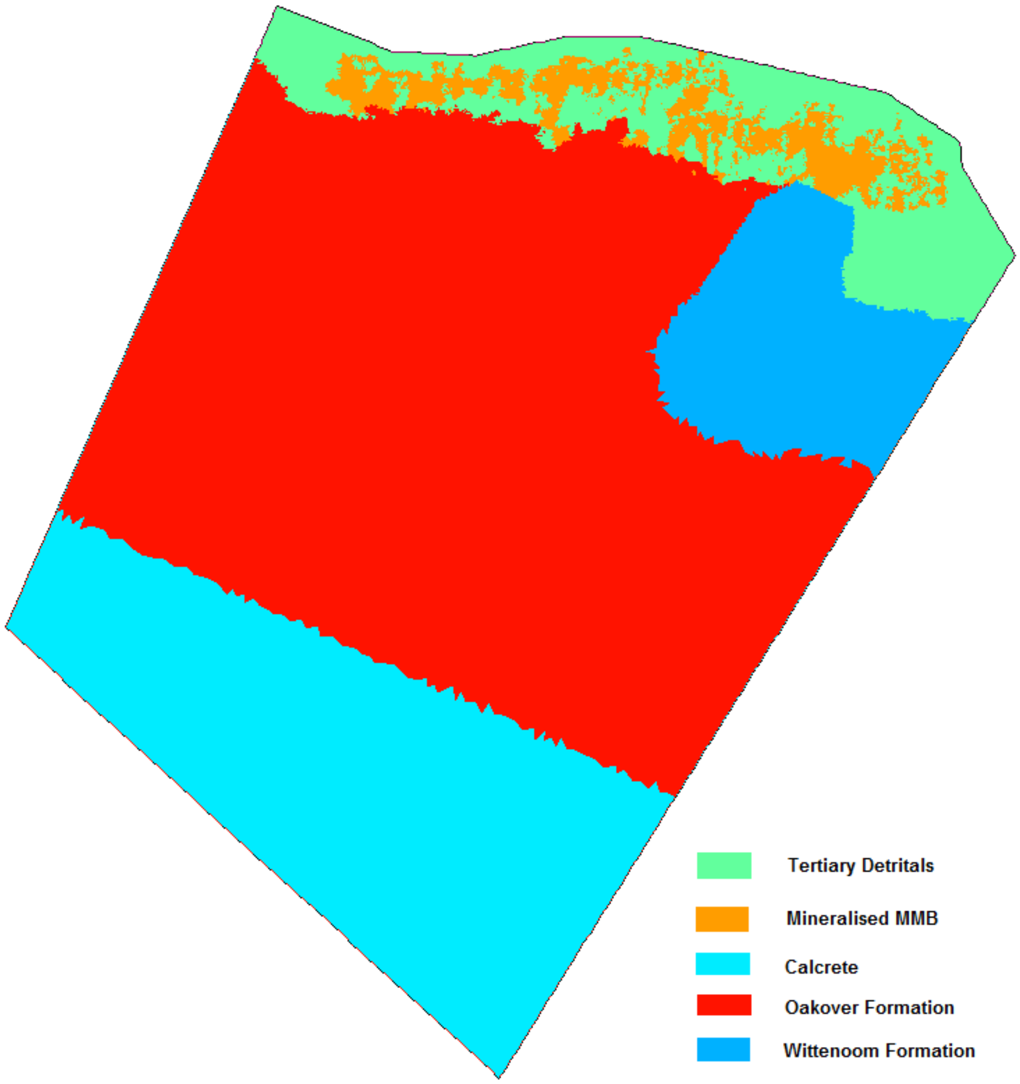


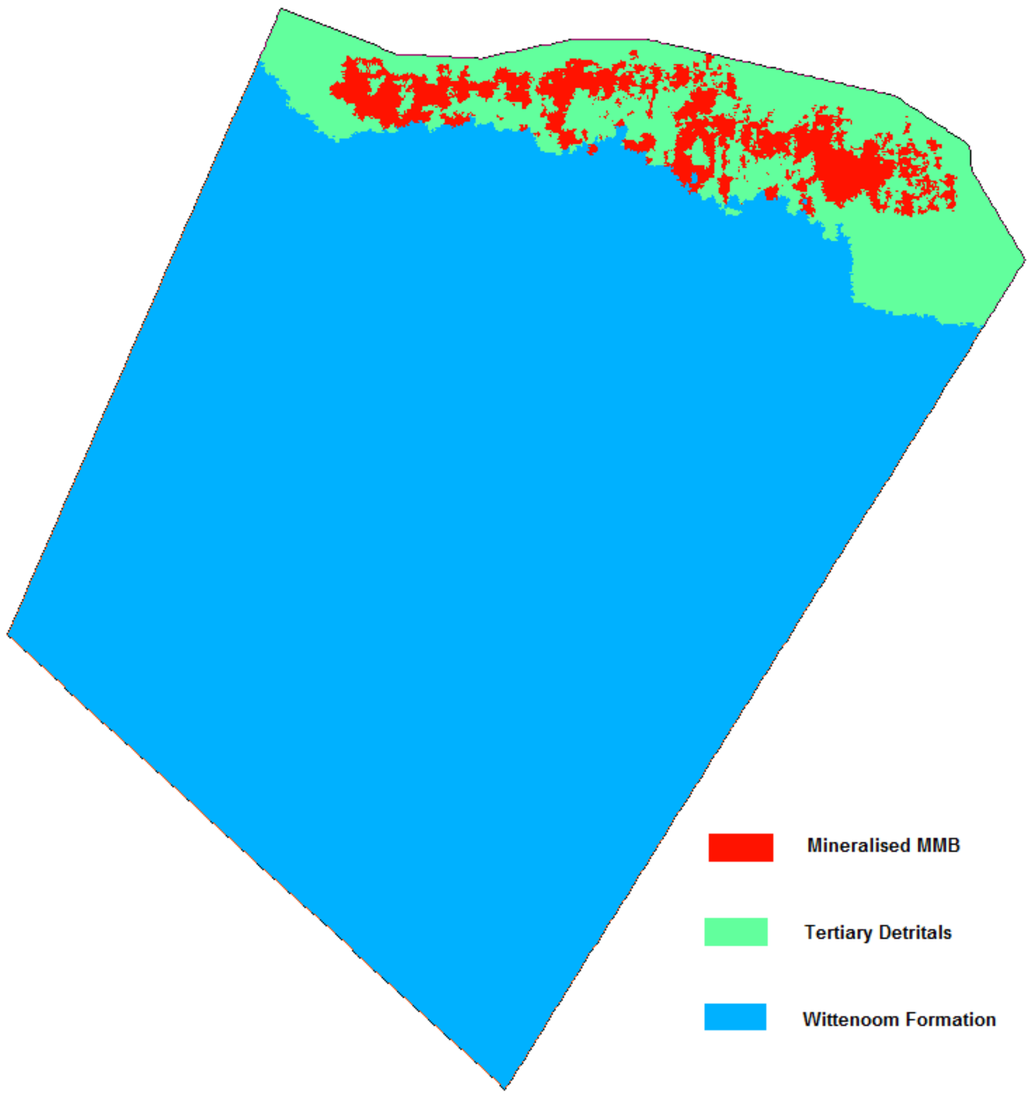
Appendix 3.1: Distribution of hydraulic property zones in numerical layer 1.

Appendix 3.2: Distribution of hydraulic property zones in numerical layer 2.

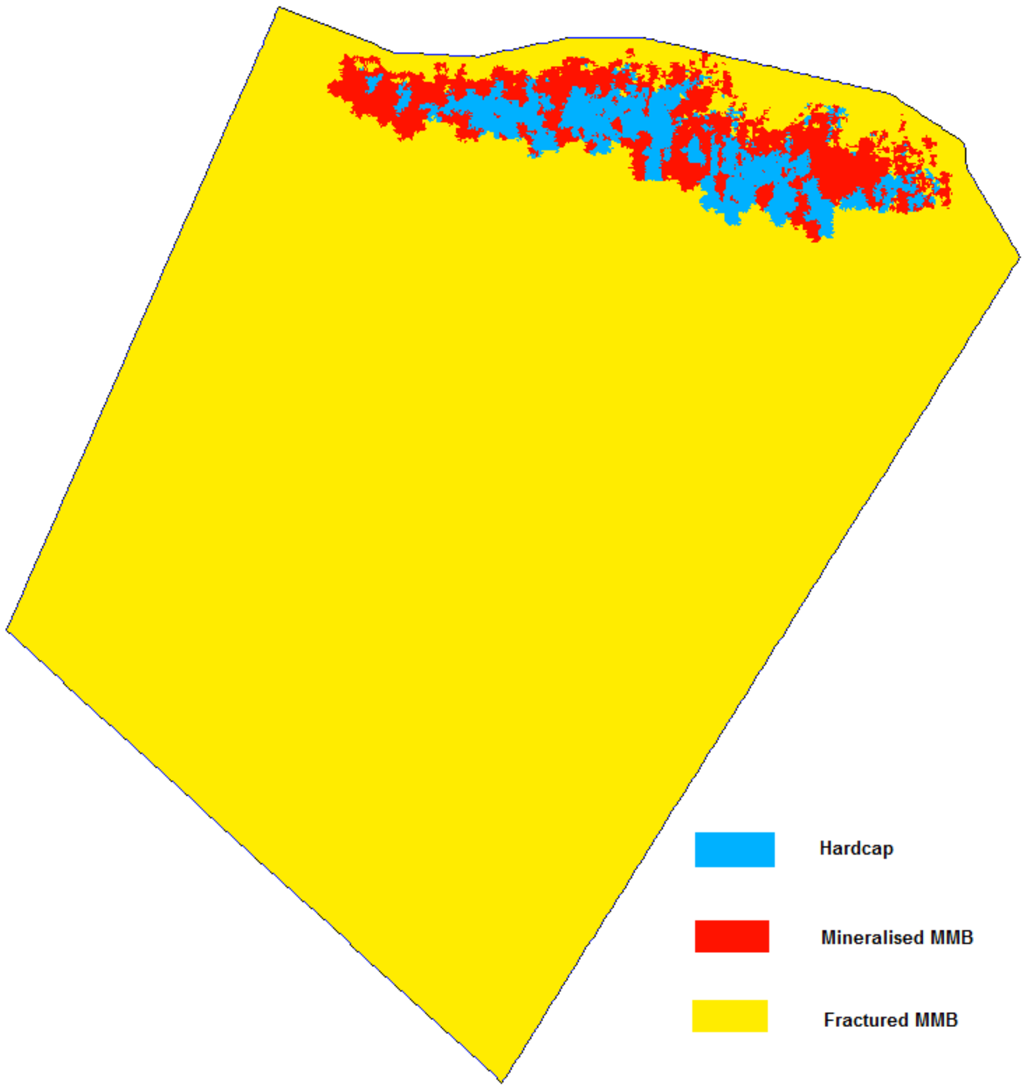
Appendix 3.3: Distribution of hydraulic property zones in numerical layer 3.



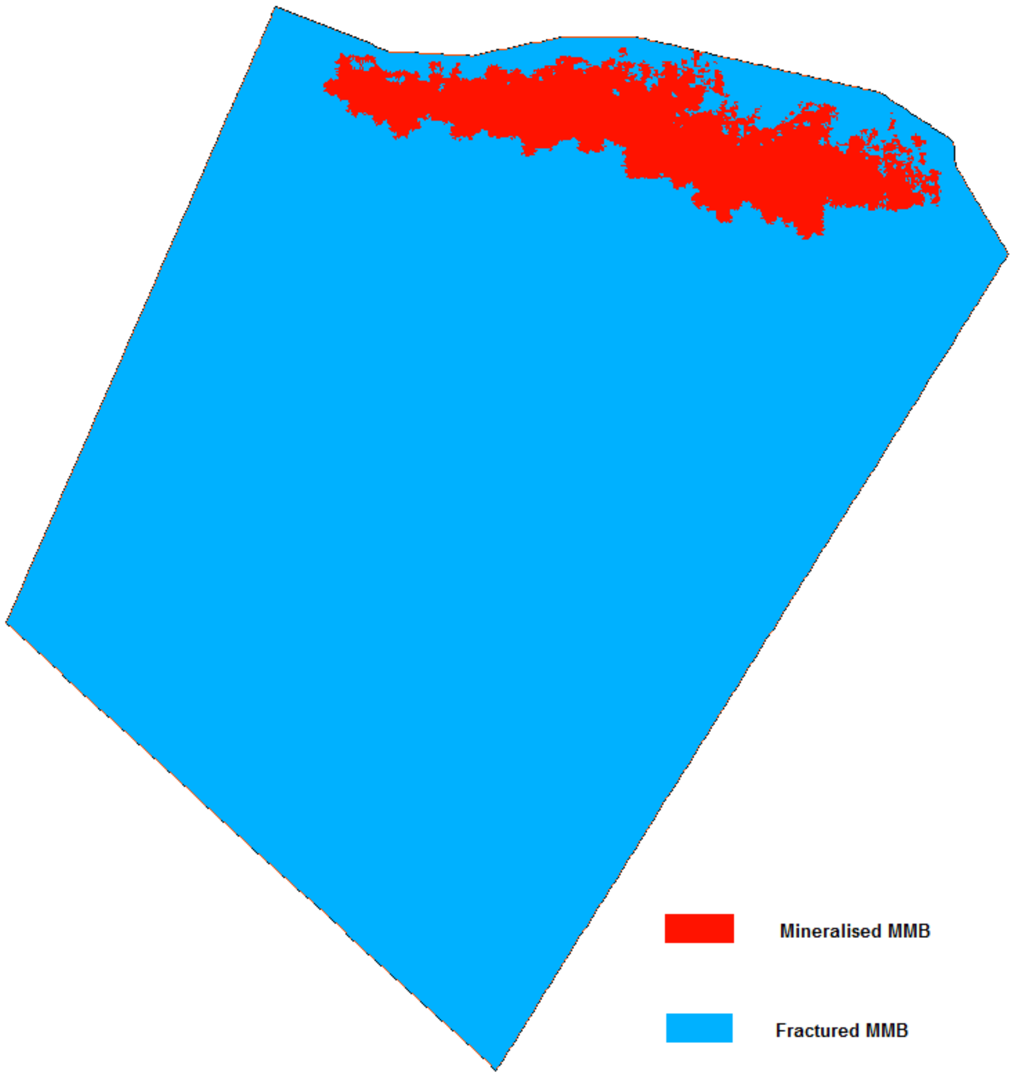
Appendix 3.4: Distribution of hydraulic property zones in numerical layer 4.



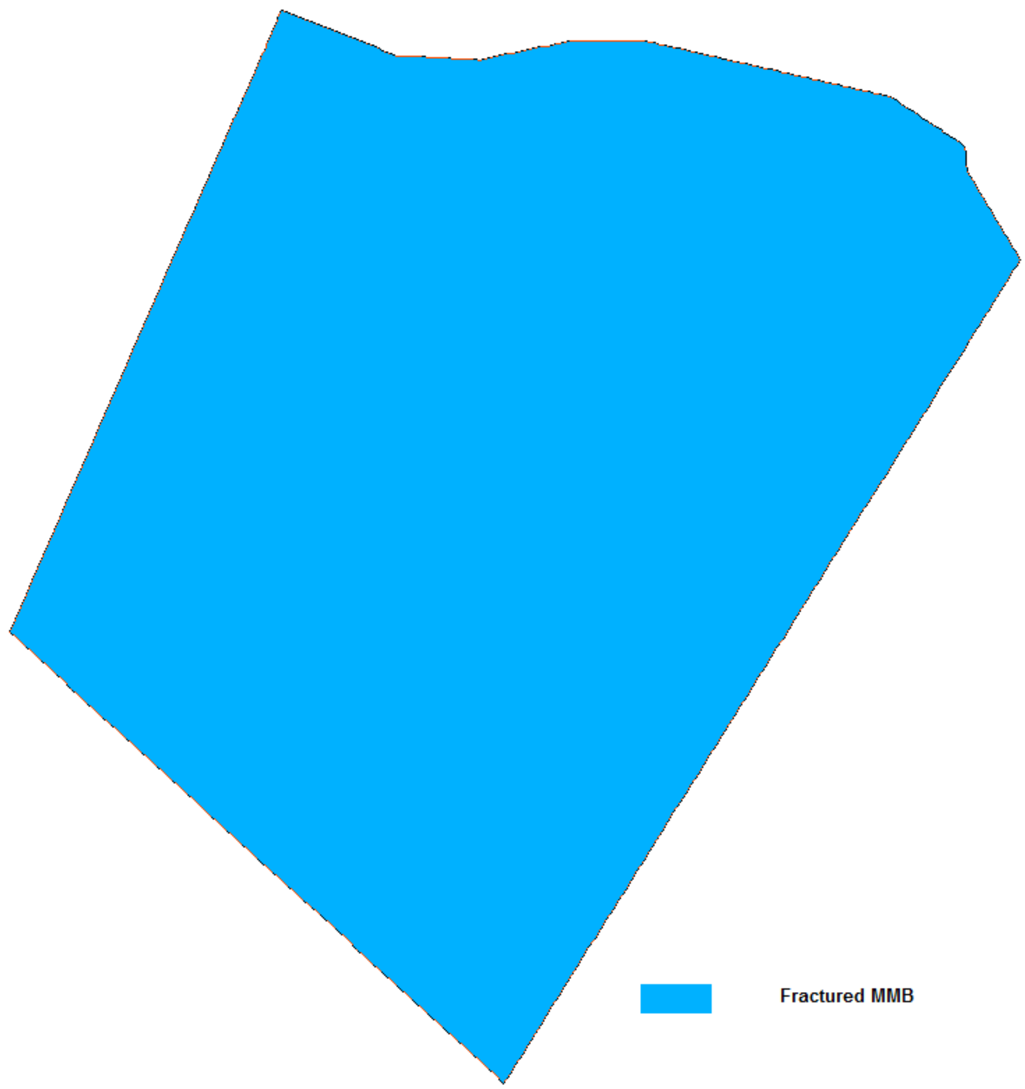
Appendix 3.5: Distribution of hydraulic property zones in numerical layer 5.



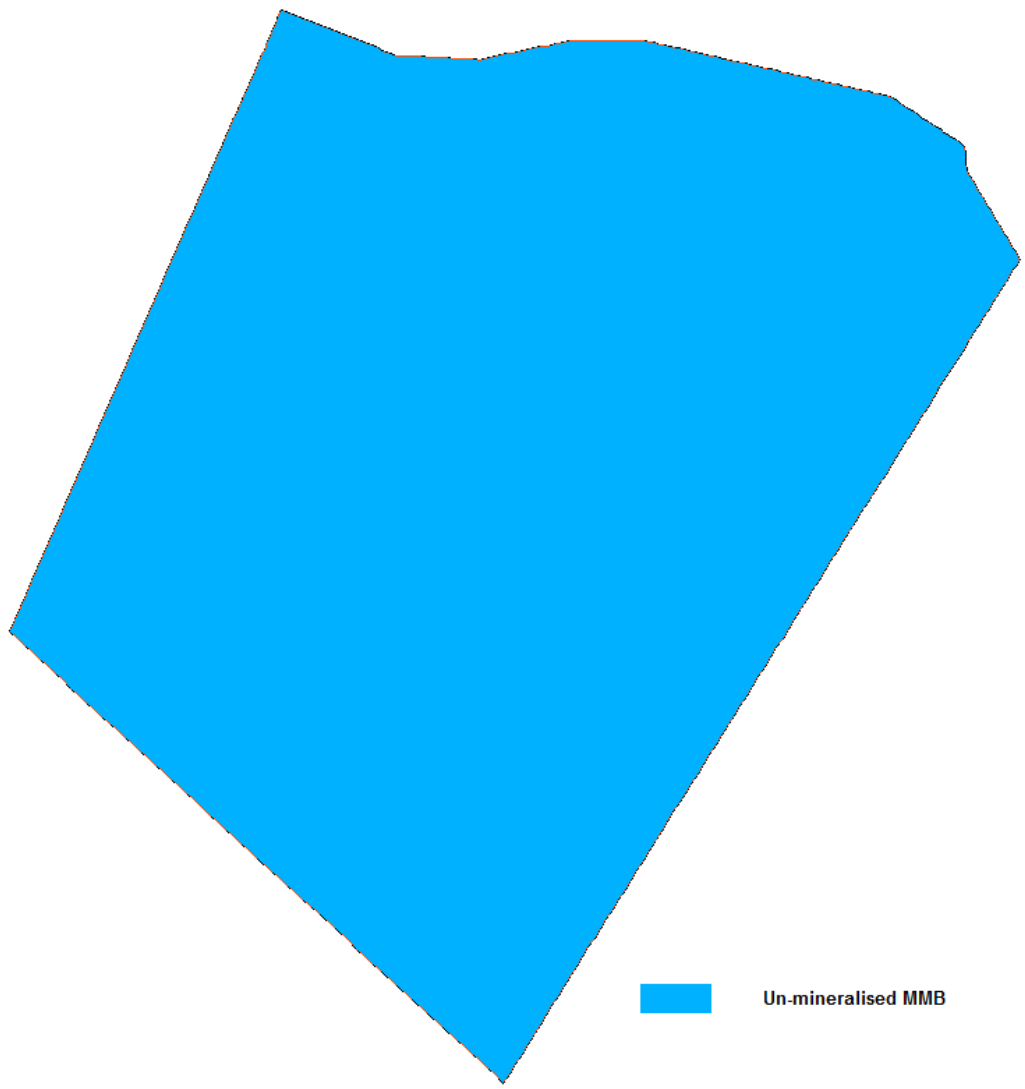
Appendix 3.6: Distribution of hydraulic property zones in numerical layer 6.



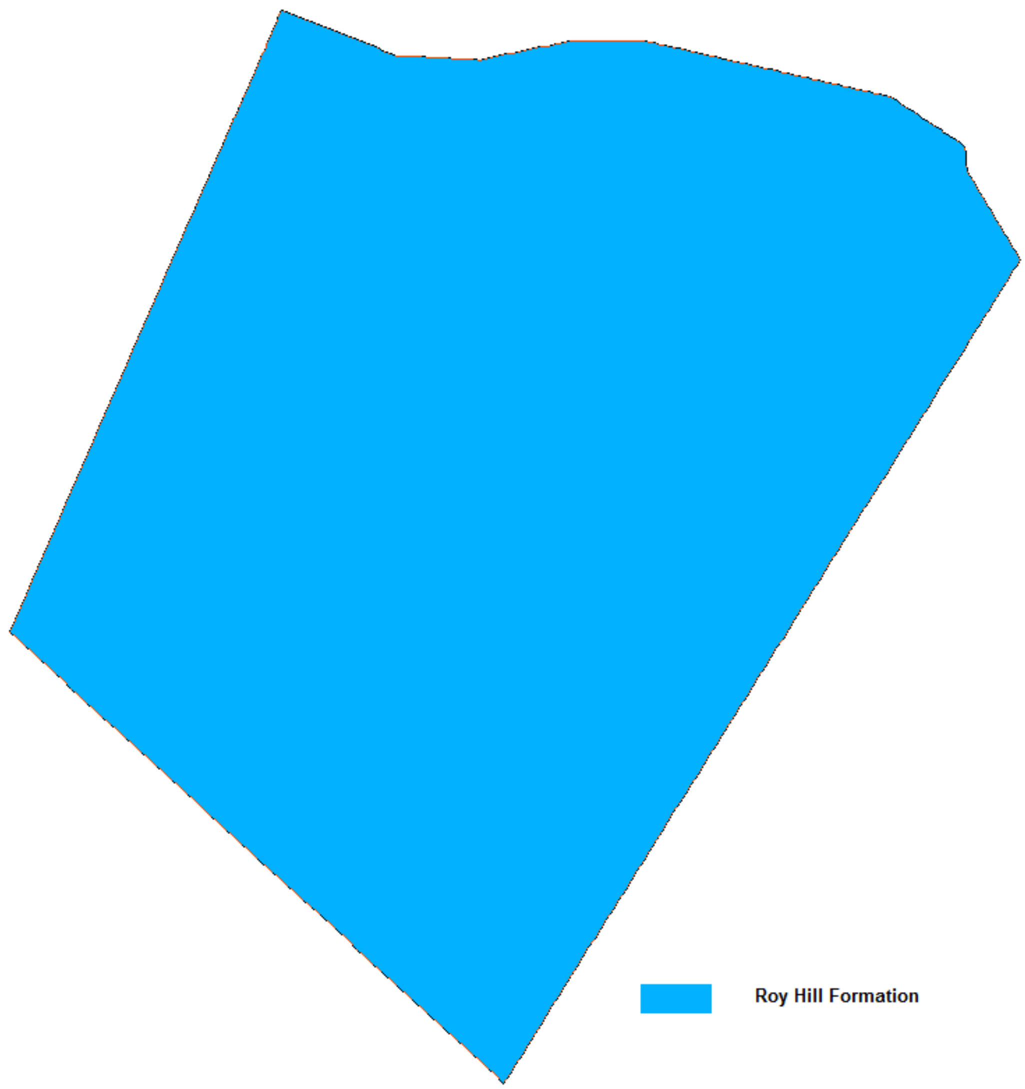
Appendix 3.7: Distribution of hydraulic property zones in numerical layers 7 and 8.



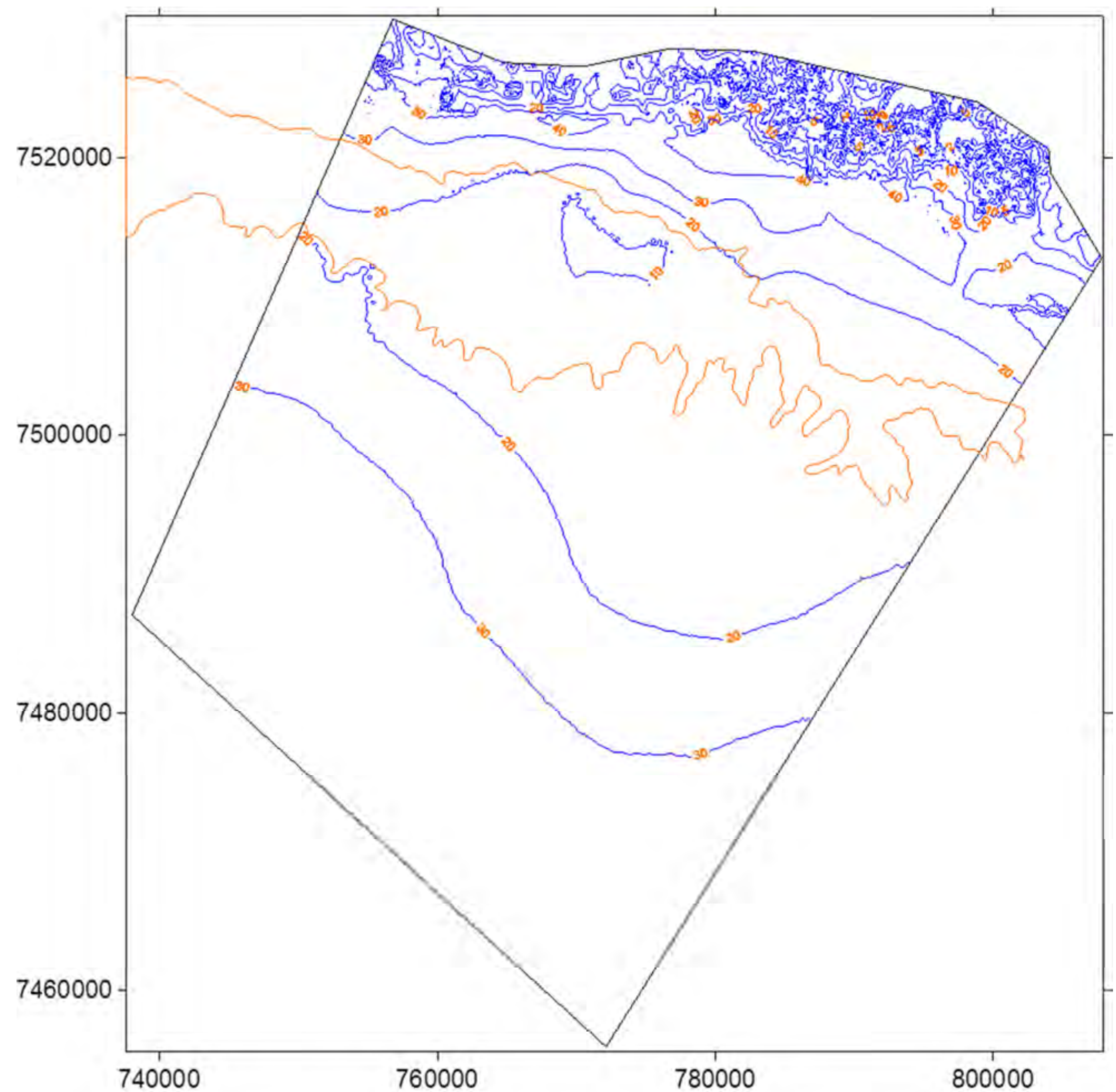
Appendix 3.8: Distribution of hydraulic property zones in numerical layer 9.



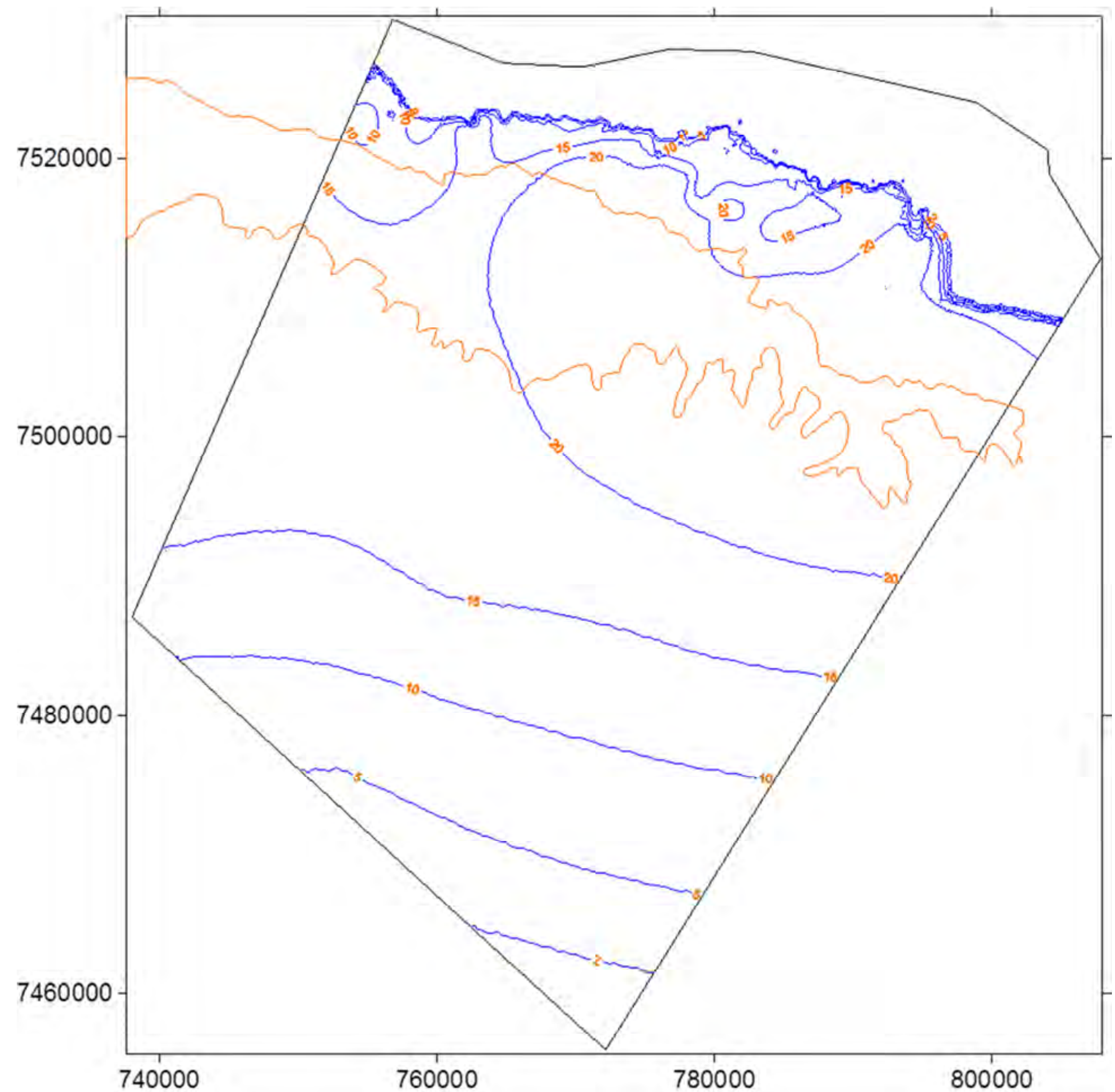
Appendix 3.9: Distribution of hydraulic property zones in numerical layer 10.



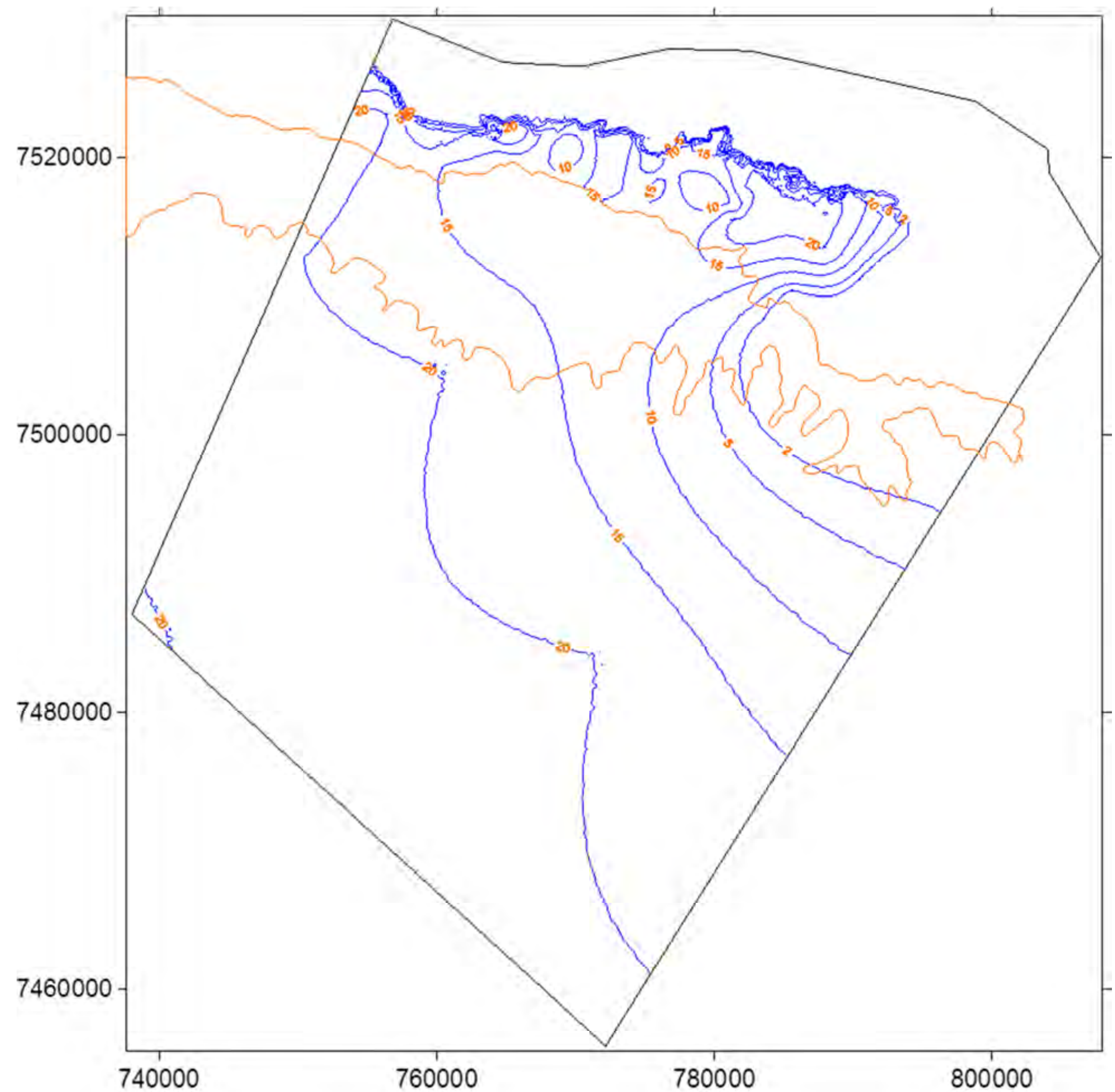
Appendix 3.10: Distribution of hydraulic property zones in numerical layer 11.



