Roy Hill Holdings Pty Ltd

Roy Hill Life of Mine Water Management Strategy - Groundwater Change Assessment

January 2019

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ABBREVIATIONS

DEM	Digital elevation model
DST	Dust Suppression Task
EVT	Evapotranspiration package (MODFLOW)
g/L	gram per litre
GL/yr	gigalitre per yer
GWOS	Groundwater operating strategy
K	Hydraulic conductivity (m/d)
LiDAR	Light detection and ranging (surveying technology)
LoM	Life of mine
MAR	Manage aquifer recharge
mg/L……………….	miligram per litre
ML/d	megalitre per day
MNW2	Multi node well package, version 2 (MODFLOW)
MPIB	Mining pit injection borefield
MPMAR	Mining pit MAR
PPT	Process Plant Task
RCH	Recharge package (MODFLOW)
RHIO	Roy Hill Iron Ore
RHWMS	Roy Hill Water Management Strategy
RMAR	Remote MAR
RMS	Root mean square error
SRMS	Scaled RMS
Ss	Specific storage (dimensionless)
SWIB	Southwest injection borefield
Sy	Specific yield
TSFT	Tailings Storage Facility Task
WEL	Well package (MODFLOW)
WTPT	Water Treatment Plant Task

1. Introduction

1.1 Background

Roy Hill (RH) is an iron ore mining, rail and port project (Project) developed in Western Australia's Pilbara region (Figure 1-1). Much of mining in the Chichester Range takes place under the water table, resulting in the need for dewatering of the mining pits.

Roy Hill maintain a Water Management Strategy (RHWMS) for dewatering, water supply and surplus water disposal to ensure alignment with business, environmental and stakeholder objectives.

RH have updated the Life of Mine (LoM) mining strategy, ore processing strategy and waste (tailings) disposal strategy, as of July 2018, which forms the basis of the revised LoM RHWMS for dewatering, water supply and surplus water disposal. The RHWMS identifies the requirement for additional surplus water disposal capacity to address increases in forecast dewatering rates and surplus non-return process water. The proposed revision to the LoM RHWMS incorporates Managed Aquifer Recharge (MAR) as a surplus water disposal solution.

RH has developed a MAR project for purpose of disposing and/or storing surplus groundwater into Proterozoic and Cainozoic formations within the mining area. RH submitted the MAR proposal including groundwater change assessment for a 2-year period to the EPA in early 2018. In mid-2018 the EPA approved implementation of the proposal. The EPA requested that RH present an updated LoM RHWMS and groundwater change assessment to support approval for MAR beyond the two year period.

The revised RHWMS includes the current MAR project(s) and expansion of the MAR project to locations south of the Fortescue River, referred to as Remote MAR North (RMAR North) and Remote MAR South (RMAR South) (Figure 1-1).

GHD has been requested by RH to carry out an update to the groundwater change assessment of the revised LoM RHWMS.

1.2 Purpose and scope of this report

The objective of this project is to assess groundwater change for the revised LoM RHWMS.

The LoM RHWMS proposes an expanded footprint of operations. Assessment of the feasibility and related groundwater change for the expanded operational footprint requires development of a suitable conceptual model for the regional groundwater system, and a numerical groundwater modelling system for quantitative analysis of the groundwater response. Addressing these requirements is the focus for this study. This new numerical tool builds on existing models, in particular RH's FEFLOW dewatering model as well as previous MODFLOW models developed by MWH (2009, 2015).

In fulfilment of this study the following will be provided:

- Description of receiving environment (including hydrogeological setting);
- Hydrogeological conceptualisation (update);
- Development of the numerical model, modelling of RHWMS, and prediction of water level change;
- Proposed monitoring of groundwater impacts,

The assessment described in this report also builds on and refers to existing MAR assessments and studies, including RH's OP-REP-00510 (Hydrogeological Assessment for Roy Hill Managed

Aquifer Recharge System Report, March 2018) and Managed Recharge's report, Roy Hill Remote MAR Project – Phase 1 (May 2018).

Due to the nature, feasibility level and regional scale of this assessment, these LoM impacts will be evaluated from the regional rather than localised, operational perspective.

1.3 Document overview

This content of this document is structured as follows:

- Section 1 provides an introduction;
- Section 2 provides an overview of the RHWMS, including water balance tasks and operating conditions for dewatering, water supply and surplus water disposal;
- Section 3 describe the methodology and outcomes for the groundwater change assessment;
- Section 4 describes the planning approach (incorporating monitoring) for the RHWMS;
- Section 5 presents conclusions; and
- Appendices present additional information (geological description details, land system descriptions, modelled results – hydrograph plots, change maps, etc).

1.4 Study limitations

This report: has been prepared by GHD for Roy Hill Holdings Pty Ltd and may only be used and relied on by Roy Hill Holdings Pty Ltd for the purpose agreed between GHD and the Roy Hill Holdings Pty Ltd as set out in this report.

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The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report. GHD disclaims liability arising from any of the assumptions being incorrect.

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Investigations undertaken in respect of this report are constrained by the particular site conditions, such as the location of infrastructure, services and vegetation. As a result, not all relevant site features and conditions may have been identified in this report.

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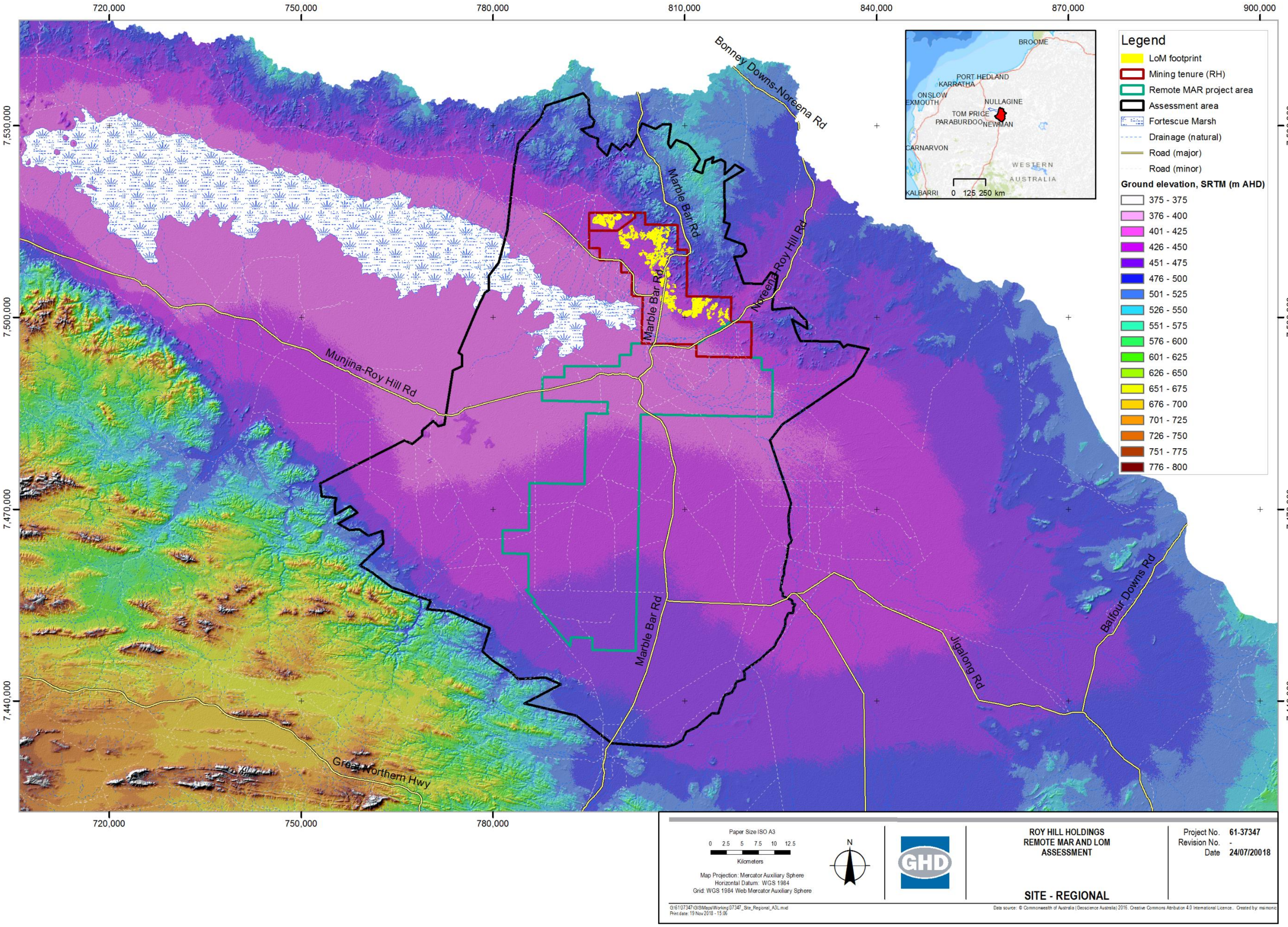

Figure 1-1: Regional setting of the study area

2. Roy Hill Water Management Strategy update

2.1 Roy Hill Water Management Strategy update – key business drivers

The basis of the LoM RHWMS update is the July 2018 RH LoM Plan. The LoM plan describes the product, mining, ore processing and waste management strategy. Key parameters of this plan that influence the LoM RHWMS include:

2.1.1 Product strategy

The product strategy exerts a strong influence on the RHWMS. Chloride is an important ore quality parameter that is influenced by water quality. The water supply strategy (including process water reuse) is required to satisfy quality terms of reference to ensure the product quality specifications for chloride is achieved.

2.1.2 Mining strategy

The mining strategy is the principal driver of dewatering rates. Key parameters influencing dewatering rates at a LoM scale is the planned open areas (mine pits) below water table.

In general, there has been an increase in the footprint of simultaneously operating pits throughout the LoM mine plan, which has a direct influence (increase) on dewatering abstraction rates.

In addition, the scale of the active mining footprint is a key factor in determining dust suppression requirements for the LoM.

2.1.3 Ore processing and waste (tailings) management strategy

The (solids and water) mass balance of the ore processing facility is a key driver for water demand. Factors such as throughput, processing yield and tailings solids concentration are key parameters in determining water needs for ore processing. Recovery of process water from tailings storage facilities (TSF) is necessary for maximising consolidation and subject to water balance assumptions for the TSF.

As mentioned above product chloride concentrations is an important parameter, and therefore the solids and water balance for chloride is an important consideration in determining water supply and process water reuse.

2.2 Roy Hill Water Management Strategy update – key objectives

A key objective for the RHWMS update is to build resilience and adaptability to manage multiple business, environmental and stakeholder objectives.

The RHWMS strategy maintains a focus on minimising environmental and stakeholder impacts by maintaining water reuse as a high priority for the business.

2.3 Roy Hill Water Management Strategy – key updates

For water balance planning purposes, the RHWMS defines seven primary 'water balance' tasks. Water balance tasks describe the water inputs and outputs for the parts of the operation that make up the overall mine site water balance. A schematic illustrating the water balance tasks is shown in Figure 2-1. The RHWMS defines the following water balance tasks:

- Mining and Dewatering task (MDT); consists of inputs only, includes ore moisture (pore water) and mine dewater streams (i.e. fresh, brackish and saline).
- Raw Water Supply Task (RWST); consists of inputs only, includes supplementary raw water inputs.
- Water Treatment Plant Task (WTPT); water inputs (feed water) and outputs (wash water and reject water) of the water treatment facility.
- Process Plant Task (PPT); water inputs and outputs (tailings, product moisture) of the ore processing facility
- TSF Task (TSFT); water inputs and outputs of the tailings storage facility
- Dust Suppression Task (DST); water inputs and outputs for dust suppression
- Surplus Water Disposal Task (SWDT); water outputs to disposal (multiple components).

Tasks may comprise one or multiple components. For example the mining and dewatering task comprises multiple pits and water quality streams.

The RHWMS update retains the previous tasks and components with addition of MAR components to the surplus water disposal task as the main change. Table 2-1 provides a summary of the key RHWMS tasks and components, including description of change from previous RHWMS. An illustrative map showing the current and proposed locations of the RHWMS components is presented in Figure 2-2. The update to the RHWMS address the operating conditions described in Section 2.4.

It should be noted that this study focuses on assessment of groundwater change related to the dewatering task and surplus water disposal tasks in the RHWMS.

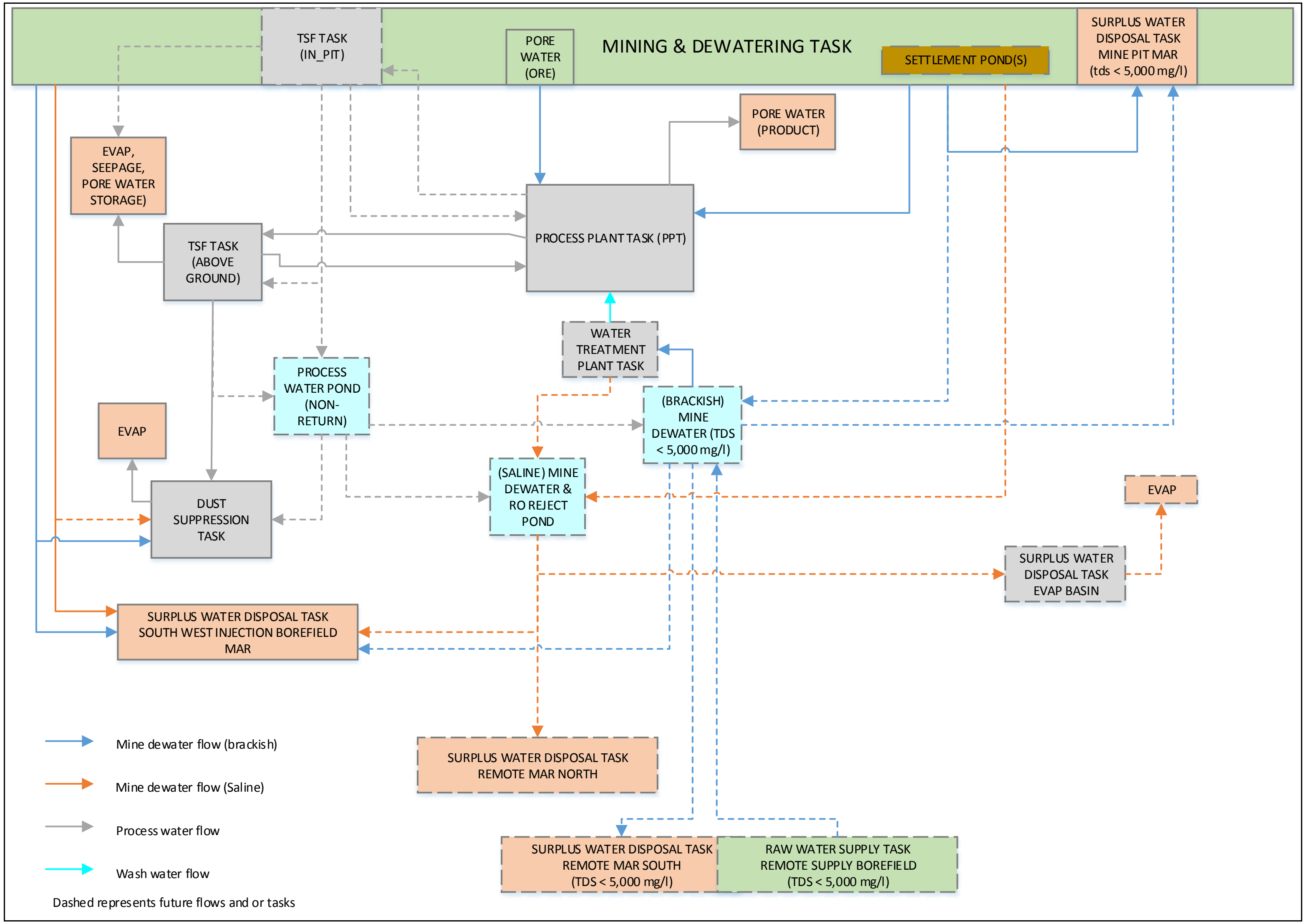

Figure 2-1: RHWMS – Tasks and components

Table 2-1: Roy Hill Water Management Strategy: key updates

Task	Components	RHWMS update
Mining & Dewatering Task (MDT)	Pit Dewatering (multiple pits) Fresh (<800 ppm Cl) Brackish (<5,000 mg/l TDS) Saline (>5,000 mg/l TDS)	Dewatering of mine pits remains a core water management activity. Increased dewatering forecast due to increase in concurrent below watertable mine pits, and as required by in-pit TSFs.
Raw Water Supply Task (RWST)[1]	Remote water supply borefield	Remote water supply was previously proposed (Stage 2 borefield) and assessed for abstraction of up to 40 ML/d. Remote water supply remains in the strategy to address operating conditions where water quality prohibits reuse of mine dewatering and non-return process water.
Water Treatment Plant Task (WTPT)	Water Treatment Plant	Water treatment remains a key component of the water supply strategy to address water quality requirements of the ore processing facility
Process Plant Task (PPT)	Ore Processing facility	Multiple operating conditions considered to address water demand and product quality objectives. Processing changes including WHIMS are considered in determining future water demand
TSF Task (TSFT)	Above ground TSF In-pit TSF	In-pit tailings storage is proposed to replace the current above ground facility. On average 20 ML/d process water recovery is estimated to be required to optimise in-pit storage capacity
Dust Suppression Task (DST)	Dust suppression	Dust suppression supplied from surplus groundwater and or non-return process water
Surplus Water Disposal Task (SWDT)	South West Injection Borefield (SWIB MAR)	The SWIB MAR is developed in the south west part of the mining tenement. Disposal of surplus water in the SWIB is currently approved for a two year period
	Mine Pit (MPMAR)	Disposal of surplus water in future & completed mine pits. Disposal of surplus water in the future mining area (Stage 1 borefield) is currently approved for a two year period
	Remote MAR South borefield (RMAR South)	Surplus (brackish) water greater than capacity for re-use and local disposal is identified under some operating conditions. Development of MAR capacity south of the Fortescue River is proposed for additional surplus brackish water (<5,000 mg/l).
	Remote MAR North borefield (RMAR North)	Surplus (saline, >5,000 mg/L) water greater than capacity for re-use and local disposal is identified under some operating conditions. Development of MAR capacity south of the Fortescue River is proposed for additional surplus brackish and/or saline water
	Evaporation Basin	Disposal of surplus water via an evaporation basin was previously proposed and assessed. An evaporation basin remains part of the LoM strategy. Implementation of the evaporation basin is largely considered a contingency, however operating conditions requiring an evaporation basin is considered

[1] Supplementary to dewatering

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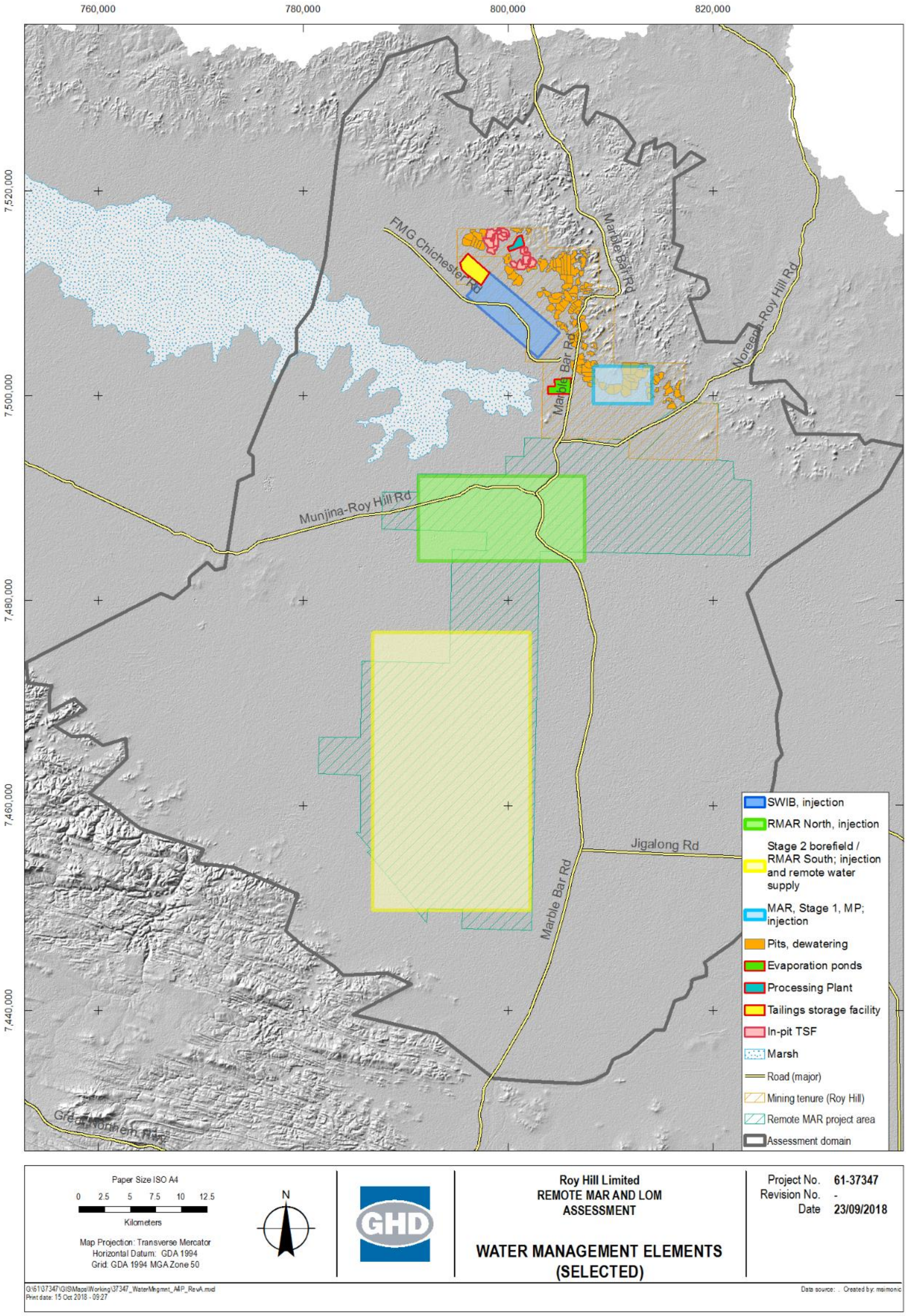


Figure 2-2: Spatial distribution of key water management areas/components

2.4 Roy Hill Water Management Strategy update –operating conditions

The LoM RHWMS tasks and components are presented schematically in **Error! Reference source not found.**Figure 2-2. Water balances for multiple realistic operating conditions form the basis. Operating conditions are influenced by multiple factors including dewatering flows and quality of the LoM and flow and quality constraints for each of the other tasks. For example, the dewatering flows and quality changes over time and at certain thresholds represent a change to the operating condition triggering requirement for additional surplus water disposal components and or raw water supply components.