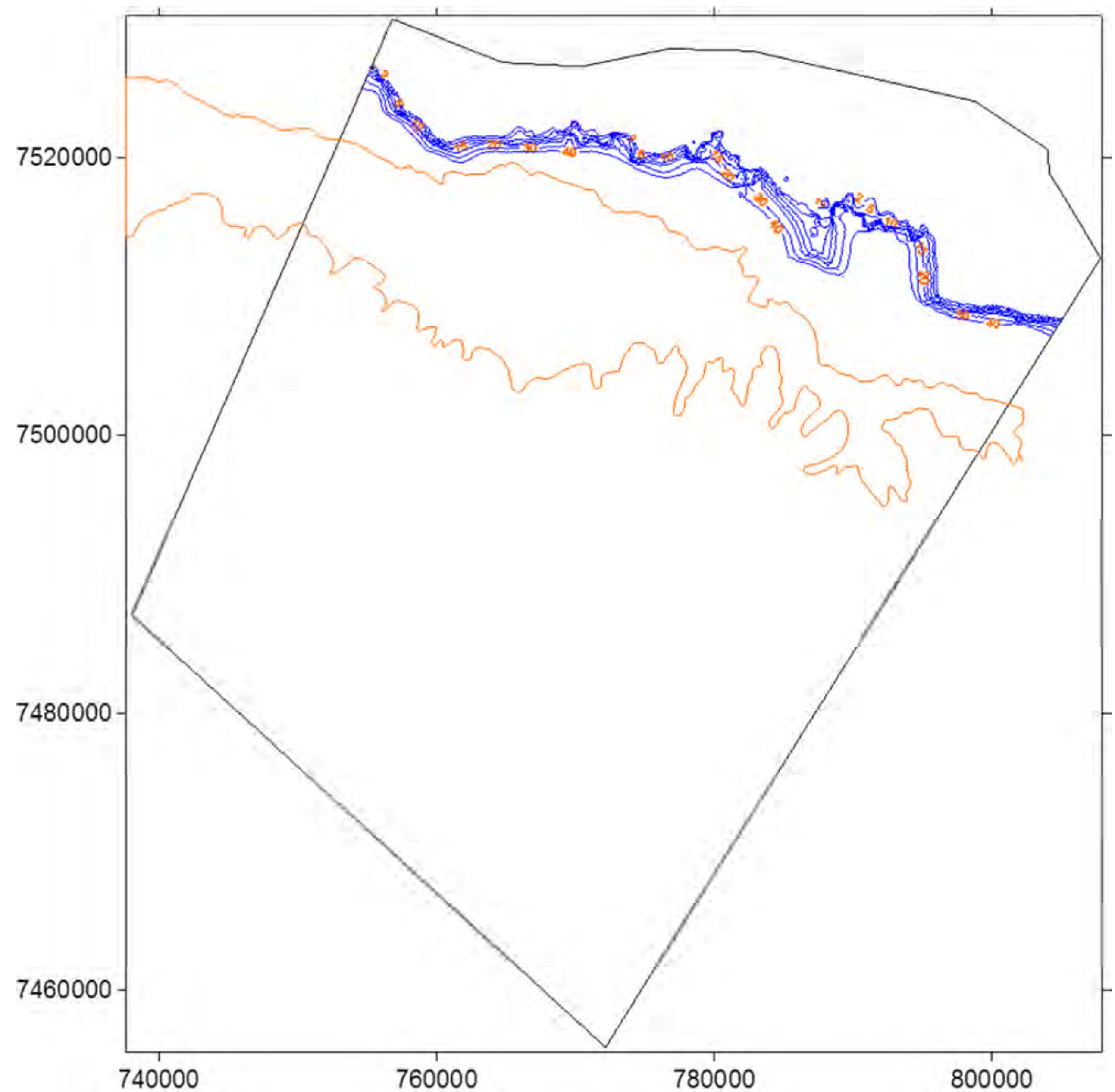
Appendix 3.11: Distribution of thickness of tertiary Detritals.



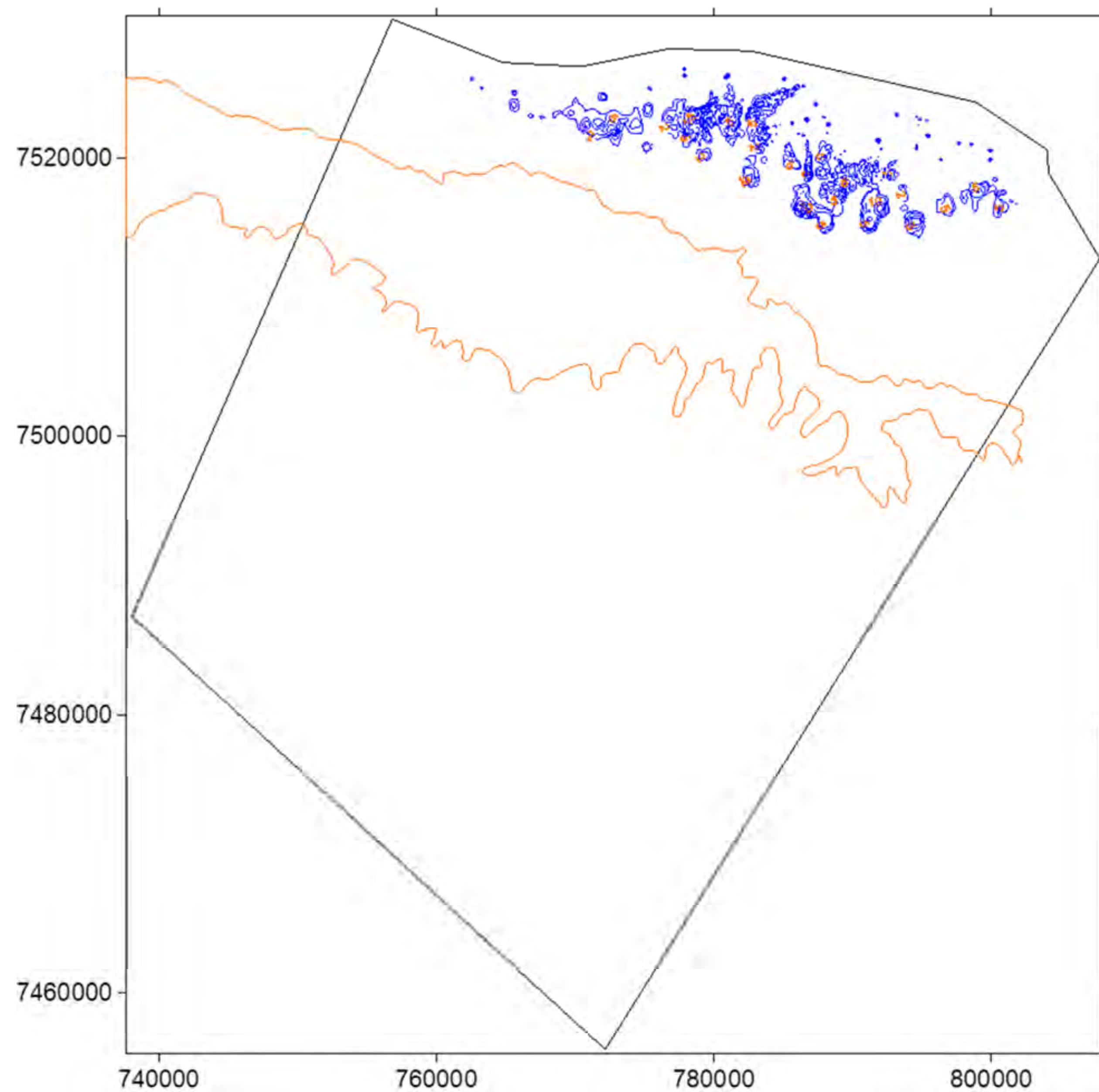
Appendix 3.12: Distribution of thickness of Alluvial Clay



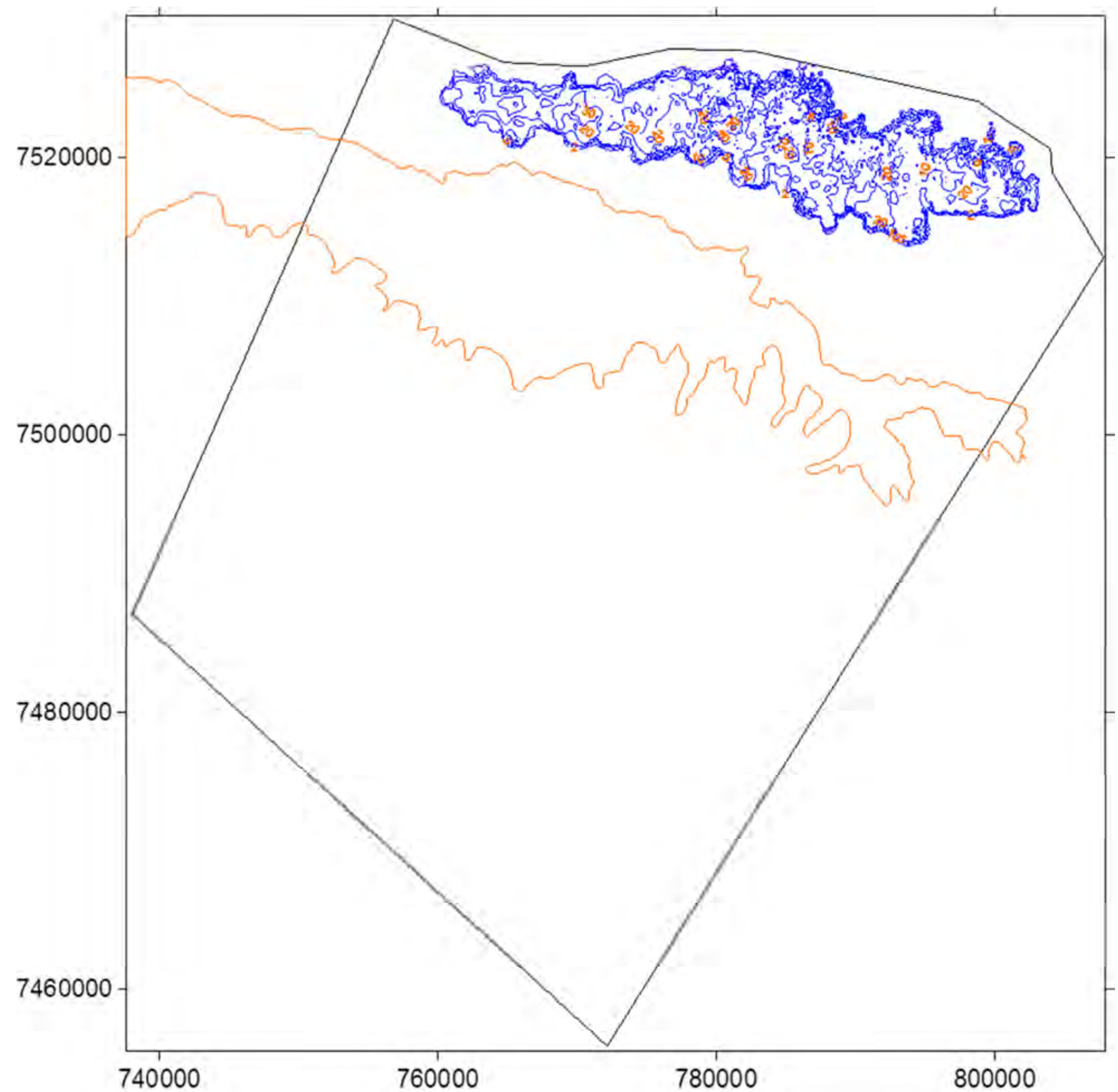
Appendix 3.13: Distribution of thickness of Oakover Formation



Appendix 3.14: Distribution of thickness of Wittenoom Formation



Appendix 3.15: Distribution of thickness of Hardcap



Appendix 3.15: Distribution of thickness of Mineralised MMB

Appendix 4: Numerical model calibration - Measured hydrographs at monitoring bores compared to those predicted by the calibrated model

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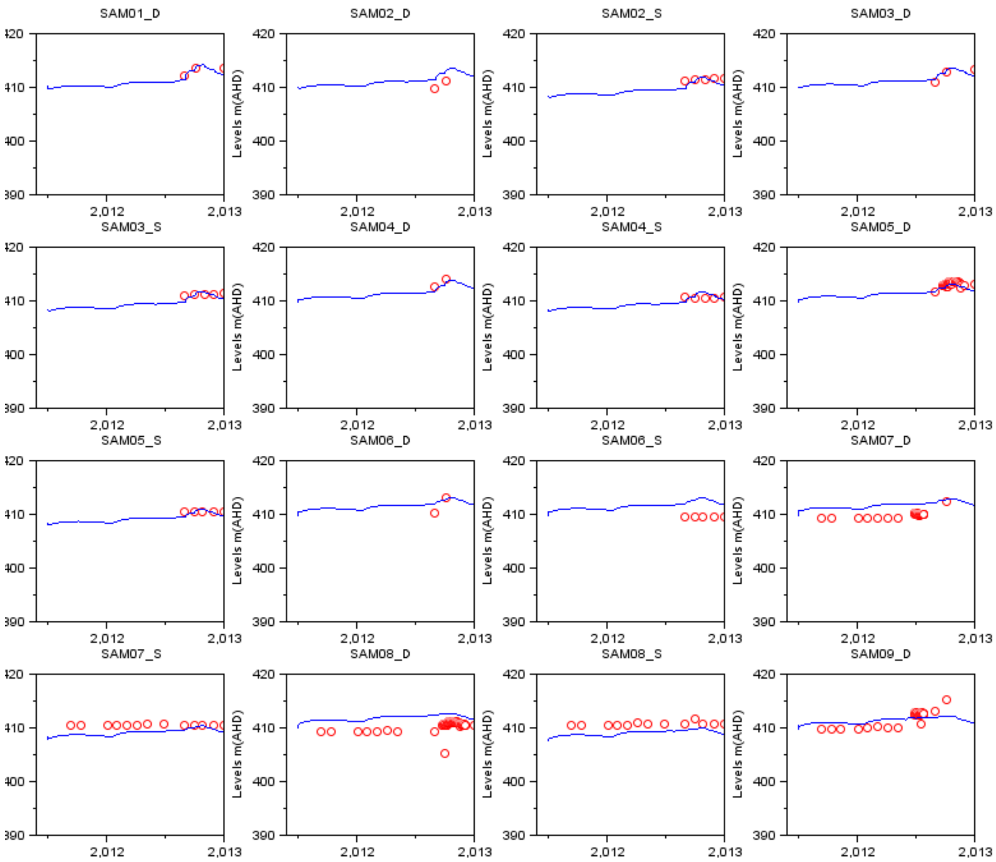
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SAM02_D
SAM02_S
SAM03_D
SAM03_S
SAM04_D
SAM04_S
SAM05_D
SAM05_S
SAM06_D
SAM06_S
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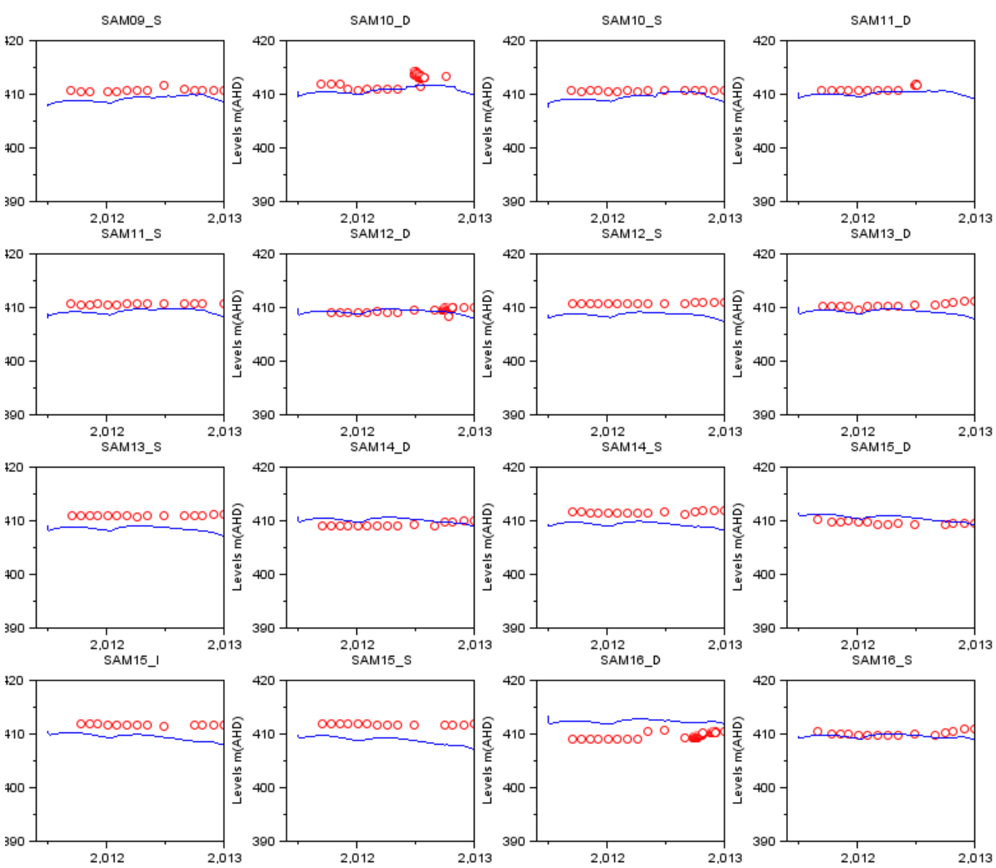
400
390
2,012
2,013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SAM10_D
SAM10_S
SAM11_D
SAM11_S
SAM12_D
SAM12_S
SAM13_D
SAM13_S
SAM14_D
SAM14_S
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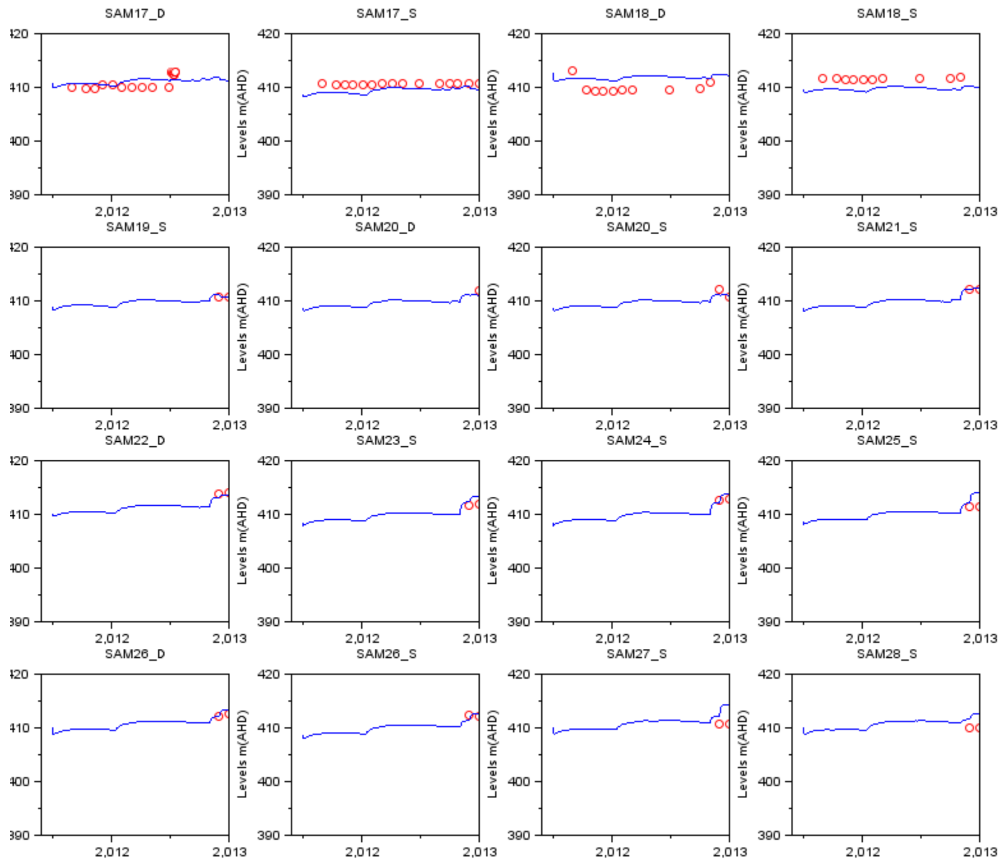
400
390
2,012
2,013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SAM18_D
SAM18_S
SAM19_S
SAM20_D
SAM20_S
SAM21_S
SAM22_D
SAM23_S
SAM24_S
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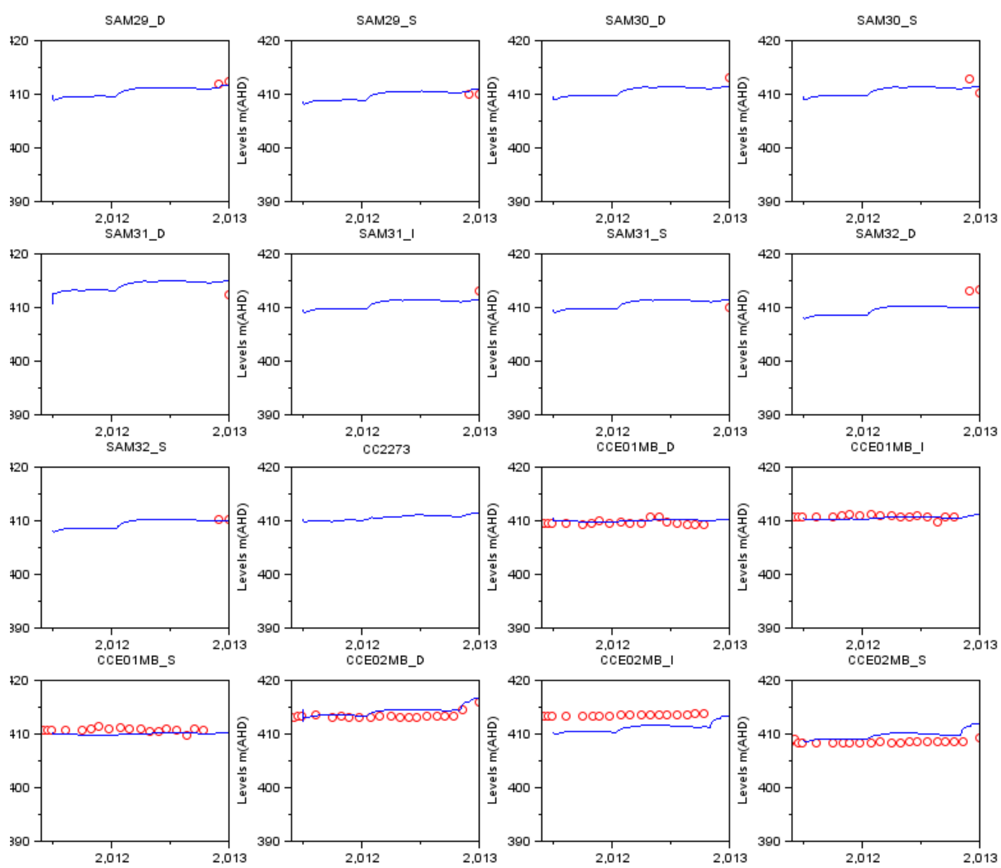
410
420
2,012
2,013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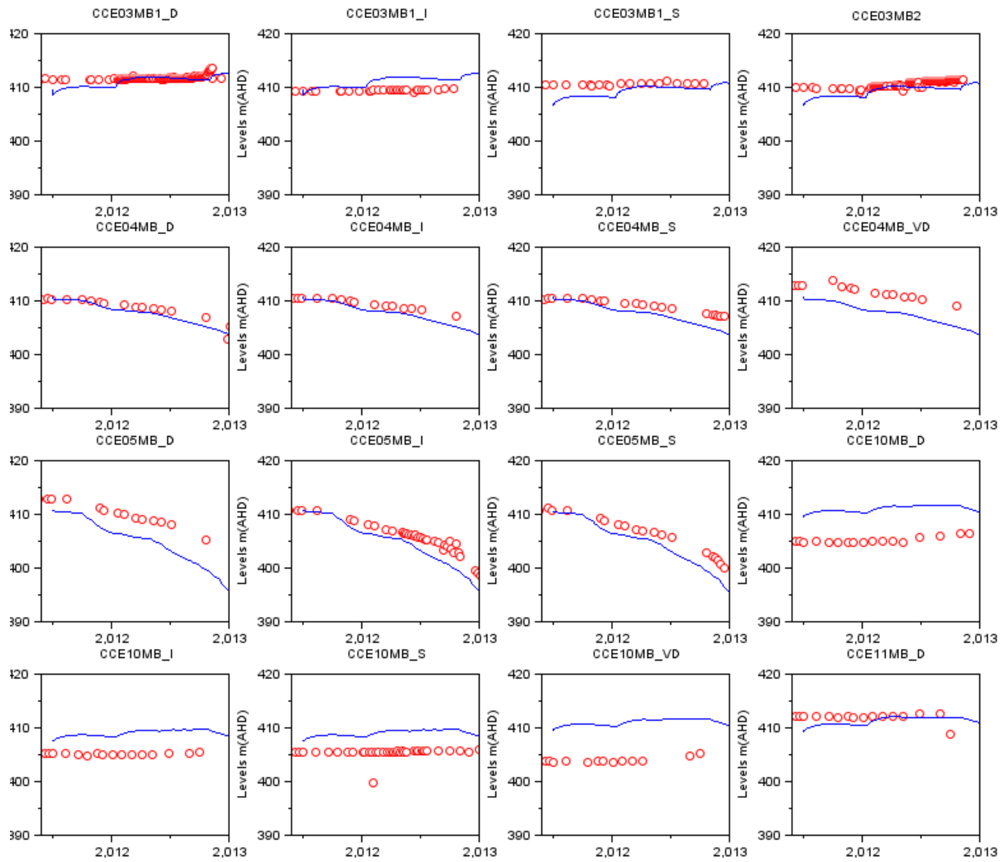
SAM29_S
SAM30_D
SAM30_S
SAM31_D
SAM31_I
SAM31_S
SAM32_D
SAM32_S
CC2273
CCE01MB_D
CCE01MB_I
CCE01MB_S
CCE02MB_D
CCE02MB_I
CCE02MB_S
Levels m(AHD)
390
400
410
420
2,012
2,013