Another example is the multiple operating conditions for water inputs to the process plant task. Product quality specifications may place a constraint on reuse of process water in the process plant, which necessitates an alternate operating condition for alternate use and/or disposal of the process water and replacement of the supply (eg additional dewatering and/or raw water supply).

It is important for RH to consider the realistic operating conditions that may require implementation and undertake planning for these operating conditions to mitigate production risk. Quantitative water balances describing current, LoM average and LoM peak operating conditions are presented in the following sections.

2.4.1 Current operating condition

The water balance for the current operating condition is presented in Table 2-2 and Figure 2-3.

The mining and dewatering task (MDT) consists of inputs from dewatering and pore water (in mined ore). The current dewatering rate is around 58 ML/d, total inputs including pore water is around 74 ML/d. Dewatering consists of three quality streams, defined below:

- Mine dewater fresh (TDS < 2,000 mg/l); maximum quality for direct feed to the Processing plant task (PPT).
- Mine dewater brackish (TDS < 5,000 mg/l); quality limit for feed to the Water treatment plan task (WTPT) for direct feed to the PPT and surplus water disposal to Mine Pit MAR and Remote MAR South.
- Mine dewater saline (TDS > 5,000 mg/l); saline water quality, disposal to SWIB and Remote MAR North.

Raw water inputs to other water balance tasks are satisfied by dewatering and therefore no supplementary raw water abstraction takes place currently.

The current quantity of mine dewater fresh is sufficient to satisfy the PPT and therefore the WTPT not required.

The PPT receives mine dewater and (ore) pore water inputs (58 ML/d) and outputs consist of (product) pore water and discharge to tailings (58 ML/d).

Tailings disposal is currently to an above ground TSF. Seepage, evaporation and entrainment in pore space account for over half of the outputs from the TSFT (27 ML/d). Other outputs are return process water to the PPT (up to 9 ML/d)) and use in the DST (up to 9 ML/d)).

The DST can receive inputs from several sources, currently non-return process water (9 ML/d).

The surplus water disposal task (SWDT) consists of outputs that are surplus to the operation. Currently surplus are mine dewater, up to 25 ML/d, disposed of to the SWIB and Mine Pit MAR.

The balance reports the total inputs and outputs of the operation which are currently around 74 ML/d.

Table 2-2: Current operating condition

Tasks	Water Balance Components	ML/d	GL/a	GL/LoM (13 yrs)
MINING & DEWATERING TASK	**MDT Inputs**			
	Mine Dewater Fresh (TDS < 2,000 mg/l)	40	15	
	Mine Dewater Brackish (TDS <5,000 mgl)	14	5	
	Mine Dewater Saline (TDS >5,000 mgl)	4	1	
	Pore Water (ore)	16	6	
	Sum Inputs	74	27	
RAW WATER SUPPLY TASK	**RWST Inputs**			
	Remote Supply Borefield brackish (TDS <5,000 mgl)	0	0	
	Sum Inputs	0	0	
WATER TREATMENT PLANT TASK	**WTPT Inputs**			
	Mine Dewater brackish (TDS <5,000 mgl)	0	0	
	Process Water (non-return)	0	0	
	Remote Supply Borefield brackish (TDS <5,000 mgl)	0	0	
	Total In	0	0	
	WTPT Outputs			
	Wash Water (Cl <400 ppm)	0	0	
	RO Reject	0	0	
	Total Out	0	0	
PROCESS PLANT TASK	**PPT Inputs**			
	Mine Dewater fresh (TDS < 2,000 mg/l)	23	8	
	Wash Water (Cl <400 ppm)	10	4	
	Process Water (Direct return)	9	3	
	Pore Water (Feed)	16	6	
	Total In	58	21	
	PPT outputs			
	Process Water (in Tailings)	-45	-16	
	Pore Water (product)	-13	-5	
	Total Out	-58	-21	
TSF TASK	**TSFT Inputs**			
	Process Water (in Tailings)	45	16	
	Total In	45	16	
	TSFT Outputs			
	TSF seepage, evap & entrainment	-27	-10	
	Process Water (Direct Return)	-9	-3	
	Process Water (Non-Return)	-9	-3	
	Total Out	-45	-16	
DUST SUP. TASK	**DST Input**			
	Process Water (Non-Return)	9	3	

Tasks	Water Balance Components	ML/d	GL/a	GL/LoM (13 yrs)
	Mine Dewater brackish (TDS <5,000 mgl)	0	0	
	Mine Dewater saline (TDS >5,000 mgl)	0	0	
	Total In	9	3	
	DST Output			
	Process Water (road evap)	-9	-3	
	Mine Dewater brackish (TDS <5,000 mgl)	0	0	
	Mine Dewater saline (TDS >5,000 mgl)	0	0	
	Total Out	-9	-3	
SURPLUS WATER DISPOSAL TASK	**SWDT Outpu**ts			
	RO Reject to SWIB MAR	0	0	
	Process Water (NR) to SWIB MAR	0	0	
	Dewater to SWIB MAR	-20	-7	
	Dewater to Mine Pit MAR (TDS <5,000 mgl)	-5	-2	
	Dewater to RMAR South (TDS <5,000 mgl)	0	0	
	Dewater to RMAR North	0	0	
	Dewater to Evaproation Basin	0	0	
	Sum Outputs	-25	-9	
BALANCE	INPUTS			
	MINING & DEWATERING TASK	74	27	
	RAW WATER SUPPLY TASK	0	0	
	Total Inputs	74	27	
	OUTPUTS			
	PROCESS PLANT TASK	-13	-5	
	TSF TASK	-27	-10	
	DUST SUP. TASK	-9	-3	
	SURPLUS WATER DISPOSAL TASK	-25	-9	
	Total Outputs	-74	-27	

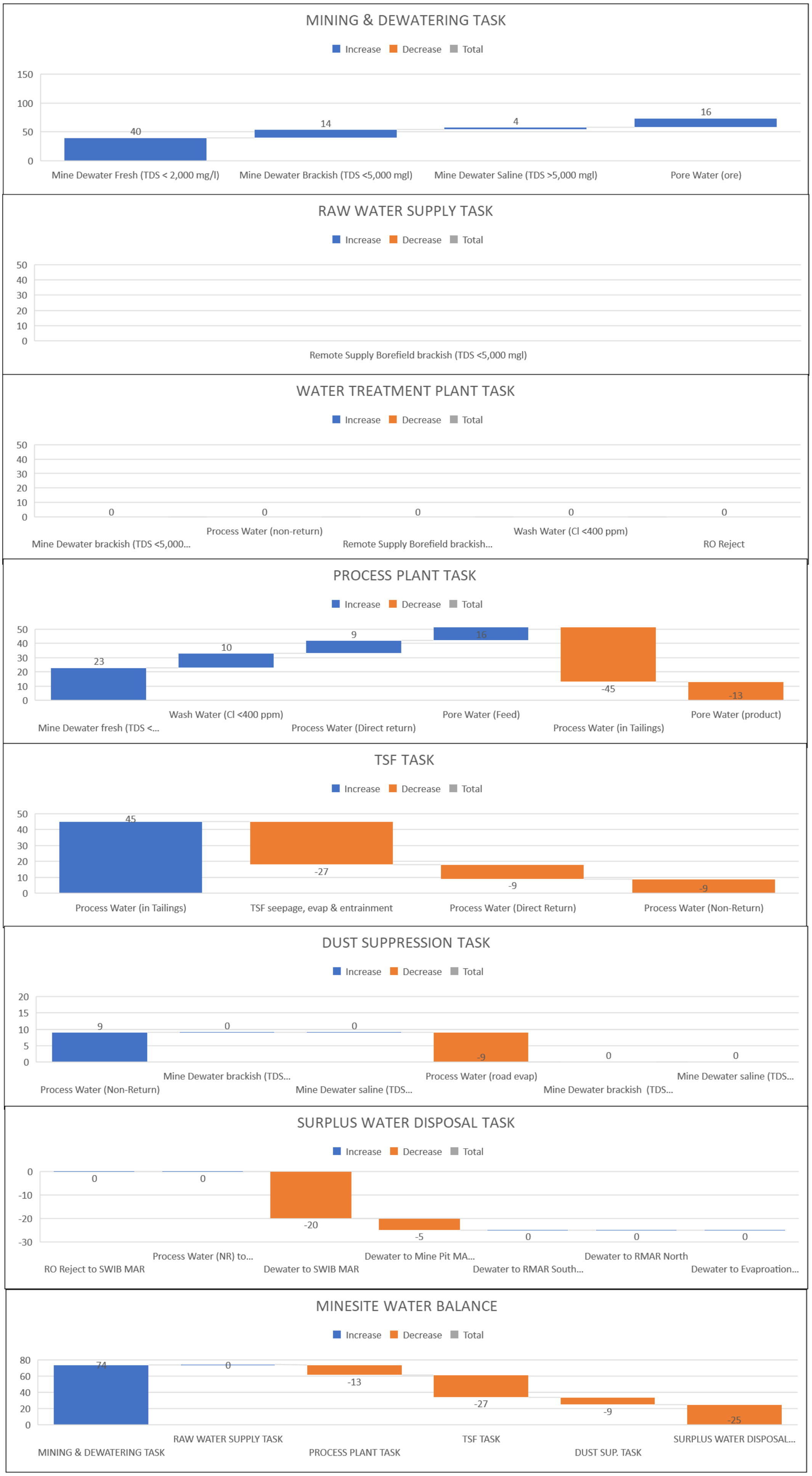


Figure 2-3: Current operating condition

2.4.2 LoM average operating condition 1

The water balance for the LoM average operating condition 1is presented in Table 2-3 and Figure 2-4.

The mining and dewatering task (MDT) consists of inputs from dewatering and pore water (in mined ore). The LoM average dewatering rate is around 132 ML/d. This LoM average condition assumes the dewatering streams are brackish (80 ML/d) and saline (52 ML/d), a mine dewater fresh stream is excluded from the LoM average as this stream is not considered sustainable over LoM.

Under this scenario the raw water inputs to other water balance tasks are satisfied by dewatering and therefore no supplementary raw water abstraction is required.

Mine dewater fresh (Cl < 2000 mg/l) is unsustainable and therefore the WTPT is required to provide the full PPT demand of 33 Ml/d. A by-product of the WTPT is a saline reject stream (6 ML/d), which is disposed of to the saline SWIB.

The PPT receives wash water (33 ML/d) and ore pore water inputs (16 ML/d) and outputs consist of product pore water and discharge to tailings (36 ML/d).

Tailings disposal is currently to an above ground TSF and from 2020 to in-pit TSF. Seepage, evaporation and entrainment in pore space account for around half of the outputs from the TSFT (16 ML/d). Other outputs are non-return process water (20 ML/d), which is disposed of to the SWIB.

The DST can receive inputs from several sources, under this scenario the DST receives around 10 ML/d from excess mine dewater saline.

The surplus water disposal task (SWDT) consists of outputs that are surplus to the operation. Under this scenario surplus water disposal is distributed in the following allocations:

- WTPT reject to SWIB (6 ML/d)
- Non-return process water to SWIB (20 ML/d)
- Mine Dewater saline to SWIB (40 ML/d)
- Mine dewater saline to RMAR North (2 ML/d)
- Mine dewater brackish to mine pit MAR (5 ML/d) (injection into other locations within the mine (drawdown) footprint will be undertaken if an opportunity presents itself in the mine plan)
- Mine dewater brackish to RMAR North (2 ML/d)
- Mine dewater brackish to RMAR south (20 ML/d)

The balance reports the total inputs and outputs of the operation which under this scenario are around 148 ML/d.

Table 2-3: LoM average operating condition 1

Task	Water Balance Components	ML/d	GL/a	GL/LoM (13 yrs)
MINING & DEWATERING TASK	**MDT Inputs**			
	Mine Dewater Fresh (TDS < 2,000 mg/l)	0	0	0
	Mine Dewater Brackish (TDS <5,000 mgl)	80	29	380
	Mine Dewater Saline (TDS >5,000 mgl)	52	19	247
	Pore Water (ore)	16	6	76
	Sum Inputs	148	54	702
WATER SUPPLY TASK	**RWST Inputs**			
	Remote Supply Borefield brackish (TDS <5,000 mgl)	0	0	0
	Sum Inputs	0	0	0
WATER TREATMENT PLANT TASK	**WTPT Inputs**			
	Mine Dewater brackish (TDS <5,000 mgl)	39	14	185
	Process Water (non-return)	0	0	0
	Remote Supply Borefield brackish (TDS <5,000 mgl)	0	0	0
	Total In	39	14	185
	WTPT Outputs			
	Wash Water (Cl <400 ppm)	-33	-12	-157
	RO Reject	-6	-2	-28
	Total Out	-39	-14	-185
PROCESS PLANT TASK	**PPT Inputs**			
	Mine Dewater fresh (TDS < 2,000 mg/l)	0	0	0
	Wash Water (Cl <400 ppm)	33	12	157
	Process Water (Direct return)	0	0	0
	Pore Water (Feed)	16	6	76
	Total In	49	18	233
	PPT outputs			
	Process Water (in Tailings)	-36	-13	-171
	Pore Water (product)	-13	-5	-62
	Total Out	-49	-18	-233
TSF TASK	**TSFT Inputs**			
	Process Water (in Tailings)	36	13	171
	Total In	36	13	171
	TSFT Outputs			
	TSF seepage, evap & entrainment	-16	-6	-76
	Process Water (Direct Return)	0	0	0
	Process Water (Non-Return)	-20	-7	-95
	Total Out	-36	-13	-171
DUST SUP. TASK	**DST Input**			
	Process Water (Non-Return)	0	0	0

Task	Water Balance Components	ML/d	GL/a	GL/LoM (13 yrs)
	Mine Dewater brackish (TDS <5,000 mgl)	0	0	0
	Mine Dewater saline (TDS >5,000 mgl)	10	4	47
	Total In	10	4	47
	DST Output			
	Process Water (road evap)	0	0	0
	Mine Dewater brackish (TDS <5,000 mgl)	0	0	0
	Mine Dewater saline (TDS >5,000 mgl)	-10	0	0
	Total Out	-10	0	0
SURPLUS WATER DISPOSAL TASK	**SWDT Outputs**			
	RO Reject to SWIB MAR	-6	-2	-28
	Process Water (NR) to SWIB MAR	-20	-7	-95
	Dewater to SWIB MAR	-40	-15	-190
	Dewater to Mine Pit MAR (TDS <5,000 mgl)	-5	-2	-24
	Dewater to RMAR South (TDS <5,000 mgl)	-20	-7	-95
	Dewater to RMAR North	-18	-7	-85
	Dewater to Evaproation Basin	0	0	0
	Sum Outputs	-109	-40	-516
BALANCE	INPUTS			
	MINING & DEWATERING TASK	148	54	702
	WATER SUPPLY TASK	0	0	0
	Total Inputs	148	54	702
	OUTPUTS			
	PROCESS PLANT TASK	-13	-5	-62
	TSF TASK	-16	-6	-76
	DUST SUP. TASK	-10	-4	-47
	SURPLUS WATER DISPOSAL TASK	-109	-40	-516
	Total Outputs	-148	-54	-702

Figure 2-4: LoM average operating condition

2.4.3 LoM average operating condition 2 (high mine dewater saline)

The water balance for the LoM average operating condition 2 is presented in Table 2-4 and Figure 2-5. Under this scenario mine dewater saline forms a higher proportion of total dewatering.

The mining and dewatering task (MDT) consists of inputs from dewatering and pore water (in mined ore). The LoM average dewatering rate is around 132 ML/d. The LoM average condition assumes the dewatering streams are brackish (50 ML/d) and saline (82 ML/d), a mine dewater fresh stream is excluded from the LoM average as this stream is not considered sustainable over LoM.

Under this scenario mine dewatering brackish only partially meets the requirements of the WTPT due to difficulties to aggregate brackish water from multiple separate mine pits. As a result, supplementary raw water is sourced from the remote supply borefield (10 ML/d).

Mine dewater fresh (Cl < 2000 mg/l) is unsustainable and therefore the WTPT is required to provide the full PPT demand of 33 Ml/d. A by-product of the WTPT is a saline reject stream (6 ML/d), which is disposed of to the saline SWIB.

The PPT receives wash water (33 ML/d) and ore pore water inputs (16 ML/d) and outputs consist of product pore water and discharge to tailings (36 ML/d).

Tailings disposal is currently to an above ground TSF and from 2020 to in-pit TSF. Seepage, evaporation and entrainment in pore space account for around half of the outputs from the TSFT (16 ML/d). Other outputs are non-return process water (20 ML/d), which is disposed of to the SWIB.

The DST can receive inputs from several sources, under this scenario the DST receives around 10 ML/d from excess mine dewater saline.

The surplus water disposal task (SWDT) consists of outputs that are surplus to the operation. Under this scenario surplus water disposal is distributed in the following allocations:

- WTPT reject to SWIB (6 ML/d)
- Non-return process water to SWIB (20 ML/d)
- Mine Dewater saline to SWIB (40 ML/d)
- Mine dewater saline to RMAR North (20 ML/d)
- Mine dewater brackish to mine pit MAR (11 ML/d) (injection into other locations within the mine (drawdown) footprint will be undertaken if an opportunity presents itself in the mine plan)
- Mine dewater brackish to RMAR South (0 ML/d)
- Mine dewater disposal to Evaporation Basin (22 ML/d)

The balance reports the total inputs and outputs of the operation which are currently around 158 ML/d.

Table 2-4: LoM average operating condition 2

Task	Water Balance Components	ML/d	GL/a	GL/LoM (13 yrs)
MINING & DEWATERING TASK	**MDT Inputs**			
	Mine Dewater Fresh (TDS < 2,000 mg/l)	0	0	0
	Mine Dewater Brackish (TDS <5,000 mgl)	50	18	237
	Mine Dewater Saline (TDS >5,000 mgl)	82	30	389
	Pore Water (ore)	16	6	76
	Sum Inputs	148	54	702
RAW WATER SUPPLY TASK	**RWST Inputs**			
	Remote Supply Borefield brackish (TDS <5,000 mgl)	10	4	47
	Sum Inputs	10	4	47
WATER TREATMENT PLANT TASK	WTPT Inputs			
	Mine Dewater brackish (TDS <5,000 mgl)	29	11	138
	Process Water (non-return)	0	0	0
	Remote Supply Borefield brackish (TDS <5,000 mgl)	10	4	47
	Total In	39	14	185
	WTPT Outputs			
	Wash Water (Cl <400 ppm)	-33	-12	-157
	RO Reject	-6	-2	-28
	Total Out	-39	-14	-185
PROCESS PLANT TASK	**PPT Inputs**			
	Mine Dewater fresh (TDS < 2,000 mg/l)	0	0	0
	Wash Water (Cl <400 ppm)	33	12	157
	Process Water (Direct return)	0	0	0
	Pore Water (Feed)	16	6	76
	Total In	49	18	233
	PPT outputs			
	Process Water (in Tailings)	-36	-13	-171
	Pore Water (product)	-13	-5	-62
	Total Out	-49	-18	-233
TSF TASK	**TSFT Inputs**			
	Process Water (in Tailings)	36	13	171
	Total In	36	13	171
	TSFT Outputs			
	TSF seepage, evap & entrainment	-16	-6	-76
	Process Water (Direct Return)	0	0	0
	Process Water (Non-Return)	-20	-7	-95
	Total Out	-36	-13	-171
DUST SUPP.	**DST Input**			

Task	Water Balance Components	ML/d	GL/a	GL/LoM (13 yrs)
	Process Water (Non-Return)	0	0	0
	Mine Dewater brackish (TDS <5,000 mgl)	0	0	0
	Mine Dewater saline (TDS >5,000 mgl)	10	4	47
	Total In	10	4	47
	DST Output			
	Process Water (road evap)	0	0	0
	Mine Dewater brackish (TDS <5,000 mgl)	0	0	0
	Mine Dewater saline (TDS >5,000 mgl)	-10	0	0
	Total Out	-10	0	0
SURPLUS WATER DISPOSAL TASK	**SWDT Outputs**			
	RO Reject to SWIB MAR	-6	-2	-28
	Process Water (NR) to SWIB MAR	-20	-7	-95
	Dewater to SWIB MAR	-40	-15	-190
	Dewater to Mine Pit MAR (TDS <5,000 mgl)	-11	-4	-52
	Dewater to RMAR South (TDS <5,000 mgl)	0	0	0
	Dewater to RMAR North	-20	-7	-95
	Dewater to Evaproation Basin	-22	-8	-104
	Sum Outputs	-119	-43	-564
BALANCE	INPUTS			
	MINING & DEWATERING TASK	148	54	702
	WATER SUPPLY TASK	10	0	0
	Total Inputs	158	54	702
	OUTPUTS			
	PROCESS PLANT TASK	-13	-5	-62
	TSF TASK	-16	-6	-76
	DUST SUP. TASK	-10	-4	-47
	SURPLUS WATER DISPOSAL TASK	-119	-43	-564
	Total Outputs	-158	-58	-749

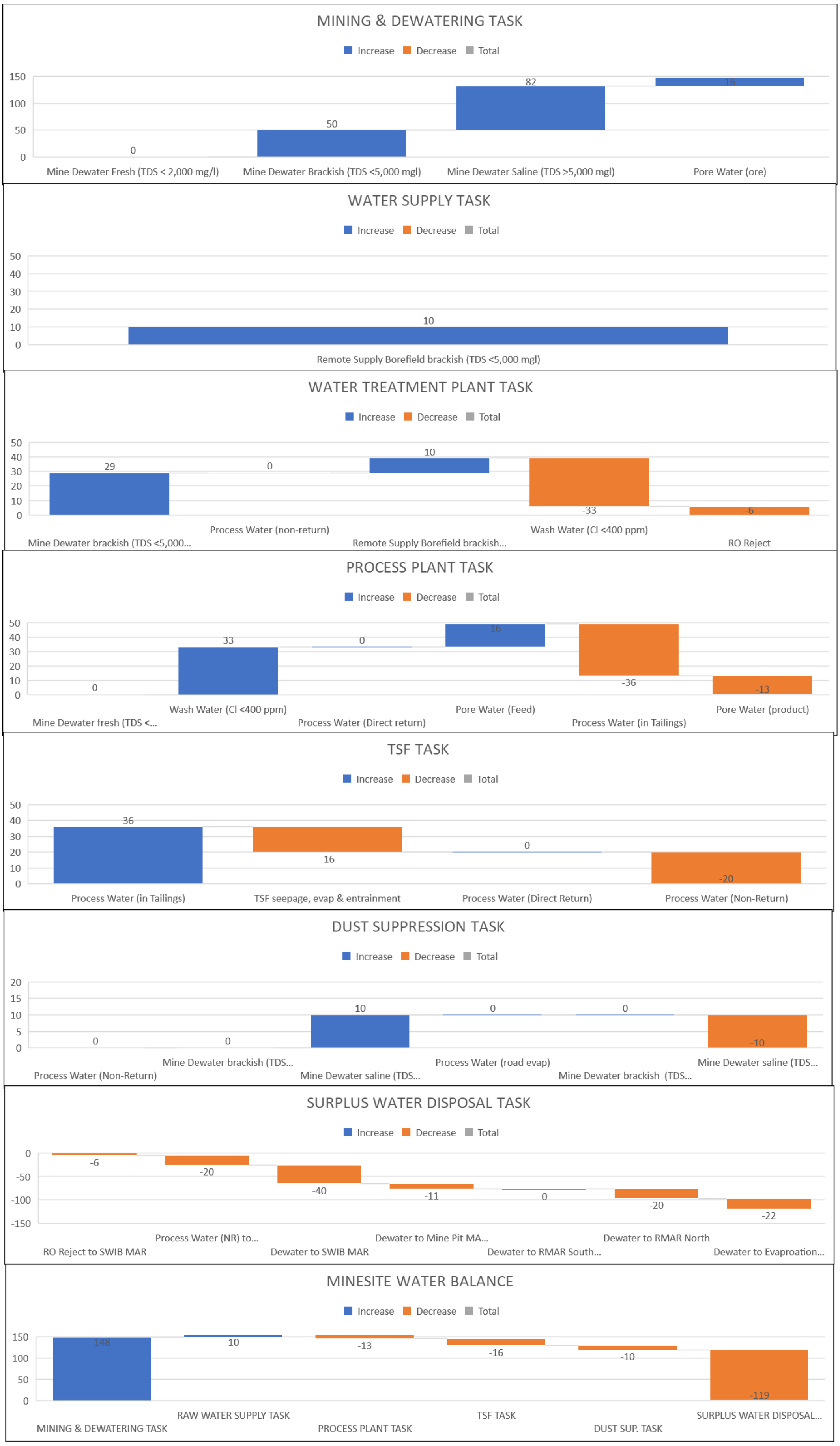


Figure 2-5: LoM average operating condition 2

2.4.4 LoM average operating condition 3 (process water re-use)

The water balance for the LoM average operating condition 3 is presented in Table 2-5 and Figure 2-6. Under this scenario mine dewater saline forms a higher proportion of total dewatering and process water re-use is feasible.

The mining and dewatering task (MDT) consists of inputs from dewatering and pore water (in mined ore). The LoM average dewatering rate is around 132 ML/d. The LoM average condition assumes the dewatering streams are brackish (50 ML/d) and saline (82 ML/d), a mine dewater fresh stream is excluded from the LoM average as this stream is not considered sustainable over LoM.

Under this scenario with re-use of process water directly to the PPT (10 ML/d), the production requirement for the WTPT is reduced to an output of 23 ML/d. the input requirements of the WTPT are met from mine dewater brackish. No supplementary raw water is required.

Due to process water re-use the WTPT is required to provide 23 ML/d of the full PPT demand of 33 Ml/d. A by-product of the WTPT is a saline reject stream (4 ML/d), which is disposed of to the saline SWIB.

The PPT receives return-process water (10 ML/d), wash water (23 ML/d) and ore pore water inputs (16 ML/d) and outputs consist of product pore water and discharge to tailings (36 ML/d).

Tailings disposal is currently to an above ground TSF and from 2020 to in-pit TSF. Seepage, evaporation and entrainment in pore space account for around half of the outputs from the TSFT (16 ML/d). Other outputs are the return-process water (10 ML/d) and non-return process water (10 ML/d), which under this scenario is used in dust suppression.

The DST can receive inputs from several sources, under this scenario the DST receives around 10 ML/d from non-return process water.

The surplus water disposal task (SWDT) consists of outputs that are surplus to the operation. Under this scenario surplus water disposal is distributed in the following allocations:

- WTPT reject to SWIB (4 ML/d)
- Non-return process water to SWIB (0 ML/d)
- Mine Dewater saline to to SWIB (60 ML/d)
- Mine dewater saline to RMAR North (20 ML/d)
- Mine dewater brackish to mine pit MAR (5 ML/d) (injection into other locations within the mine (drawdown) footprint will be undertaken if an opportunity presents itself in the mine plan)
- Mine dewater brackish to RMAR south (20 ML/d)
- Mine dewater saline to evaporation basin (0 ML/d)

The balance reports the total inputs and outputs of the operation which are currently around 148 ML/d.

Table 2-5: LoM average operating condition 3

Task	Water Balance Components	ML/d	GL/a	GL/LoM (13 yrs)
MINING & DEWATERING TASK	**MDT Inputs**			
	Mine Dewater Fresh (TDS < 2,000 mg/l)	0	0	0
	Mine Dewater Brackish (TDS <5,000 mgl)	50	18	237
	Mine Dewater Saline (TDS >5,000 mgl)	82	30	389
	Pore Water (ore)	16	6	76
	Sum Inputs	148	54	702
WATER SUPPLY TASK	**RWST Inputs**			
	Remote Supply Borefield brackish (TDS <5,000 mgl)	0	0	0
	Sum Inputs	0	0	0
WATER TREATMENT PLANT TASK	**WTPT Inputs**			
	Mine Dewater brackish (TDS <5,000 mgl)	27	10	128
	Process Water (non-return)	0	0	0
	Remote Supply Borefield brackish (TDS <5,000 mgl)	0	0	0
	Total In	27	10	128
	WTPT Outputs			
	Wash Water (Cl <400 ppm)	-23	-8	-109
	RO Reject	-4	-1	-19
	Total Out	-27	-10	-128
PROCESS PLANT TASK	**PPT Inputs**			
	Mine Dewater fresh (TDS < 2,000 mg/l)	0	0	0
	Wash Water (Cl <400 ppm)	23	8	109
	Process Water (Direct return)	10	4	47
	Pore Water (Feed)	16	6	76
	Total In	49	18	232
	PPT outputs			
	Process Water (in Tailings)	-36	-13	-171
	Pore Water (product)	-13	-5	-62
	Total Out	-49	-18	-233
TSF TASK	**TSFT Inputs**			
	Process Water (in Tailings)	36	13	171
	Total In	36	13	171
	TSFT Outputs			
	TSF seepage, evap & entrainment	-16	-6	-76
	Process Water (Direct Return)	0	0	0
	Process Water (Non-Return)	-20	-7	-95
	Total Out	-36	-13	-171
DUST SUP. TASK	**DST Input**			
	Process Water (Non-Return)	10	4	47

Task	Water Balance Components	ML/d	GL/a	GL/LoM (13 yrs)
	Mine Dewater brackish (TDS <5,000 mgl)	0	0	0
	Mine Dewater saline (TDS >5,000 mgl)	0	0	0
	Total In	10	4	47
	DST Output			
	Process Water (road evap)	-10	-4	-47
	Mine Dewater brackish (TDS <5,000 mgl)	0	0	0
	Mine Dewater saline (TDS >5,000 mgl)	0	0	0
	Total Out	-10	-4	-47
SURPLUS WATER DISPOSAL TASK	**SWDT Outputs**			
	RO Reject to SWIB MAR	-4	-1	-19
	Process Water (NR) to SWIB MAR	0	0	0
	Dewater to SWIB MAR	-62	-22	-285
	Dewater to Mine Pit MAR (TDS <5,000 mgl)	-2	-2	-24
	Dewater to RMAR South (TDS <5,000 mgl)	-20	-7	-95
	Dewater to RMAR North	-20	-7	-95
	Dewater to Evaproation Basin	0	0	0
	Sum Outputs	-109	-40	-517
BALANCE	INPUTS			
	MINING & DEWATERING TASK	148	54	702
	WATER SUPPLY TASK	0	0	0
	Total Inputs	148	54	702
	OUTPUTS			
	PROCESS PLANT TASK	-13	-5	-62
	TSF TASK	-16	-6	-76
	DUST SUP. TASK	-10	-4	-47
	SURPLUS WATER DISPOSAL TASK	-109	-40	-517
	Total Outputs	-148	-54	-702

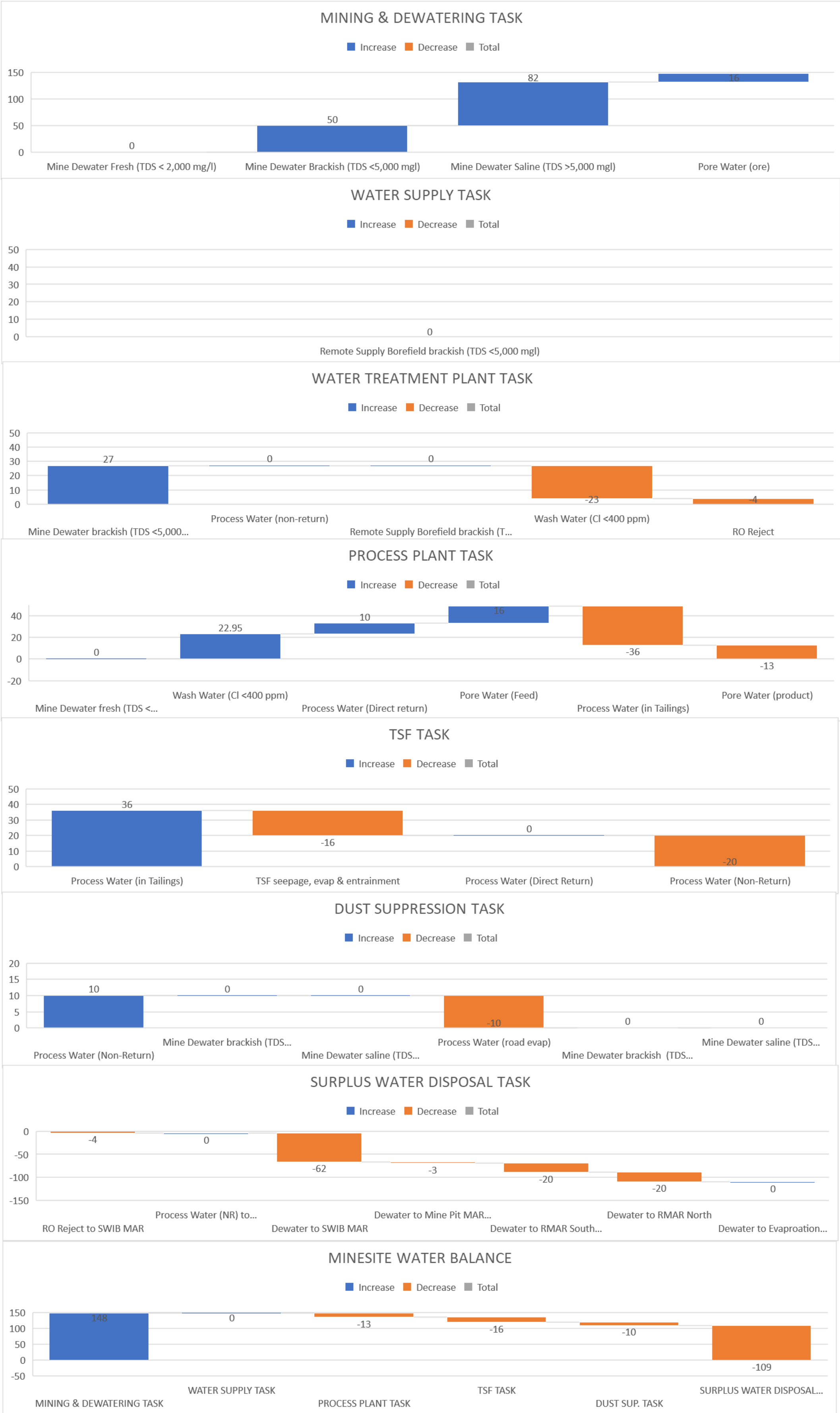


Figure 2-6: LoM average operating condition 3

2.4.5 LoM peak operating condition

The water balance for the LoM peak operating condition is presented in Table 2-6 and Figure 2-7.

The mining and dewatering task (MDT) consists of inputs from dewatering and pore water (in mined ore). The LoM peak dewatering rate is around 225 ML/d. The LoM peak operating condition assumes the dewatering streams are brackish (125 ML/d) and saline (100 ML/d), a mine dewater fresh stream is excluded from the LoM average as this stream is not considered sustainable over LoM.

Raw water inputs to other water balance tasks are satisfied by dewatering and therefore no supplementary raw water abstraction is required.

Mine dewater fresh (Cl < 2000 mg/l) is unsustainable and therefore the WTPT is required to provide the full PPT demand of 33 Ml/d. A by-product of the WTPT is a saline reject stream (6 ML/d), which is disposed of to the saline SWIB.

The PPT receives wash water (33 ML/d) and ore pore water inputs (16 ML/d) and outputs consist of product pore water and discharge to tailings (36 ML/d).

Tailings disposal is currently to an above ground TSF and from 2020 to in-pit TSF. Seepage, evaporation and entrainment in pore space account for around half of the outputs from the TSFT (16 ML/d). Other outputs are non-return process water (20 ML/d), which is disposed of to the SWIB.

The DST can receive inputs from several sources, under this scenario the DST receives around 10 ML/d from excess mine dewater saline.

The surplus water disposal task (SWDT) consists of outputs that are surplus to the operation. Under this scenario surplus water disposal is distributed in the following allocations:

- WTPT reject to SWIB (6 ML/d)
- Non-return process water to SWIB (20 ML/d)
- Mine Dewater saline to SWIB (56 ML/d)
- Mine dewater saline to RMAR North (34 ML/d)
- Mine dewater brackish to mine pit MAR (24 ML/d) (injection into other locations within the mine (drawdown) footprint will be undertaken if an opportunity presents itself in the mine plan)
- Mine dewater brackish to RMAR North (26 ML/d)
- Mine dewater brackish to RMAR south (36 ML/d)

The balance reports the total inputs and outputs of the operation which are currently around 148 ML/d.