CCE03MB1_D
CCE03MB1_I
CCE03MB1_S
CCE03MB2
CCE04MB_D
CCE04MB_I
CCE04MB_S
CCE04MB_VD
CCE05MB_D
CCE05MB_I
CCE05MB_S
CCE10MB_D
CCE10MB_I
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CCE10MB_VD
CCE11MB_D
Levels m(AHD)
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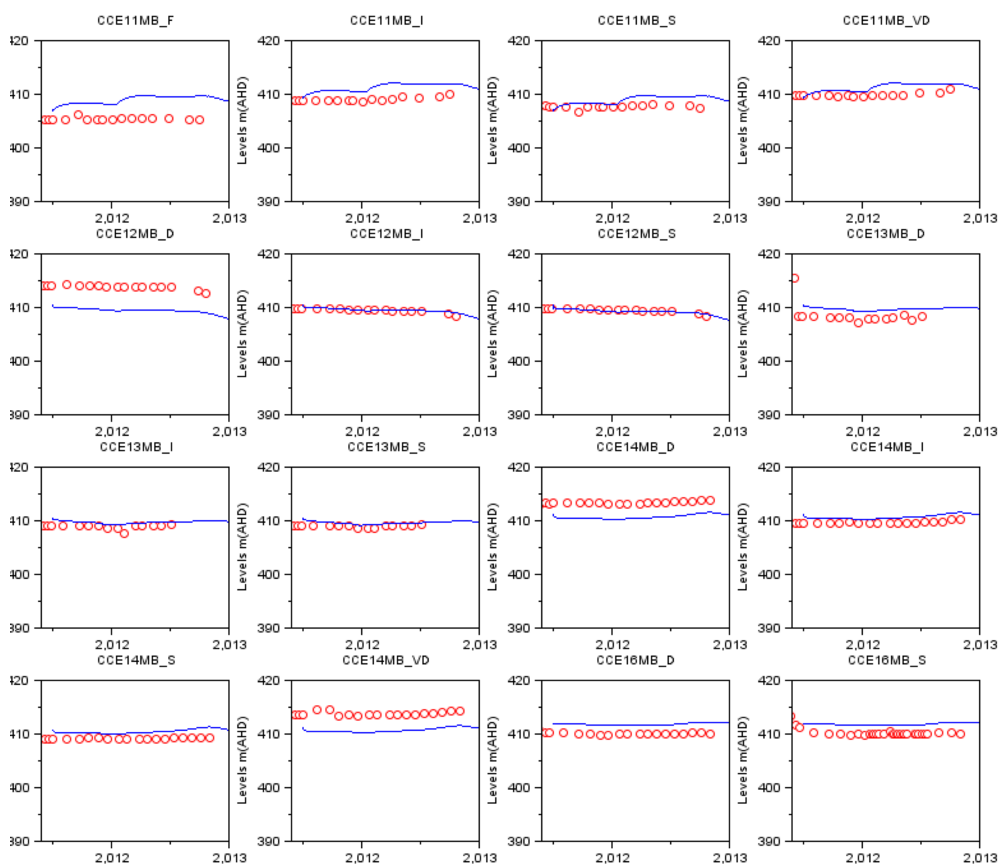
410
400
390
2,012
2,013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CCE11MB_S
CCE11MB_VD
CCE12MB_D
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CCE13MB_I
CCE13MB_S
CCE14MB_D
CCE14MB_I
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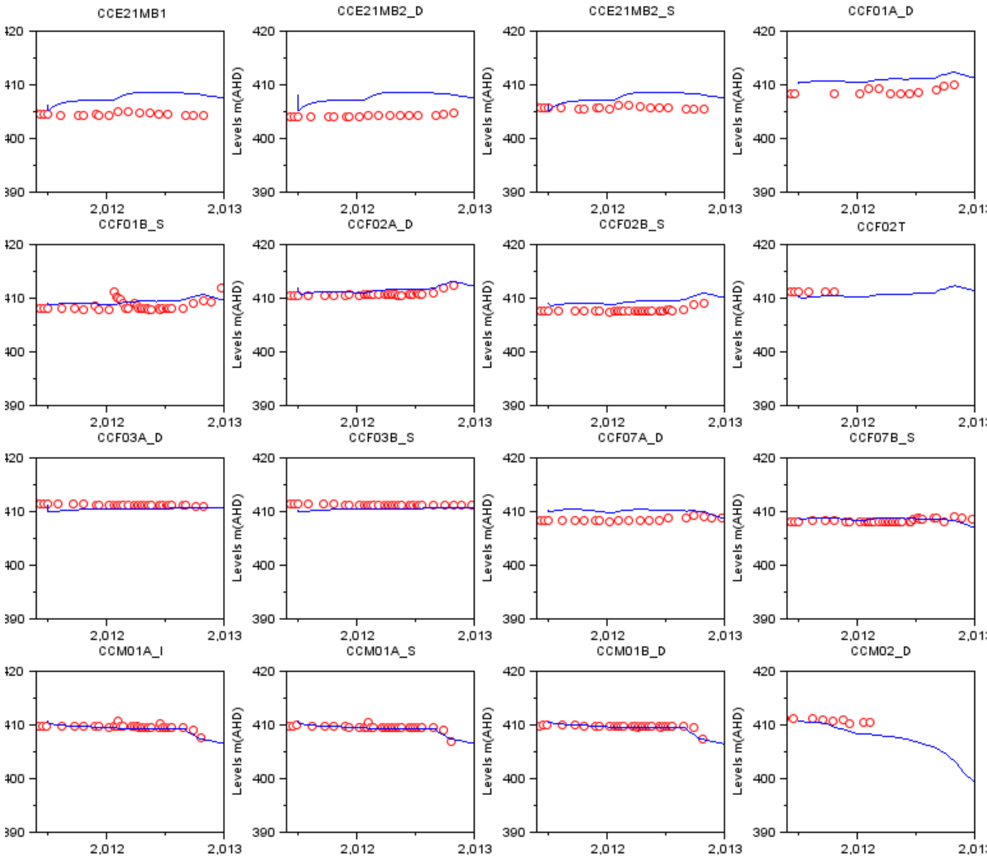
400
390
2,012
2,013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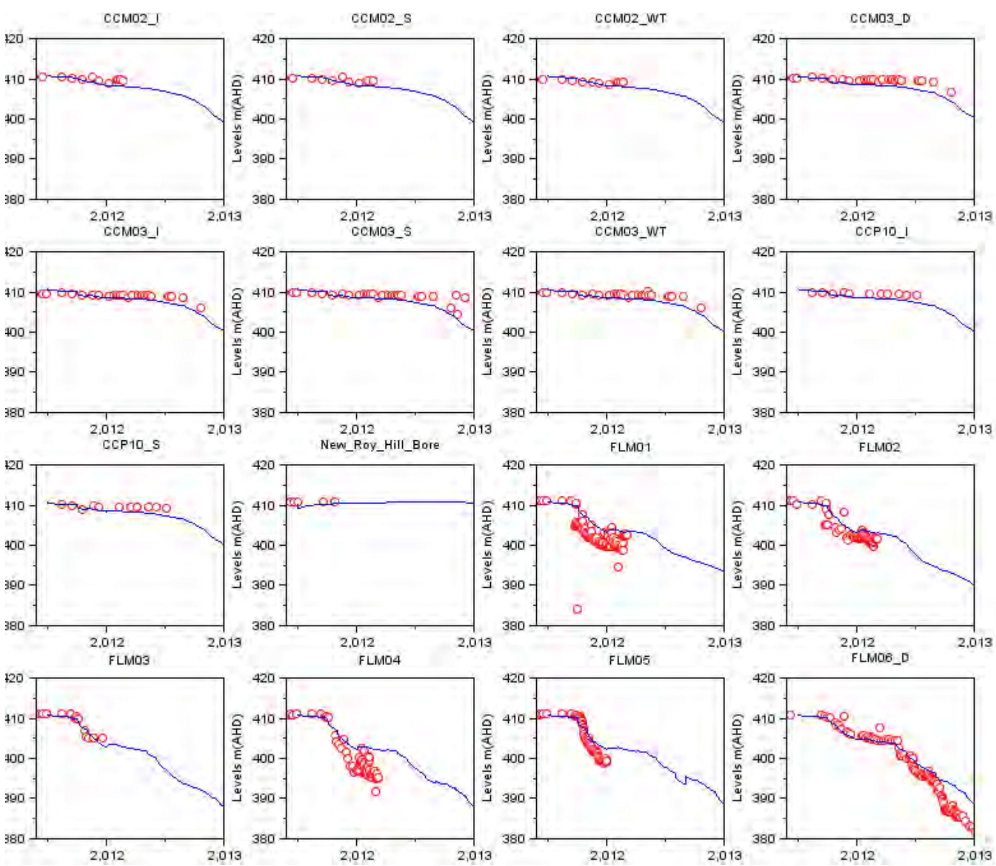
CCE21MB2_D
CCE21MB2_S
CCF01A_D
CCF01B_S
CCF02A_D
CCF02B_S
CCF02T
CCF03A_D
CCF03B_S
CCF07A_D
CCF07B_S
CCM01A_I
CCM01A_S
CCM01B_D
CCM02_D
Levels m(AHD)
420
410
400
390
2,012
2,013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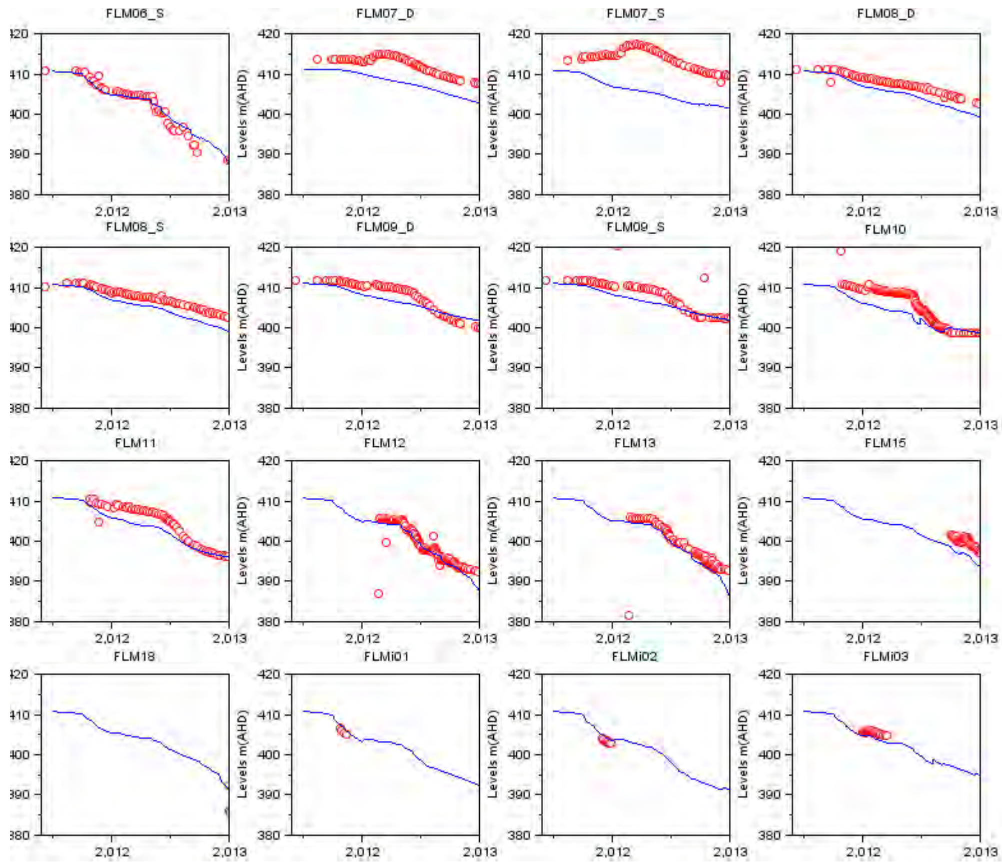
CCM02_S
CCM02_WT
CCM03_D
CCM03_I
CCM03_S
CCM03_WT
CCP10_I
CCP10_S
New_Roy_Hill_Bore
FLM01
FLM02
FLM03
FLM04
FLM05
FLM06_D
Levels m(AHD)
420
410
400
390
380
2,012
2,013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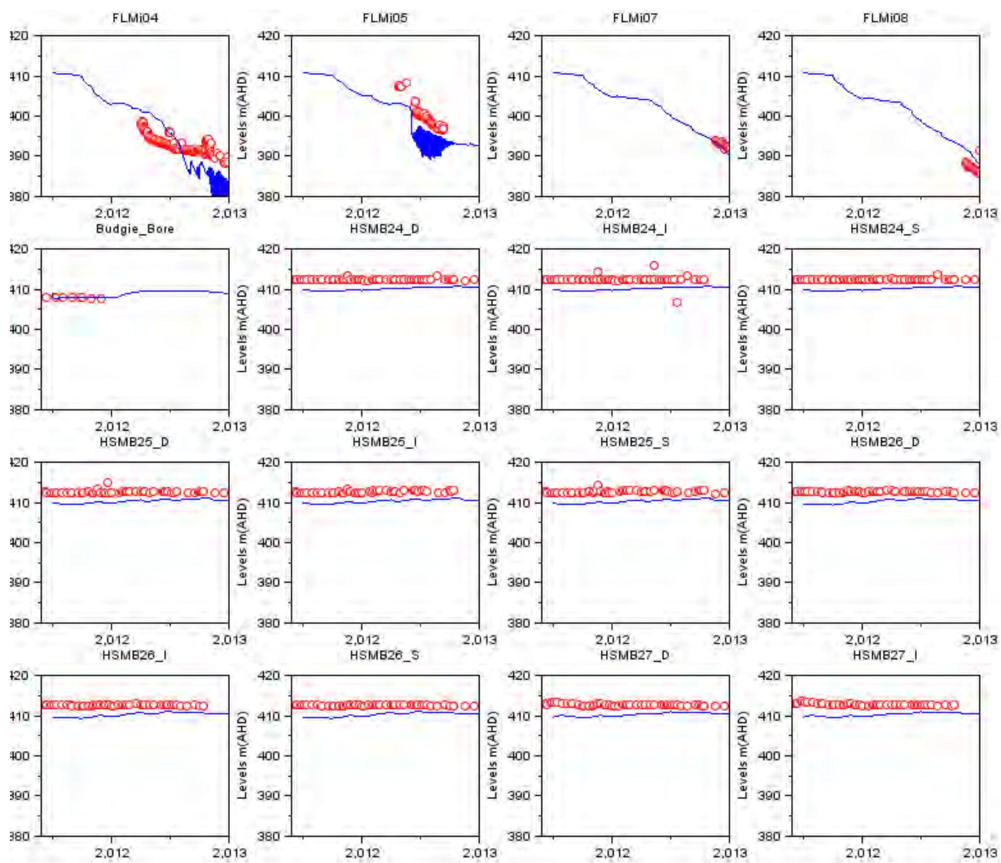
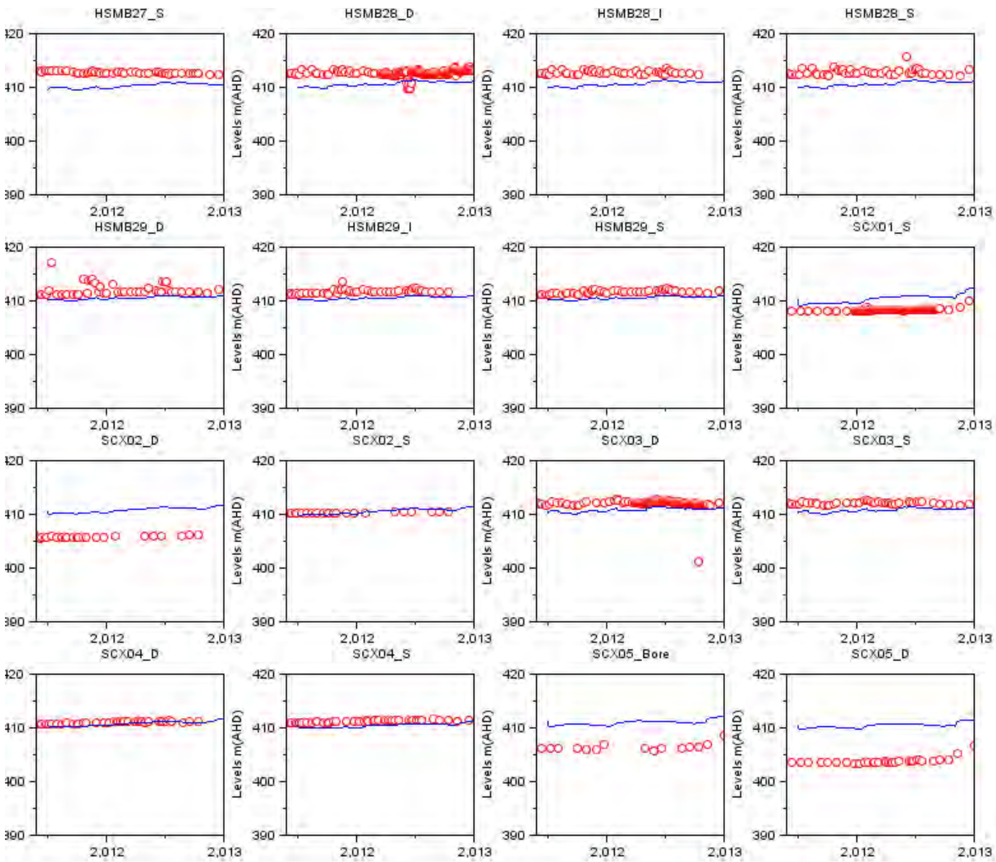
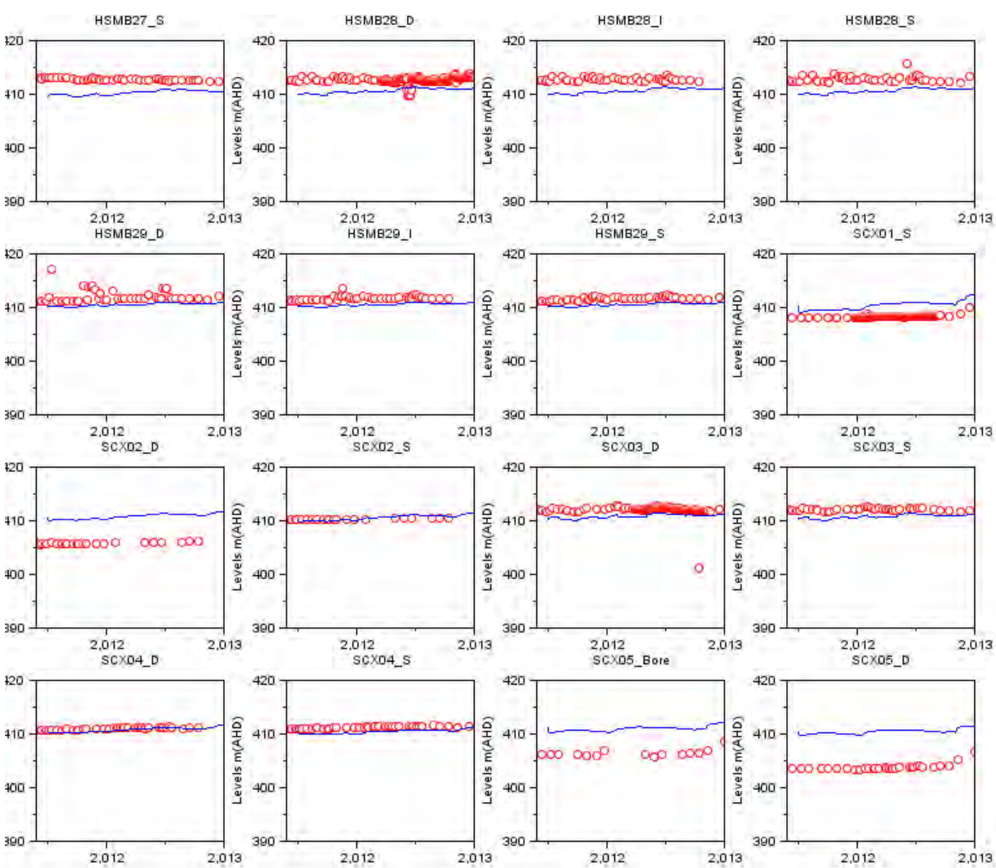
FLM08_S
FLM09_D
FLM09_S
FLM10
FLM11
FLM12
FLM13
FLM15
FLM18
FLMi01
FLMi02
FLMi03
Levels m(AHD)
420
410
400
390
380
2,012
2,013


FLMi04
FLMi05
FLMi07
FLMi08
Budgie_Bore
HSMB24_D
HSMB24_I
HSMB24_S
HSMB25_D
HSMB25_I
HSMB25_S
HSMB26_D
HSMB26_I
HSMB26_S
HSMB27_D
HSMB27_I
Levels m(AHD)
420
410
400
390
380
2,012
2,013

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HSMB28_I
HSMB28_S
HSMB29_D
HSMB29_I
HSMB29_S
SCX01_S
SCX02_D
SCX02_S
SCX03_D
SCX03_S
SCX04_D
SCX04_S
SCX05_Bore
SCX05_D
Levels m(AHD)
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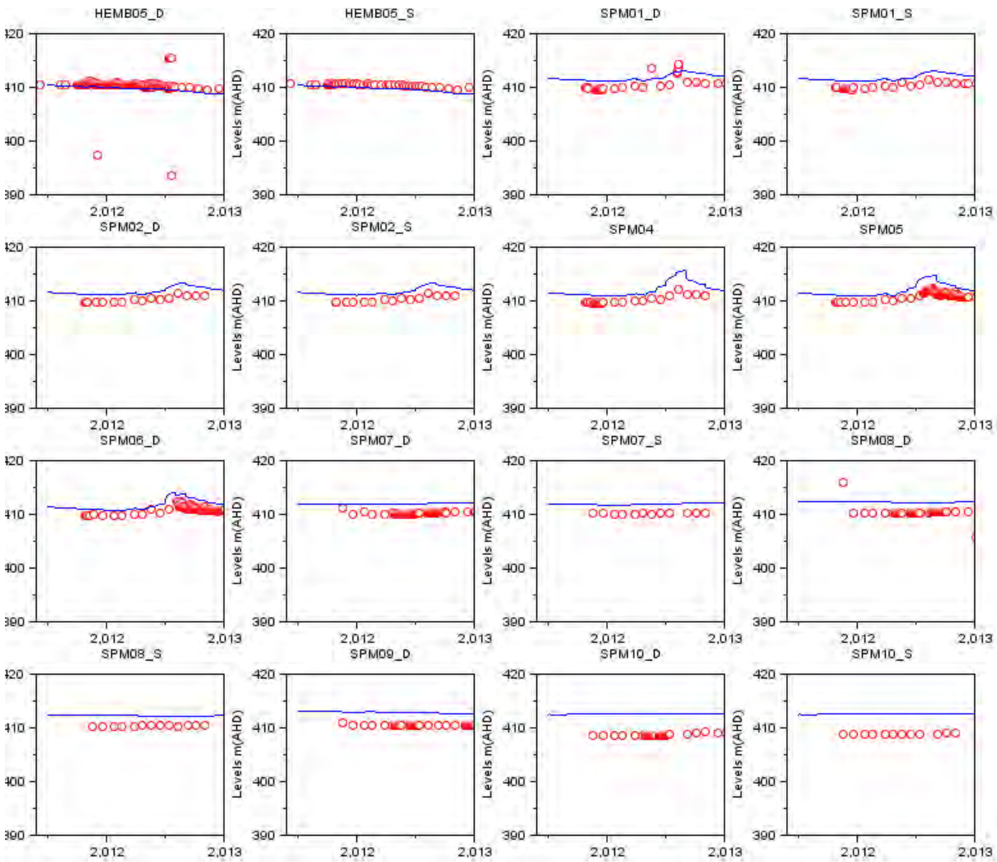
410
400
390
2,012
2,013


HEMB05_D
HEMB05_S
SPM01_D
SPM01_S
SPM02_D
SPM02_S
SPM04
SPM05
SPM06_D
SPM07_D
SPM07_S
SPM08_D
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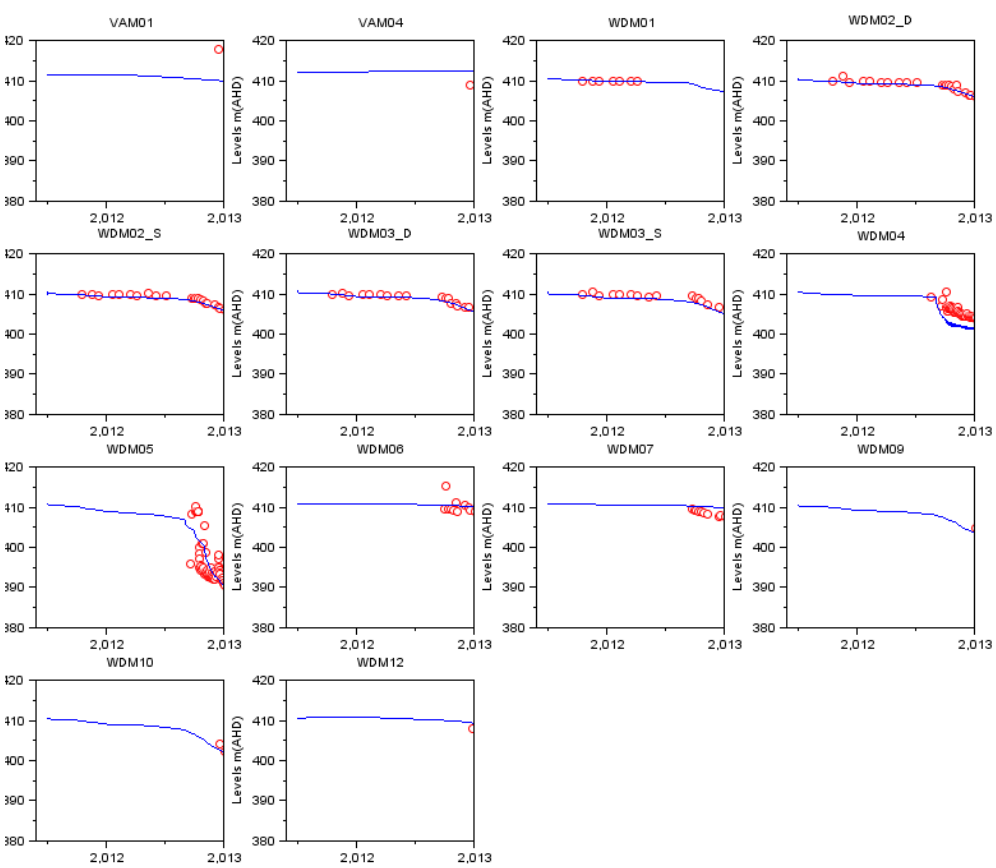
400
390
2,012
2,013


VAM01
VAM04
WDM01
WDM02_D
WDM02_S
WDM03_D
WDM03_S
WDM04
WDM05
WDM06
WDM07
WDM09
WDM10
WDM12
Levels m(AHD)
420
410
400
390
380
2,012
2,013

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Appendix 5: Hydrographs at selected key locations from all sensitivity simulations

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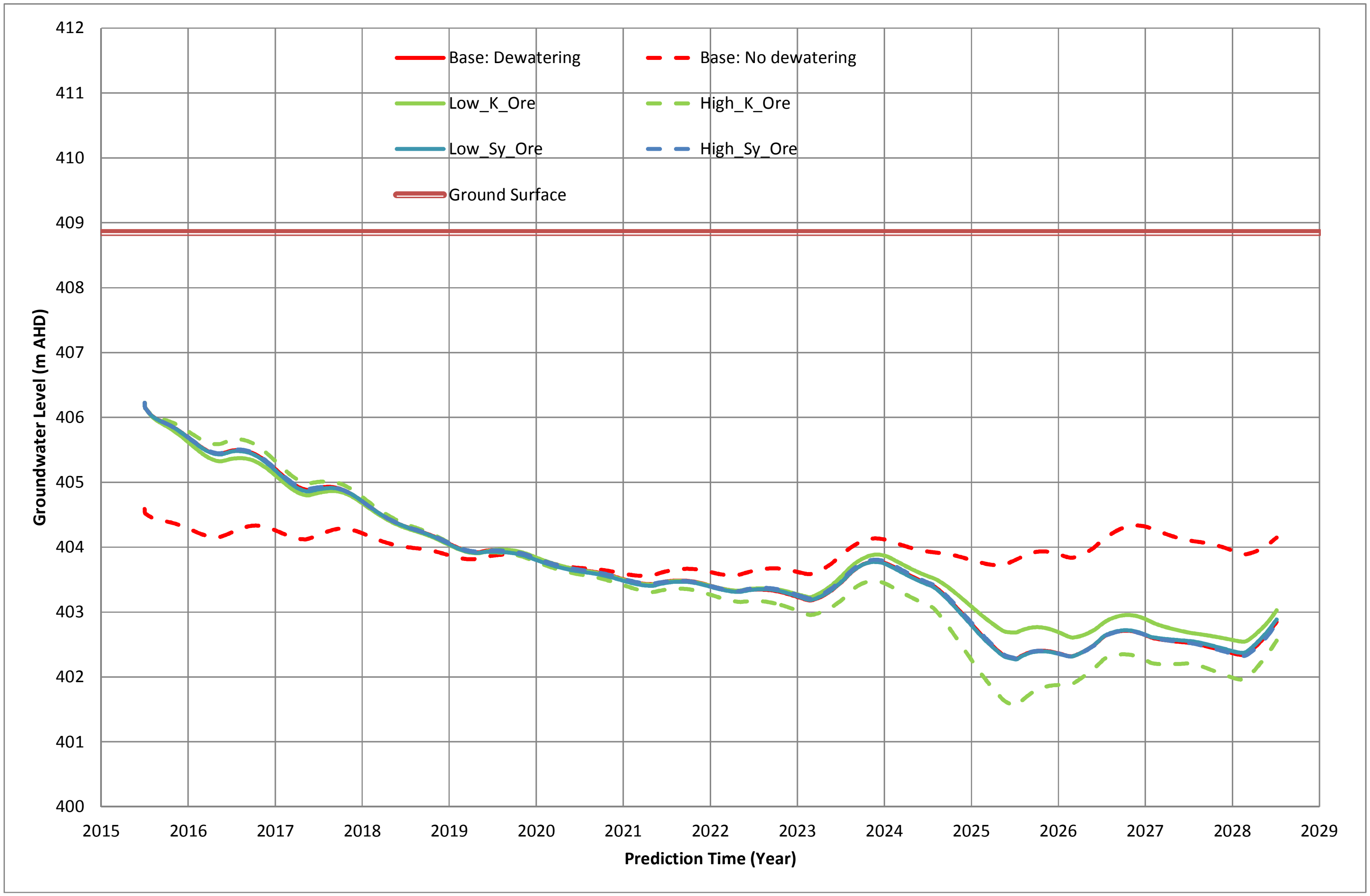
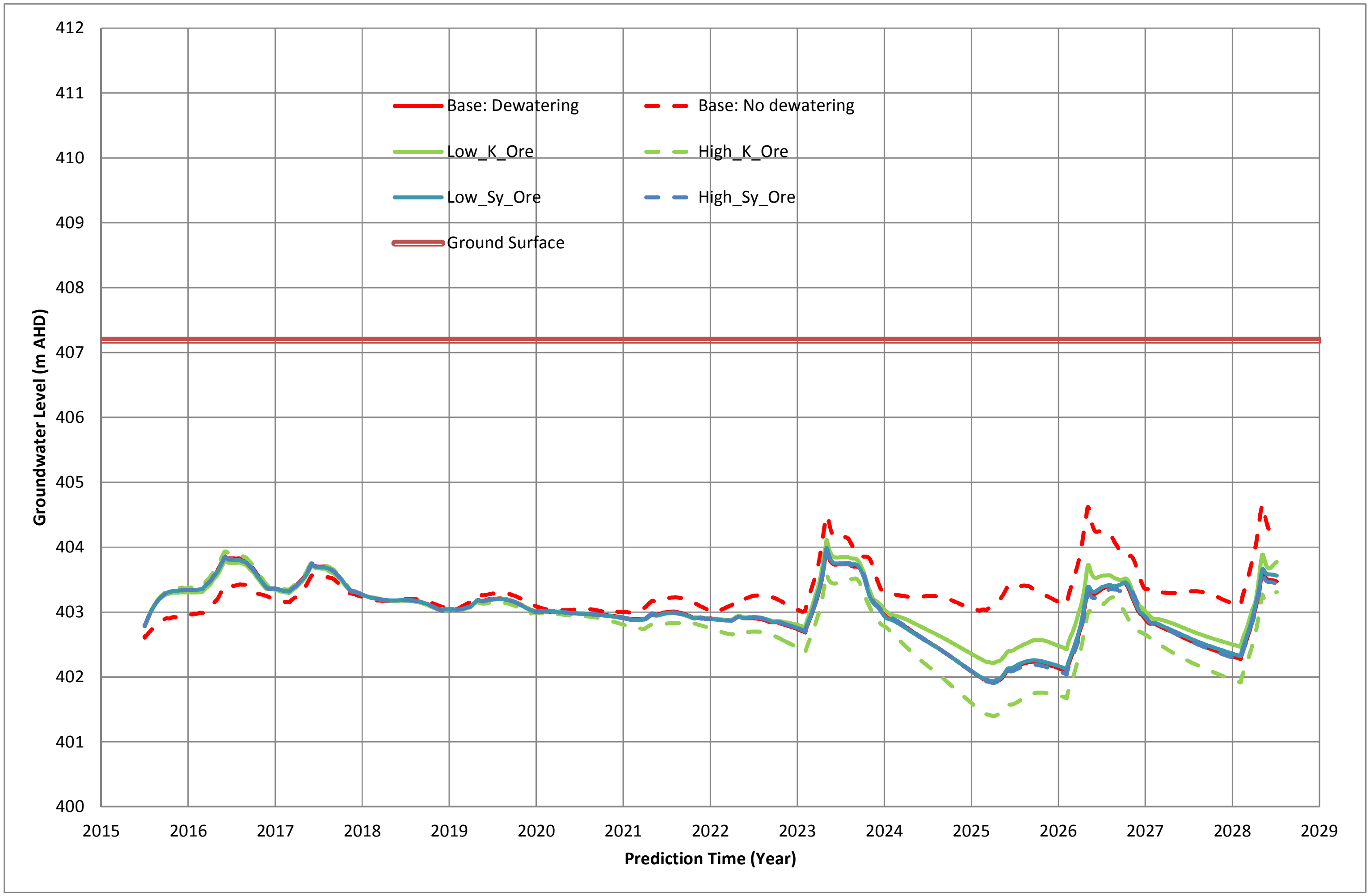
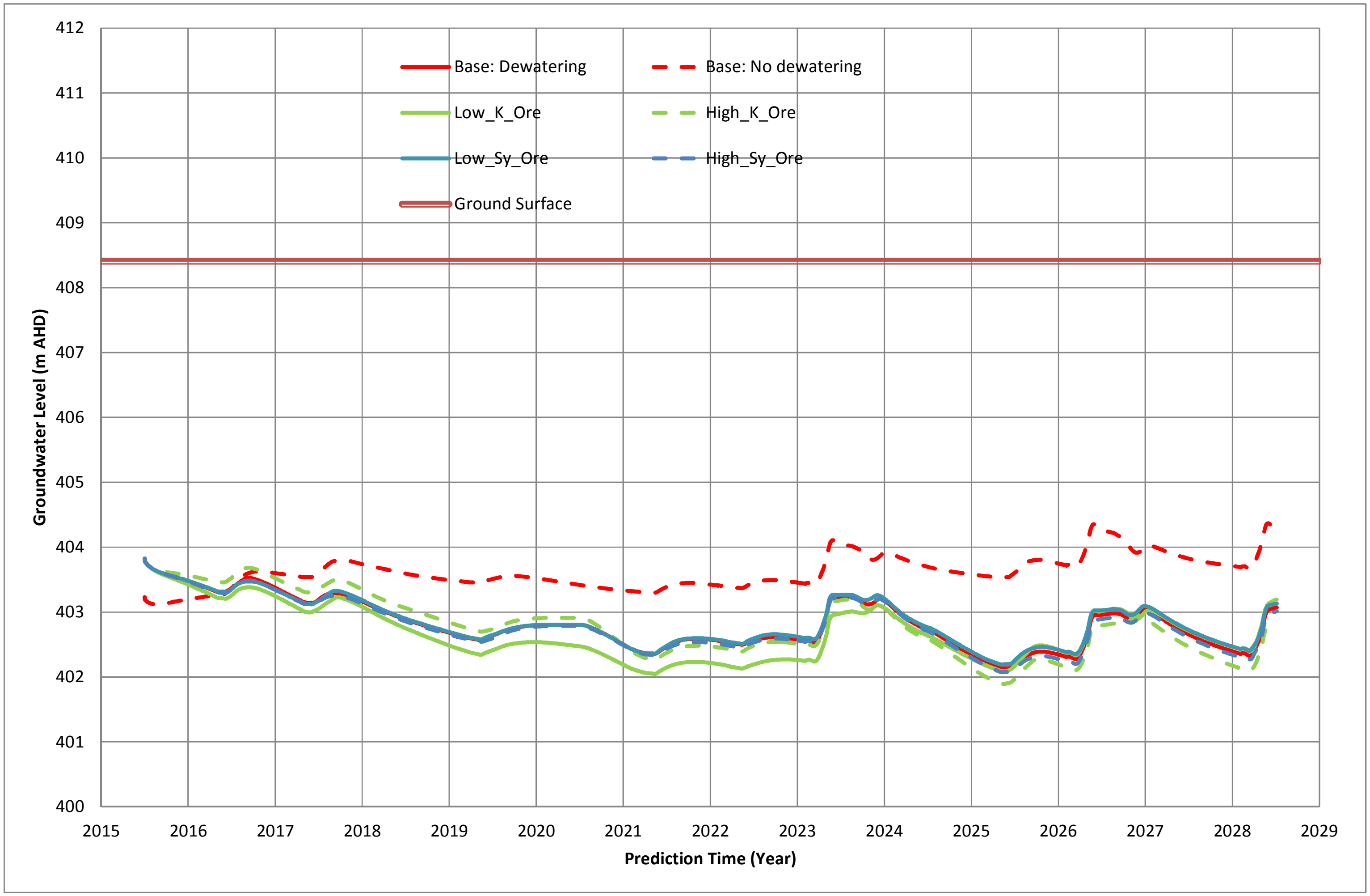


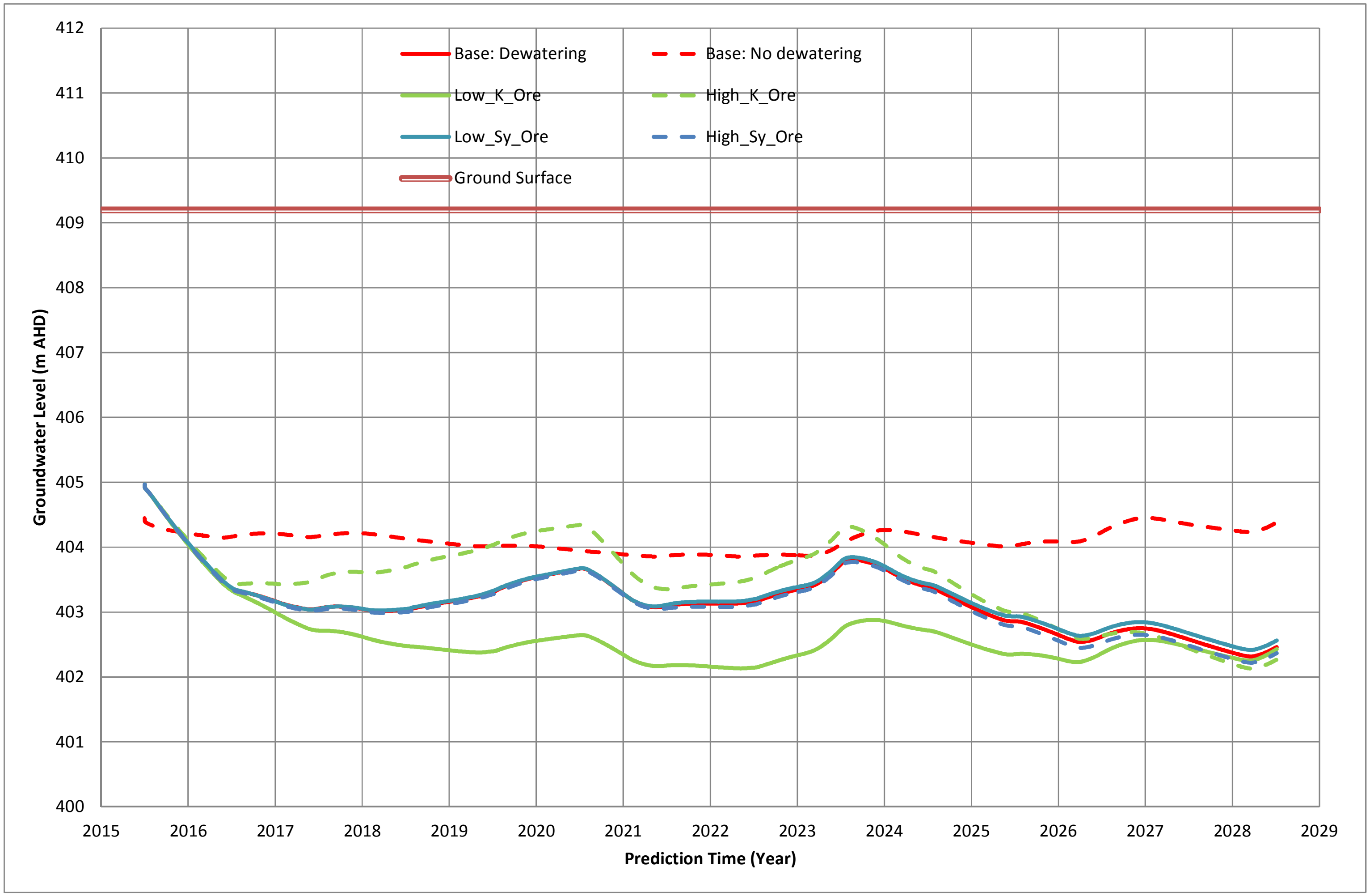
Appendix 5.1: Predicted hydrographs at CCFM01 as affected by hydraulic properties of the mineralised MMB (ore).



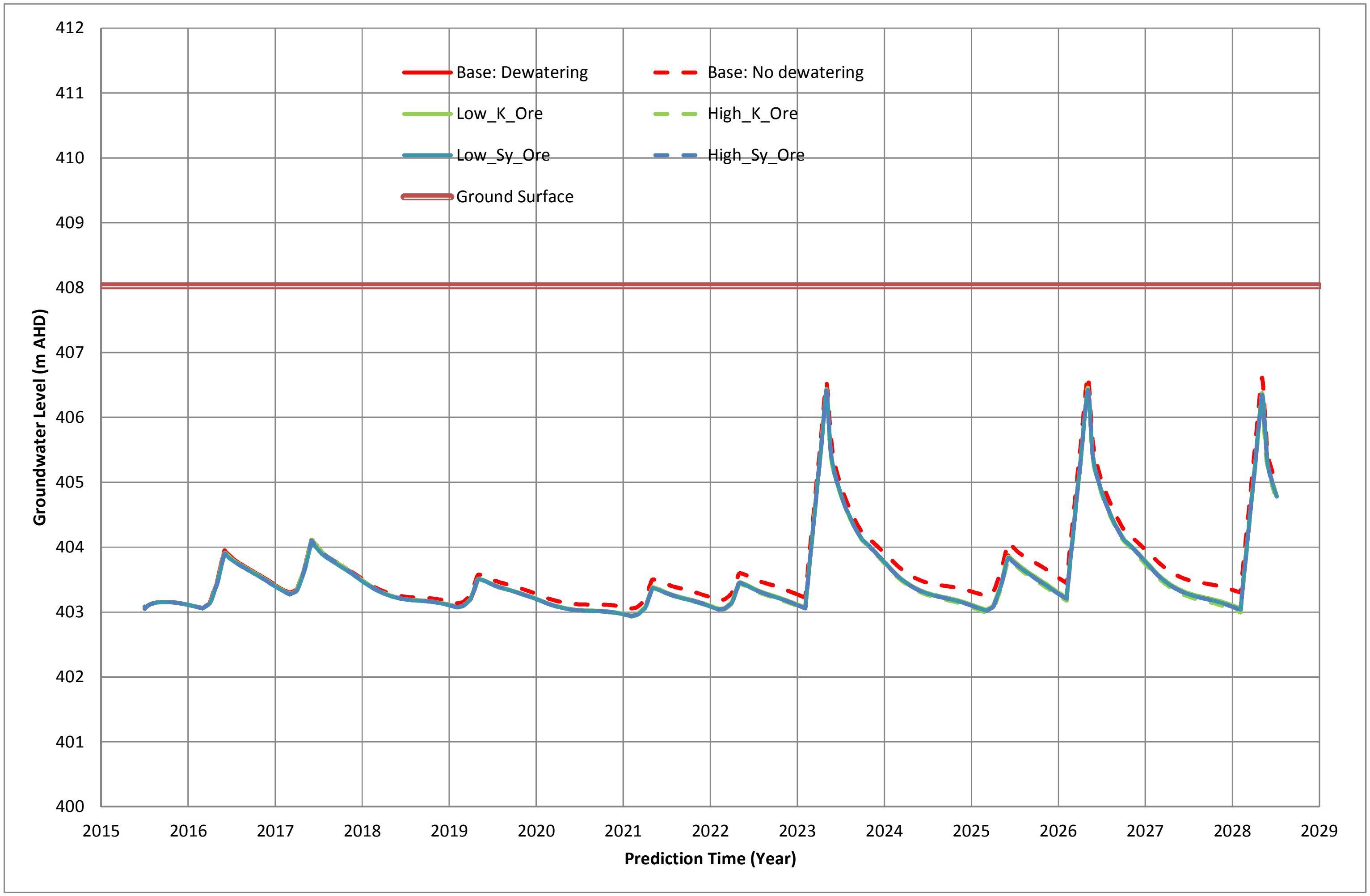
Appendix 5.2: Predicted hydrographs at CCFM02 as affected by hydraulic properties of the mineralised MMB (ore).