Table 2-6: LoM peak operating condition

Task	Water Balance Components	ML/d	GL/a	GL/LoM (13 yrs)
MINING & DEWATERING TASK	MDT Inputs			
	Mine Dewater Fresh (TDS < 2,000 mg/l)	0	0	
	Mine Dewater Brackish (TDS <5,000 mgl)	125	46	
	Mine Dewater Saline (TDS >5,000 mgl)	100	37	
	Pore Water (ore)	16	6	
	Sum Inputs	241	88	
WATER SUPPLY TASK	RWST Inputs			
	Remote Supply Borefield brackish (TDS <5,000 mgl)	0	0	
	Sum Inputs	0	0	
WATER TREATMENT PLANT TASK	WTPT Inputs			
	Mine Dewater brackish (TDS <5,000 mgl)	39	14	
	Process Water (non-return)	0	0	
	Remote Supply Borefield brackish (TDS <5,000 mgl)	0	0	
	Total In	39	14	
	WTPT Outputs			
	Wash Water (Cl <400 ppm)	-33	-12	
	RO Reject	-6	-2	
	Total Out	-39	-14	
PROCESS PLANT TASK	PPT Inputs			
	Mine Dewater fresh (TDS < 2,000 mg/l)	0	0	
	Wash Water (Cl <400 ppm)	33	12	
	Process Water (Direct return)	0	0	
	Pore Water (Feed)	16	6	
	Total In	49	18	
	PPT outputs			
	Process Water (in Tailings)	-36	-13	
	Pore Water (product)	-13	-5	
	Total Out	-49	-18	
TSF TASK	TSFT Inputs			
	Process Water (in Tailings)	36	13	
	Total In	36	13	
	TSFT Outputs			
	TSF seepage, evap & entrainment	-16	-6	
	Process Water (Direct Return)	0	0	
	Process Water (Non-Return)	-20	-7	
	Total Out	-36	-13	
DUST SUP P.	DST Input			

Task	Water Balance Components	ML/d	GL/a	GL/LoM (13 yrs)
	Process Water (Non-Return)	0	0	
	Mine Dewater brackish (TDS <5,000 mgl)	0	0	
	Mine Dewater saline (TDS >5,000 mgl)	10	4	
	Total In	10	4	
	DST Output			
	Process Water (road evap)	0	0	
	Mine Dewater brackish (TDS <5,000 mgl)	0	0	
	Mine Dewater saline (TDS >5,000 mgl)	-10	-4	
	Total Out	-10	-4	
SURPLUS WATER DISPOSAL TASK	SWDT Outputs			
	RO Reject to SWIB MAR	-6	-2	
	Process Water (NR) to SWIB MAR	-20	-7	
	Dewater to SWIB MAR	-56	-20	
	Dewater to Mine Pit MAR (TDS <5,000 mgl)	-24	-9	
	Dewater to RMAR South (TDS <5,000 mgl)	-36	-13	
	Dewater to RMAR North	-60	-22	
	Dewater to Evaporation Basin	0	0	
	Sum Outputs	-202	-74	
BALANCE	INPUTS			
	MINING & DEWATERING TASK	241	88	
	WATER SUPPLY TASK	0	0	
	Total Inputs	241	88	
	OUTPUTS			
	PROCESS PLANT TASK	-13	-5	
	TSF TASK	-16	-6	
	DUST SUP. TASK	-10	-4	
	SURPLUS WATER DISPOSAL TASK	-202	-74	
	Total Outputs	-241	-88	

Figure 2-7: LoM peak operating condition

3. Change Assessment for LoM Water Management Strategy update

3.1 Approach to hydrological impact assessment

3.1.1 Overview

This section describes methodology and results of assessing changes to the groundwater systems and associated environmental risks. The assessment period is from September 2018 to March 2031.

Water level changes were evaluated by using numerical modelling over a domain at regional scale, which includes both the mining area, part of the Fortescue Marsh, Fortescue Valley to the south of the marsh and the Roy Hill mining area, towards the northern flanks of the Hamersley Range.

The groundwater flow modelling system was developed based on integrating existing geological and groundwater data and models covering the selected domain. Existing models incorporated into or considered in the current project include:

- Roy Hill project groundwater model (described in MAR impact assessment document – Willis-Jones, 2018); and
- Stage 2 borefield model (MWH, 2009))

Previous investigation works, conceptual models and calibrated numerical models form the basis of this assessment.

The numerical model for this assessment was developed in the MODFLOW modelling code, which is an industry standard applied in numerous mining application and is considered to be a suitable code for representation of the conceptual model and proposed RHWMS.

3.1.2 Information acquisition from Roy Hill

Project data was provided by Roy Hill and included (but was not limited to):

- MWH (2009) Stage 2 Borefield hydrogeological report with description of the numerical model developed for Stage 2 borefield;
- RHIO's current geological conceptualisation, existing Leapfrog model and associated exploration data;
- RHIO's FEFLOW dewatering model (Willis-Jones, 2018);
- RHIO's groundwater monitoring data (water levels, abstraction rates, water quality);
- Predicted dewatering rates obtained from predictive FEFLOW runs for the July 2018 LoM Plan and the subsequent FEFLOW update from August 2018 LoM Plan;
- Groundwater management and aquifer review compliance documentation (e.g. Surrette, 2018);
- Current water management strategy update;
- Digital elevation model, modified from NOAA 1 second (30 m) model (Geoscience Australia);
- Climate data (BoM).

3.1.3 Other relevant works and data sources

A considerable volume of work has been published in public domain or internally within various mining companies (such as FMG, BHP Billition, Rio Tinto, Roy Hill/HPPL) and in collaboration with University of Western Australia on the Fortescue Marsh environment, its hydrology and hydrogeology.

FMG developed a detailed hydrogeological conceptualisation and several versions of numerical models of the northern part of the Fortescue Marsh (e.g. Brandes de Roos and Youngs (2010)) and the Chichester Range including their mining tenement and the surrounds. The available documentation is a useful reference on major aquifer units and their parameterisation. It is noted however that despite similarities with Roy Hill tenement, some of the hydrological and hydrogeological settings show minor or more prominent differences, for example in the extent and the role of calcrete aquifer or the connectivity with the Fortescue Marsh.

BHP Billiton commissioned an ecohydrological assessment of the entire Fortescue Marsh Catchment as part of assessment of all their operations in the Pilbara. The results of this assessment which includes description and water balance of hydrological and groundwater systems and their functioning with respect to environmental receptors are compiled in Simonic et al (2015).

UWA published several publications on the hydrological history and functioning of the Fortescue Marsh. Of particular interest is the reconstruction of flooding events in the Marsh over the last century and their association with large scale (cyclonic) rainfall events. UWA in collaboration with Rio Tinto has been undertaking a hydrogeological exploration and monitoring program of the Marsh and the Fortescue Valley, the results of which have yet to be processed and released.

3.1.4 Data gap analysis

The modelling tools represent an inevitably simplified understanding of what is potentially a complex hydrological system. This is partly due to the scattered nature of information on geological structure, distribution and variation of hydraulic properties and variations due to seasonal and climatic changes.

Some of the geological boundaries were extrapolated based on best available interpretation which may change if new data becomes available. In particular, there is site-based evidence that the Marra Mamba unit contains highly permeable zones, however their detailed delineation, both laterally and vertically is uncertain and often limited to areas with dense exploration data cover.

Assessment of groundwater level change and its effect on some environmental receptors is dependent on accurate representation of ground by means of a digital elevation model (DEM), since this is used to establish the values of depth to groundwater. This is important in the low-lying areas around the marsh and in the northern part of the remote MAR area where the existing watertable is generally shallow (less than 10 m).

Hydrological data regarding flows in major drainage courses such as Fortescue River, or larger creeks, is not available to directly investigate interaction between groundwater and surface water features and to determine, with greater accuracy the recharge/discharge relationships.

3.1.5 Assumptions

The following assumptions were made in this assessment:

- The presented conceptual model and its parameterisation is broadly valid for the scale of assessment;

- Mean annual rainfall and evaporation are considered representative for the modelled period (inter-annual variations are neglected); rainfall and evapotranspiration is uniform within recharge and evapotranspiration zones (no intra-zonal variability);
- Large rainfall events do not have a lasting effect on the groundwater system;
- Fortescue Marsh and Fortescue River do not have marked effects on groundwater flow under prevailing conditions (other than being terminal discharge areas for groundwater)
- Recharge effect of creeks in the ranges is included in fan and break of slope recharge and aggregated in range outcrop recharge, occasional extreme flow conditions not considered;
- Density-driven flow effects were not included (considered relevant in the Marsh area only)
- The 30 m DEM is sufficient representation of ground surface for the regional-scale model (undue/suspect deviations – "noise" - from a more accurate representation are noted in the Fortescue Marsh area);
- Homogeneous bulk hydraulic properties are applied for the major aquifer units considered in this conceptual and numerical model;
- Groundwater flow at a regional scale can be approximated with porous flow characteristics;
- The mining plan is as of July 2018, with small update in August 2018.

3.2 Regional setting and hydrological knowledge

3.2.1 Study area

The study focuses on the eastern part of the Upper Fortescue Valley around the eastern perimeter of the Fortescue Marsh in the Pilbara, approximately between 60 and 120 km north of Newman.

The study area spans the southern slopes of the Chichester Range which hosts RH's mining RH's operations on the northeastern edge of the Fortescue Valley. It then crosses the Fortescue Valley to the south, where the Stage 2 borefield and RMAR are situated, towards the Hamersley Range at the southern edge of the Fortescue Valley.

The eastern limit of the area is broadly defined by the course of Fortescue River, the western limit of the study area follows the catchment boundary (of the Coondiner Creek catchment area) within the Fortescue Valley, crosses the eastern part of Fortescue Marsh and a major drainage line within the Chichester Range. The boundaries of the study are set such that they are beyond the assumed effects of RH's mining operations. The receiving environment with the delineated study area was shown in Figure 1-1.

3.2.2 Topography

The regional topography features two prominent east-west trending hilly structures, the Chichester and Hamersley Ranges, separated by the east-west trending Fortescue River Valley. The Marsh is a brackish to saline, endorheic wetland formed in the drainage terminus of the Upper Fortescue River within the Fortescue Valley.

The main drainages in the area, the Fortescue River and the ephemeral creeks draining the ranges, further sculpture the topography of the area by dissecting the range slopes and forming relatively narrow catchment areas.

The Fortescue Marsh, at around 400 m AHD, or slightly below in places, forms the lowest points in the study area. Outside of the Fortescue Marsh the valley terrain gently rises to elevations of

450 m AHD before reaching approximately 550 m AHD in the Chichester Range and over 800 m AHD in the Hamersley Range (Figure 1-1).

3.2.3 Land systems

Western Australia Department of Agriculture and Food (DAFWA) surveyed the wider Pilbara area for the purposes of land classification, and resource evaluation, based on topography, geology, soils and vegetation.

Van Vreeswyk et al. (2004) grouped the land systems into land surface types using a combination of more generic landforms, soils, vegetation and drainage patterns. This grouping is useful for understanding ecological values of the region, for hydrogeological conceptualisation and understanding features such as recharge, evapotranspiration and groundwater surface water interaction, and for environmental impact assessment.

The land surface types found in the study area are described in detail in **Appendix A** and their spatial distribution is presented in Figure 3-1.

The mining area is characterised by the expression of Newman, Jamindie and Turee systems. The Newman system forms the hilly parts of the Chichester Range, with frequent outcrops and shallow, stony soils supporting only spinifex grasslands. They gradate to hardpan plains with low rises and widely spaced drainage features of the Jamindie and Turee systems. The soils are often loamy with fractions of gravels and loose stones.

The remote borefield and MAR tenement extends over the Turee system in the north crossing through Coolibah, Narbung systems around the perimeter of the Fortescue Marsh and along the Fortescue River to the Fan system characterising the majority of the remote borefield (Stage 2) area.

Active floodplains and alluvial plains along the Fortescue River with deep red cracking clays of the Cooliba system supporting the woodlands of the species after which it was named represent the depositional surfaces downgradient of the Turee system. They are complemented by flat alluvial washplains with localised drainage and no defined channel structures of the Narbung system with sandy duplex soils. The Fan system is characterised by groved Acacia shrublands and banded vegetation on relatively flat washplains and gilgai plains with deep red loams.

3.2.4 Climate

The climate of the study area is semi-arid to arid, characterised by high temperatures and low, irregular rainfall. Most rainfall occurs between December and March in association with tropical cyclones and localised thunderstorms. Available meteorological stations in the area (e.g. 7151-Newman; 5009-Marillana, 5023-Roy Hill) indicate that rainfall has a large degree of intra-annual (within-year) and inter-annual variation. Mean annual rainfall may vary from 300 to 500 mm/yr; however, in any given year the amount and timing of rainfall is unreliable (e.g. Simonic et al, 2015). Average annual pan evaporation is between 2,800 and 3,200 mm/yr (BoM website, map coverages), which is an order of magnitude higher than the average annual rainfall.

During cyclones, daily rainfall events of between 70 and 400 mm/day have been recorded. This usually results in a distinct peak in rainfall distribution over any given month. Cyclonic and other large magnitude rainfall events are important for the generation of surface water flows and groundwater recharge.

They are also responsible for periodic accumulation of water in the Fortescue Marsh. In general, the rainfall of 75 mm/month often has a wetting effect (i.e. induce ponding) on the Fortescue Marsh, while 30 mm/month is insufficient to generate any effect on the marsh (Rouillard et al., 2015).

3.2.5 Regional hydrology

Setting and key features

The Fortescue River is the main source of surface water inflows into the study area. Other significant drainages include Coondiner Creek in the Hamersley Range, and Kulbee Creek / Christmas Creek / Kulkinbah Creek in the Chichester Range (Figure 3-2).

The Upper Fortescue River, with a total catchment area of 16,281 km^2, contributes significant surface water flow volumes into the eastern end of the Marsh. These flows are largely derived from upland areas, and delivered through numerous tributaries such as Homestead Creek, Whaleback Creek and Jimblebar Creek (outside of the study area).

Since the completion of Ophthalmia Dam in December 1981, natural flows emanating from the upper catchment have been partially attenuated. Downstream of Ophthalmia Dam, at the entrance of the Fortescue River to Fortescue River Valley (Ethel Gorge), there is a major deltaic feature.

The surface water hydrology is characterised by variable rainfall-runoff response with lower rainfall-runoff response associated with deeper soils and flatter areas (the Fortescue Valley); and higher rainfall-runoff response associated with steeper slopes and shallower soils (the Ranges).

The drainages are better defined in the steeper part of the slopes of the Chichester and Hamersley Ranges. They become less defined and braided or dispersed in flat areas at the lower slopes. Following the major events they drain to the Marsh. Smaller events, do not activate drainage to the Marsh, the flow terminates in smaller isolated pools (yintas) the periphery of the Marsh.

Fortescue Marsh is a large episodically inundated samphire marsh, a terminal surface water feature for surface water flows and groundwater. While it is dry most of the time, cyclonic rainfall events cause occasional water ponding in summer months. It is almost 100 km long, however only its easternmost extension is part of the evaluated study area. No published flood level data is available for the Marsh. Examination of satellite imagery against ground elevation data suggests that flood levels of approximately 407 m RL have occurred.

Stream flow

The drainage systems are ephemeral and flow in direct response to rainfall. Streamflow mainly occurs during the summer months of December to March and is generally associated with the major rainfall events such as the passage of tropical cyclones. Runoff can persist for periods of weeks to months.

The Fortescue River flows are highly variable and while they are not gauged within the study area, annual flows into the marsh from the Fortescue River catchment were estimated at 34 GL/a (Simonic et al, 2015).

Some of the larger ephemeral creeks also periodically bring water to the Fortescue Valley area. Large alluvial fans were formed at their outlets to the valley. The most notable alluvial fan in the study area is associated east and parallel with Coondiner Creek (spanning north from the Hamersley Range), but smaller fans dot the landscape where the ranges meet the valley floor.

On the northern side of the study area minor surface water contributions from Christmas, Kulbee, No Name and Kulkinbah Creeks are present, with examples of ephemeral inflows exhibited by these creeks and their association with summer rainfall events shown in Figure 3-3.

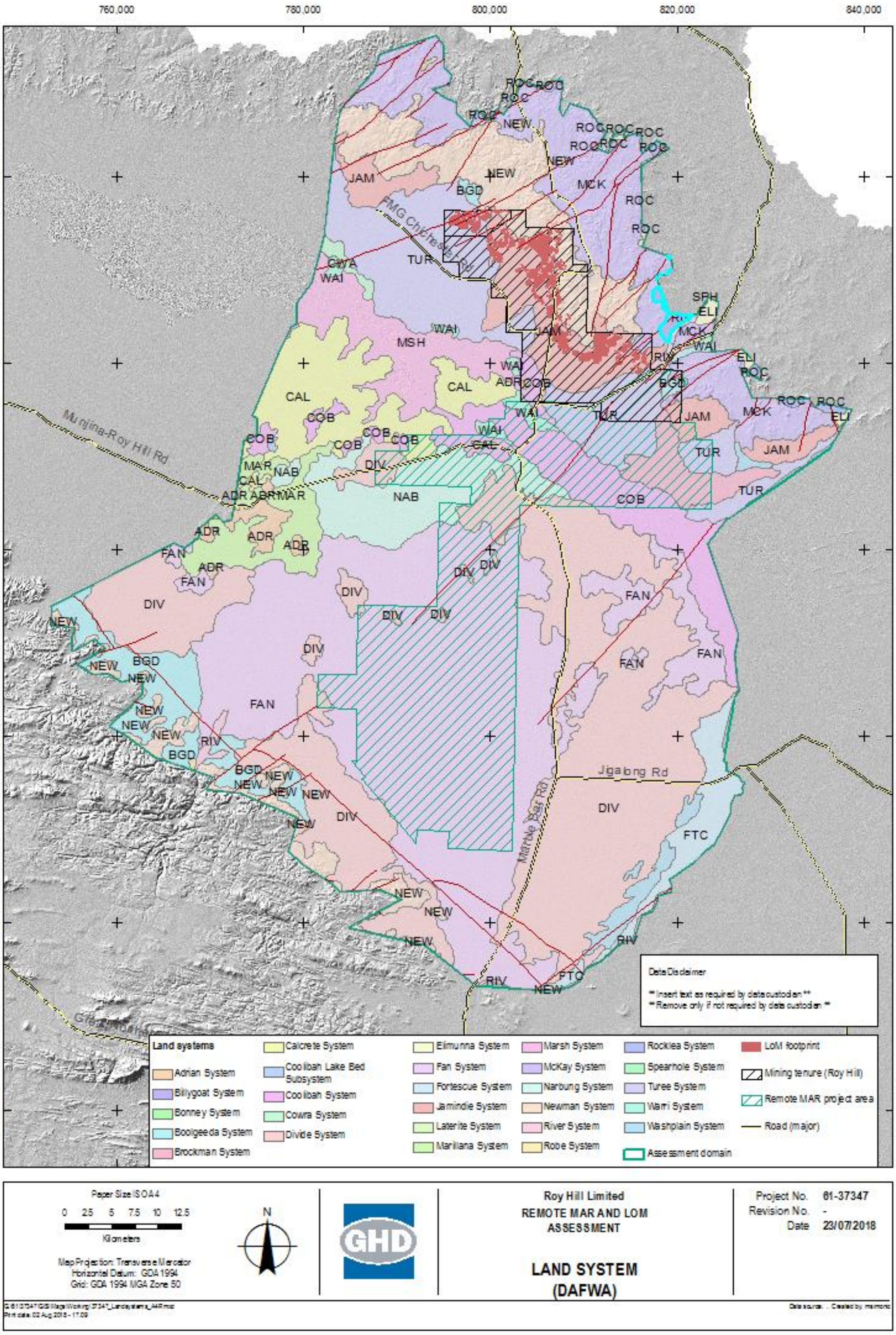


Figure 3-1: Land groups

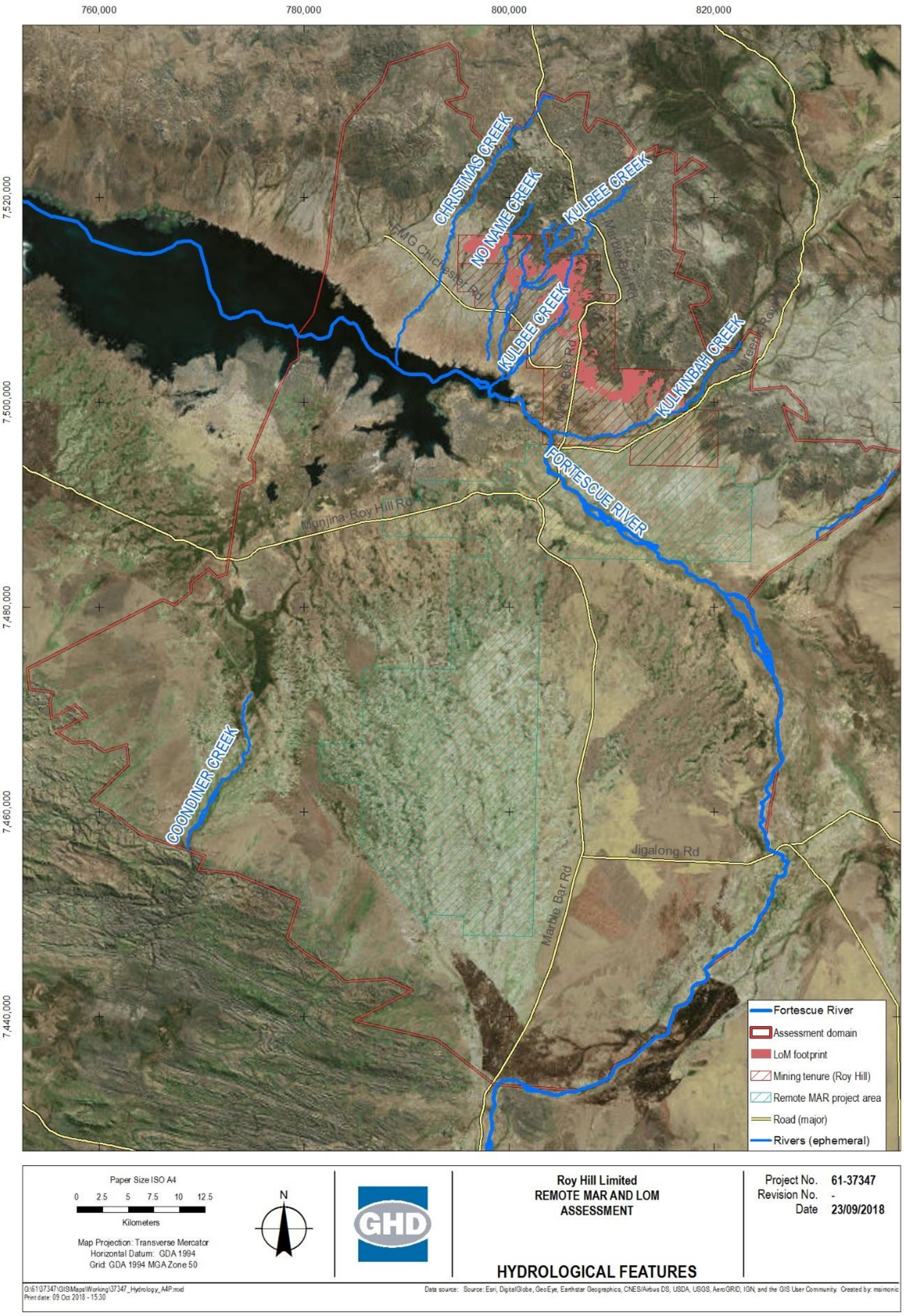


Figure 3-2: Key surface water features in the study area

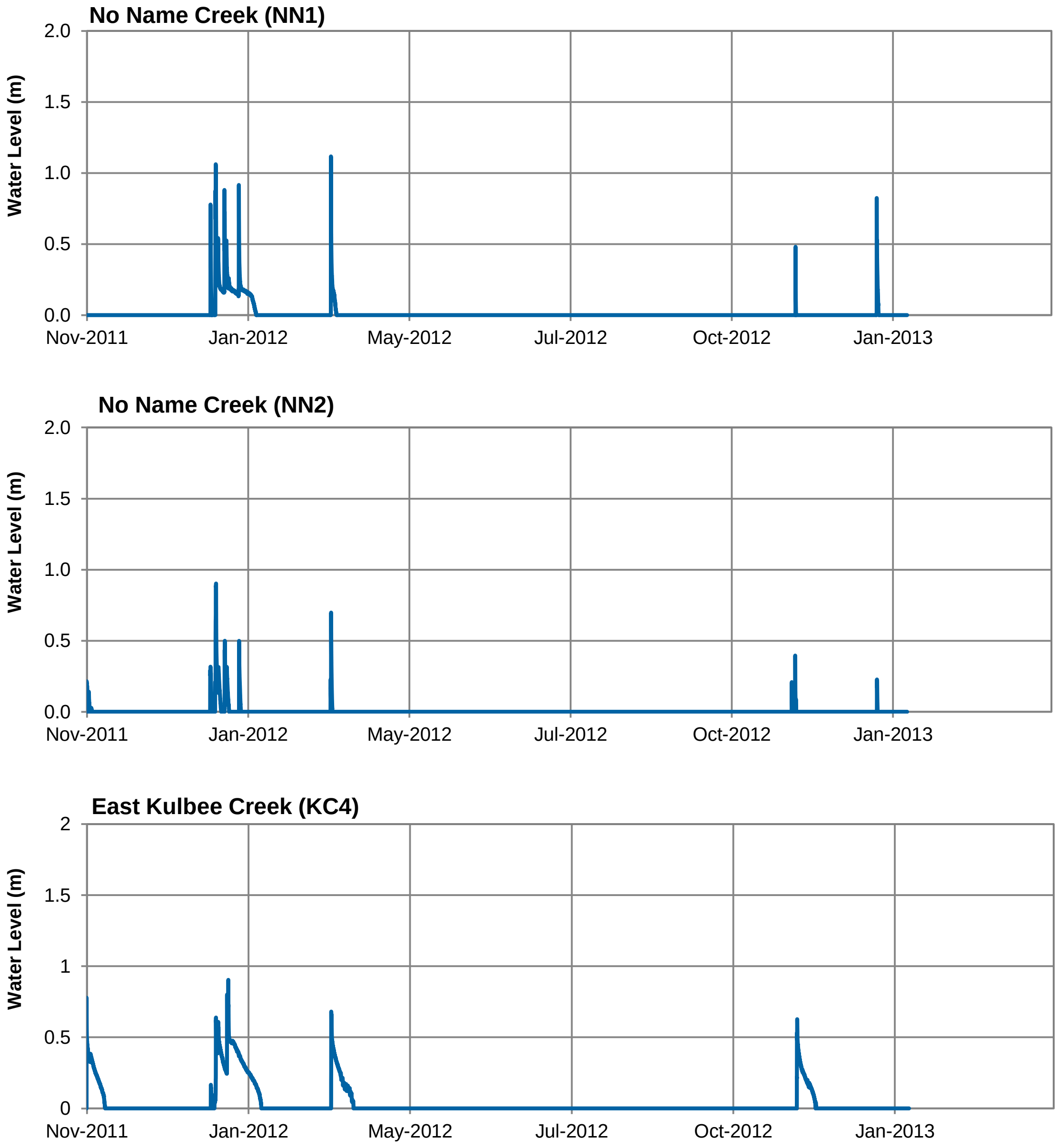


Figure 3-3: Ephemeral flows from the Chichester Range creeks as measured during 2011 to 2013 (after Simonic et al, 2015)

Catchment response

Catchment response to rainfall is attributable to catchment physical characteristics. Surface water runoff is the result of excess rainfall, i.e. rainfall available for surface runoff after infiltration and evaporation/evapotranspiration losses. Factors impacting the amount of runoff include antecedent soil moisture conditions, duration and intensity of rainfall, in addition to landscape characteristics.

Major flooding events are generally the result of large, intense cyclonic rainfall events, with runoff coefficients varying significantly between rainfall events. Streamflow mainly occurs during the summer months of December to March.

Surface runoff which follows larger rainfall and in particular summer cyclonic events takes place as follows:

- Hill-slope runoff
- Channel flow (typical for RH mining area)

- Diverging flow (typical for RH Mining area)
- Sheetflow.

The Marsh's eastern basin forms part of the study area. The Upper Fortescue River provides the majority of surface water flow to the Marsh, with a catchment area of approximately 31,000 km^2.

Periodic flooding of the Marsh area is generally associated with cyclonic rainfall and runoff in the summer months, with larger-scale inundation events (more than 20% of the marsh area) estimated to occur once in every five years. The unusually large inundation experienced in April 2000 is considered to be a 1/1000 year event. The maximum flooding extent of the Fortescue Marsh covers a total area of 210 km^2.

Inundation of the east and west basins may have different footprints for smaller events. Accumulations of surface water along the marsh shores are known as yintas and form at low topographic points. They are semi-permanent and fed by catchment inflows from the Chichester Range.

3.2.6 Regional geology

Geology of the region has been described in a number of sources (Willis-Jones, 2018; Simonic et al, 2015, Rouillard et al., 2015, MWH, 2009, Brandes de Roos and Youngs, 2010; Surrette and Clark, 2010 and others.). The area is characterised by Archaean to Proterozoic geology overlain by younger, predominantly Tertiary-age sediments and alluvial and colluvial deposits.

The early Proterozoic Hamersley Group, which consists of various metasedimentary rocks including cherty banded iron formation, chert and carbonates interbedded with minor felsic volcanic rock and intruded by dolerite dykes dominates the basement geology. The Hamersley Group lies unconformably on the Archaean metasediments and metavolcanics of the Fortescue Group.

The Fortescue Valley is an extensive sequence of Quaternary and Tertiary alluvial, colluvial and lacustrine sediments overlying the Proterozoic basement, in particular weathered and fresh dolomite and chert. The alluvial deposits increase in thickness away from the ranges towards the Marsh.

A typical N-S geological section through the Fortescue Valley is shown in Figure 3-4 (Simonic et al, 2015), which demonstrates the common configuration of the key lithological units within the valley area and on its southern and northern flanks. The conceptualisation followed in this study also considers an important clay layer which has not been specifically delineated in Figure 3-4. This clay layer, at the base of Tertiary detritals overlies and confines the weathered dolomite and separates it hydraulically from the overlying shallow aquifer hosted in Tertiary detritals and alluvial sediments. The clay layer is considered in the sequence as shown in **Appendix C**.

The study area is intersected by several regional scale faults (Figure 3-5), however their impact (if any) on groundwater flow is not well understood. Another set of faults cut in a SW-NE direction and is expressed in the ranges on both sides of the Fortescue Valley. They are likely to extend across the valley beneath the Tertiary/Quaternary cover. A series of dolerite dykes which also trend SW-NE may occur in the study area. Dolerite dykes commonly constitute low-permeability barriers to groundwater flow, however the thermal contact during their formation can often increase the permeability of host rocks in the contact zone.

Surface geology of the study area is presented in Figure 3-6.

3.2.7 Groundwater

Major aquifer systems

The regional aquifer system in the Fortescue Valley is hosted in Tertiary detritals and the underlying Wittenoom Formation (dominated by dolomite of the Paraburdoo Member). Tertiary calcrete or pisolitic limonite formed within valley-fill sequences are both often highly permeable. The flanks of the valley rise into ranges comprising fractured-rock aquifers of low permeability and storage. In places, these basement rocks have more transmissive sections associated with orebodies and form localised aquifers.

The extent of these orebody aquifers and their connectivity with larger groundwater flow systems may be enhanced by faulting or erosion or other structural features, and as such can vary widely and is site specific.

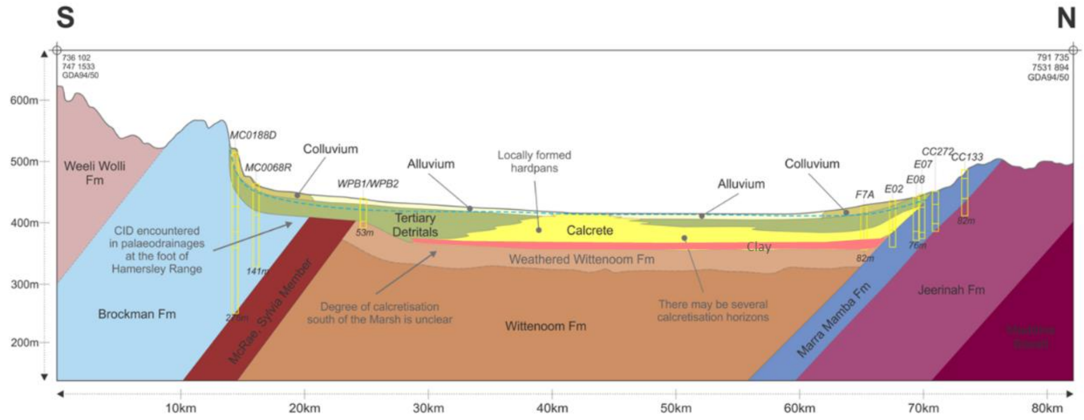


Figure 3-4: Conceptual geological section across the Upper Fortescue River Catchment (adapted from Simonic et al., 2015)

The **Chichester Range** comprises Cainozoic alluvial and detrital sediments, Hamersley Group Marra Mamba Formation and Fortescue Group's youngest formation, the Jeerinah Formation.

Hydrogeologically productive and transmissive Nammuldi Member is the basal unit of Marra Mamba Formation and is 10 to 60 m thick. Its thickness is assumed to be progressively reduced on the southern flanks of the Chichester Range and may also thin out or erode in the drainage systems of creeks intersecting the Chichester Range. It overlies the Roy Hill Shale, the uppermost member of the Jeerinah Formation. The Nammuldi member has high hydraulic permeability in supergene zones and forms a discontinuous aquifer. Unmineralised Marra Mamba Formation has generally low storage and permeability.

The **Fortescue Valley** comprises a sequence of Quaternary and Tertiary sediments which generally overlie the weathered and fresh dolomite of the Wittenoom Formation. The area also hosts large expressions of calcrete which is ascribed to Oakover Formation, however there can be several calcrete horizons within the sequence. The base elevation of the Tertiary calcrete is generally at 400 m AHD, consistent with deeper parts of the Fortescue Marsh ground surface. Calcrete-described occurrences in the Fortescue Marsh area also often form surficially or sub-surficially expressing hardpans or claypans which facilitate ponding of surface water or rainfall during major rainfall events.

Tertiary detritals comprise silty and clayey playa deposits, with low permeability clay at the base. Their thickness increases towards the valley's central axis and may reach up to 70 m. A rather homogeneous clay layer present at the base of detritals with thickness of 10 to 20 m has likely confining effects on the underlying weathered dolomite aquifer (pumping tests conducted in the weathered dolomite aquifer did not induce any significant response from the overlying shallow aquifer, e.g. Johnston K and R Hamilton, 2018); and its base is generally at 380 m AHD.

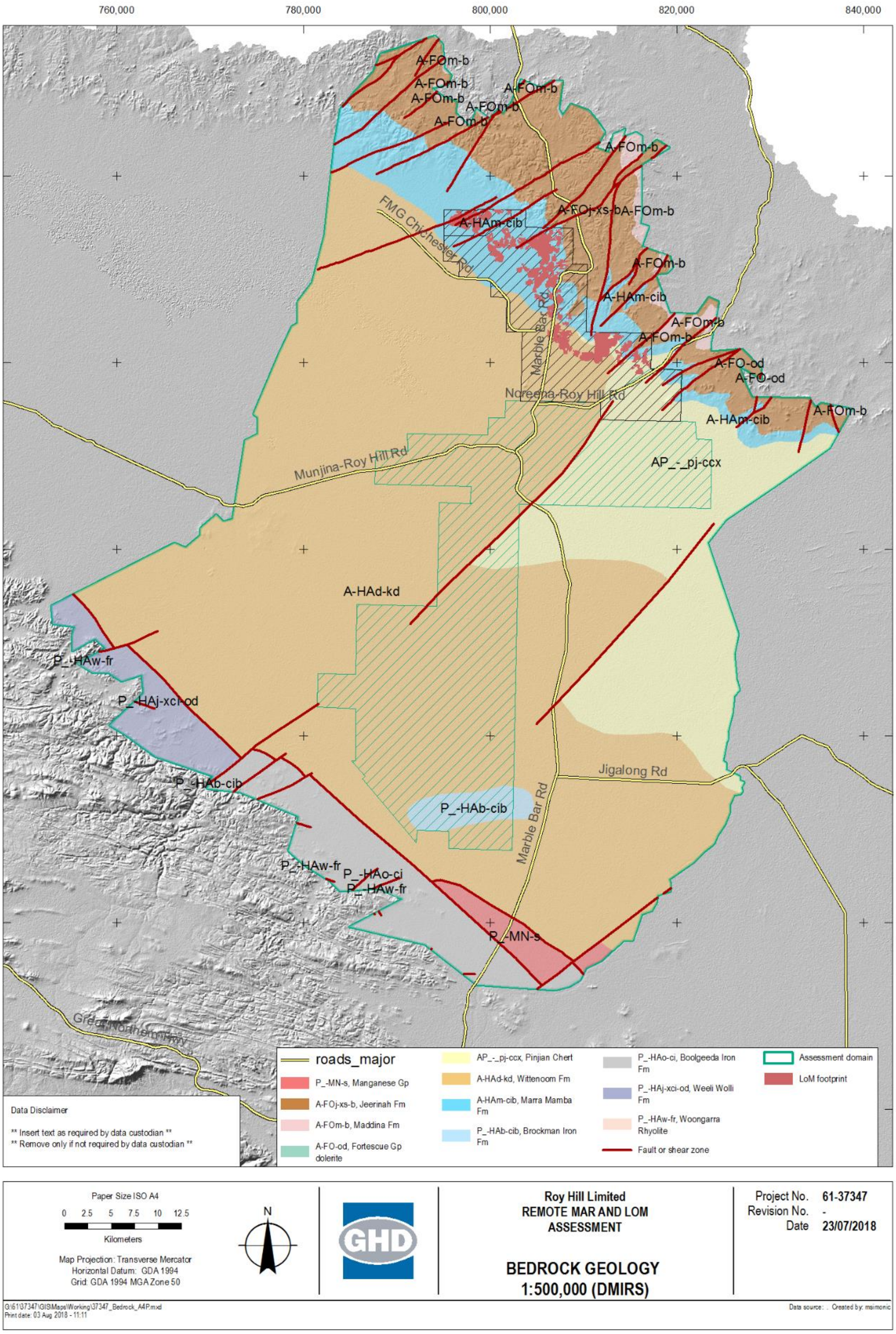


Figure 3-5: Pre-Cainozoic geology

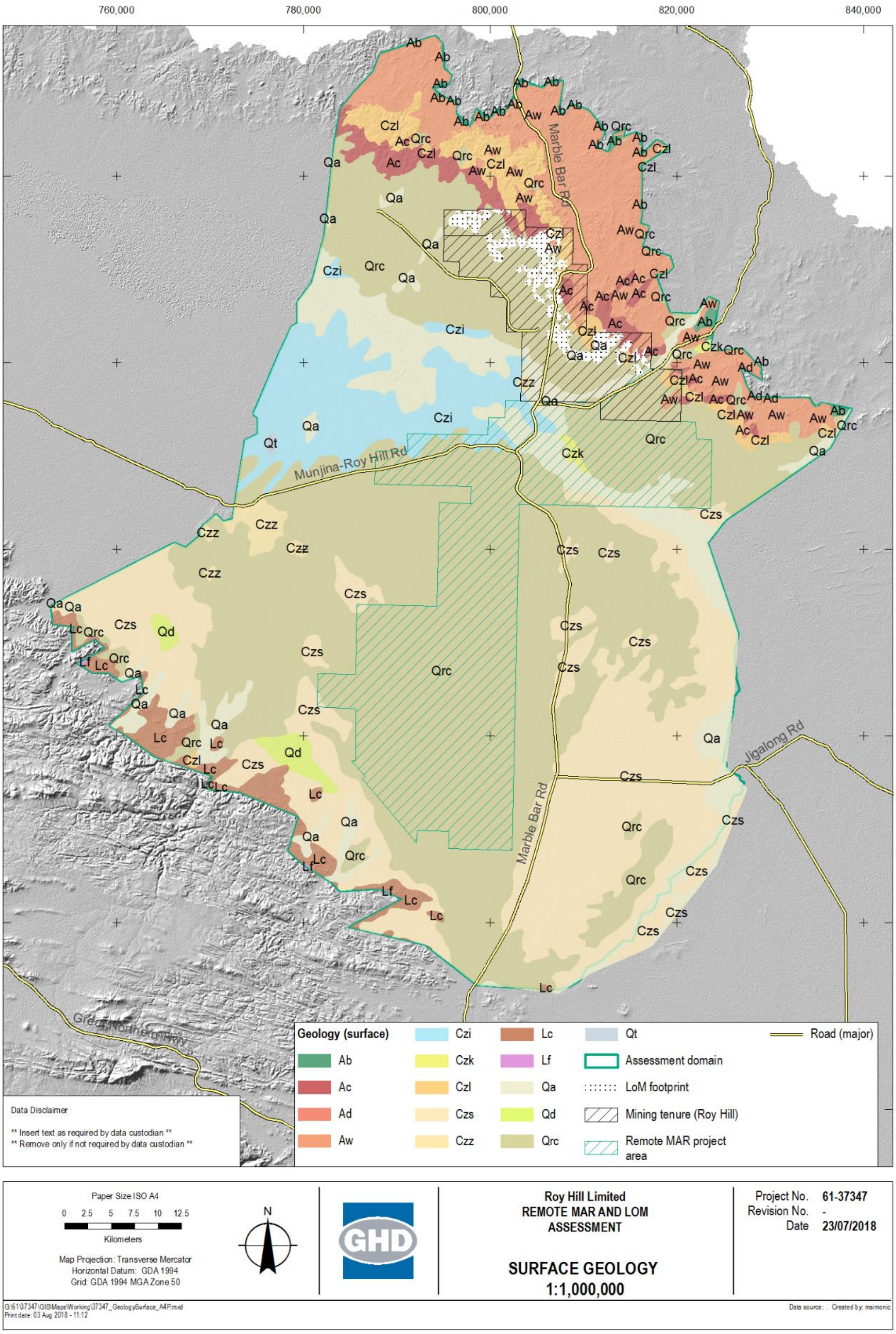


Figure 3-6: Surface geology

Alluvial fans are also a notable feature in the Cainozoic landscape and occur at the outflows of creeks from the Ranges (e.g. Coondiner Creek in the Hamersley Range and Christmas Creek in the Chichester Range).