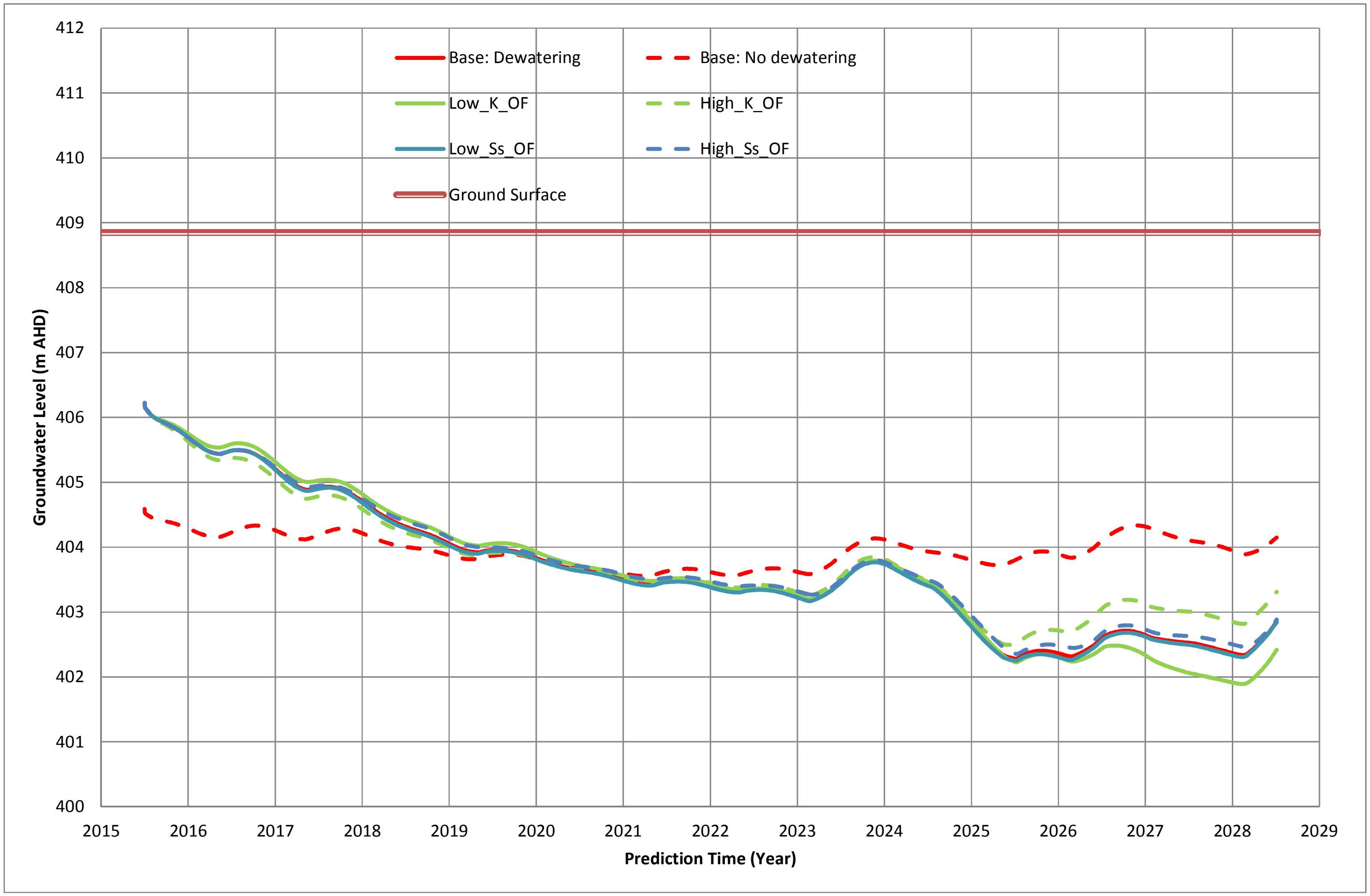
Appendix 5.3: Predicted hydrographs at CCFM03 as affected by hydraulic properties of the mineralised MMB (ore).



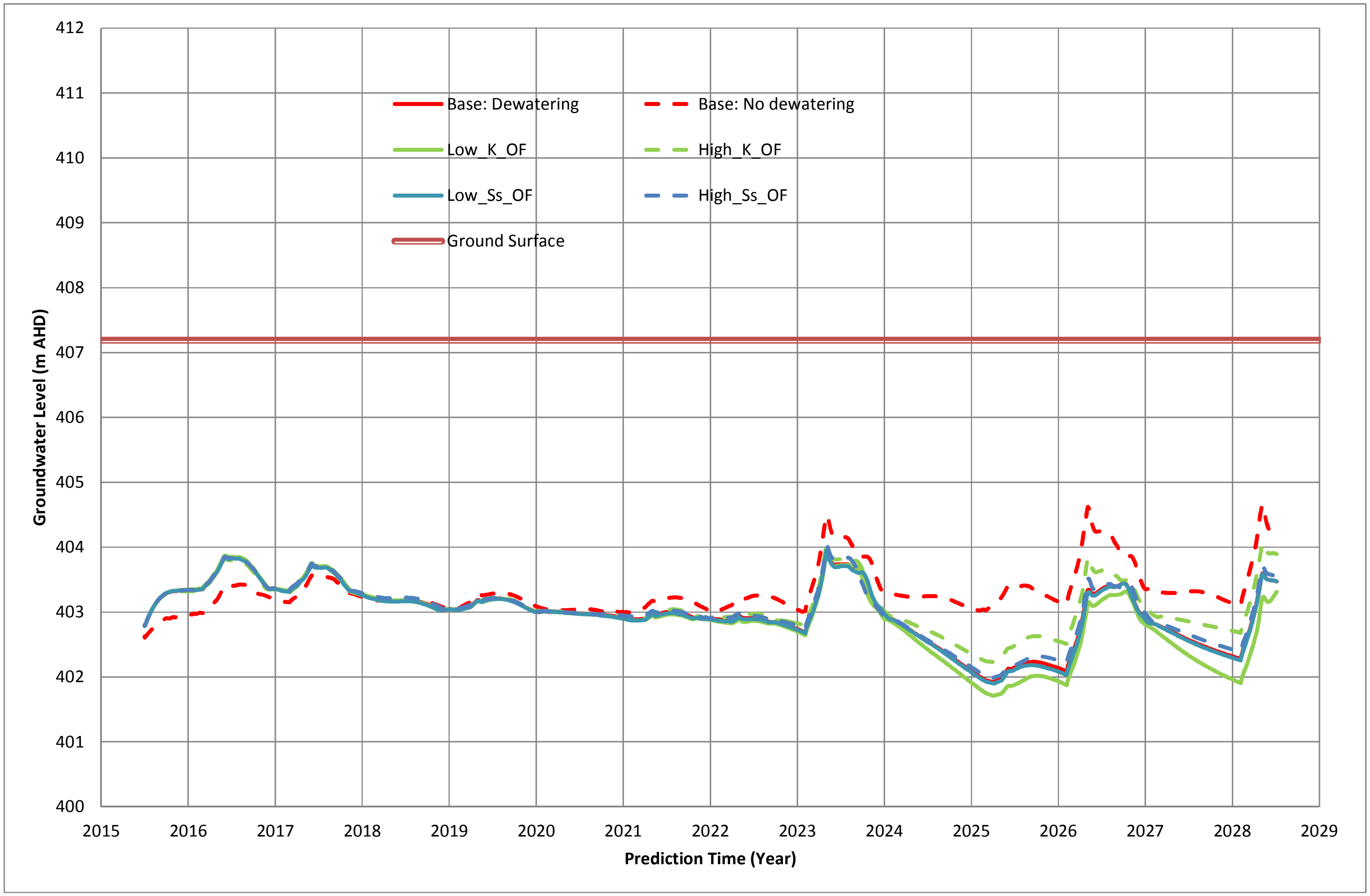
Appendix 5.4: Predicted hydrographs at CCFM04 as affected by hydraulic properties of the mineralised MMB (ore).



Appendix 5.5: Predicted hydrographs at CCFM05 as affected by hydraulic properties of the mineralised MMB (ore).

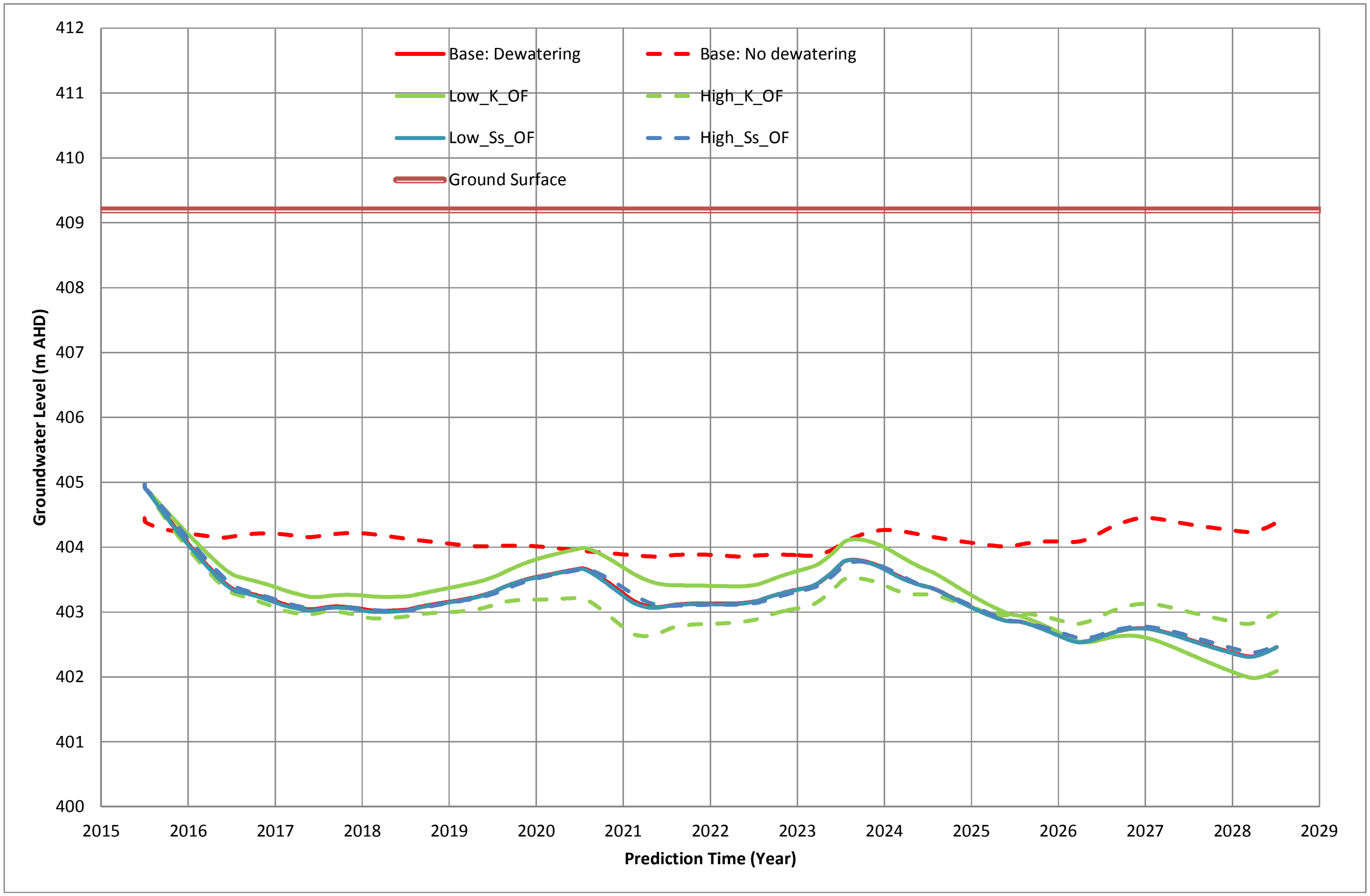


Appendix 5.6: Predicted hydrographs at CCFM01 as affected by hydraulic properties of the Oakover Formation.

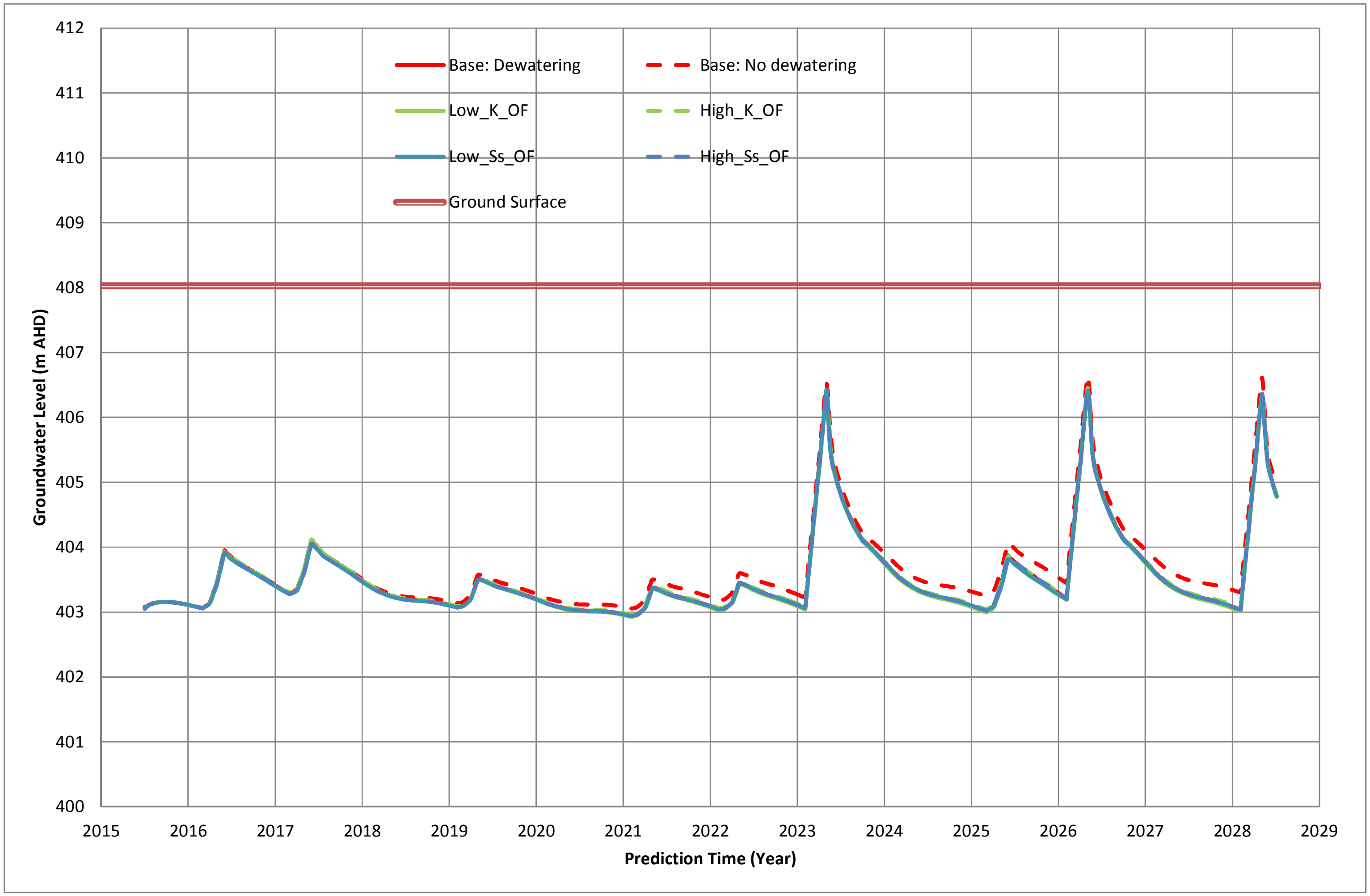


Appendix 5.7: Predicted hydrographs at CCFM02 as affected by hydraulic properties of the Oakover Formation.

Appendix 5.8: Predicted hydrographs at CCFM03 as affected by hydraulic properties of the Oakover Formation.



Appendix 5.9: Predicted hydrographs at CCFM04 as affected by hydraulic properties of the Oakover Formation.



Appendix 5.10: Predicted hydrographs at CCFM05 as affected by hydraulic properties of the Oakover Formation.

Appendix 6: Distribution of drawdown/mounding and depth to groundwater predicted under dry and wet climatic simulations

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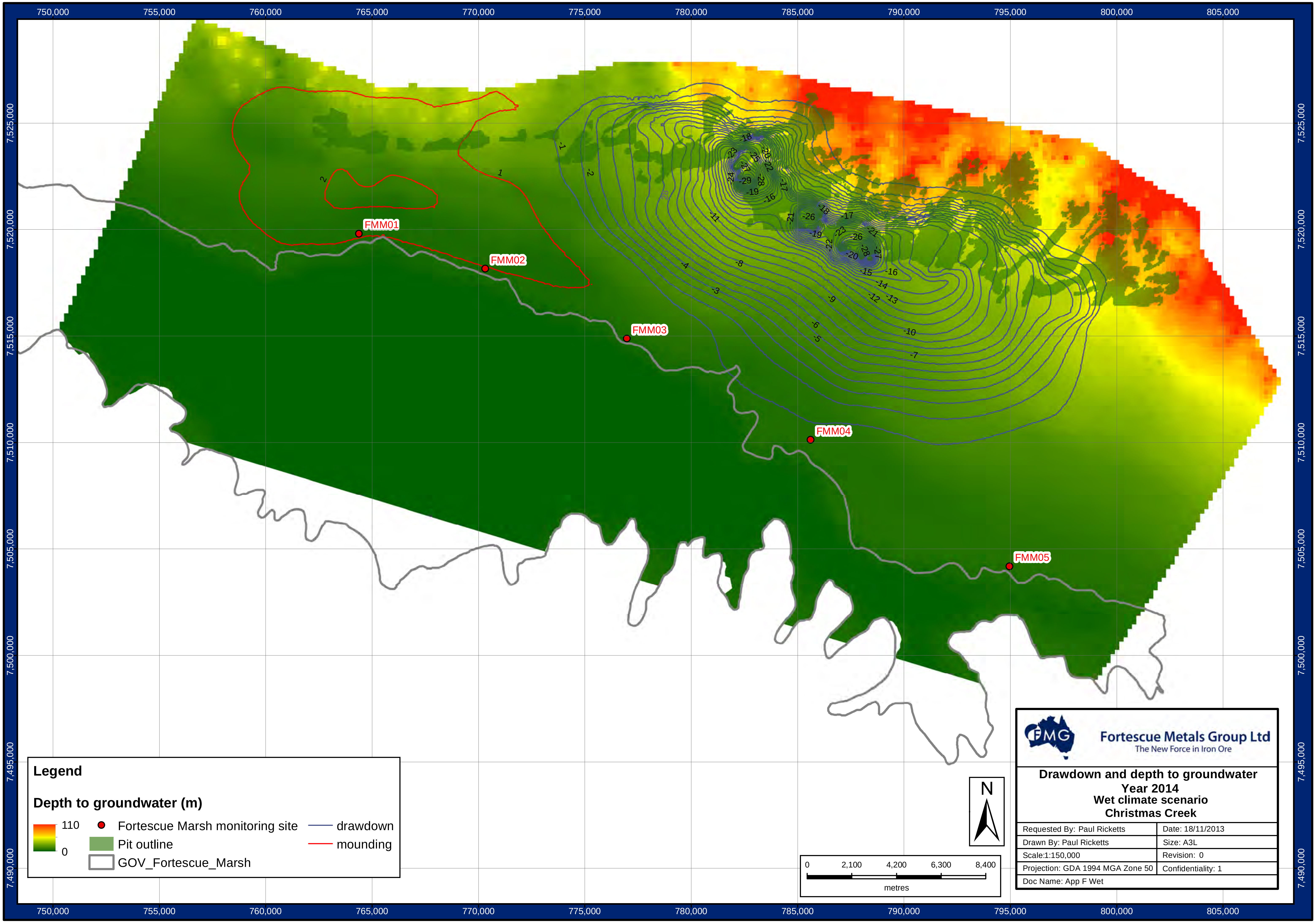
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755,000
760,000
765,000
770,000
775,000
780,000
785,000
790,000
795,000
800,000
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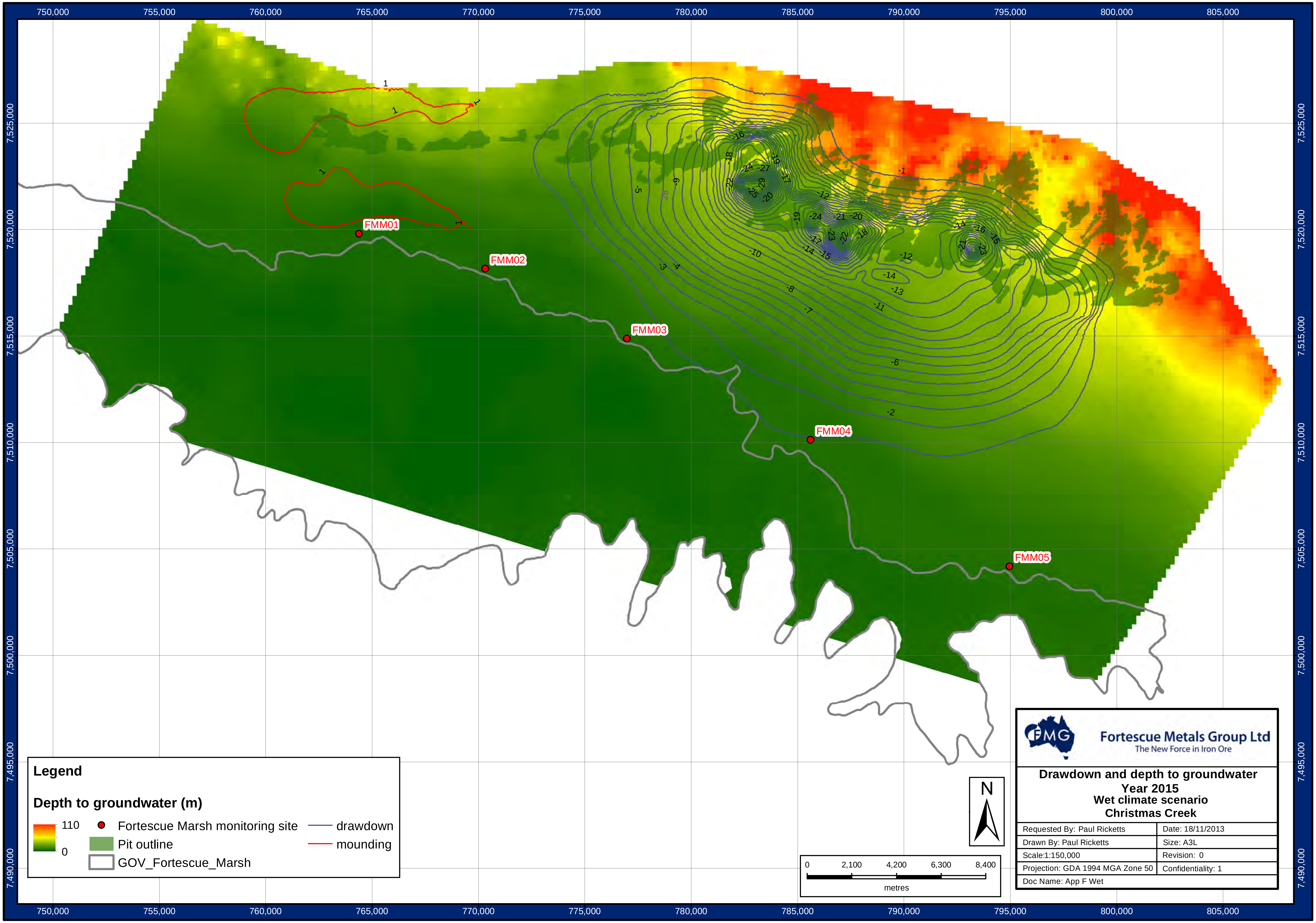
7,525,000
7,520,000
7,515,000
7,510,000
7,505,000
7,500,000
7,495,000
7,490,000
FMM01
FMM02
FMM03
FMM04
FMM05
Legend
Depth to groundwater (m)
110
0
Fortescue Marsh monitoring site
Pit outline
GOV_Fortescue_Marsh
drawdown
mounding
N
0
2,100
4,200
6,300
8,400
metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2014
Wet climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 18/11/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
Doc Name: App F Wet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765,000
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795,000
800,000
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7,520,000
7,515,000
7,510,000
7,505,000
7,500,000
7,495,000
7,490,000
FMM01
FMM02
FMM03
FMM04
FMM05
Legend
Depth to groundwater (m)
110
0
Fortescue Marsh monitoring site
Pit outline
GOV_Fortescue_Marsh
drawdown
mounding
N
0
2,100
4,200
6,300
8,400
metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2015
Wet climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 18/11/2013
Drawn By: Paul Ricketts
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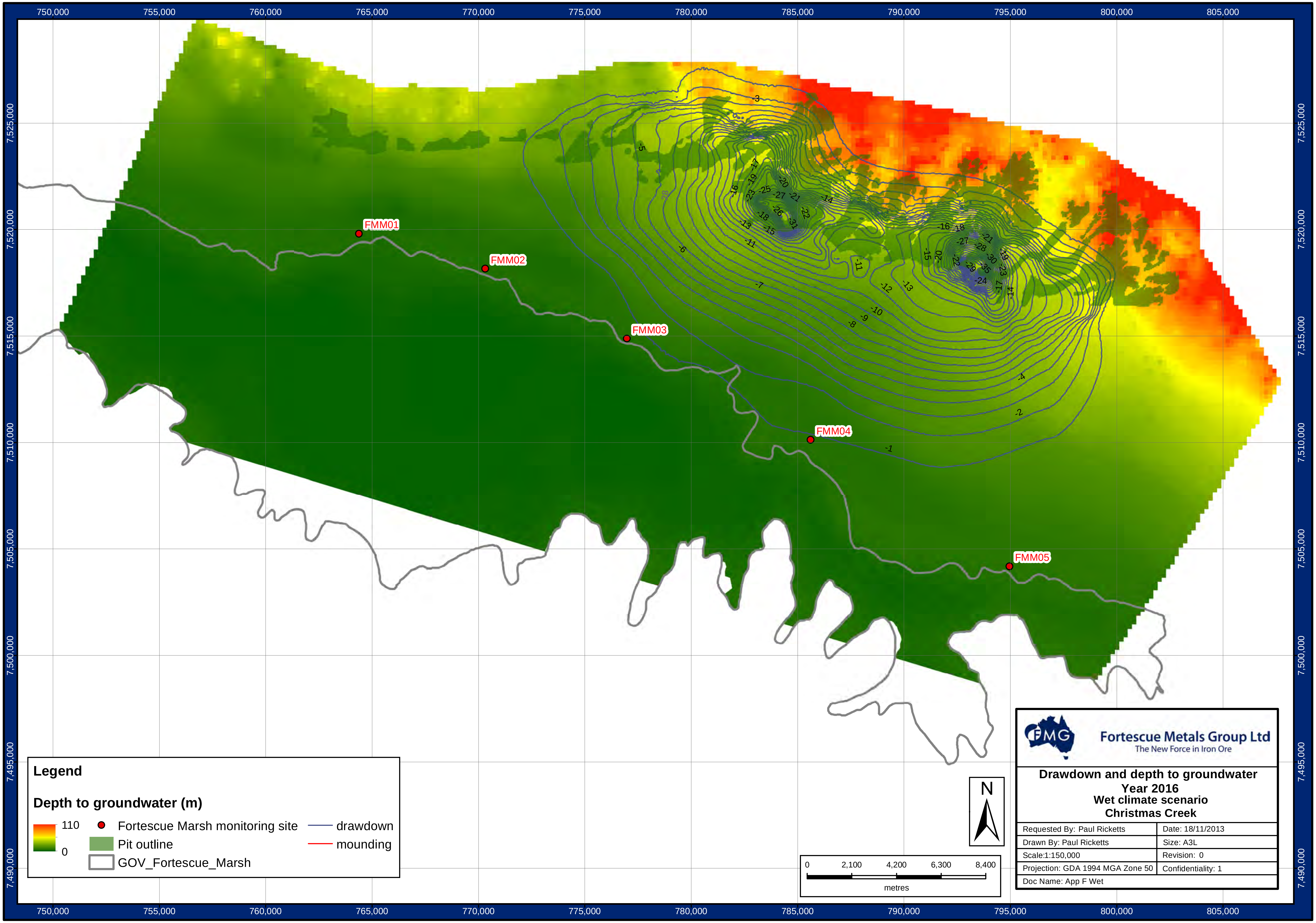
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785,000
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7,515,000
7,510,000
7,505,000
7,500,000
7,495,000
7,490,000
FMM01
FMM02
FMM03
FMM04
FMM05
Legend
Depth to groundwater (m)
110
0
Fortescue Marsh monitoring site
Pit outline
GOV_Fortescue_Marsh
drawdown
mounding
N
0
2,100
4,200
6,300
8,400
metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2016
Wet climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 18/11/2013
Drawn By: Paul Ricketts
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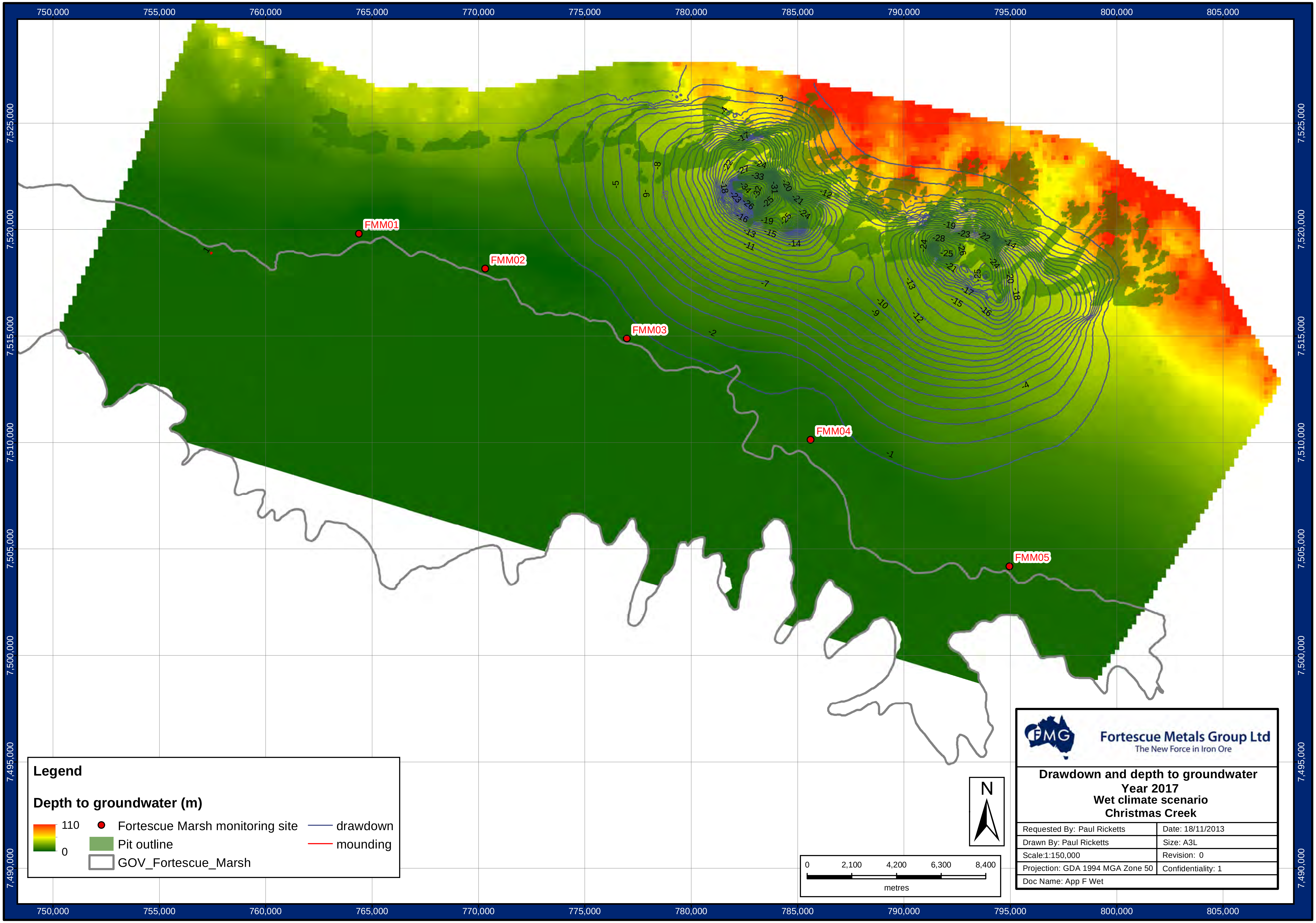