The upper section of the Wittenoom dolomite is weathered and often karstified and sometimes erroneously described as 'calcrete'. Dolomite is interbedded with chert and may contain manganese which weathers into localised black manganiferous clay. Depth of weathering is variable but the available logs suggest that weathering ceases at an elevation of 350 to 360 m AHD, suggesting an average thickness of the weathered dolomite unit being 20 to 30 m.

The pre-Cainozoic landscape is intersected by regional faults which may have influence on groundwater flows and salinity contrasts. The faults may be accompanied by dolerite dykes which could facilitate localised compartmentalisation.

The bedrock geology of the Fortescue Valley is offset against the basement rocks of the Hamersley Range to the south of the of the assessment area. This contact is a regional fault system, the part of which is known as the Poonda Fault System. The Wittenoom Formation in this part of the assessment area is offset against the upper members of the Hamersley Group sequence, including the low-permeability Mt McRae and Mt Sylvia Formations.

Detailed stratigraphy of the study area is summarised in **Appendix B** and indicative cross-sections are available in **Appendix C**.

Hydraulic properties

The aquifer units in the area generally show high variations in hydraulic properties, namely hydraulic conductivity (K) or transmissivity (T), specific storage (Ss) and specific yield (Sy). Parameterisations of individual aquifer units has been reported in previous modelling reports both for the Chichester Range (mining footprint) and the Fortescue Valley area (e.g. Willis-Jones, 2018; Brandes de Roos and Youngs, 2010, MWH, 2009).

Indications from existing dewatering at RH mining tenement are that permeability of some of the units (e.g. Nammuldi Member) has been previously underrepresented in some parts of the mining footprint and needs to be adjusted. This seems to be consistent with some results obtained from Stage 1 Borefield (MWH, 2015) and also from other hydrogeological investigations in similar hydrogeological conditions. Johnston and Hamilton (2018) suggest that some of the previously considered aquifer parameters in the RMAR area are higher than previously considered.

Aquifer hydraulic parameters from the mining tenement are adopted as per RHIO's dewatering model (Willis-Jones, 2018), and their values updated in August 2108 (Firmani, personal communication). The adopted value for the resource part and initial estimates for the RMAR area are provided in Table 3-1. Hydraulic parameters were subsequently adjusted, where needed, during the calibration runs.

Groundwater recharge

Groundwater recharge is associated with major cyclonic events that are episodic and relatively short-lived resulting in some short-term mounding within the shallow groundwater system. The major component of recharge during the majority of inter-cyclonic events is lateral inflow from the ranges, with the majority of the valley sediments not recording any significant recharge during those times.

Ponding in the marsh is facilitated by the presence of presumably low permeability clay and silcrete/calcrete hardpans in the surficial sediments of the marsh. While it has been previously asserted that accumulated water in the marsh feeds the surficial alluvial deposits where more permeable material in the ponding surface occurs in some areas of the Marsh facilitating the seepage of flood waters into the sub-surface it is quite likely that ponding occurs because water levels in surficial sediments also rise during large scale rainfall events.

Table 3-1: Summary of hydraulic parameters for the study area

HSU	RH code	Kh (m/d)	Kv (m/d)	Ss (m-1)	Sy
Alluvium (Quaternary cover)	01_Alluvials	5	0.5	0.00001	0.1
Tertiary Detritals (clay, calcrete)	02_Detritals, 02b_Calcrete, 02c_Detritals_downstream, 02d_detritals_under_creek, 03_Detritals_DID	0.01 to 6	0.001 to 0.6	0.00001	0.02 to 0.2
Nammuldi Member (part of Marra Mamba Fm)	04_HNAM, 05_ONAM, 06_SONAM, 07_NAM_BIF, 07_NAM_BIF_undiff, 07_NAM_BIF_Zulu_area	1.7 to 40	0.17 to 40	0.00001 to 0.00005	0.01 to 0.12
Jeerinah Fm	08_Jeerinah, 08_Jerr_under_creek	0.045 to 10	0.0045 to 1	0.000001 to 0.00001	0.01 to 0.05
Weathered dolomite	n/a	5 to 50	0.5 to 25	0.00001	0.02 to 0.05
Dolomite	n/a	0.01	0.01	0.000001	0.005 to 0.01

The recharging effect of the Marsh inundation and contributions from creek and river flows (if present) are relatively short-lived since the rising groundwater is rapidly lost to evapotranspiration in the groundwater discharge zone.

In the Chichester Range, the Marra Mamba Formation outcrops receive direct recharge from higher magnitude rainfall events. Intense rainfall may not result in substantial infiltration in the hills due to the sloped land surface, but is likely to cause surface runoff that infiltrates into the ground when it reaches the break-of-slope areas or within the permeable sections of the drainage lines. The latter is probably evident in the hydrograph of RHPZ0012, located close to the Kulkinbah Creek which recorded several water level peaks after 2008, 2010 and 2011 rainfall events with daily rainfall exceeding 50 mm.

Recharge is expected to be enhanced in outcrop and subcrop zones near (and south of) the Chichester Range’s break of slope, where the Chichester Range’s hilly zones transition to alluvial fan systems extending to the Fortescue Marsh, most notably along the Christmas Creek. These break-of-slope regions include outcrop/subcrop with drainage-incisions resulting in direct connection between surface water and aquifers. Willis-Jones (2018) presented a hydrograph of RHPZ0010, situated at a break of slope area but screened in Marra Mamba, which recorded water level rises following large rainfall events between 2005 and 2012. The bore recorded four major water level rises during that period, ranging to up to two metres. This marked response is not reciprocated in bores which are more proximal to the Fortescue Marsh (for example RHPZ0022B), possibly due to the thickening of alluvial sediments which will a dampening effect on recharge pulses.

The high-level recharge calculation is based on lithological units. An estimate of recharge rates and volumes is presented in Table 3-2:

Table 3-2: Recharge rate and volume estimates

Zone	Area (km^2)	Rate (mm/yr)	Proportion of rainfall (%)	Recharge (GL/yr
Chichester Range, basement outcrops and subcrops	577	3	1	1.7
Chichester Range break of slope, alluvial fans	180	11	4	2.0
Hamersley Range, basement outcrops and subcrops	289	3	1	0.9
Hamersley Range, break of slope, alluvial fans	200	11	4	2.2
Alluvium/colluvium cover (valley)	2,800	0 to 2	0 to 0.5	0 (to 5.6)
Fortescue Marsh footprint and claypan/hardpan "calcrete flats"	439 + 214	0	0	0
Total				**6.8 (to 12.4)**

[1] – The total study area covers 4,622 km^2, however the marsh footprint is not used in recharge estimate calculation

Groundwater levels and flows

Groundwater flow directions are oriented towards the Fortescue Marsh in a concentric radial manner (Figure 3-7). Groundwater flow gradients are highest at the margins of the Fortescue Valley reflecting increasing topographic elevations and shallower depth to low permeability basement. In the Fortescue Marsh area, the groundwater flow gradients become gradually smaller and are considered to be significantly slowing down the groundwater flow rates. Groundwater is eventually removed by evapotranspiration when it becomes close to the ground level on the fringes of the marsh.

Ponding in the marsh is assumed to be facilitated by the presence of relatively low permeability clay and silcrete/calcrete hardpans in the surficial sediments of the marsh. Accumulated water in the marsh feeds the surficial alluvial deposits where more permeable material in the ponding surface occurs in some areas of the Marsh expediting the seepage of flood waters into the sub-surface. While the exact locations of seepage points are unknown, the CSIRO work (Barron, 2013) suggests the connectivity may be present in patchy areas with vegetation that is known to use groundwater.

This mode of flow resulted in accumulation of salts and formation of brines in the Marsh area. The dense contrasts between the brine and the incoming freshwater from the Ranges forces fresh water to move against the saline interface and towards the surface. The concentration of brines is estimated to be up to 100 to 150 g/L.

Flow (and salinity) characteristics are also likely to be influenced by contribution of water from alluvial fans emanating from the ranges, and possibly by other undefined structural features. There appears to be a significant freshwater front from the south intruding into a body of saline water in its flow north to northeast towards to Fortescue Marsh (Figure 3-7), which shows some apparent correlation to SW-NE structural features running across the assessment area.

Depth to groundwater varies being the shallowest beneath the Fortescue Marsh. It becomes deeper towards the flanks of the Fortescue Valley and in the adjacent ranges. While the marsh is the terminal point for groundwater flow, groundwater contribution to the Fortescue Marsh water balance is minor when compared to surface water contributions. The Marsh is however underlain by a large storage of saline to hypersaline groundwater.

Depth to groundwater in the RMAR area increases from north to south, from less than 10 m to 20 m below ground level or more. Increasing thickness in the central and southern portion of the RMAR occurs to the presence of sizeable Tertiary and Quaternary deposits accumulated in the outflow fans from the creeks in the Hamersley Range which reach over large distances into the Fortescue Valley. The general trends in depth to groundwater can be viewed in Figure 3-8.

Groundwater levels are generally stable across the RMAR area and do not show any important upward or downward trends other than small seasonal variations. The RMAR dataset (presented in **Appendix C**), summarising water levels for the last five years (2014 to 2018) suggests that the area receives a relatively steady diffuse recharge for the majority of time (or is maintained by lateral inflow from the Hamersley Range). This is consistent with the presence of the thick unsaturated and heterogeneous zone which would attenuate individual recharge events.

Prior to the depicted period of 2014 to 2018 (in **Appendix E**) an apparent recharge event has been recorded during 2011 to 2012. Observed water levels show a nominal peak for that period, with a lag of several months, suggesting that event-driven periodic recharge events are periodically present in addition to diffuse (or laterally driven) recharge. They correlate with flooding of the Fortescue Marsh during the same period.

They are also accompanied by increased flows in the Fortescue River and increased flow contributions from creeks that divert surface runoff from the Ranges. These are rather infrequent, based on the record of the monitoring bores in the area. Although other subsequent and potentially smaller peaks may have occurred post 2014, they have not been recorded in the monitoring data possibly due to the low recording frequency of water level measurements in the area.

These intermittent event peaks appear to be short-lived, with water levels returning to the pre-event levels within the matter of months and as such they do not have a dominant recharge impact on the regional groundwater system.

Groundwater levels in deeper bores in the Fortescue Valley are higher than corresponding water levels in Cainozoic sediments suggesting an upward pressure of water levels from the underlying dolomite aquifer. The pressure differences are up to three metres.

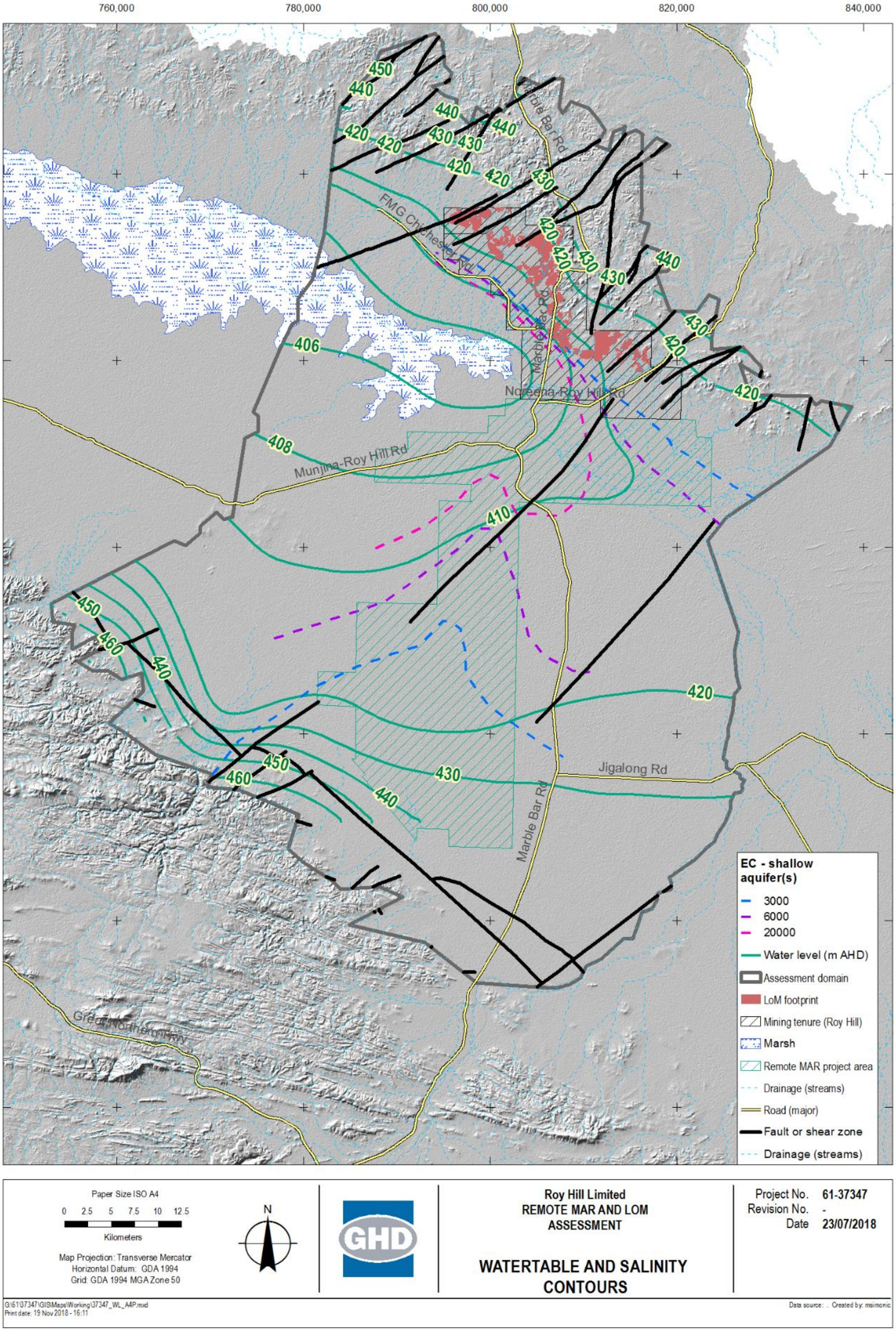


Figure 3-7: Groundwater level and salinity contours (adapted from Simonic et al, 2015)

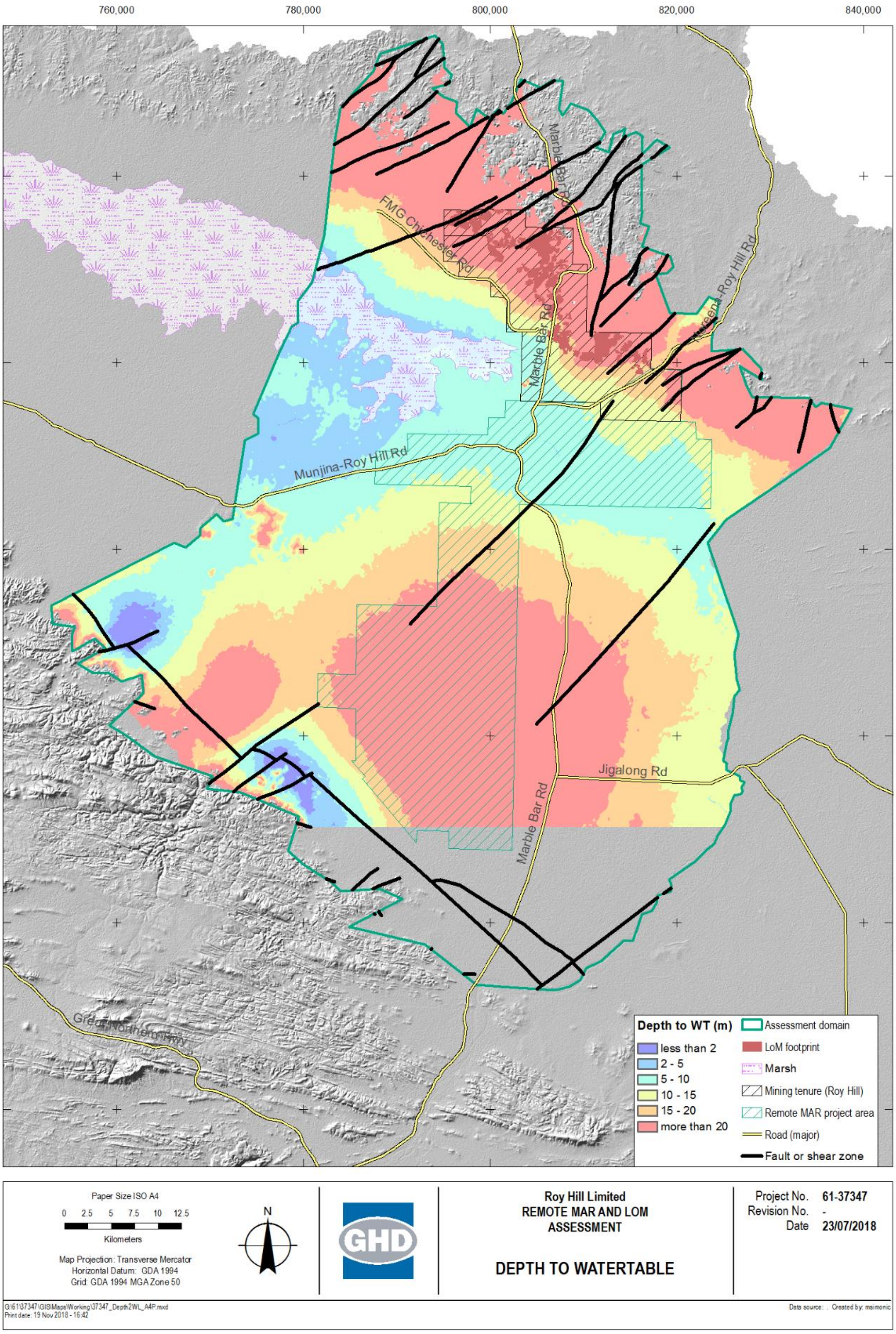


Figure 3-8: Depth to groundwater

Groundwater discharge and losses

The groundwater system in the study area reports to the Fortescue Marsh and potentially to surface expressions of groundwater table locally known as yintas where the groundwater flow is being removed by evapotranspiration. The typical groundwater gradients in the fringing areas are small and combined with low permeability they result in relatively small groundwater flows (compared to periodic surface water inflows).