750,000
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765,000
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7,500,000
7,495,000
7,490,000
FMM01
FMM02
FMM03
FMM04
FMM05
Legend
Depth to groundwater (m)
110
0
Fortescue Marsh monitoring site
Pit outline
GOV_Fortescue_Marsh
drawdown
mounding
N
0
2,100
4,200
6,300
8,400
metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2017
Wet climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 18/11/2013
Drawn By: Paul Ricketts
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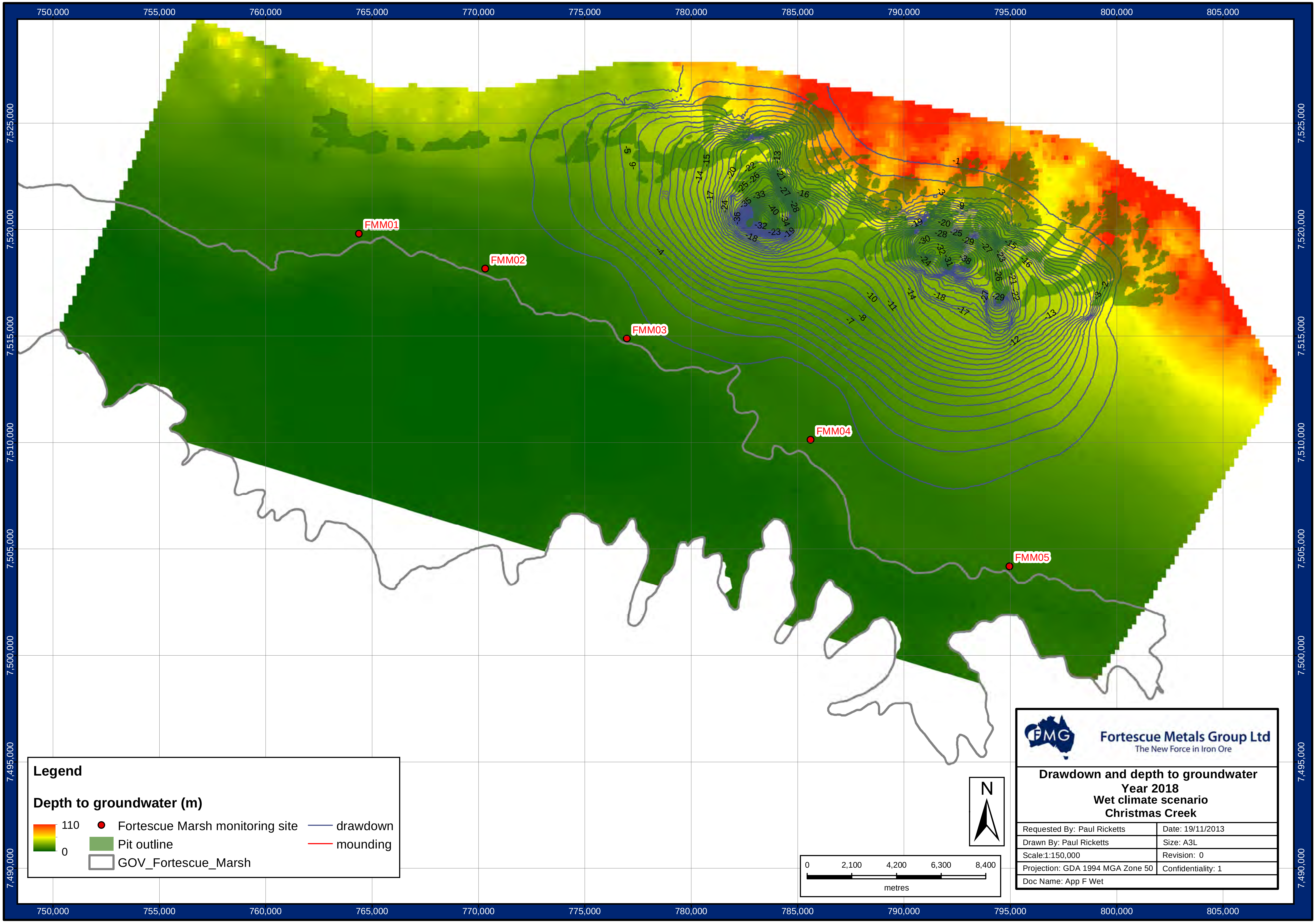

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765,000
770,000
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795,000
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7,515,000
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7,505,000
7,500,000
7,495,000
7,490,000
FMM01
FMM02
FMM03
FMM04
FMM05
Legend
Depth to groundwater (m)
110
0
Fortescue Marsh monitoring site
Pit outline
GOV_Fortescue_Marsh
drawdown
mounding
0
2,100
4,200
6,300
8,400
metres
N
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2018
Wet climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 19/11/2013
Drawn By: Paul Ricketts
Size: A3L
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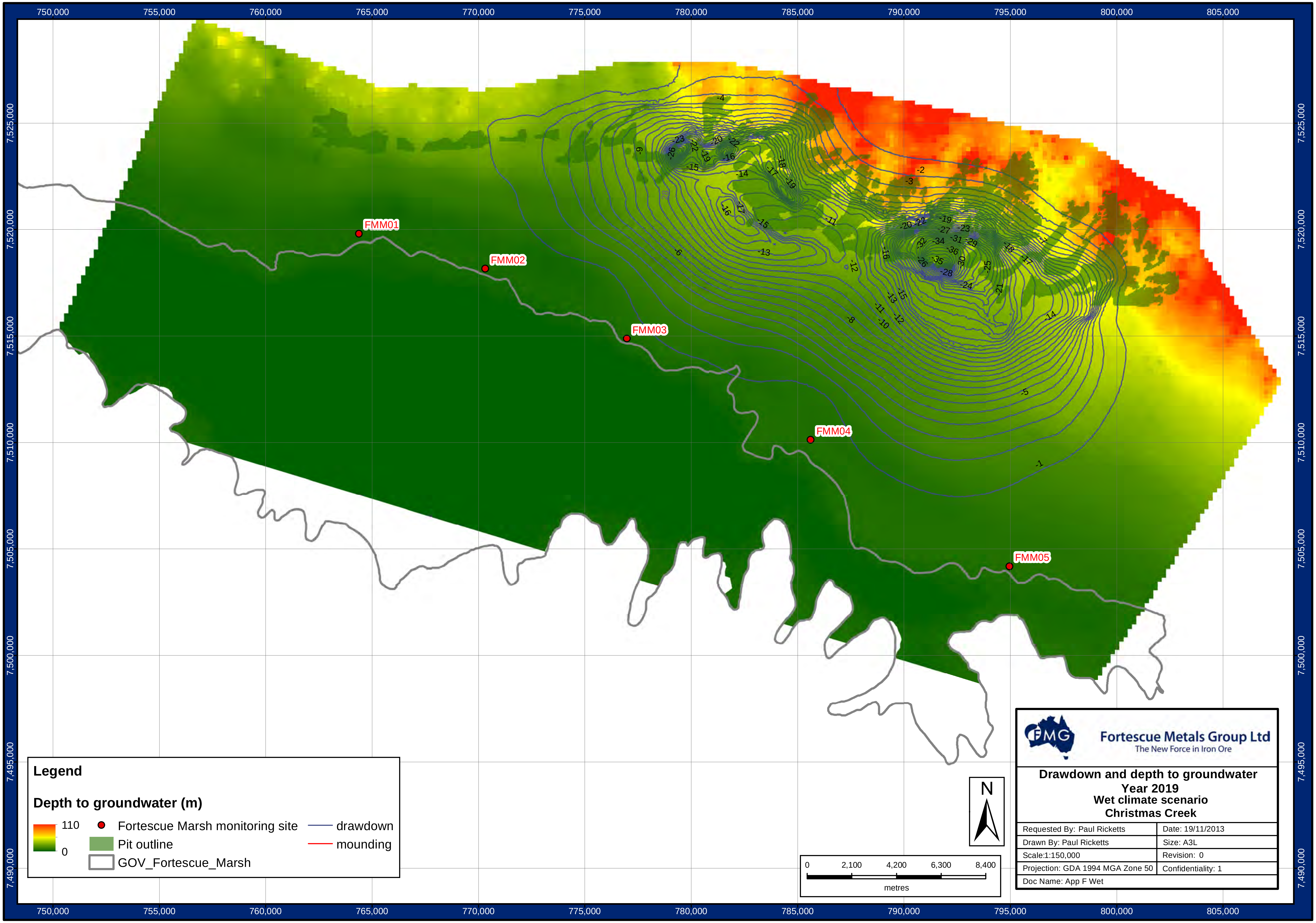

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Fortescue Marsh monitoring site
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Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2019
Wet climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 19/11/2013
Drawn By: Paul Ricketts
Size: A3L
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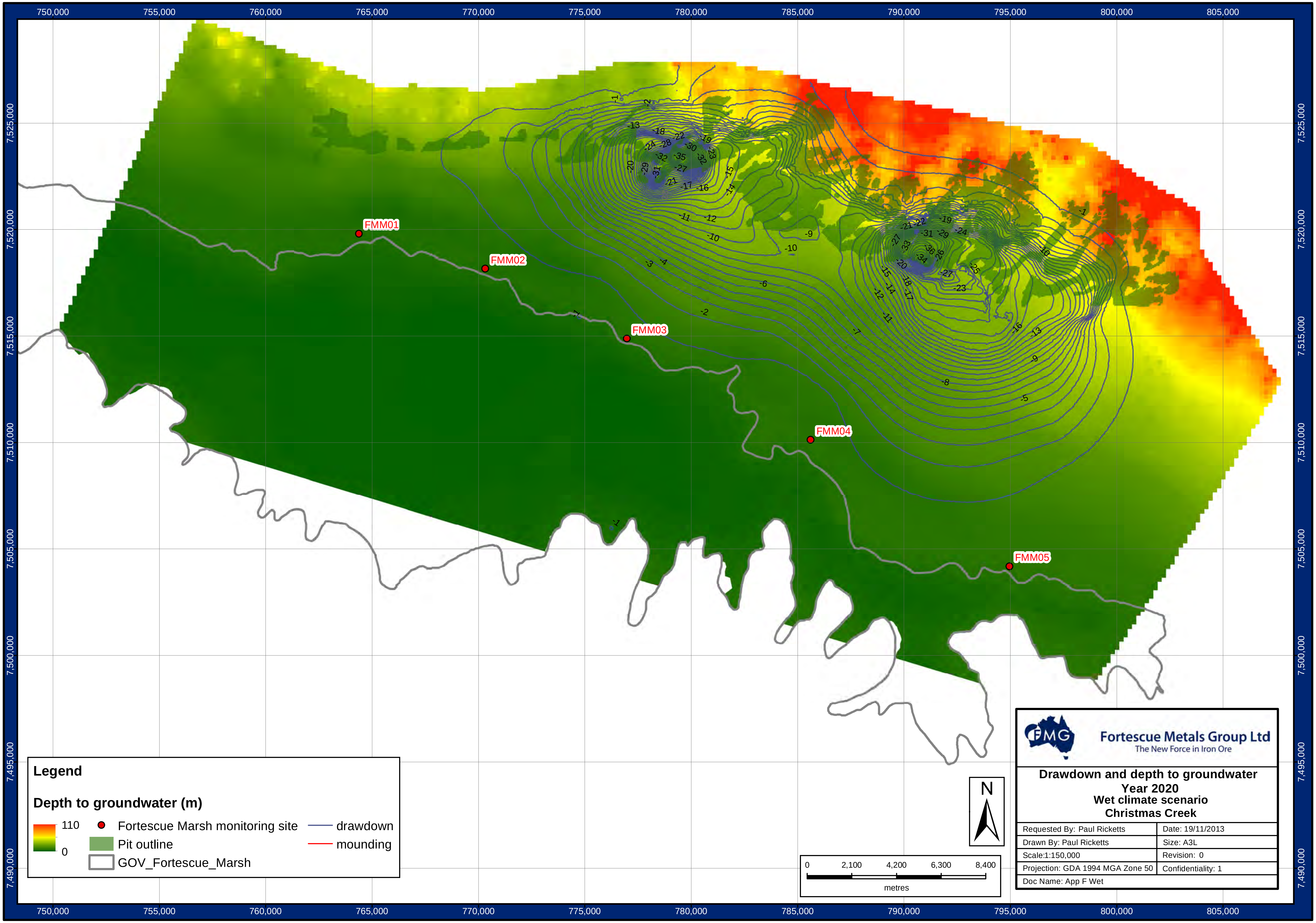

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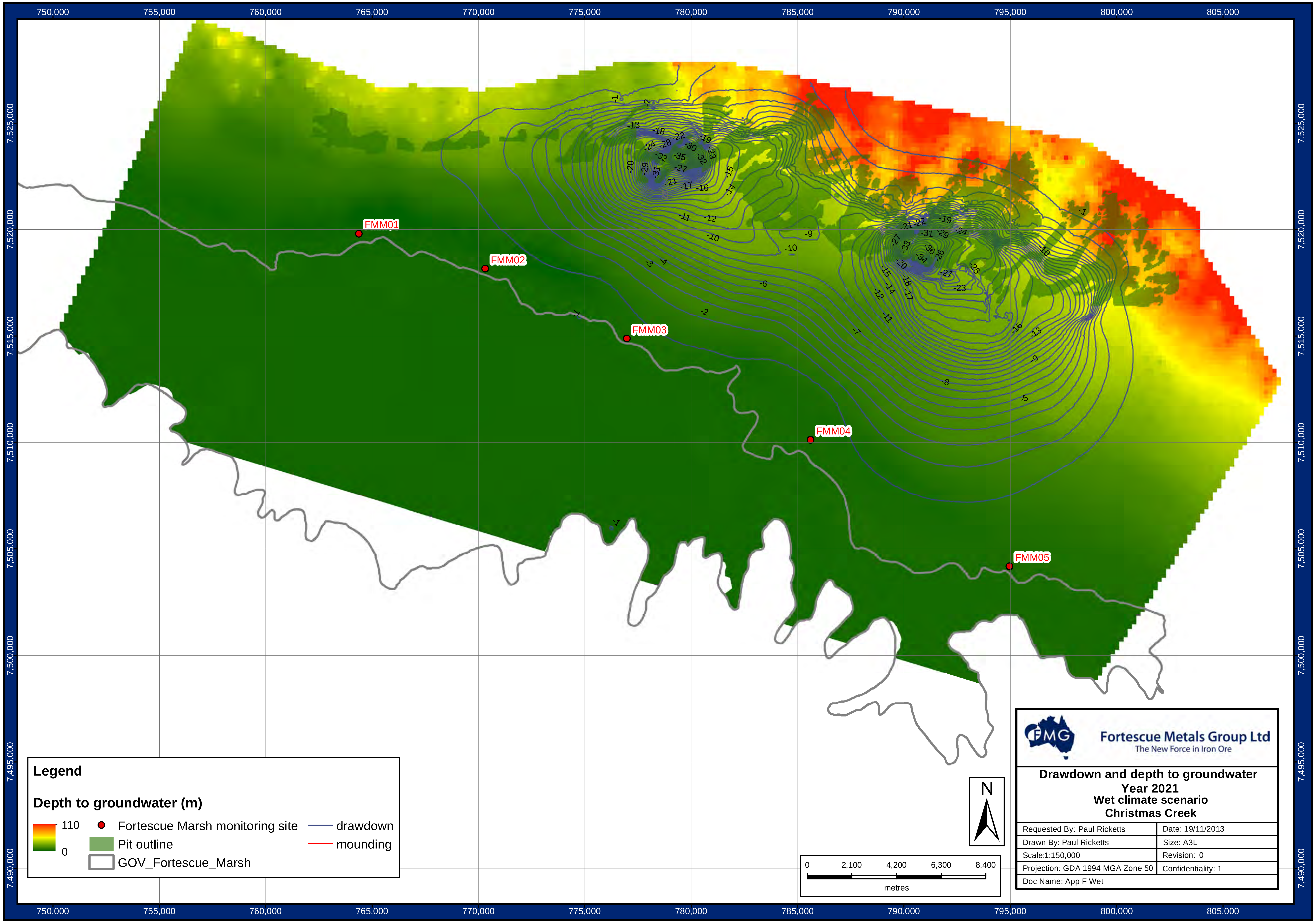
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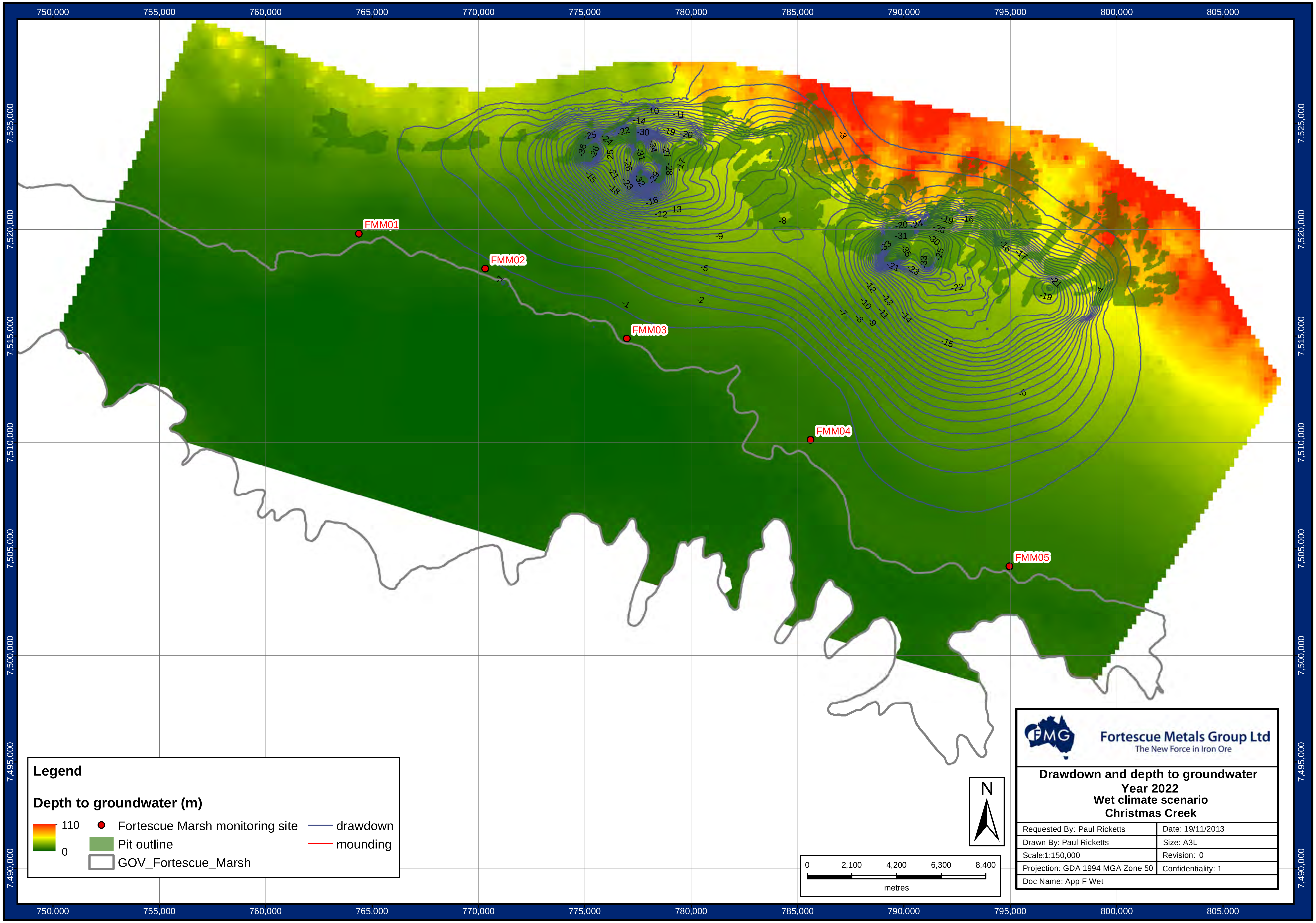

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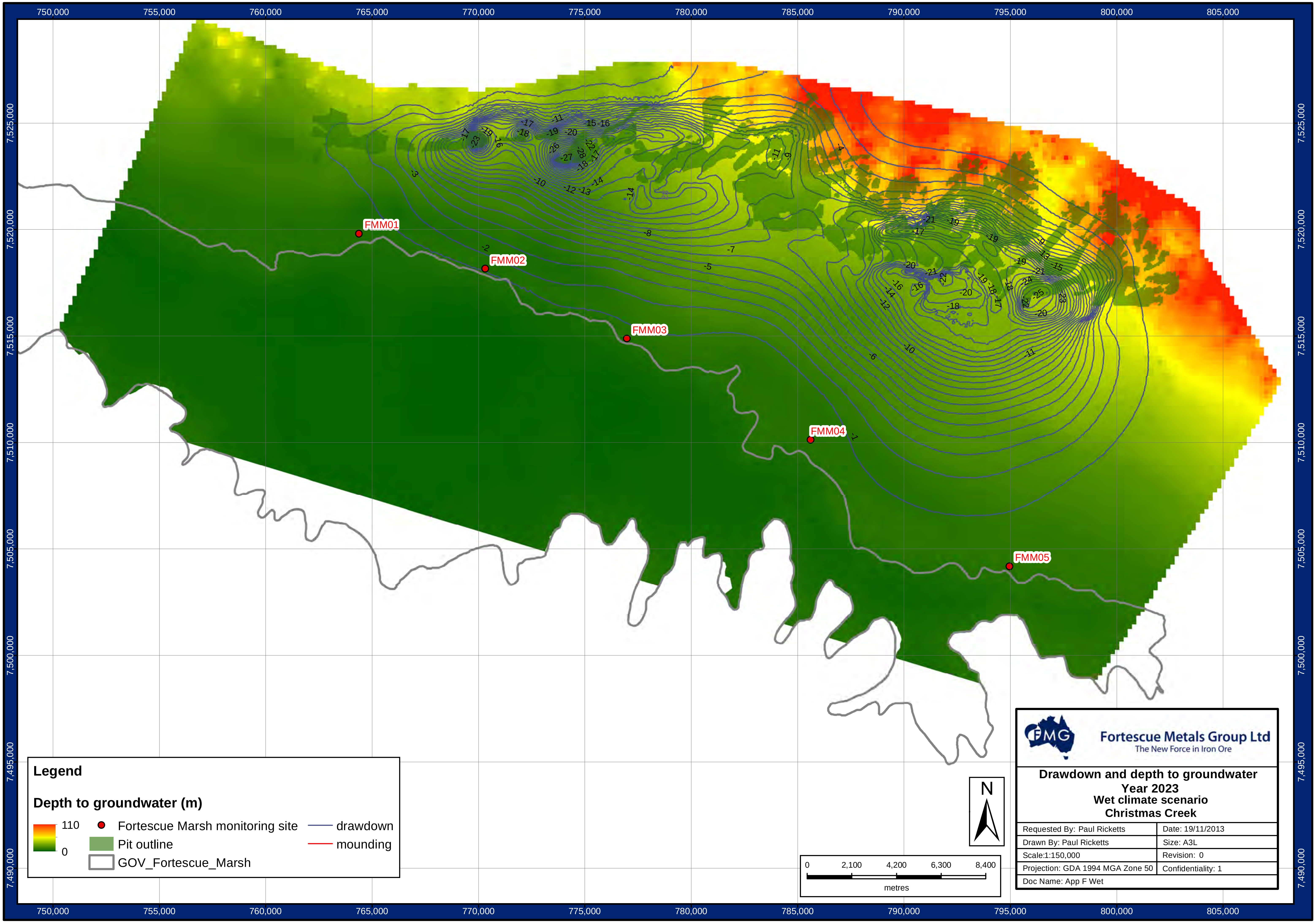

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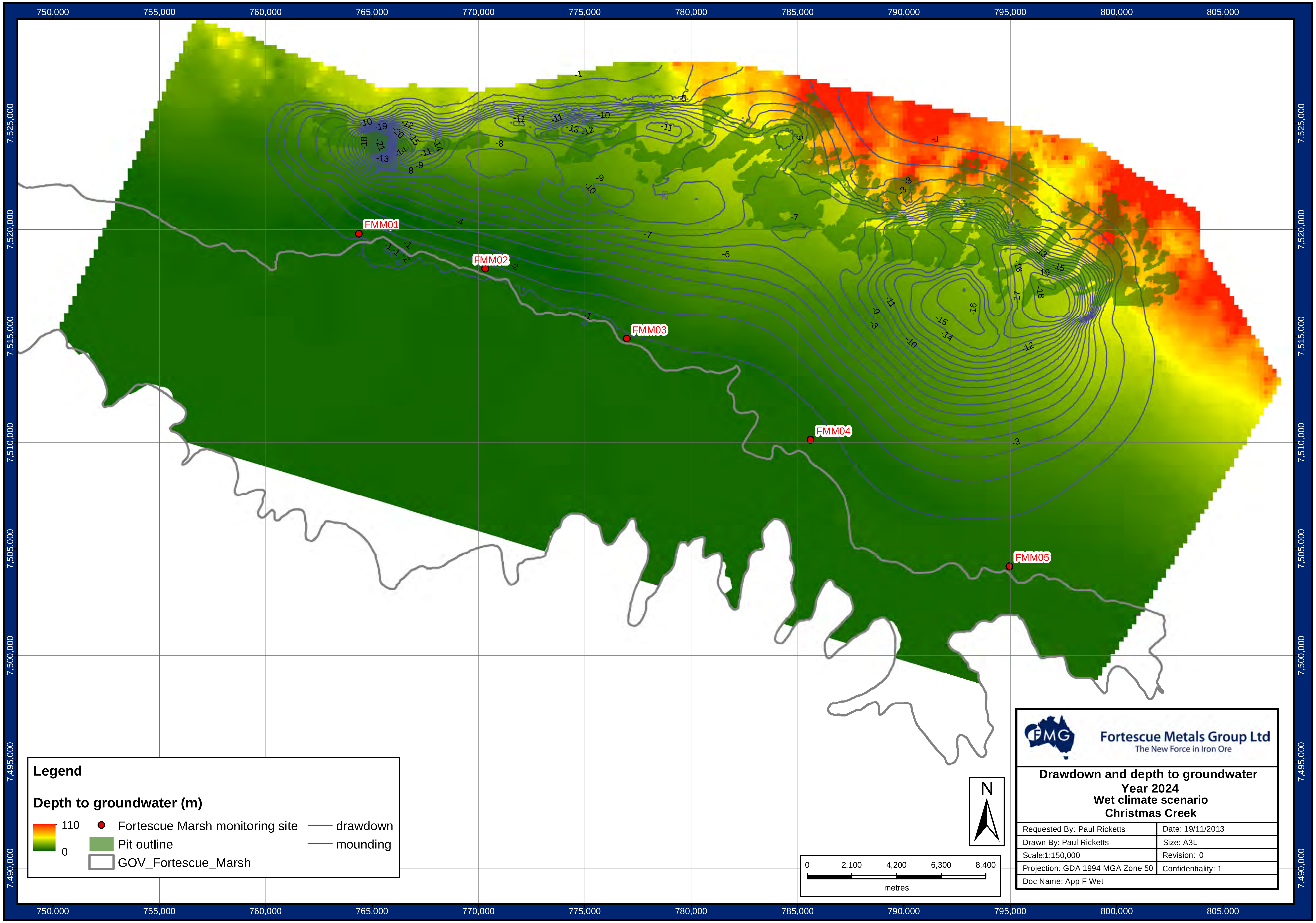

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Drawdown and depth to groundwater
Year 2024
Wet climate scenario
Christmas Creek
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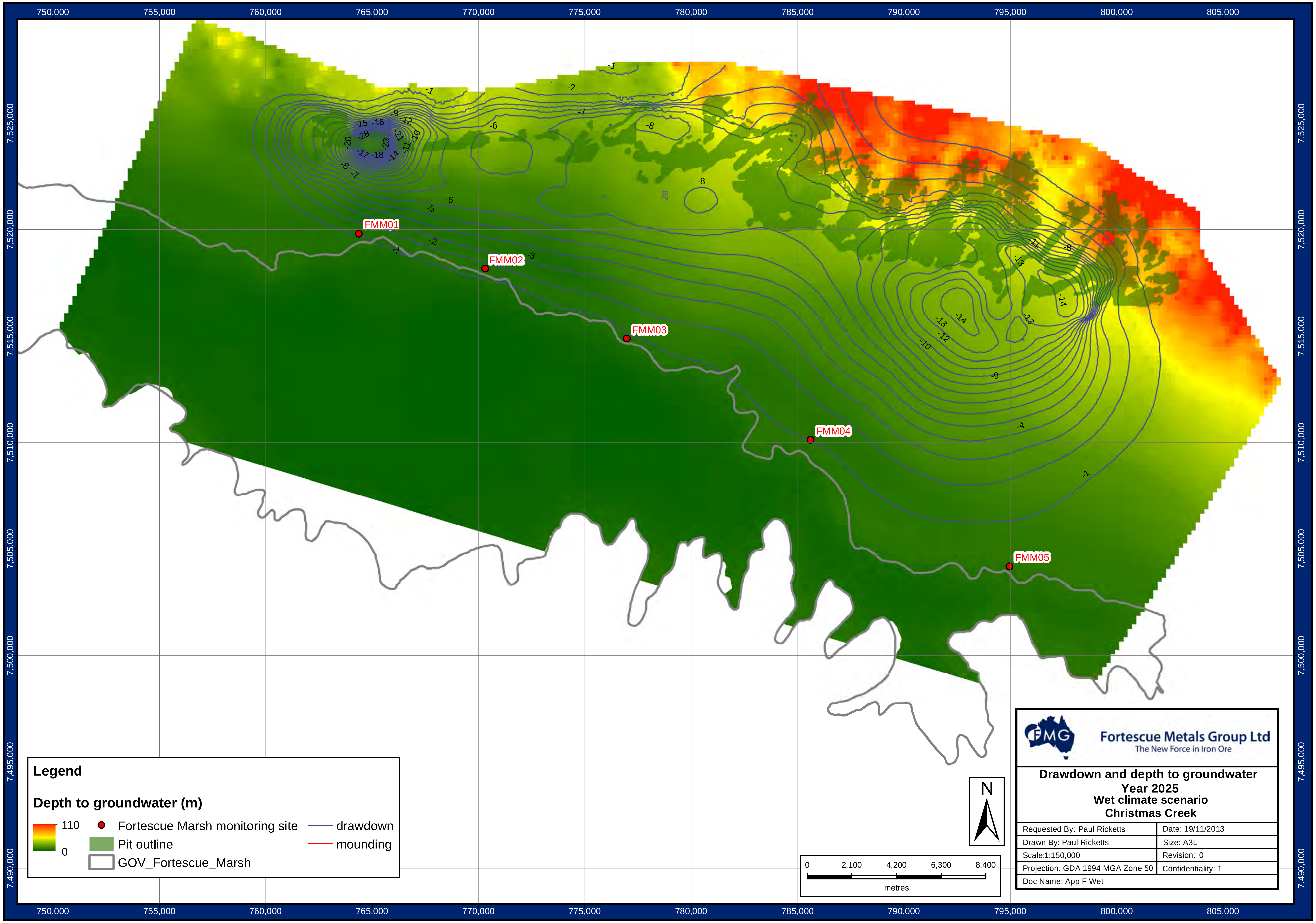

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The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2025
Wet climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 19/11/2013
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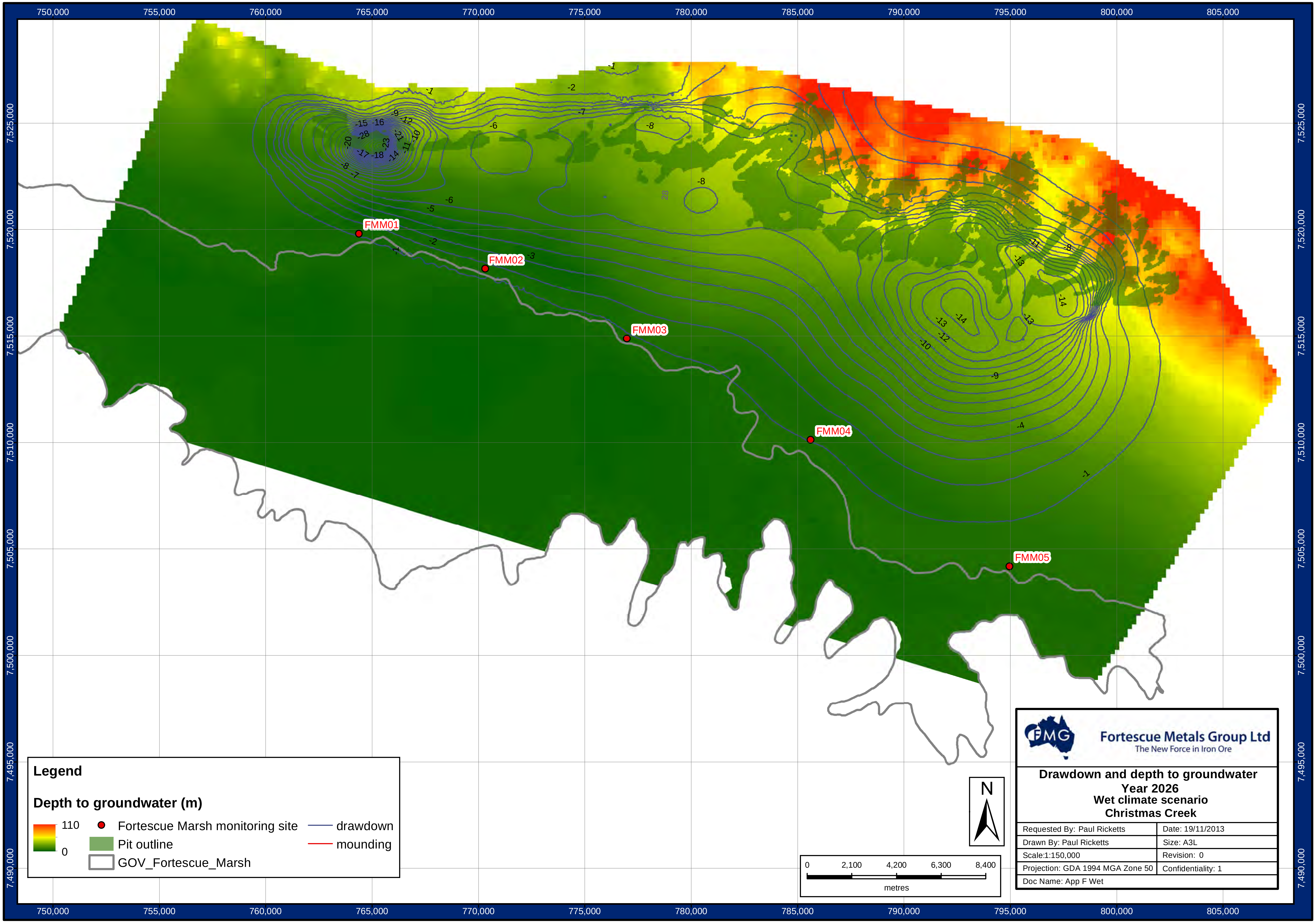

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Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2026
Wet climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 19/11/2013
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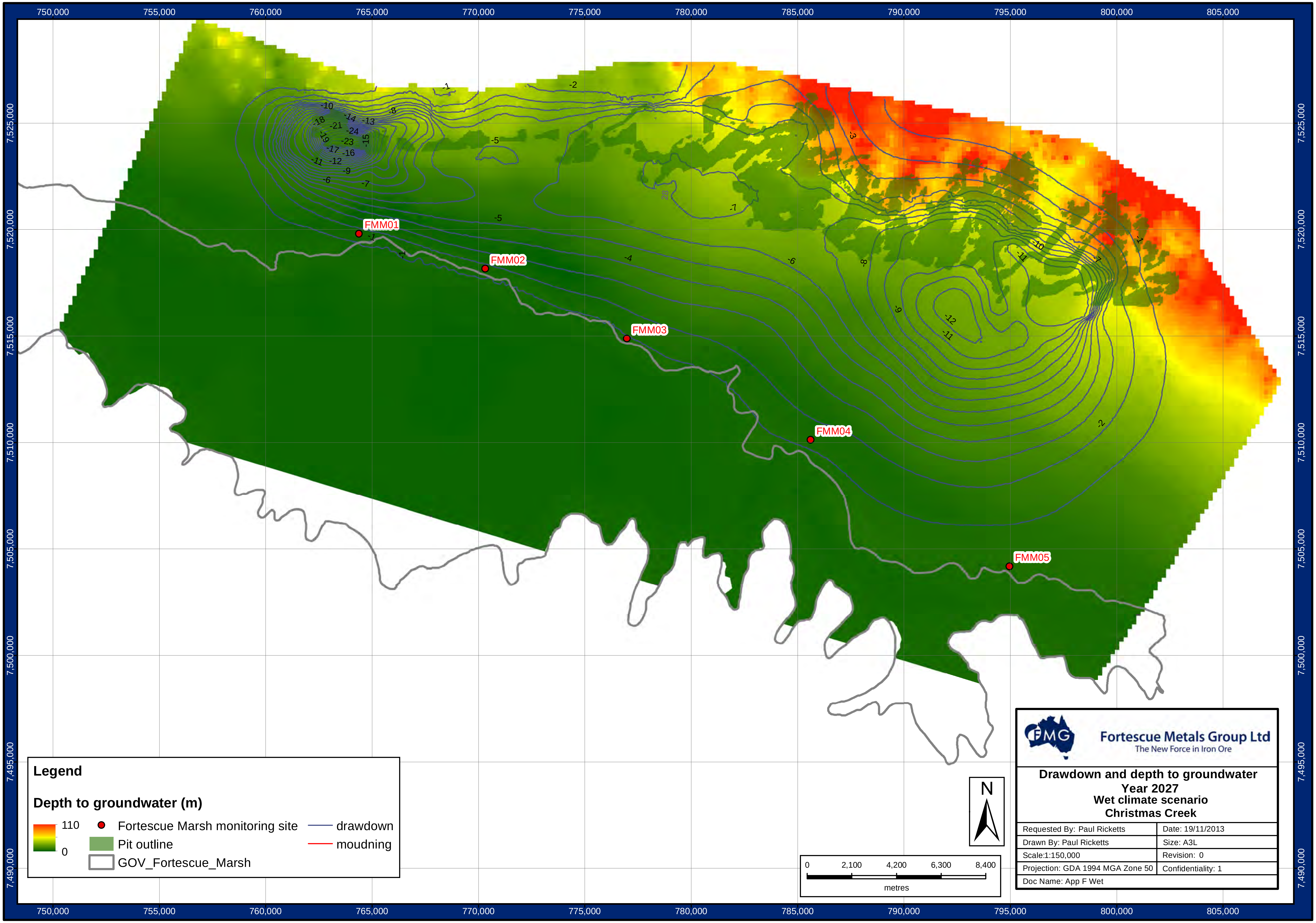
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The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2027
Wet climate scenario
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Requested By: Paul Ricketts
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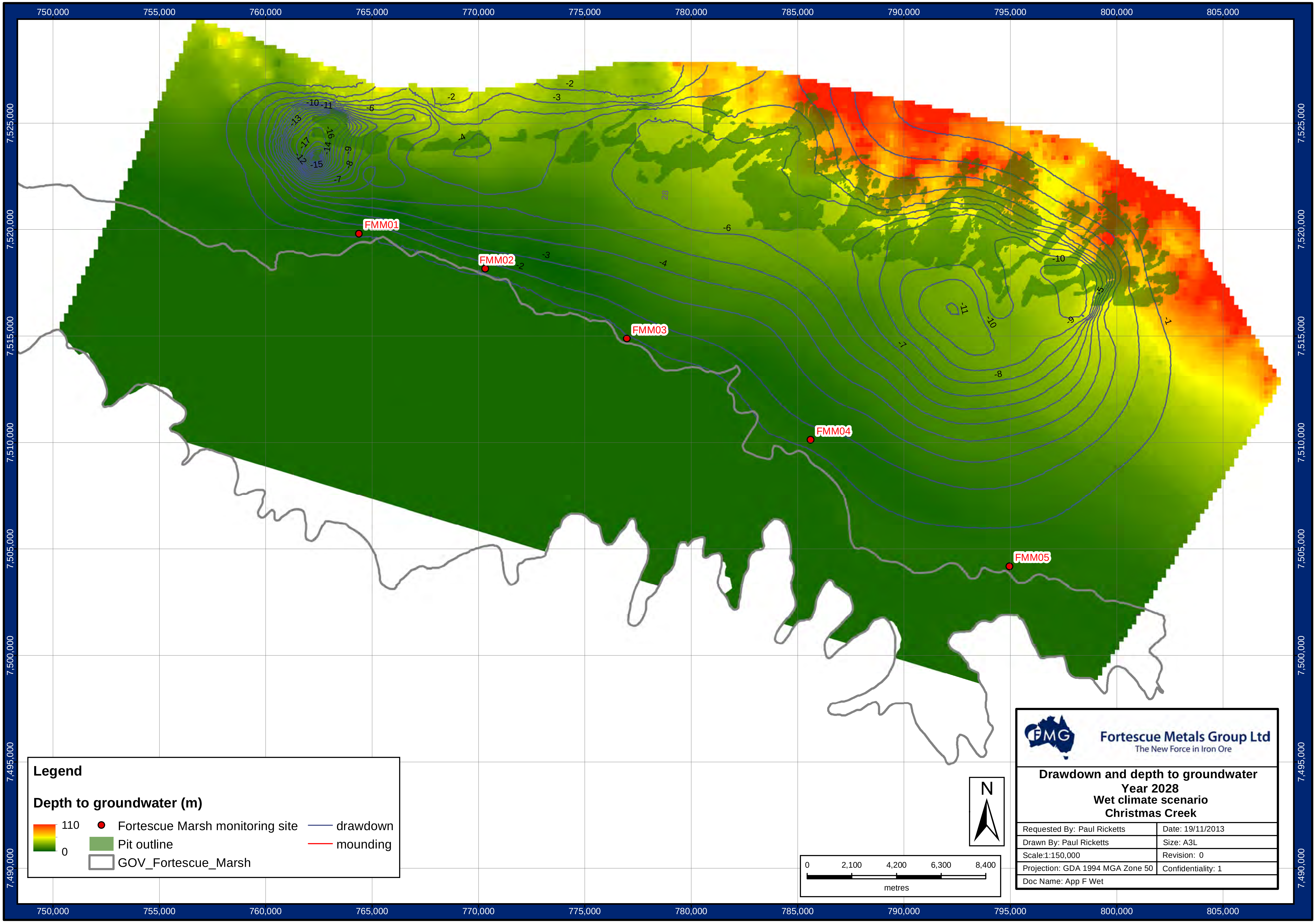

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Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2028
Wet climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 19/11/2013
Drawn By: Paul Ricketts
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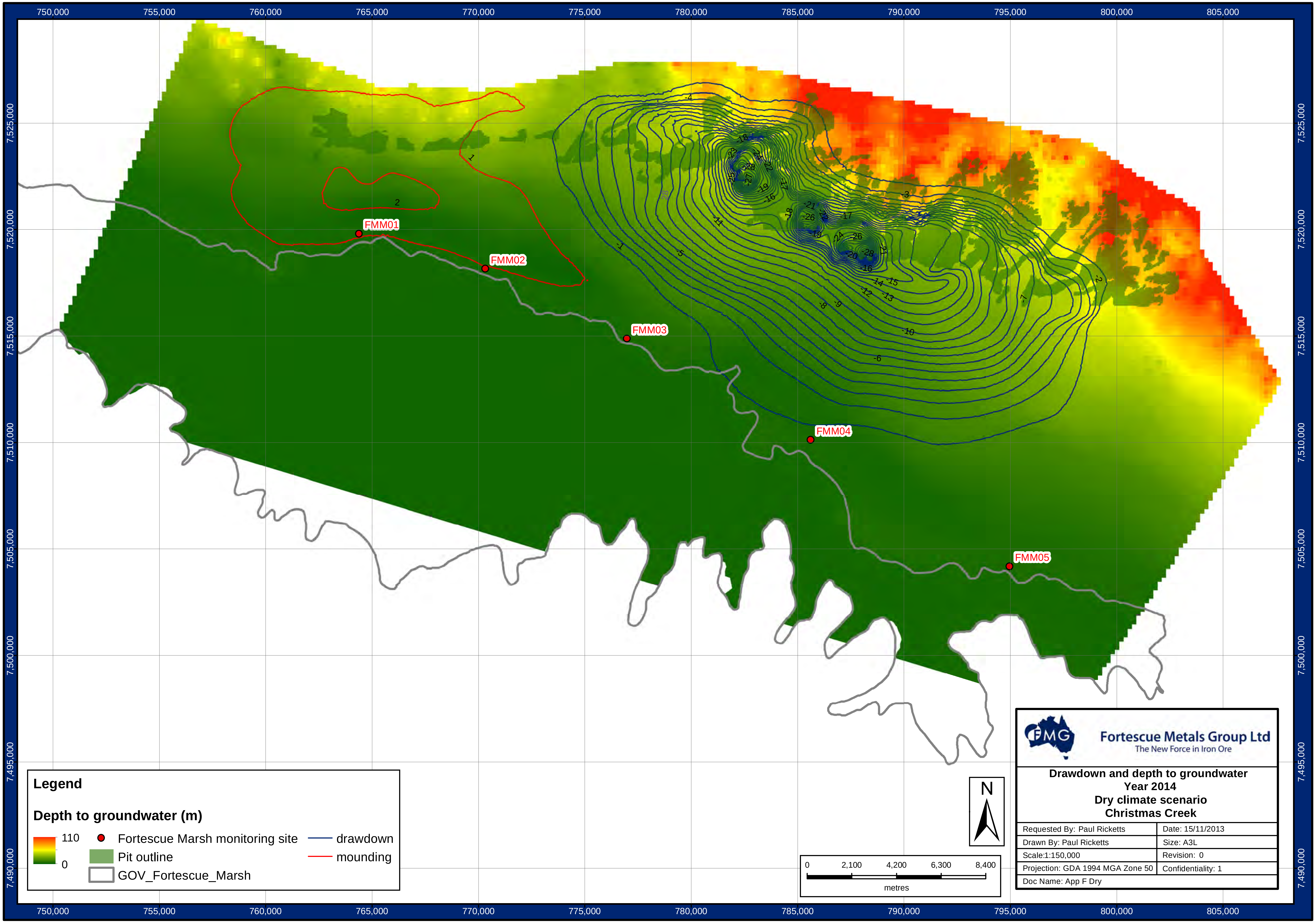

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Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2014
Dry climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 15/11/2013
Drawn By: Paul Ricketts
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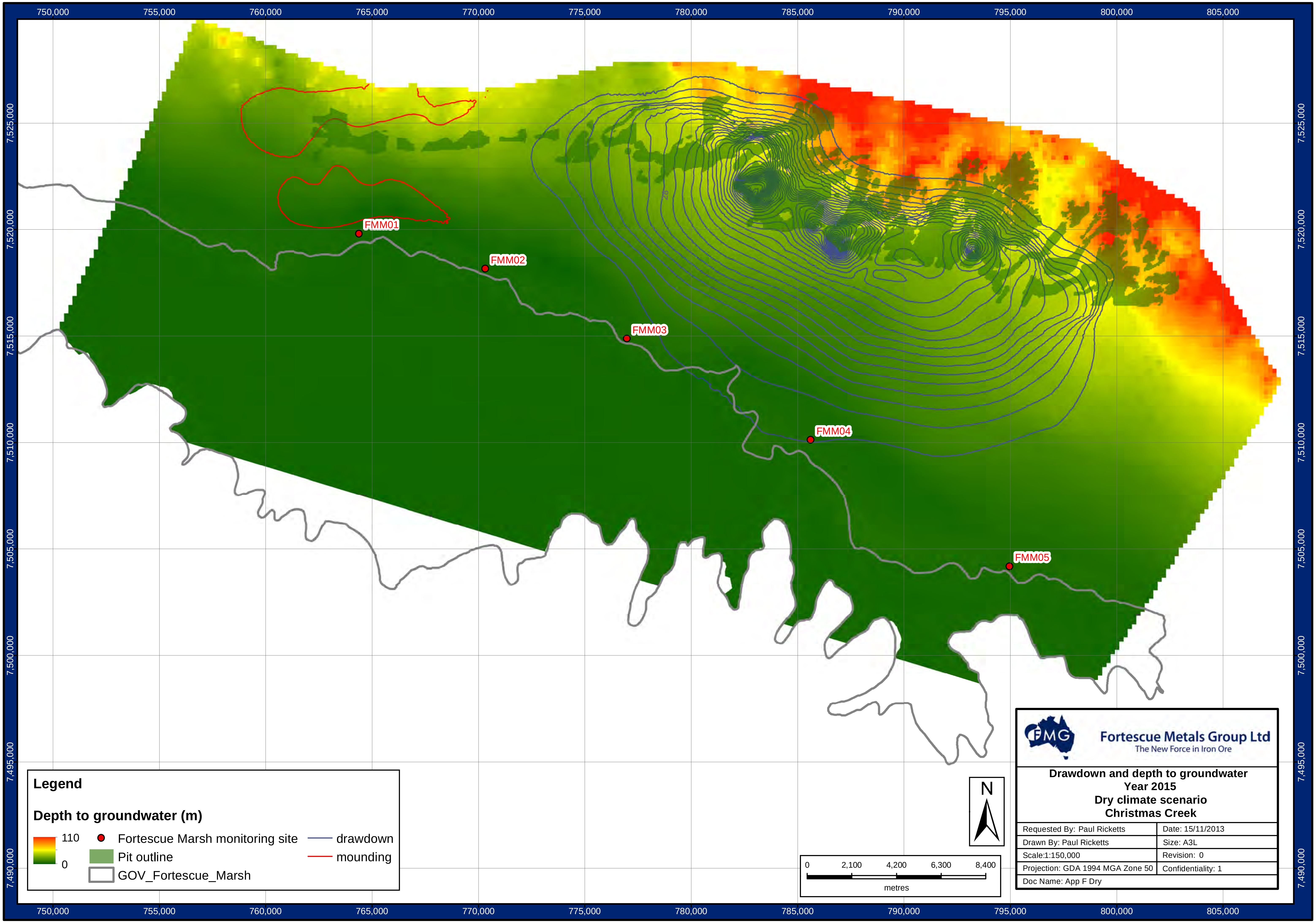

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Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2015
Dry climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 15/11/2013
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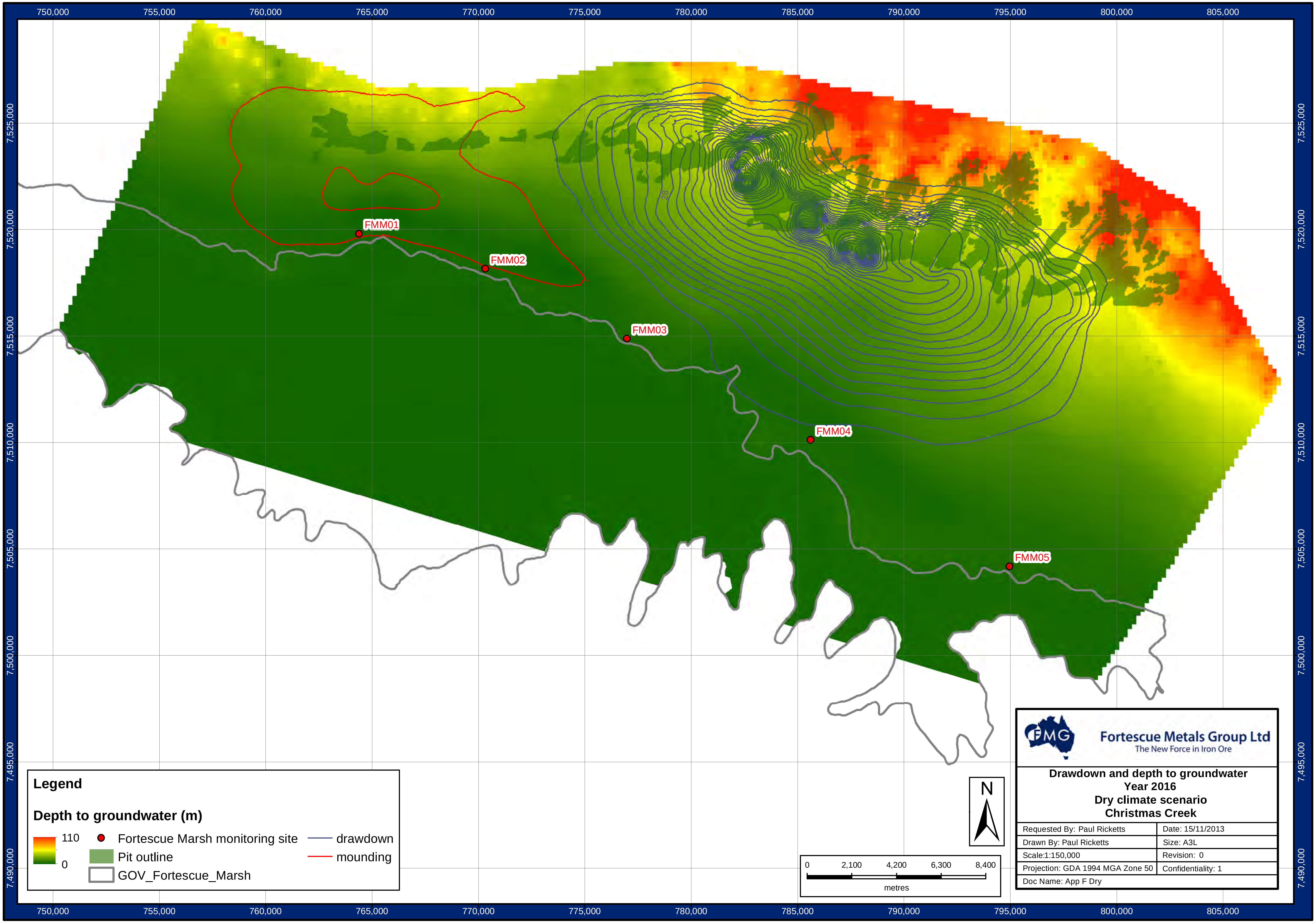

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The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2016
Dry climate scenario
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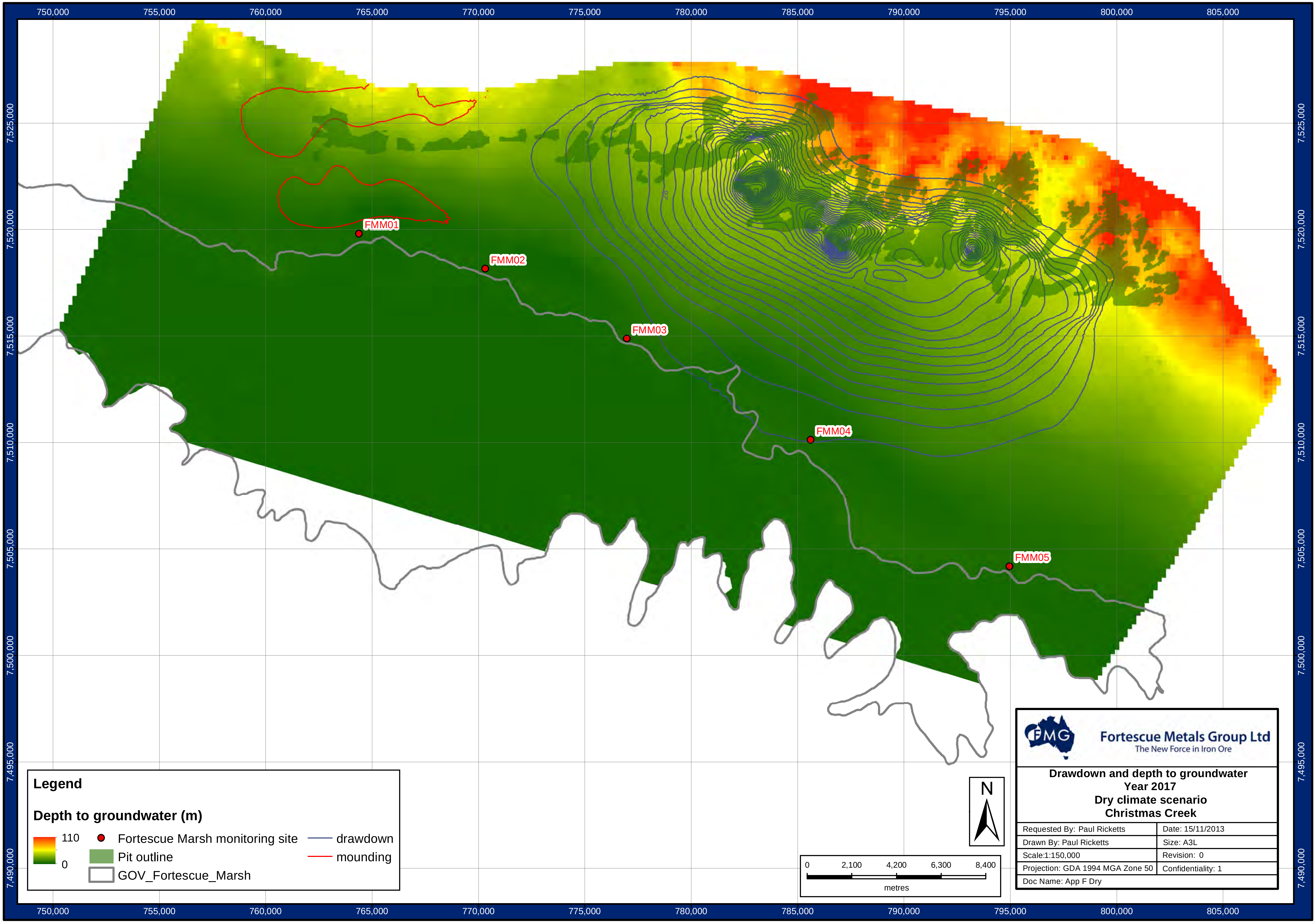

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Drawdown and depth to groundwater
Year 2017
Dry climate scenario
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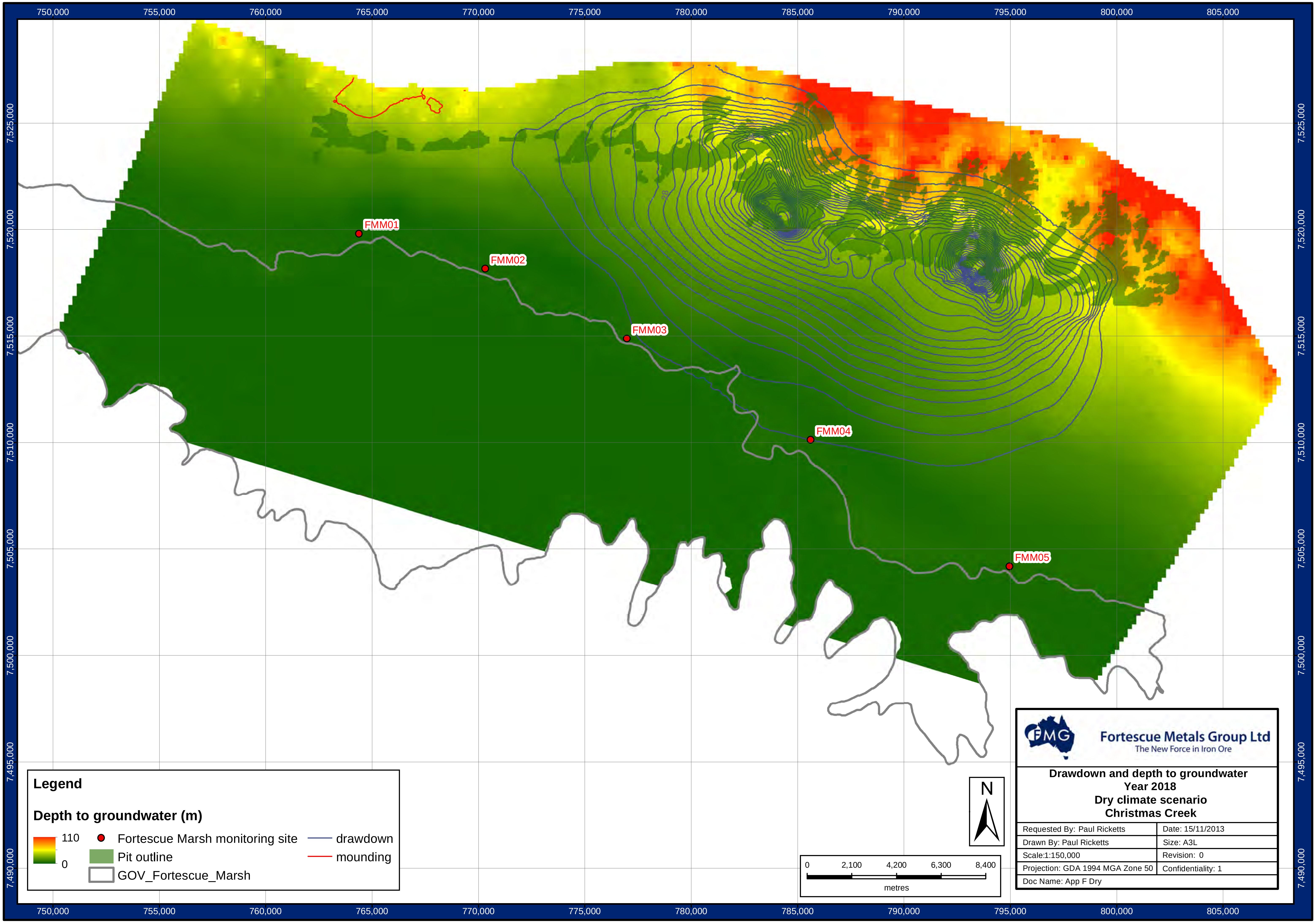

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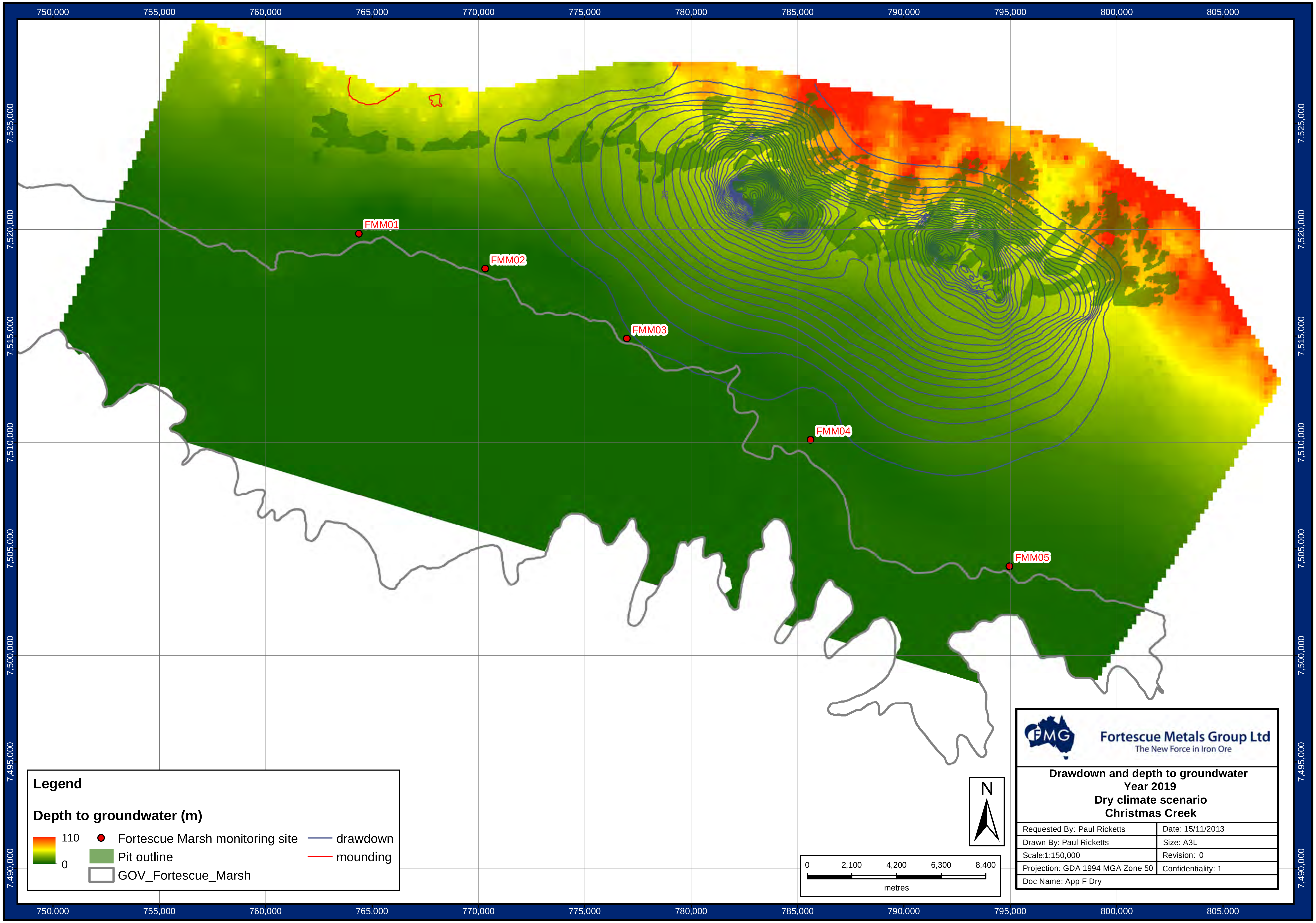

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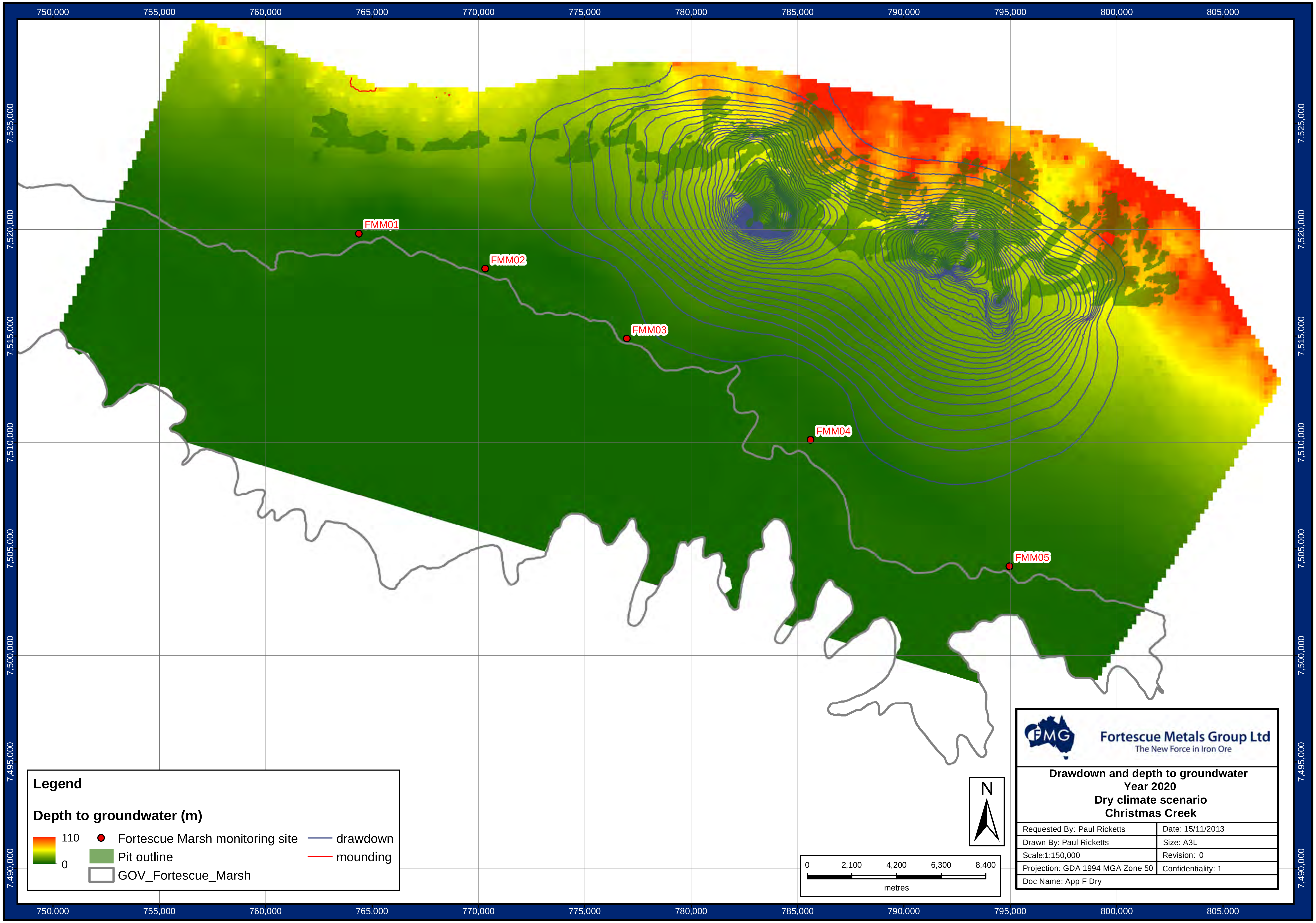
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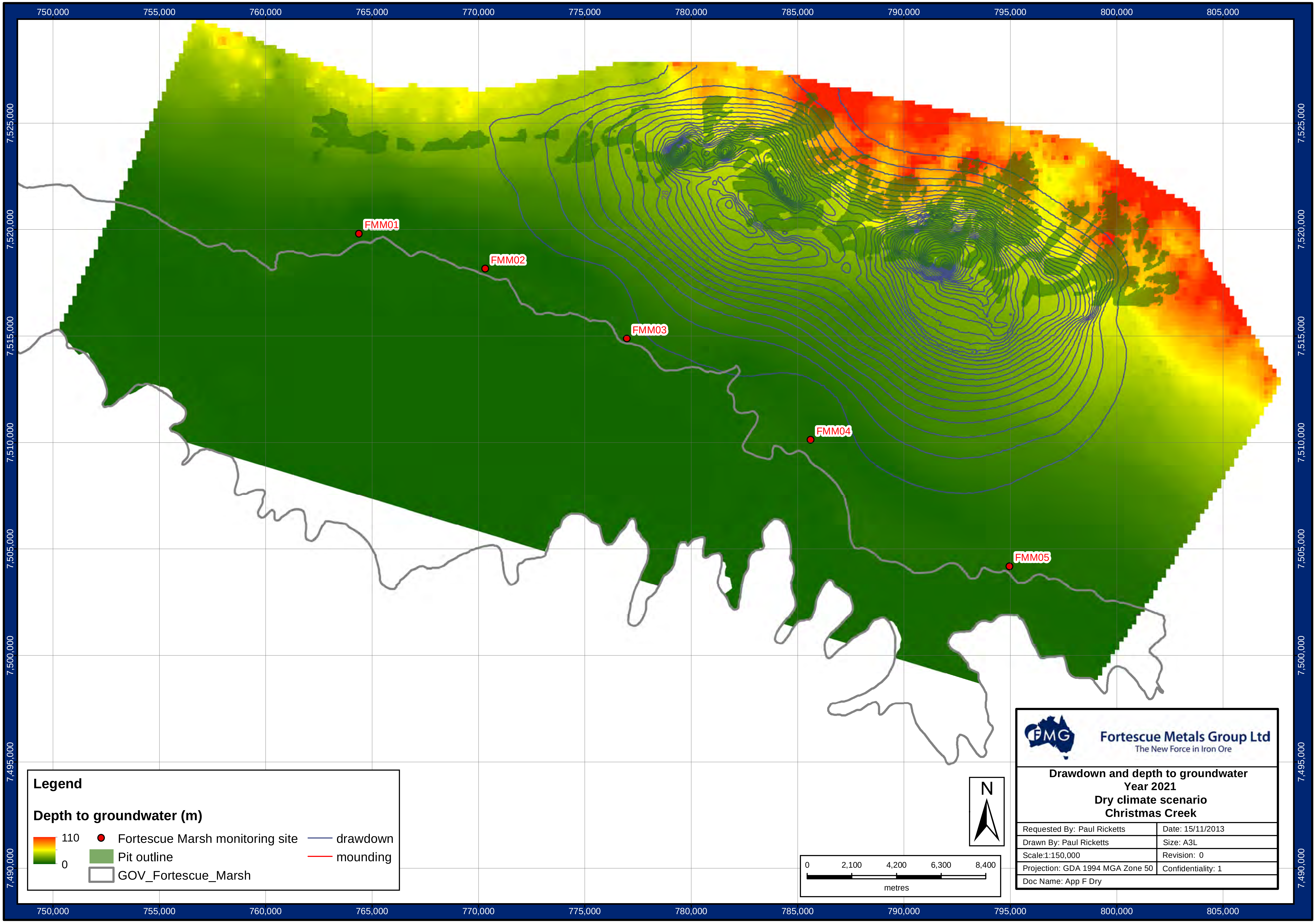