The Fortescue Marsh and its peripheral shallow groundwater system can be in one of the three dynamic phases (FMG, 2010):

- Flood phase – fresh water in the marsh partly infiltrates into shallow groundwater zone and raises the water level creating a recharging mound
- Inter-flood phase – the volume of water in the lake reduces due to evaporation and is accompanied by reduction of shallow water levels due to evaporative discharge
- Drying phase – the system returns to the pre-flood condition characterised by the balance between groundwater inflow forced against the saline interface and the subsequent loss through evapotranspiration.

The key dynamics states of the groundwater flow with respect to the Fortescue Marsh, the occasional flooding event and the prevailing 'drying' state (discharge of regional groundwater flow) is shown in Figure 3-9:

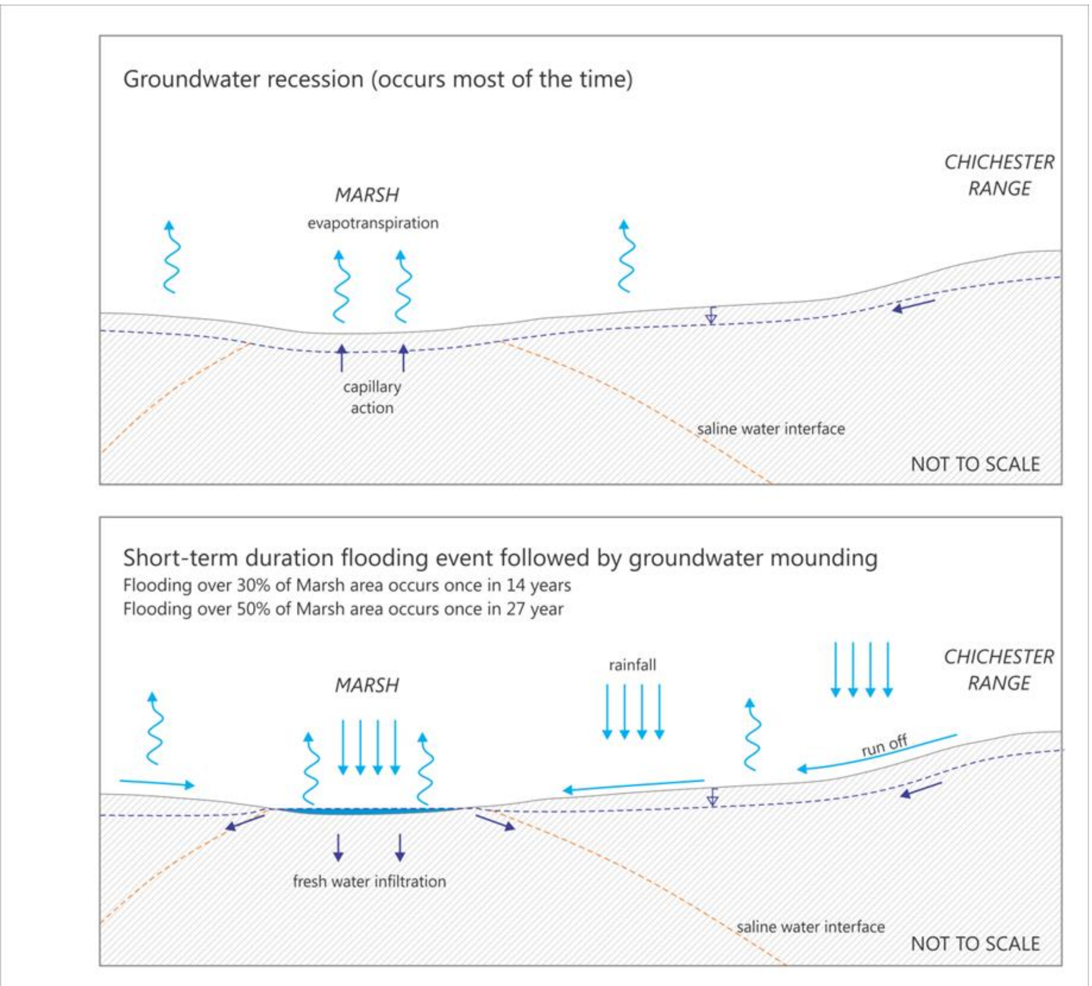


Figure 3-9: Conceptual flow dynamics of the Fortescue Marsh (after Simonic et al, 2015)

These processes occur within a relatively narrow shallow horizon since the groundwater level even in the dry period is relatively shallow, at one to two metres below ground surface. Flooding of the Fortescue Marsh has been associated with an influence on shallow groundwater up to several kilometres from the Marsh in the Cloudbreak and Christmas Creek areas of FMG (e.g. Brandes de Roos and Youngs, 2010), which are mining areas to the west of RHIO's tenement.

Ponding in the Fortescue Marsh can however be a result of the general increase of groundwater level in response to a recharge pulse generated by a cyclonic event in which case ponding would not necessarily have a mounding effect.

Groundwater / surface water interaction

The Cainozoic cover is in direct hydraulic connection to the Marsh, which forms the largest, albeit ephemeral, surface water feature; and with rivers and creeks. This relationship is preserved in the depositional sequence which transitions from the fan-dominated environment to lacustrine/playa depositional sequence.

There are no useable surface flow records to allow estimation of baseflow contribution or stream losses to the subsurface, however historical reconstructions of the marsh inundation events correlate with limited groundwater hydrograph data available (e.g. Rouillard et al., 2015).

The marsh is primarily a terminal surface water and groundwater discharge feature, and it was postulated in previous studies by others that during short-term events, when flooded, it will recharge groundwater on its perimeter.

The Fortescue River, the largest flowing stream in the area, also intermittently recharges and potentially refreshes the underlying groundwater.

Depth to groundwater in large areas of the assessment domain remains large (in excess of 20 m) and the effect of groundwater on surface water is negligible these areas. The estimated area where depth to groundwater is less than six metres is approximately 460 km^2 (10% of the study area). This area covers lowland major channel systems (along the Fortescue River) and lowland receiving areas (Fortescue Marsh and its fringes) and potentially outflow points of creeks from the ranges where they intersect break-of-slope zones. Yintas on the northern fringes of the Fortescue Marsh may be expressions of local watertable and often endpoints of irregular inflows from creeks.

Groundwater extraction

Non-mining groundwater use in the area is minor. Key groundwater extraction has commenced with dewatering of RHIO's mining pits and it will continue up to 2031. The groundwater extraction rates required for dewatering were previously estimated (MWH, 2015) at up to 84 ML/d, however these have been recently updated to average rates over 131 ML/d, with peak rates of 225 ML/d.

3.2.8 Groundwater chemistry and salinity

Groundwater salinity in the Roy Hill mining and MAR areas is controlled by topographic elevation, hydraulic gradient and location in the landscape (factors that are all linked to groundwater residence time) often to a larger degree than by the mineral composition of rocks and sediments through which groundwater flows.

Groundwater is generally fresh in the ranges, close or underneath creeks and alluvial fans and also in the top layer under the Fortescue Marsh. Deeper groundwater under the marsh and floodplains is saline as a result of an on-going evapotranspirative concentration of salts in the areas of terminal phases of groundwater flow and the formation of a distinct saline or brine body of water at depth. Detailed delineation of the brine body is an on-going effort undertaken by mining companies and research institutions and has been progressed more in the areas to the west of the study area.

Relative abundance of major ions is a function of processes occurring in geological matrix, some of which may be mediated microbiologically. These include dissolution, precipitation, adsorption, ion exchange, and redox processes. The position in the groundwater flow cycle – i.e. being close to recharge or discharge areas, the length of residence time, and potential interaction with surface water also influence both the hydrochemical type of groundwater and resulting concentrations. The similarity in hydrochemical signatures between groundwater with low and high concentrations suggest that a number of units are at their leachability limit.

While the groundwater quality differences between individual hydrostratigraphic units appear to be less distinct the following sections provide an overview based on main units occurring in the area.

Alluvium

This unit includes a mixture of shallow clastic units in ranges and floodplains. The distinction between alluvium and the Tertiary detrital sediments is sometimes unclear or the samples represent a mix between the two units.

Concentrations of shallow groundwater are generally low with a number of samples having EC less than 2,000 μS/m while other samples in the mining area are in the range of 2,000 to 5,000 μS/m (Figure 3-10). A sample from the marsh, from its shallowest horizon also suggests fresh water condition (less than 2,000 μS/m). These relatively low concentrations represent active recharge, either diffuse or along creek lines. There is a group of several monitoring bores to the west of Stage 1 borefield and close to the Fortescue Marsh in which higher concentrations occur (50,000 to 100,000 μS/m), unlike in the Stage 1 borefield which has a relatively fresh range of concentrations.

Shallow groundwater in the Fortescue Valley southeast of the Fortescue Marsh is discussed with Tertiary detritals but similar to the sample from the Chichester Range they show the concentration range of up to 5,000 μS/m, with one exception in which concentration is above 5,000 μS/m.

Hydrochemical composition of major ions is suggestive of dominance of sulphate in the mining areas and chloride in areas closer to the marsh. Sulphate is indicative of oxidation of sulphides in the mining area. Sulphate and chloride exceed bicarbonate concentrations indicating that groundwater picks up residual salinity along its flowpath, a process which may mask the recharge, bicarbonate-dominant, signature of these samples. Alluvium samples in the mining area typically have no dominant cations, however sodium is dominant in the samples from the floodplains and marsh areas.

Ion composition plots shown in Figure 3-11 are expressed in miliequivalents and can be used to directly derive their hydrochemical signatures, i.e. $Na\text{-}SO_4$ or $Ca\text{-}Mg\text{-}SO_4$ in the mining area and Na-Cl in the Fortescue Valley.

Tertiary Detritals

Salinity of Tertiary detritals is generally low, similar to other shallow aquifer samples (Figure 3-12). There is, however a spatial pattern on the western boundary of the mining tenement of bores with up to hypersaline signatures. The samples closest to the Fortescue Marsh have concentrations in excess of 100,000 mg/L.

In contrast the Tertiary detrital samples from the Fortescue Valley, in the RMAR area, have relatively fresh signatures, within the 5,000 μS/m.

Hydrochemical signatures are similar (Figure 3-13) to other shallow aquifer samples (alluvium) indicating that both groups undergo similar hydrogeochemical processes. Three distinct groups can be delineated spatially based on dominance of major ions:

- Mixed hydrochemical signatures in the mining area to be dewatered, with occasional slight dominance of sulphate as major anion and calcium or magnesium as major cations
- Sodium chloride signature in areas proximal to the Fortescue Marsh and some samples in the RMAR area
- Calcium bicarbonate signature in two samples in the RMAR, reflecting dissolution of the calcrete layer

Nammuldi Member (Marra Mamba Formation)

This group includes Nammuldi Member samples and also samples from bores which span across more than one unit in the area to be dewatered. Due to identification challenges some of the samples may not be genuine Nammuldi Member samples.

In general groundwater salinity in elevated areas is low (Figure 3-14), within the 2,000 or 2,000 to 5000 μS/m ranges suggesting that dewatering output would be low salinity water suitable for re-injection. A distinct grouping of hypersaline samples is evident in the south-west injection borefield area, indicating the potential proximity to the saline wedge in this area.

Hydrochemical signatures (Figure 3-15) often suggest slight dominance of calcium, and in some cases magnesium over other cations and sulphate or in fewer cases chloride over other anions. A few samples also show bicarbonate dominance in the SWIB and west of Marble Road.

Jeerinah Formation and Wittenoom Formation

This group contains samples described as Jeerinah Formation which in some cases are probably Wittenoom Dolomite samples, as well as dolomite samples from the RMAR area. The samples of this group are likely to reflect the spatial distribution of the saline wedge extending from the footprint of the Fortescue Marsh. Groundwater salinity of this group varies widely from relatively fresh signatures along the upslope perimeter of the mining tenement to hypersaline in the SWIB area and around the Fortescue Marsh (Figure 3-16). Groundwater salinity freshens away from the Fortescue Marsh, to the south-east in the RMAR area, with EC values in the range of less than 2,000 up to 5,000 μS/m.

Since this group represents a relatively deep groundwater with longer residence times, the hydrochemical signatures reflect this residence-time driven maturity with dominant sodium chloride water types masking the natural dolomite carbonate signature.

Nitrate in groundwater

Groundwater nitrate concentrations are available from the mining area. Nitrate in this area may include naturally occurring nitrate but also nitrate from explosives used in mining. There is an indication of a concentric pattern in nitrate spatial distribution (Figure 3-18). Lower nitrate concentrations (up to 20 mg/L) are found on the perimeter of the mining tenement while higher nitrate concentrations (20 to 45 mg/L) generally tend to be found closer to the centre axis of the tenement.

Concentrations above 45 mg/L are infrequent and mainly in the centre of the tenement, with an occurrence also in the SWIB.

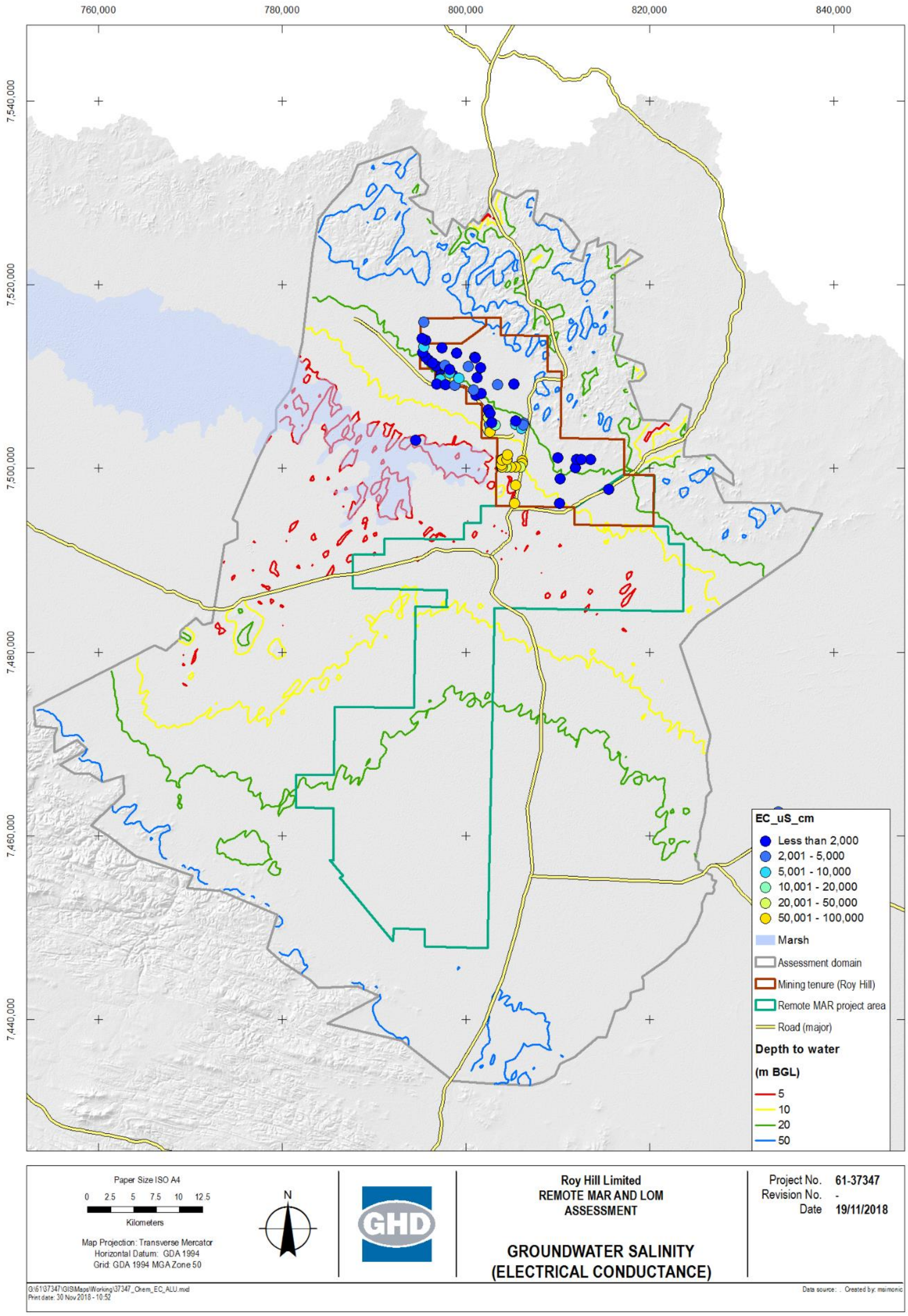


Figure 3-10: Groundwater salinity, alluvium (shallow groundwater)

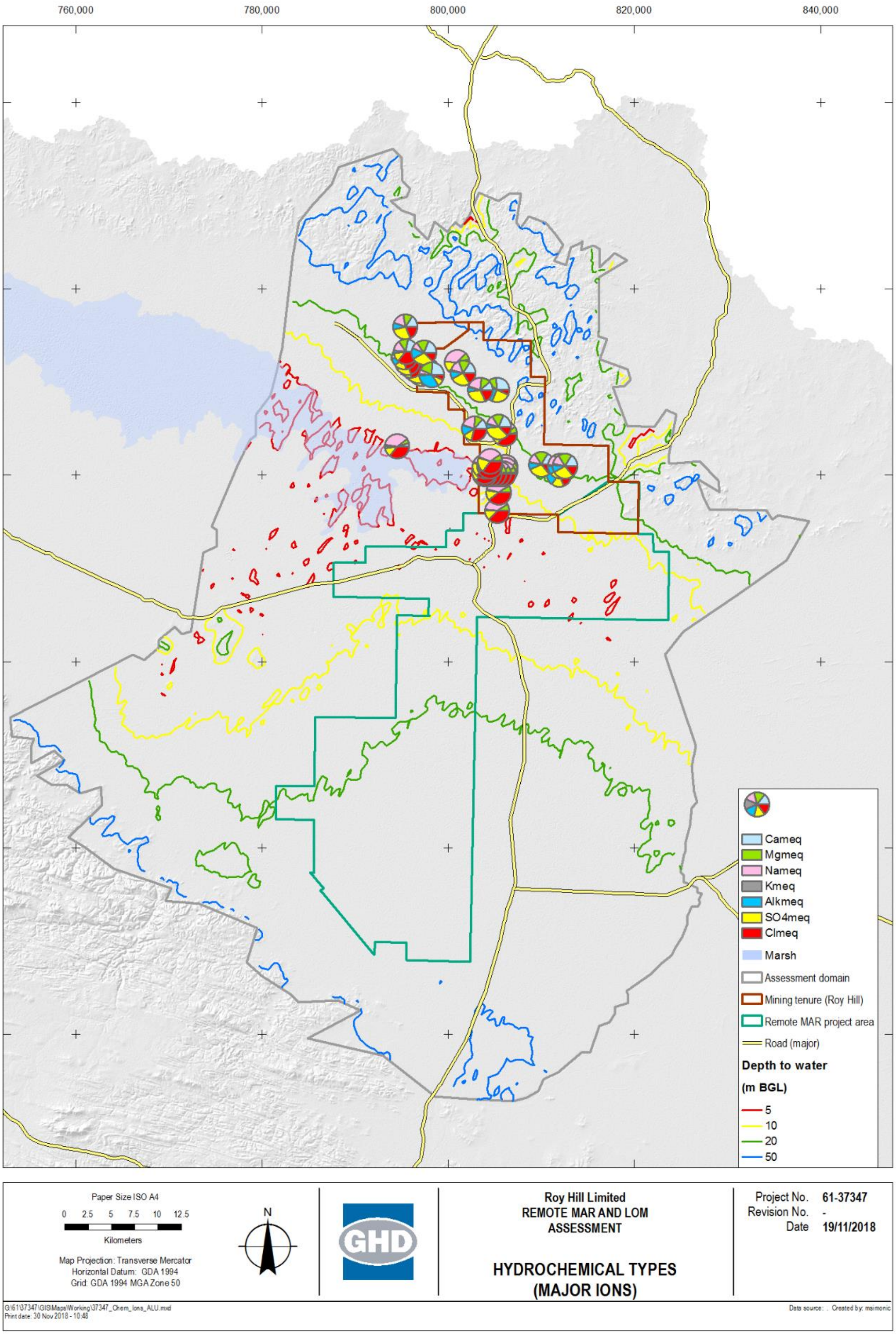


Figure 3-11: Major ion composition, alluvium (shallow groundwater)