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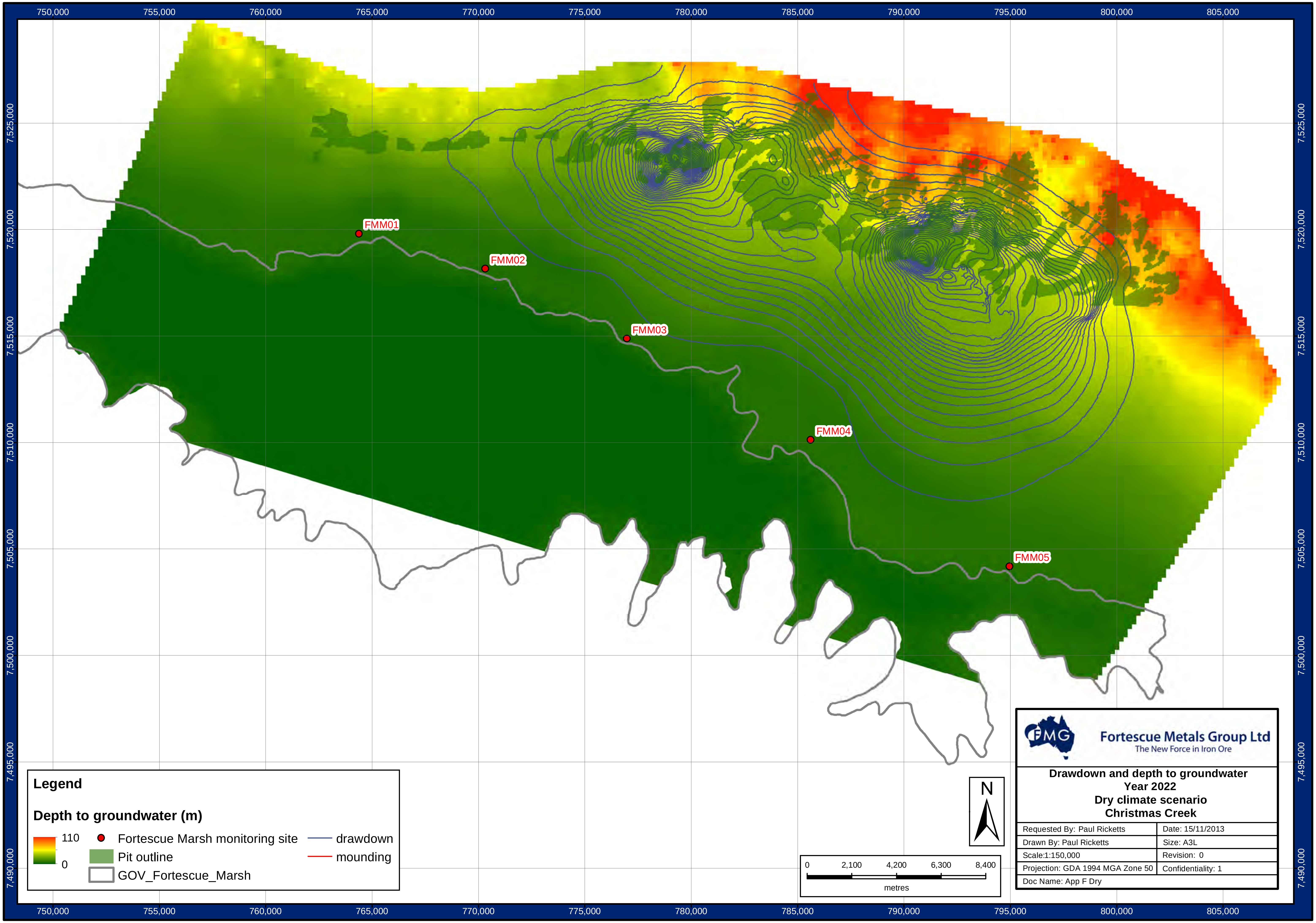

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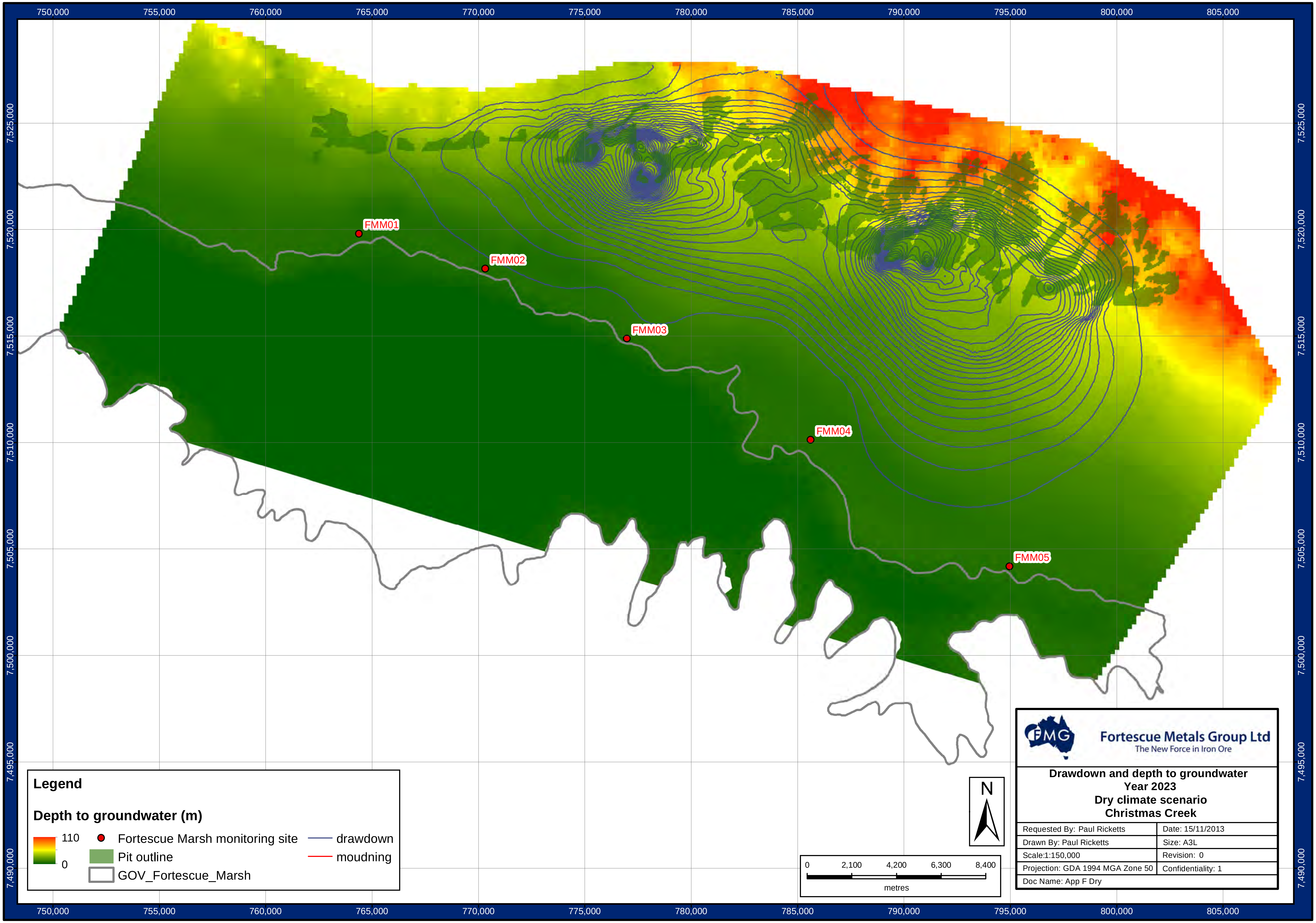

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Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2023
Dry climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 15/11/2013
Drawn By: Paul Ricketts
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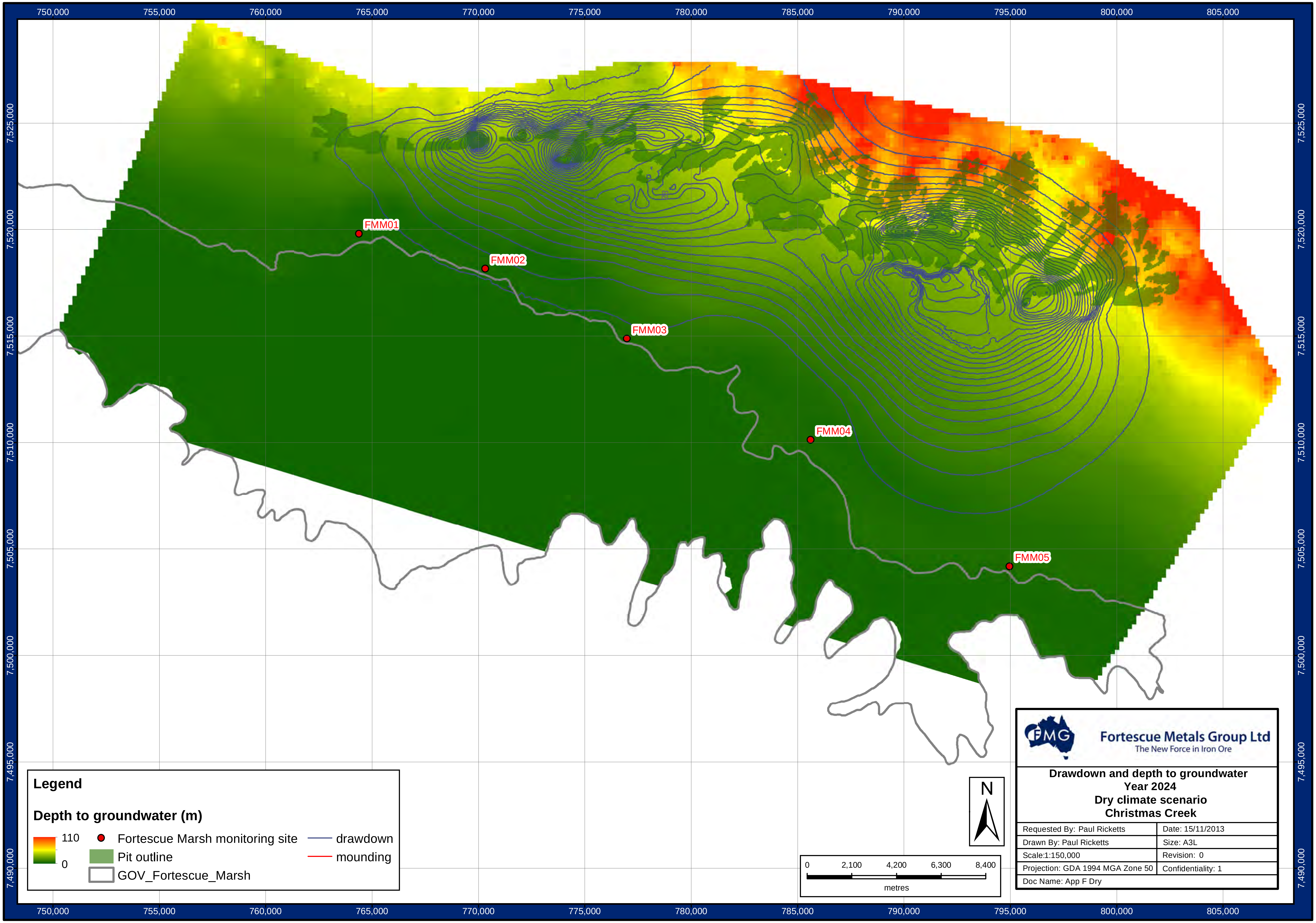

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Fortescue Marsh monitoring site
Pit outline
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The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2024
Dry climate scenario
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Requested By: Paul Ricketts
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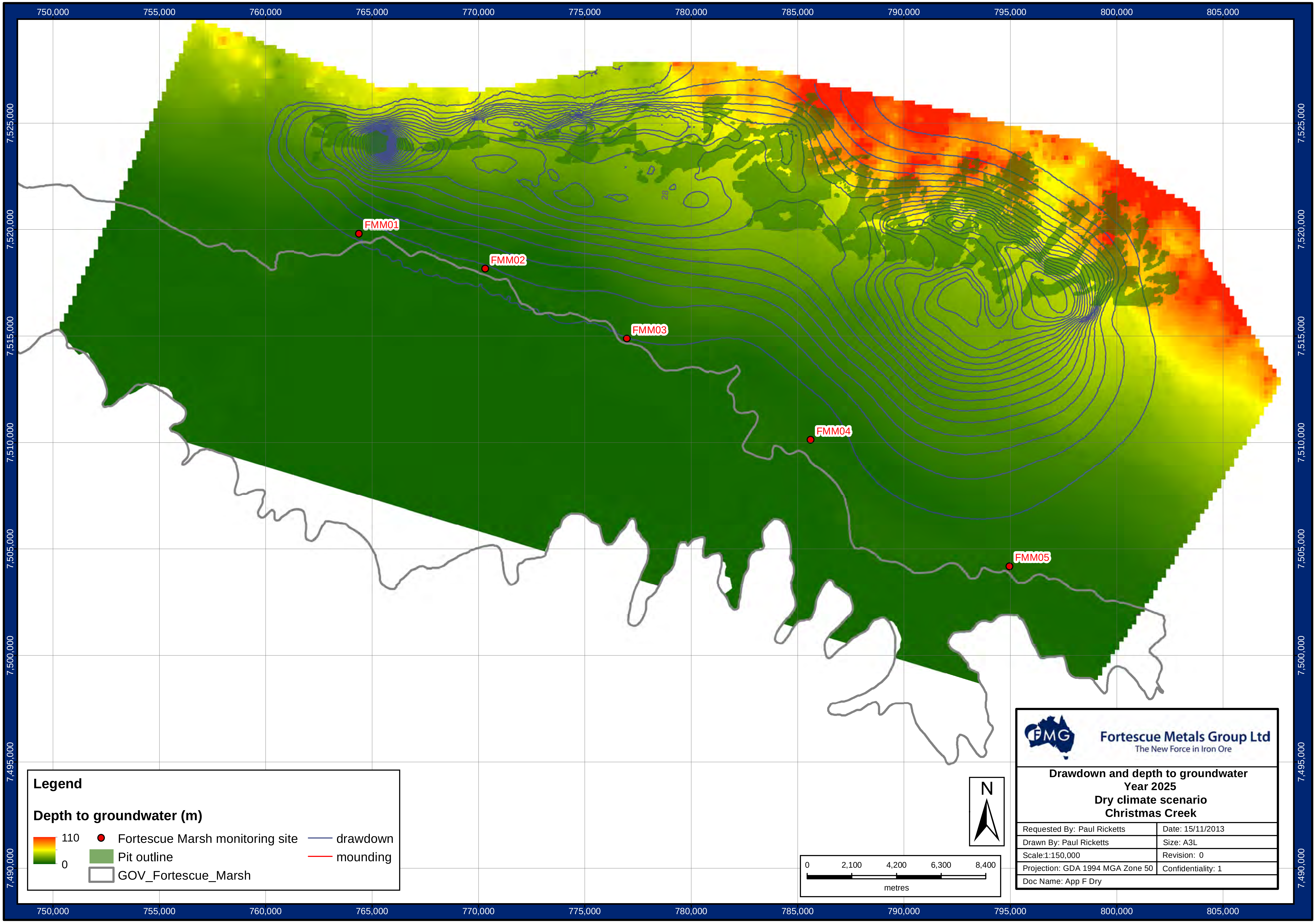

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Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2025
Dry climate scenario
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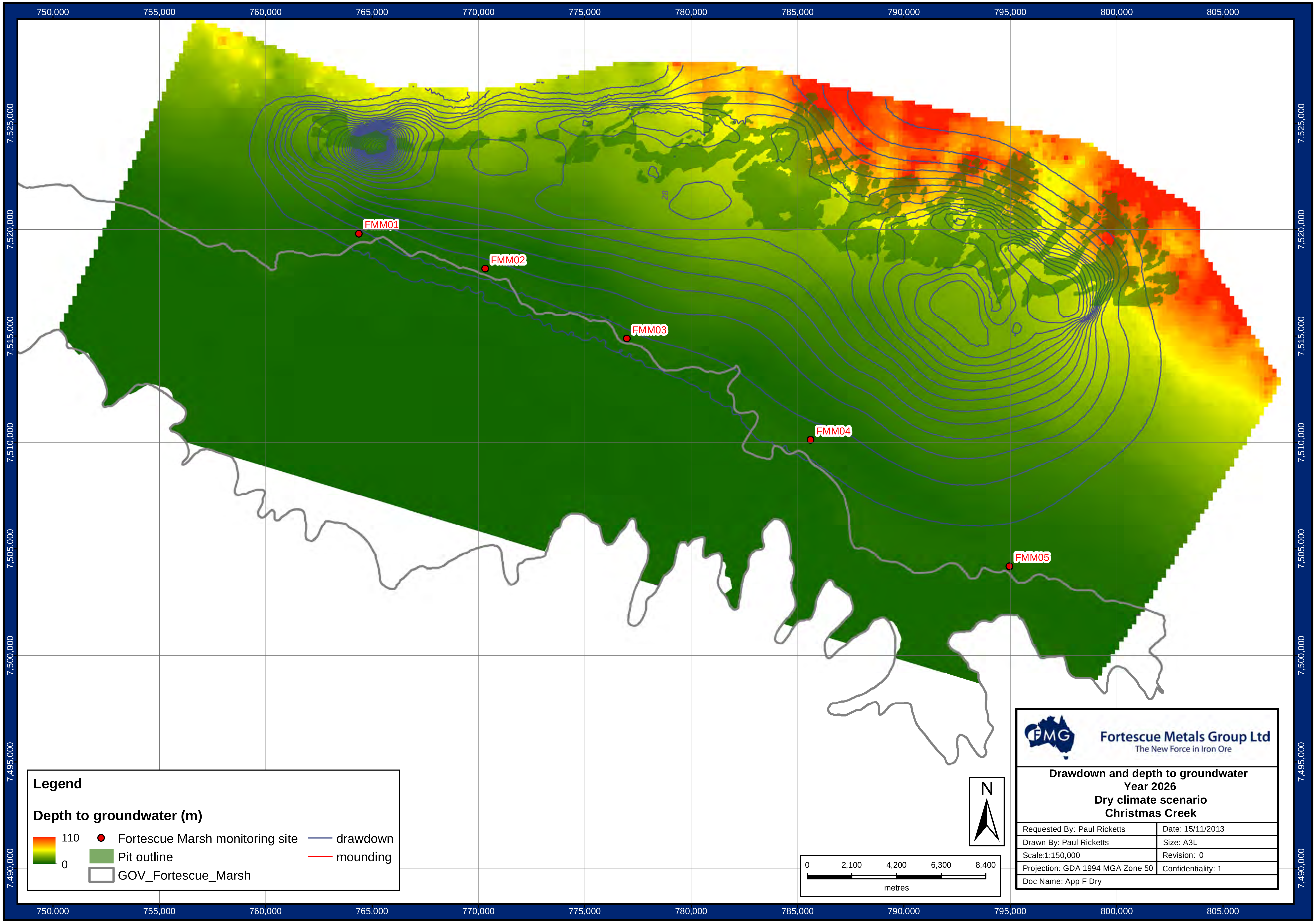

Drawdown and depth to groundwater
Year 2026
Dry climate scenario
Christmas Creek
Fortescue Metals Group Ltd
The New Force in Iron Ore
FMG
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Depth to groundwater (m)
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Fortescue Marsh monitoring site
Pit outline
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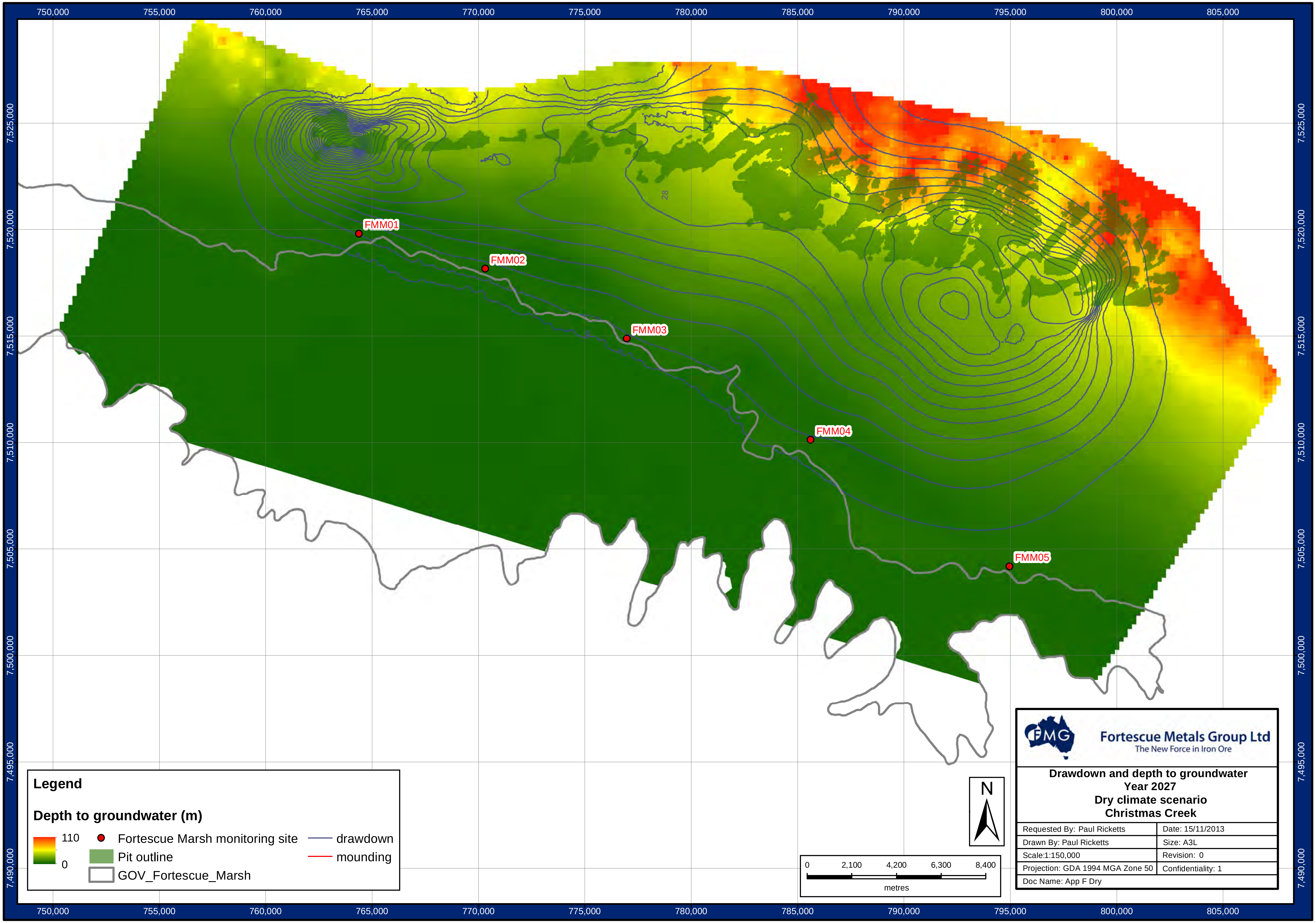

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Legend
Depth to groundwater (m)
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Fortescue Marsh monitoring site
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metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2027
Dry climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 15/11/2013
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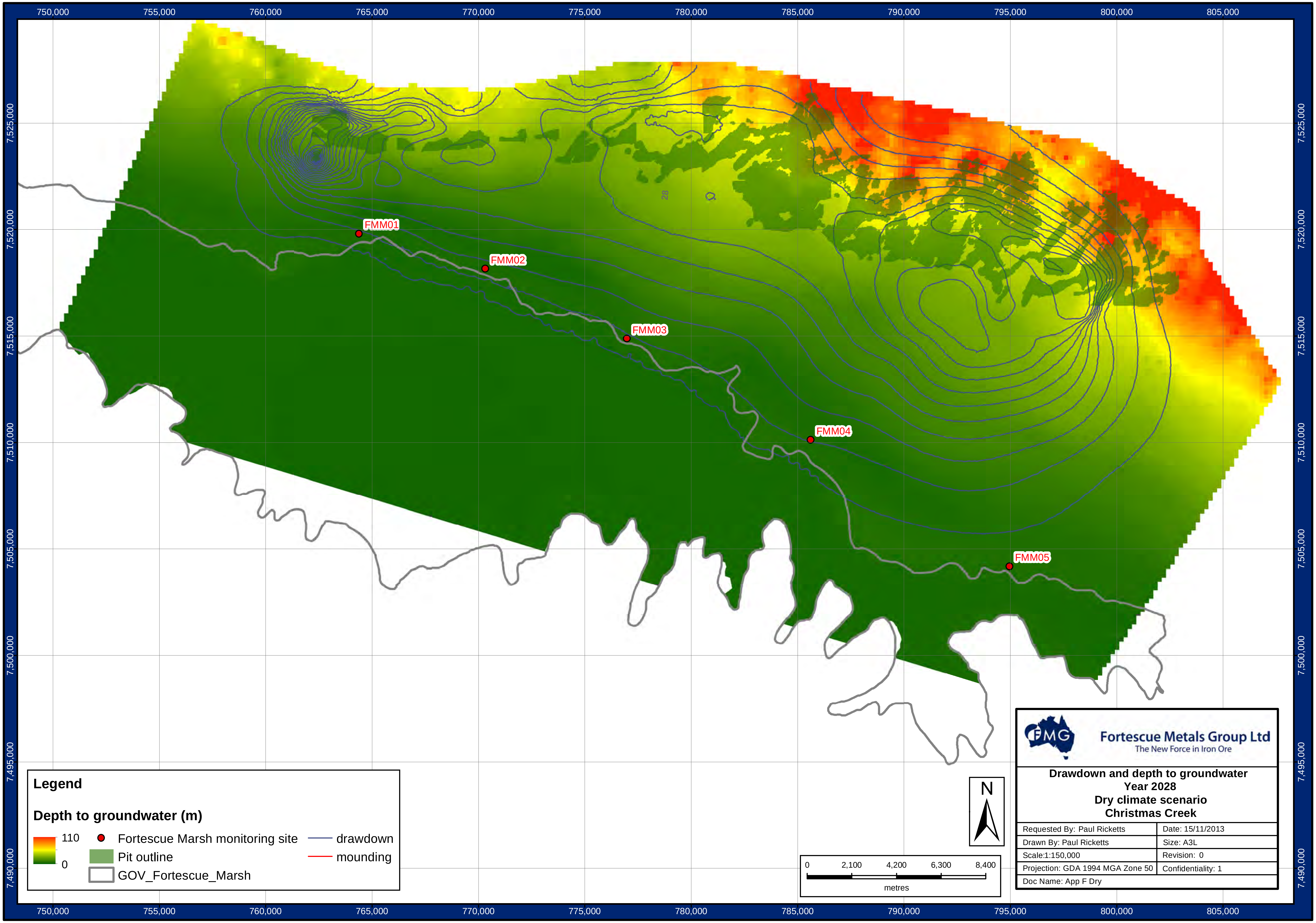

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Legend
Depth to groundwater (m)
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Fortescue Marsh monitoring site
Pit outline
GOV_Fortescue_Marsh
drawdown
mounding
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metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Drawdown and depth to groundwater
Year 2028
Dry climate scenario
Christmas Creek
Requested By: Paul Ricketts
Date: 15/11/2013
Drawn By: Paul Ricketts
Size: A3L
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Appendix 7: Groundwater level recovery after mine closure

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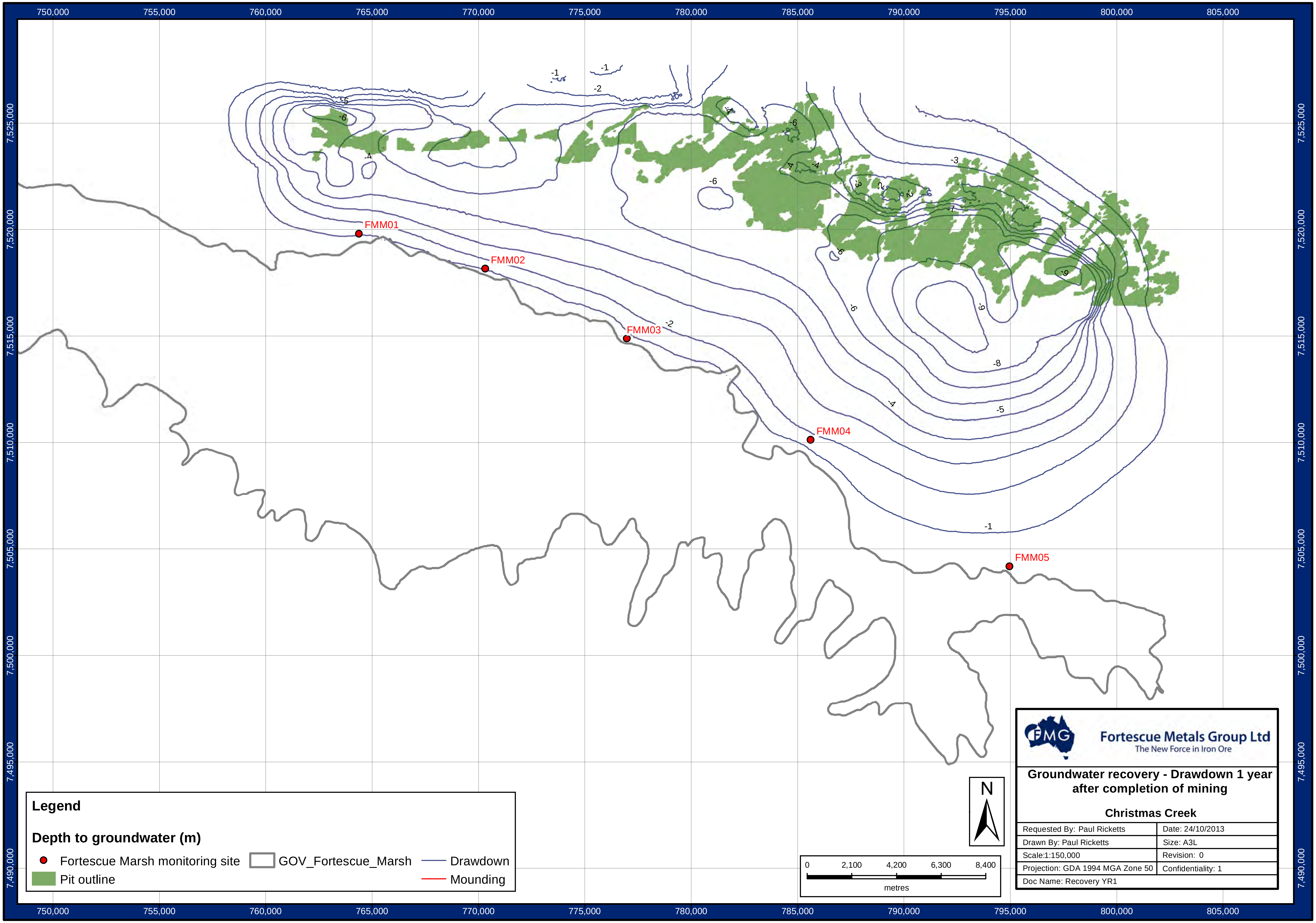

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Legend
Depth to groundwater (m)
Fortescue Marsh monitoring site
GOV_Fortescue_Marsh
Drawdown
Pit outline
Mounding
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FMG
Fortescue Metals Group Ltd
The New Force in Iron Ore
Groundwater recovery - Drawdown 1 year after completion of mining
Christmas Creek
Requested By: Paul Ricketts
Date: 24/10/2013
Drawn By: Paul Ricketts
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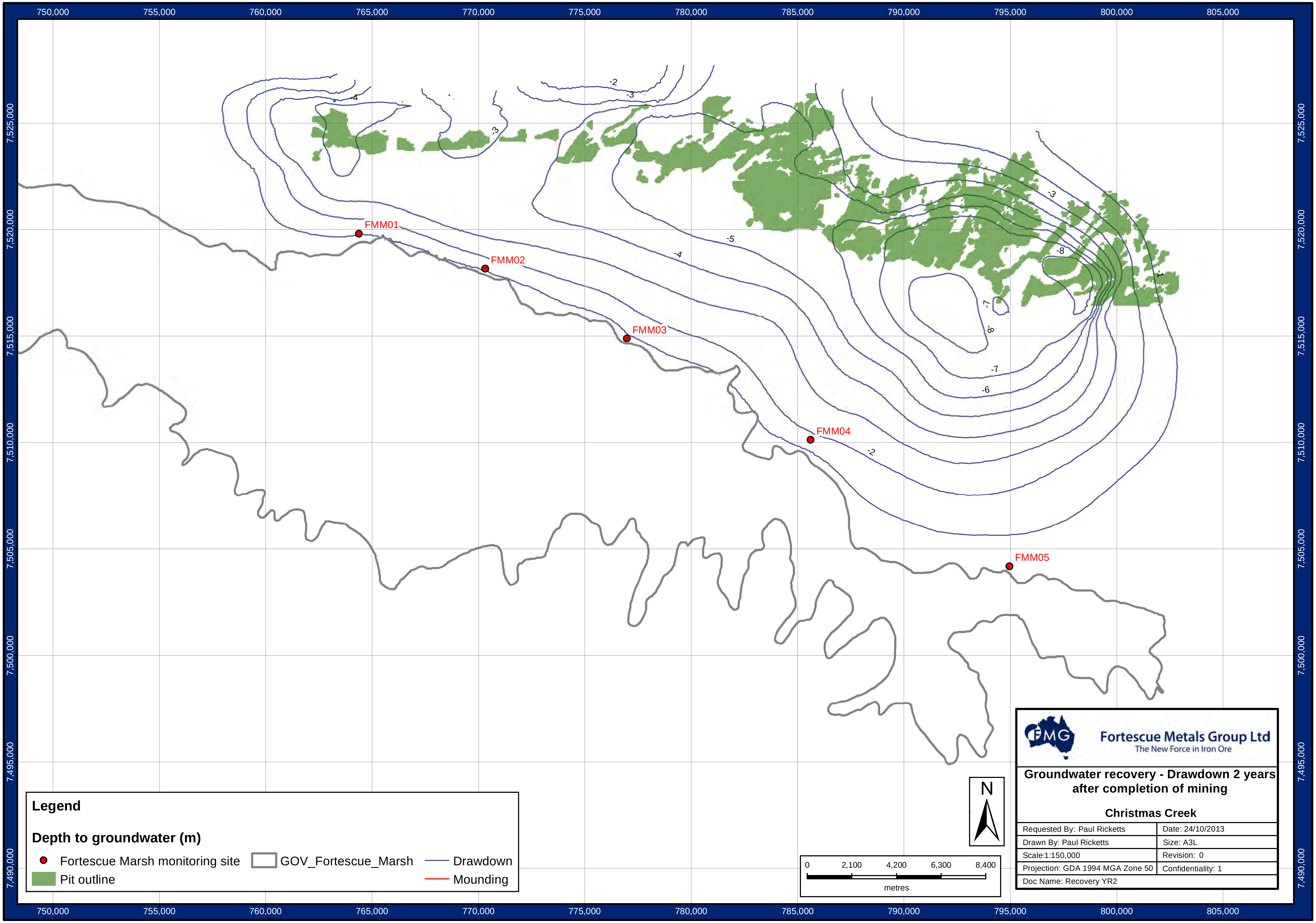
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The New Force in Iron Ore
Groundwater recovery - Drawdown 2 years after completion of mining
Christmas Creek
Requested By: Paul Ricketts
Date: 24/10/2013
Drawn By: Paul Ricketts
Size: A3L
Scale:1:150,000
Revision: 0
Projection: GDA 1994 MGA Zone 50
Confidentiality: 1
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Depth to groundwater (m)
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GOV_Fortescue_Marsh
Drawdown
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Mounding
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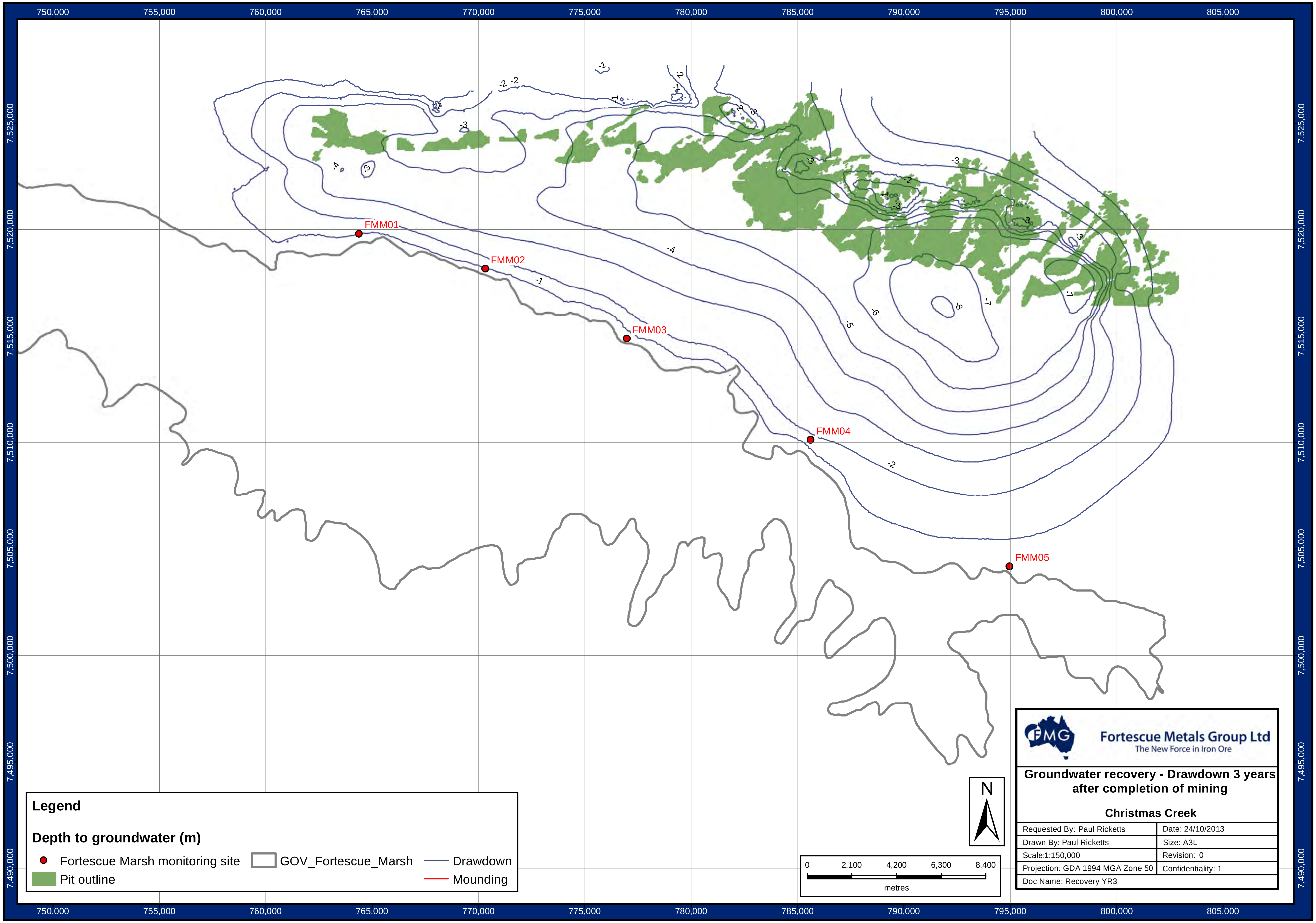
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Legend
Depth to groundwater (m)
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Pit outline
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Drawdown
Mounding
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metres
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Fortescue Metals Group Ltd
The New Force in Iron Ore
Groundwater recovery - Drawdown 3 years after completion of mining
Christmas Creek
Requested By: Paul Ricketts
Date: 24/10/2013
Drawn By: Paul Ricketts
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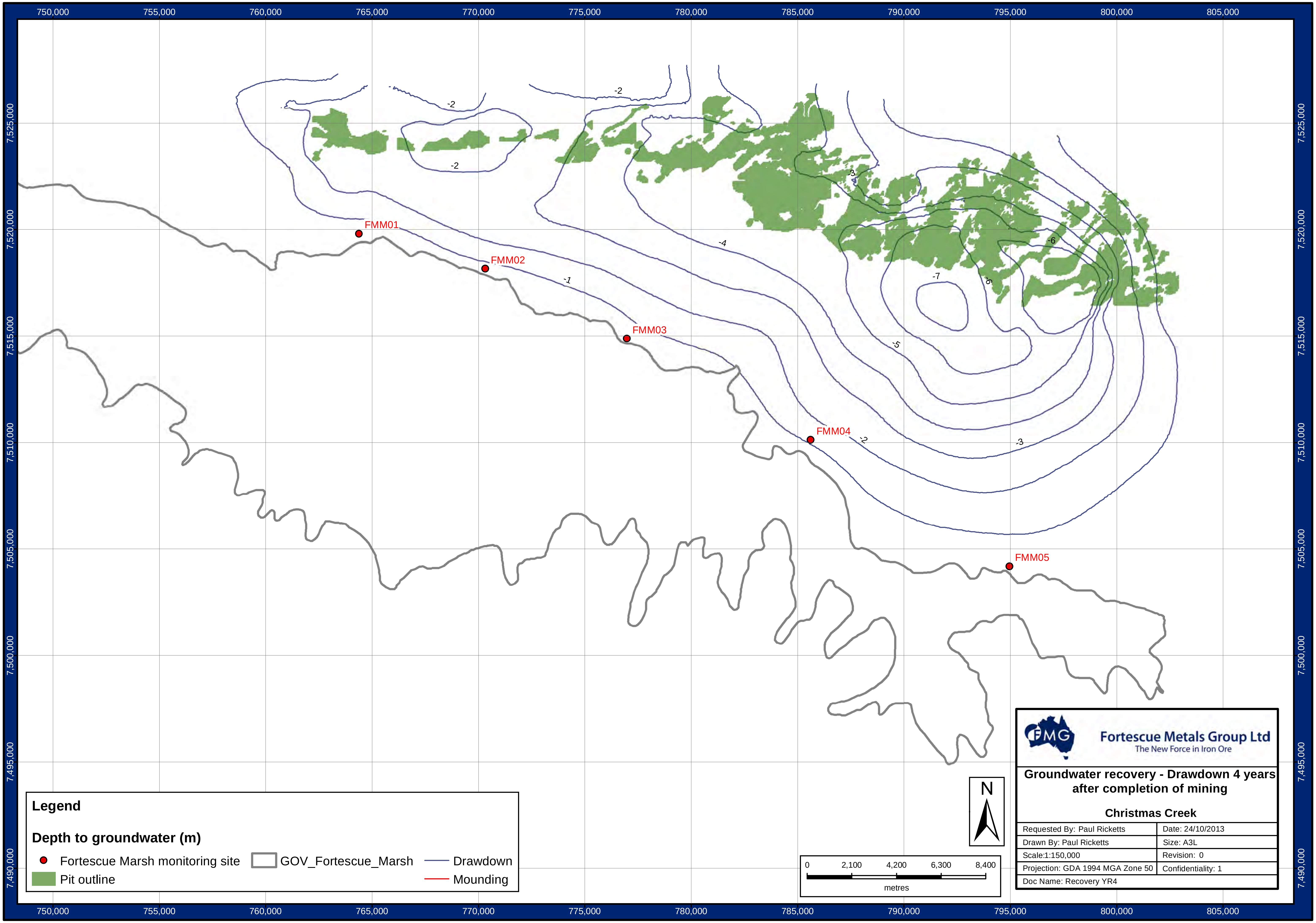

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Legend
Depth to groundwater (m)
Fortescue Marsh monitoring site
Pit outline
GOV_Fortescue_Marsh
Drawdown
Mounding
Fortescue Metals Group Ltd
The New Force in Iron Ore
Groundwater recovery - Drawdown 4 years after completion of mining
Christmas Creek
Requested By: Paul Ricketts
Date: 24/10/2013
Drawn By: Paul Ricketts
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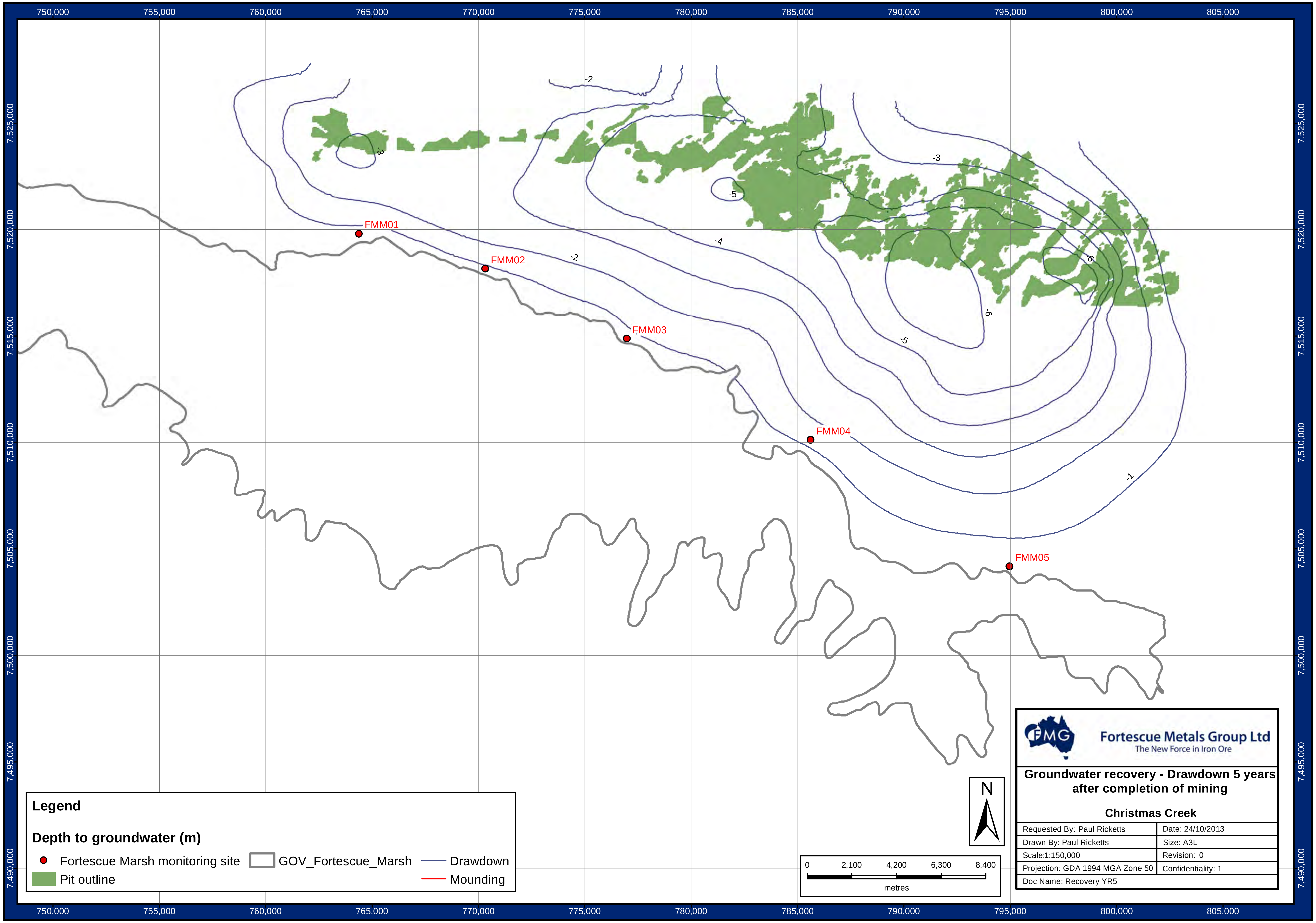

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metres
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FMG
Fortescue Metals Group Ltd
The New Force in Iron Ore
Groundwater recovery - Drawdown 5 years after completion of mining
Christmas Creek
Requested By: Paul Ricketts
Date: 24/10/2013
Drawn By: Paul Ricketts
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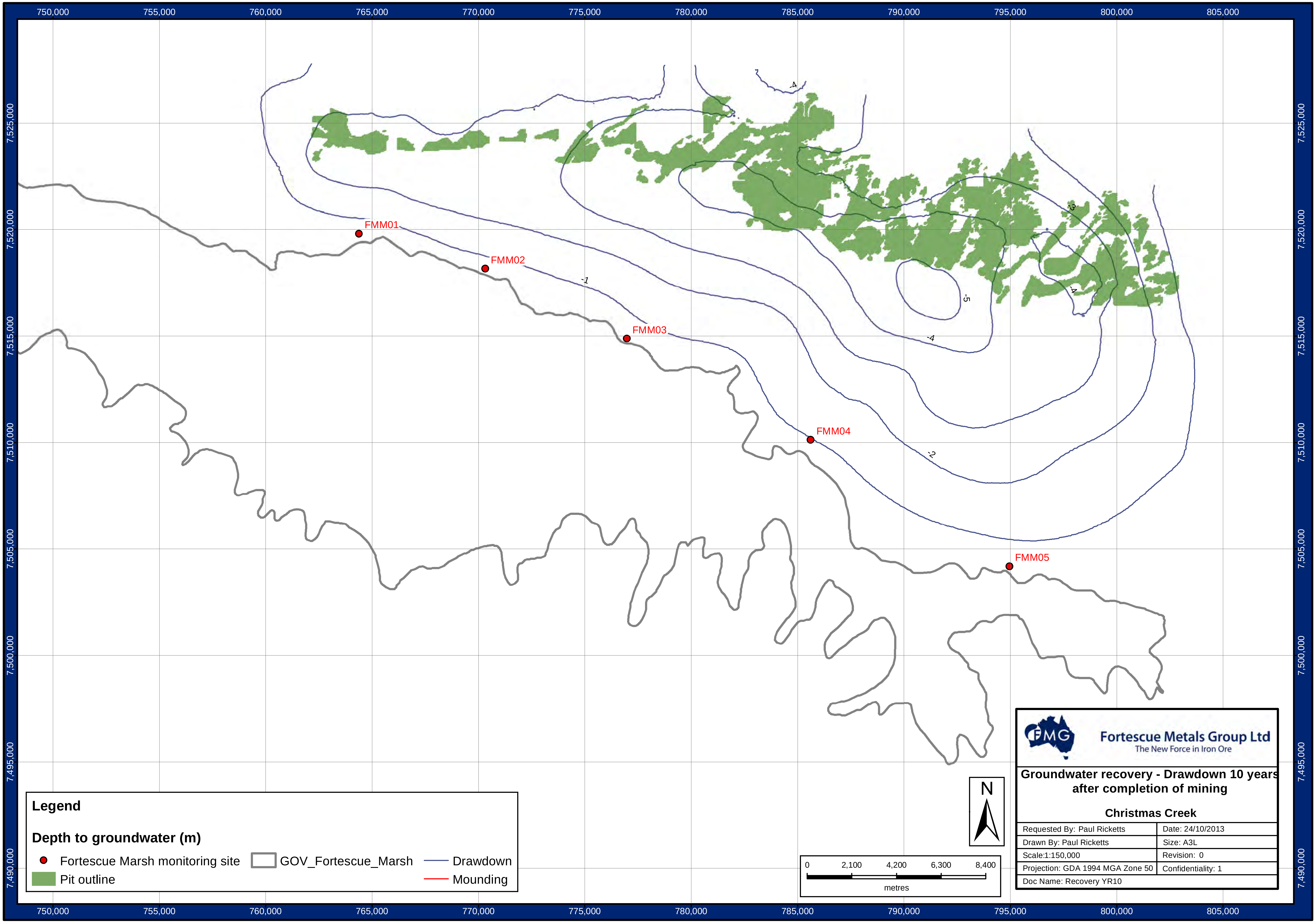

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metres
Fortescue Metals Group Ltd
The New Force in Iron Ore
Groundwater recovery - Drawdown 10 years after completion of mining
Christmas Creek
Requested By: Paul Ricketts
Date: 24/10/2013
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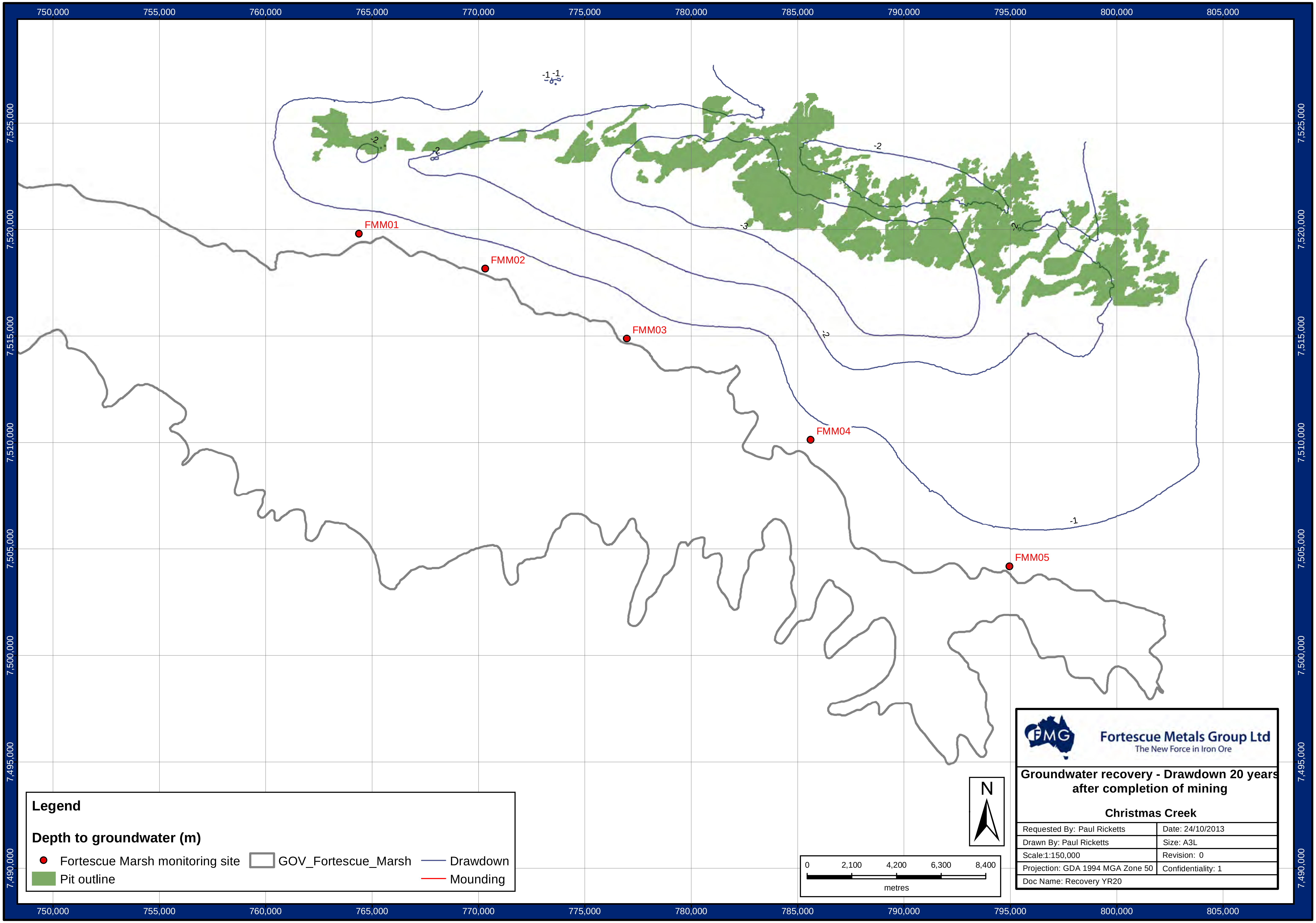

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Pit outline
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Fortescue Metals Group Ltd
The New Force in Iron Ore
Groundwater recovery - Drawdown 20 years after completion of mining
Christmas Creek
Requested By: Paul Ricketts
Date: 24/10/2013
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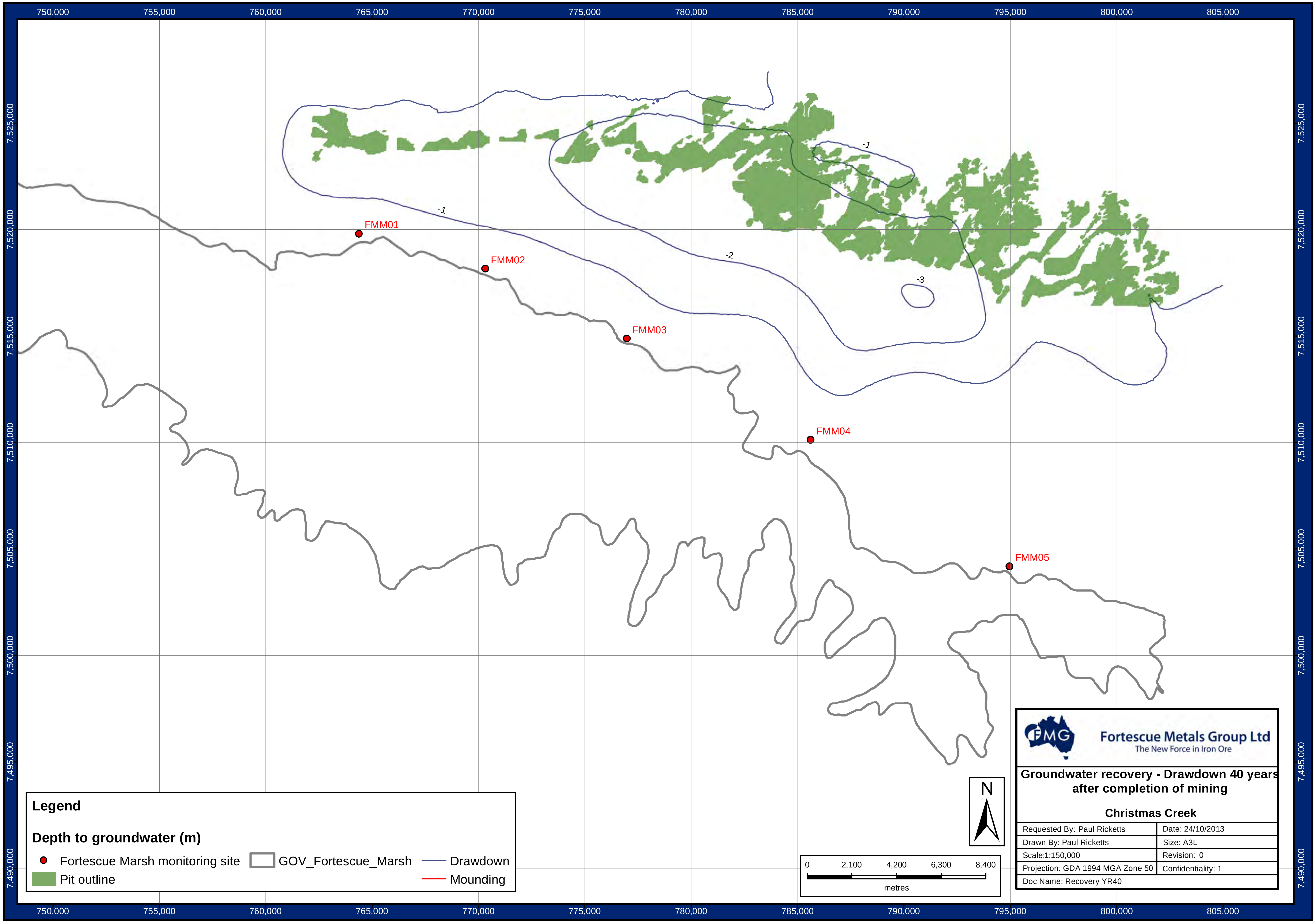

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Legend
Depth to groundwater (m)
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Pit outline
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Drawdown
Mounding
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metres
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Fortescue Metals Group Ltd
The New Force in Iron Ore
Groundwater recovery - Drawdown 40 years after completion of mining
Christmas Creek
Requested By: Paul Ricketts
Date: 24/10/2013
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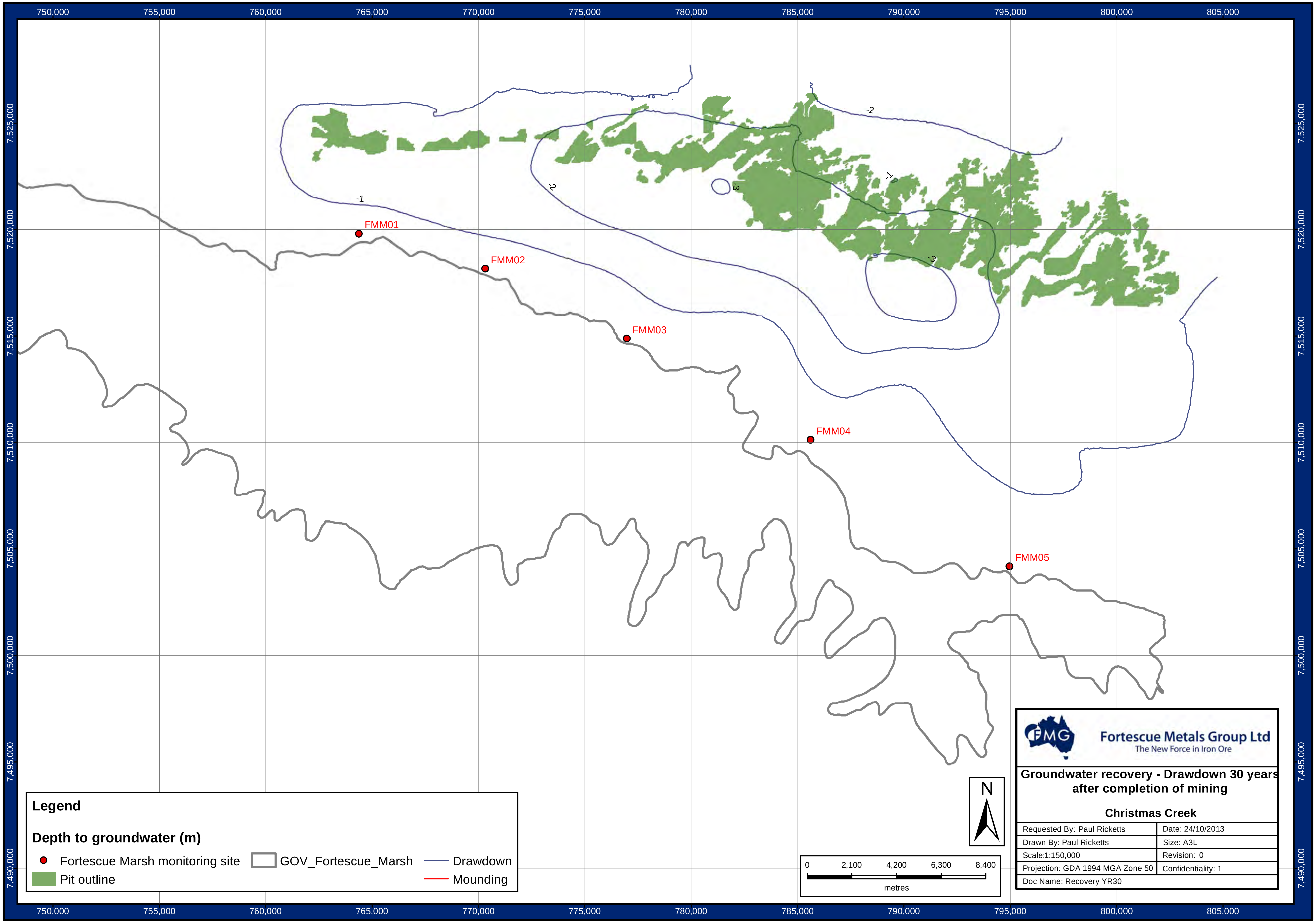
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Legend
Depth to groundwater (m)
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Drawdown
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FMG
Fortescue Metals Group Ltd
The New Force in Iron Ore
Groundwater recovery - Drawdown 30 years after completion of mining
Christmas Creek
Requested By: Paul Ricketts
Date: 24/10/2013
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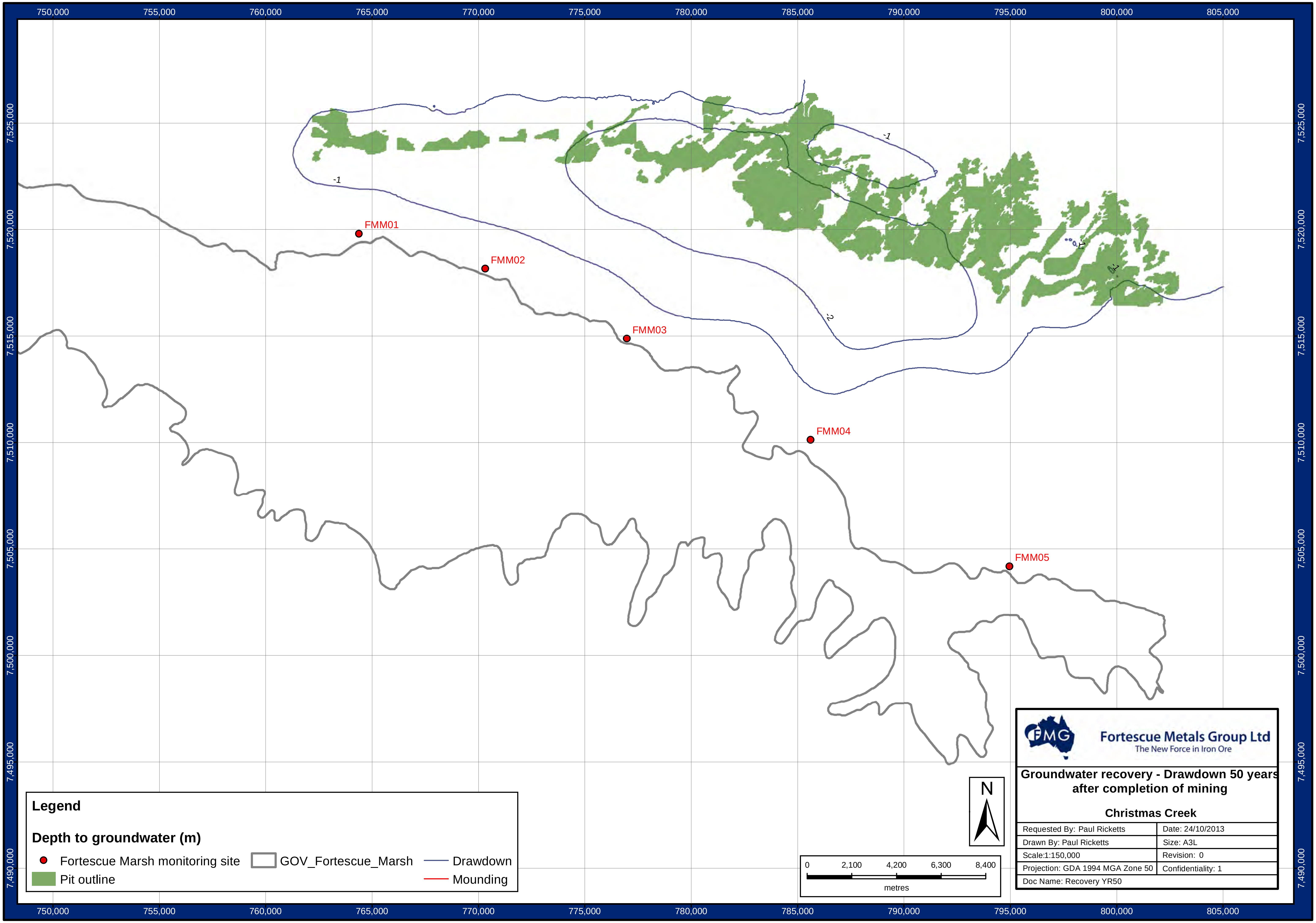

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metres
Legend
Depth to groundwater (m)
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Drawdown
Pit outline
Mounding
Fortescue Metals Group Ltd
The New Force in Iron Ore
Groundwater recovery - Drawdown 50 years after completion of mining
Christmas Creek
Requested By: Paul Ricketts
Date: 24/10/2013
Drawn By: Paul Ricketts
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Appendix 8: Effect of hydraulic property of backfilling materials on model predictions

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Effect of the Hydraulic Properties of Pit Backfilling Materials

Based on FMG's mine closure plan, all mined pits will be backfilled with waste materials. The hydraulic properties of the backfilling materials are usually different from those of the original overburden and the ore. Although not actually measured, the hydraulic conductivity of the backfilling materials is likely larger than the conductivity of the original overburden, but smaller than that of the original ore. Since backfilling materials cannot be packed as dense as the original overburden, its specific yield should be larger than that of the original overburden.

Assuming that the conductivity of backfilling materials is 10 m/day (between overburden (2.5 m/day and ore (70 m) conductivities) and specific yield is 0.052 (30% larger than overburden), a simulation was setup. The results from this simulation are compared to those from the simulation that didn't consider the change of hydraulic properties after mining and the difference in dewatering volumes is presented in Figure H.1. The difference in dewatering volumes between these two simulations is less than 2.5 GL/a, except in year 2020 (3.9 GL/a). The average difference in annual dewatering volumes is only bout 4%, which is small compared to prediction uncertainties associated with other factors, such as spatial variations in hydraulic conductivity. Similarly, the difference in the spatial distribution of groundwater drawdown/mounding between the two simulations are marginal (not shown here).

In summary, neglecting the change in hydraulic parameters after mining in our model setup would not significantly change our model predictions. Therefore, all numerical simulations were conducted without considering the temporal change in hydraulic properties before and after mining.

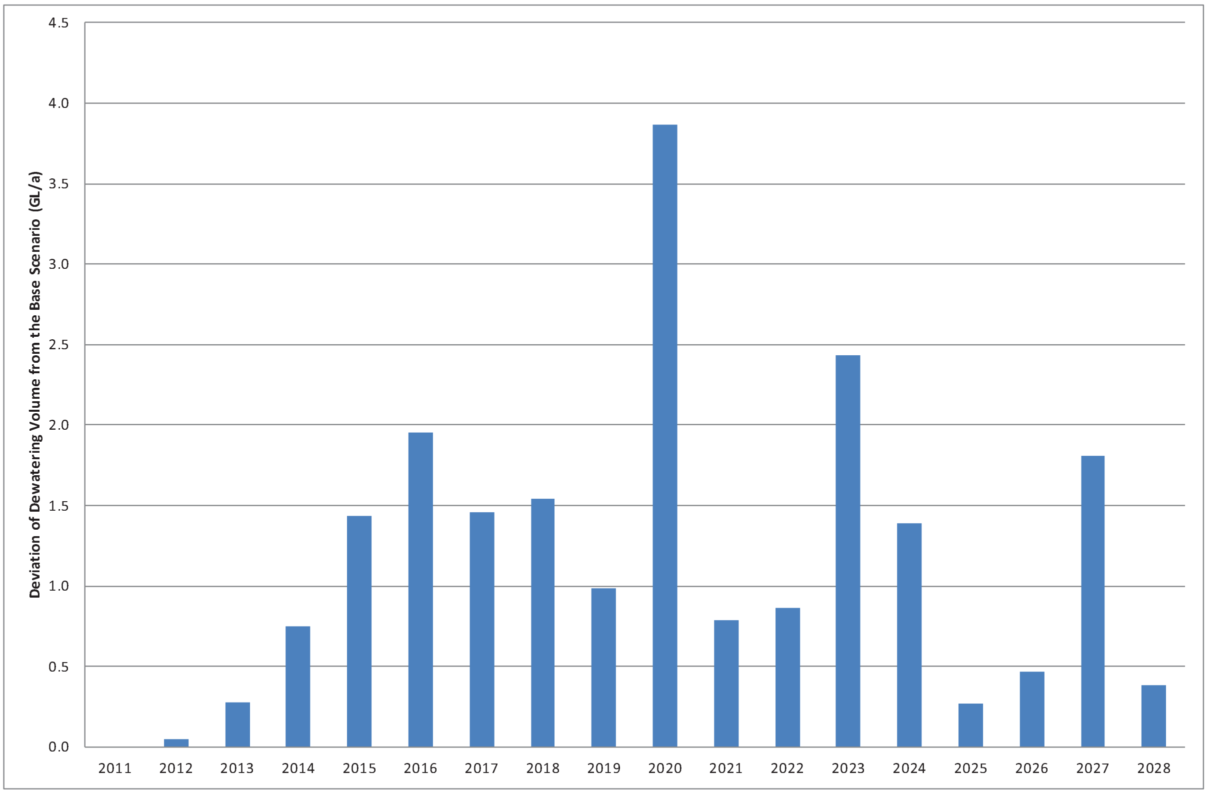

Figure H.1: Dewatering volume differences between the Base Scenario simulation and the simulation considering the changes in hydraulic properties after pits being backfilled.