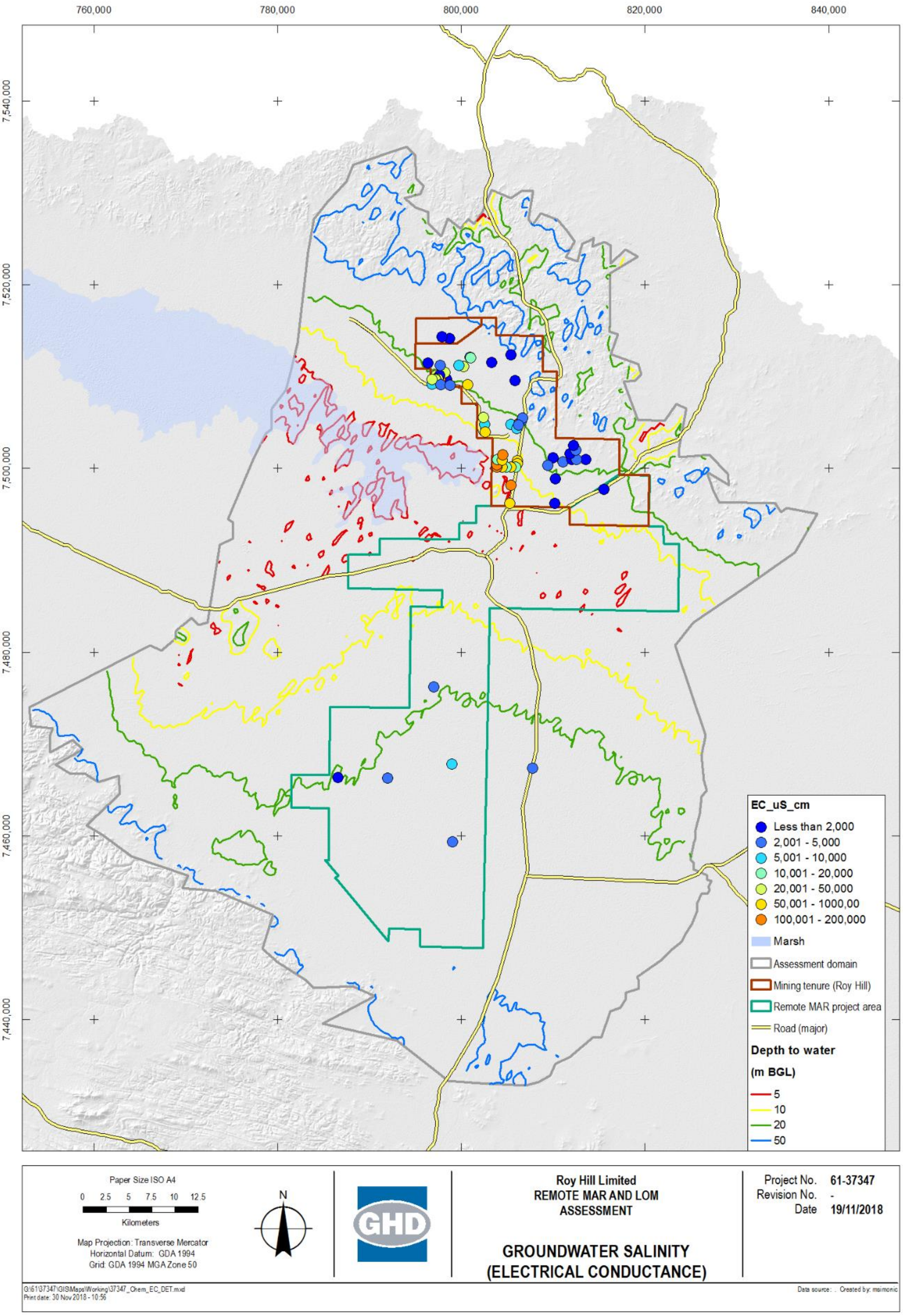


Figure 3-12: Groundwater salinity, Tertiary detritals

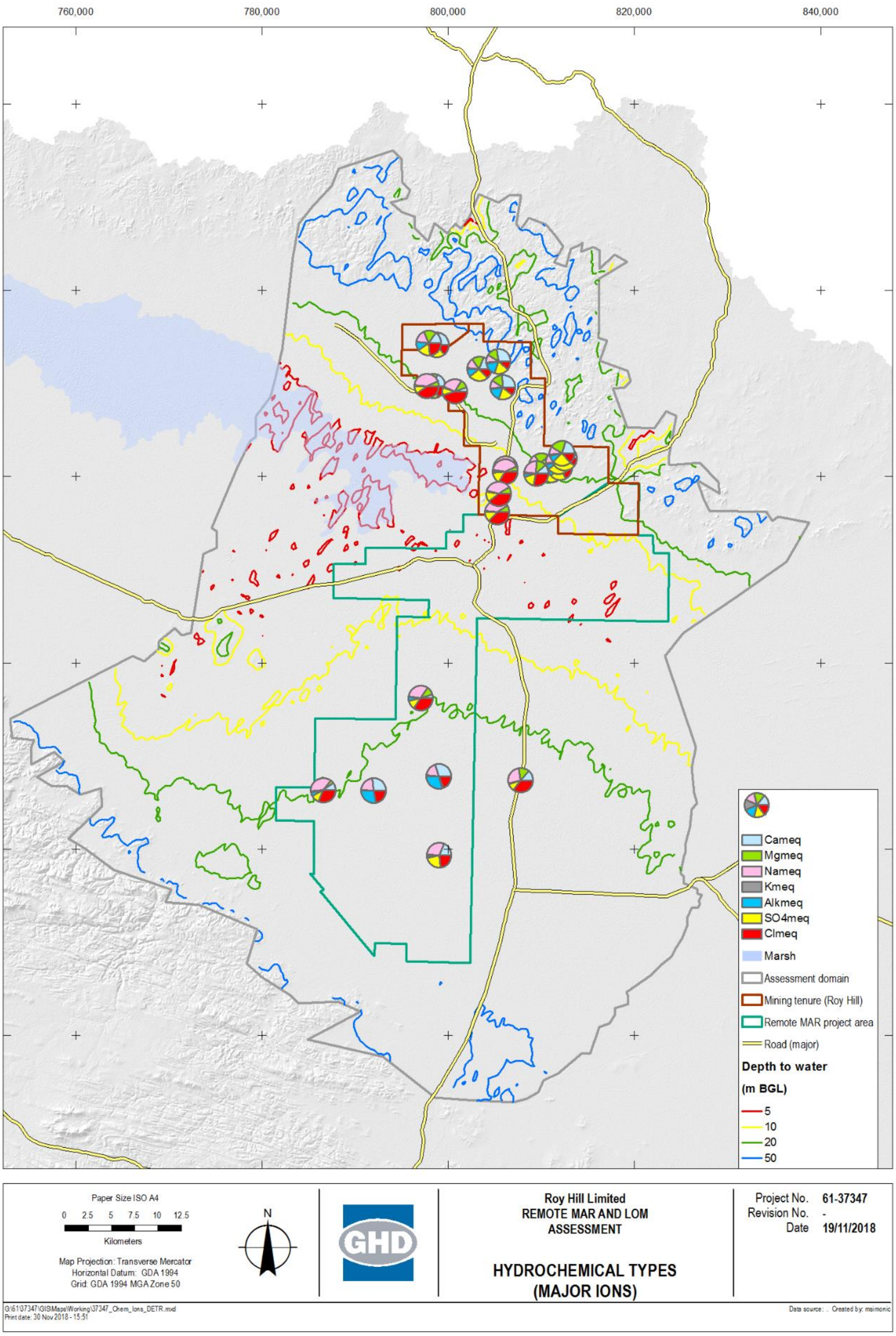


Figure 3-13: Major ion composition, Tertiary detritals

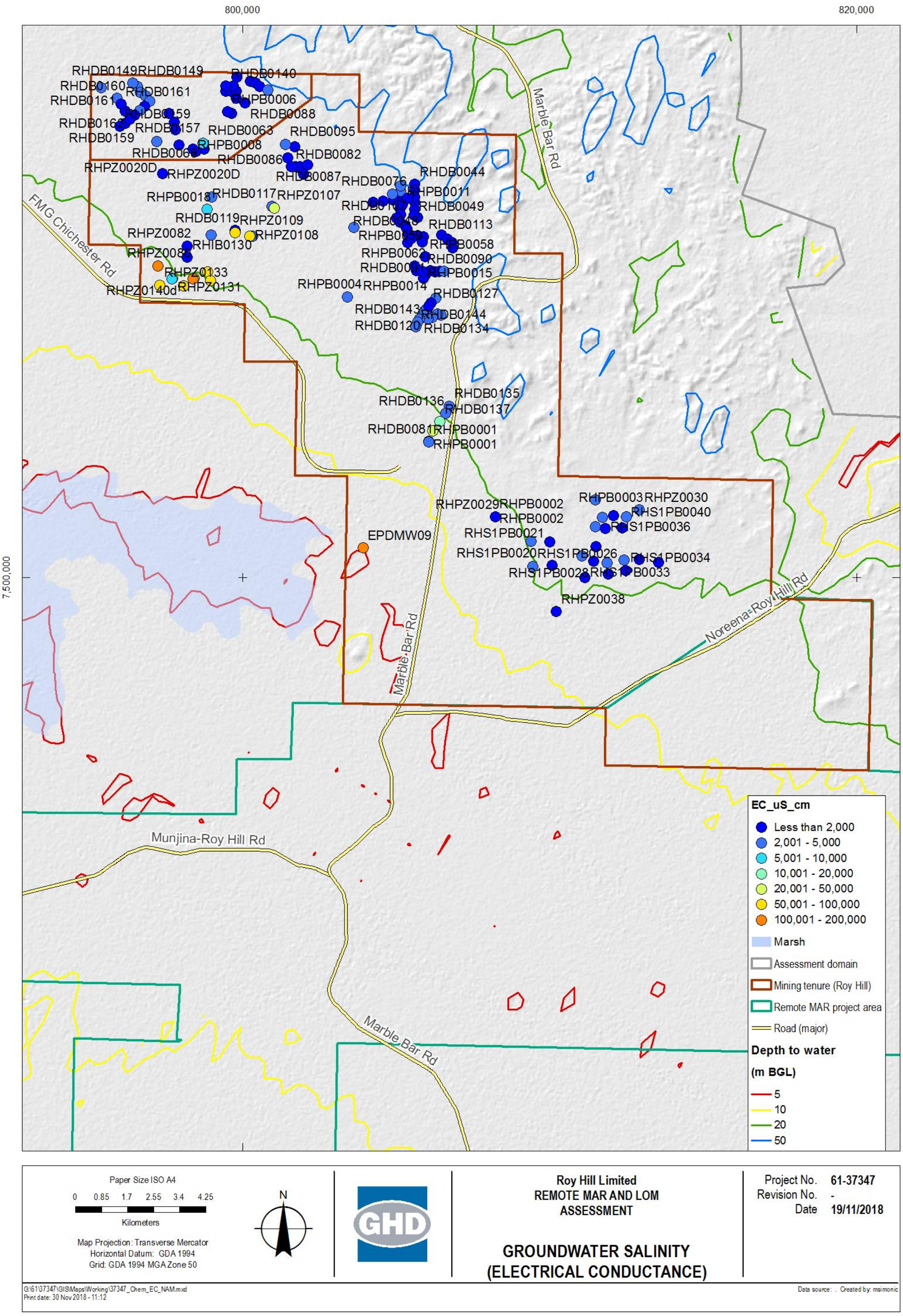


Figure 3-14: Groundwater salinity, Nammuldi Member (or Marra Mamba Formation)

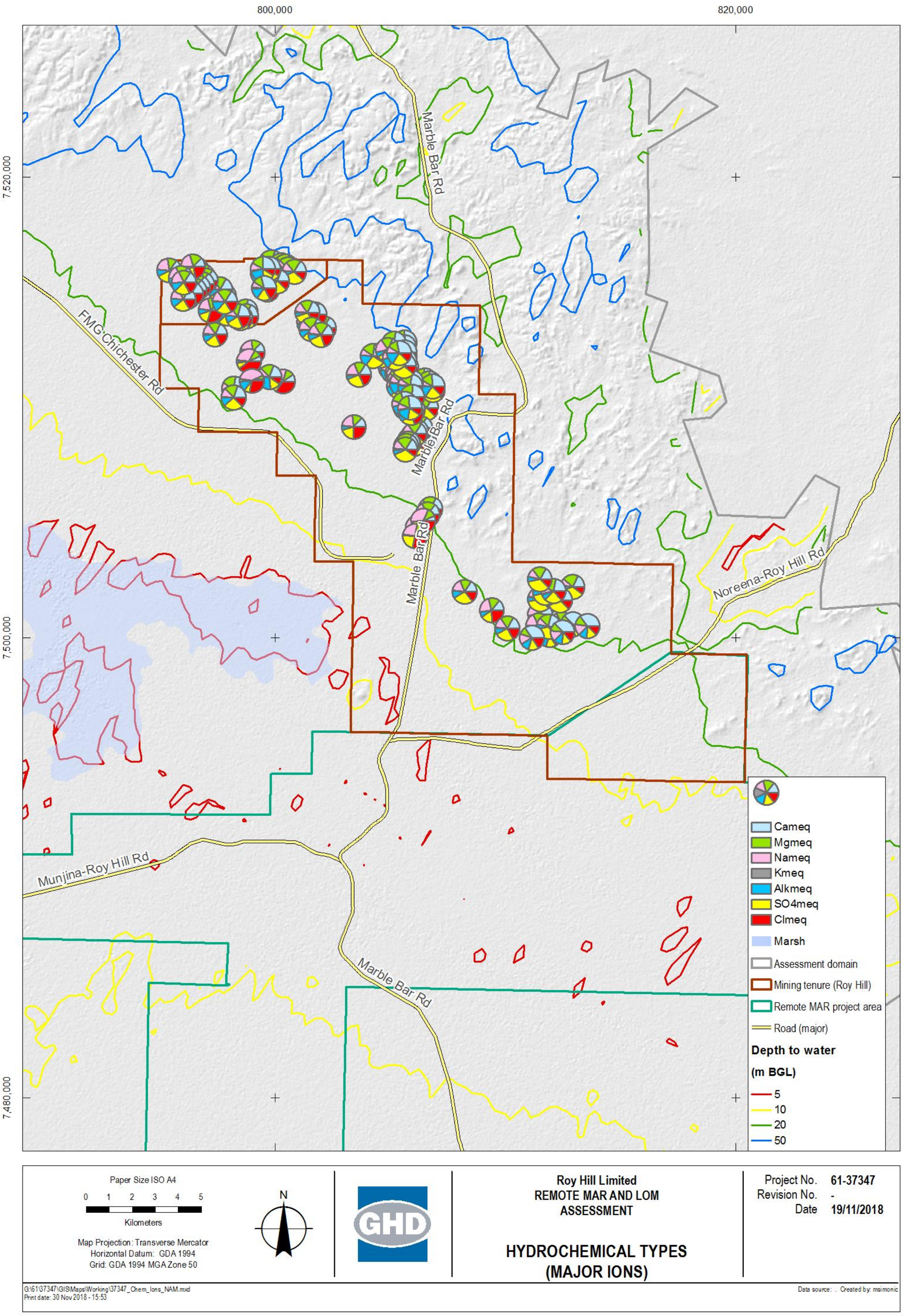


Figure 3-15: Hydrochemical signature (major ion composition), Nammuldi Member (Marra Mamba Formation)

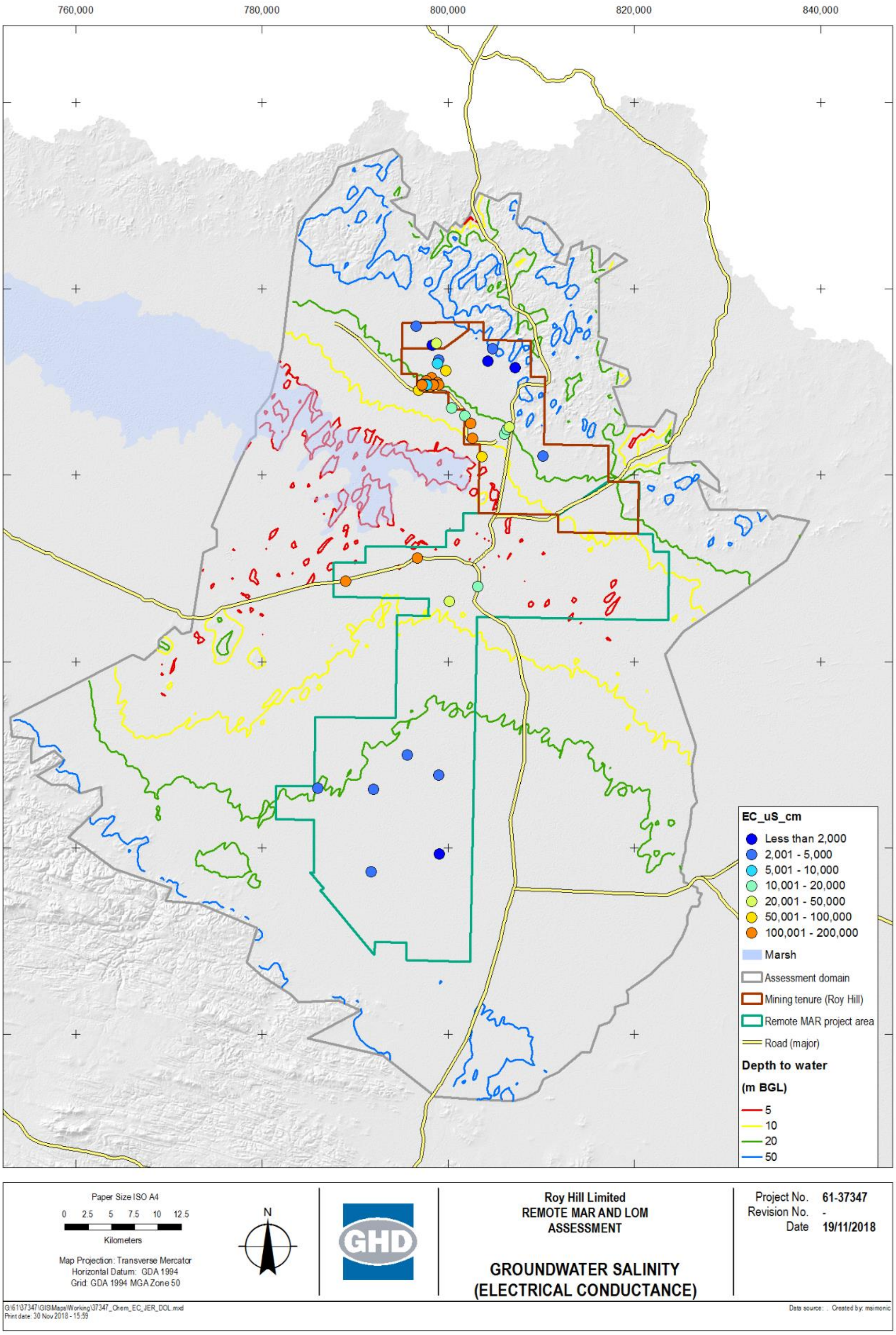


Figure 3-16: Groundwater salinity, Jeerinah Formation, Wittenoom Formation

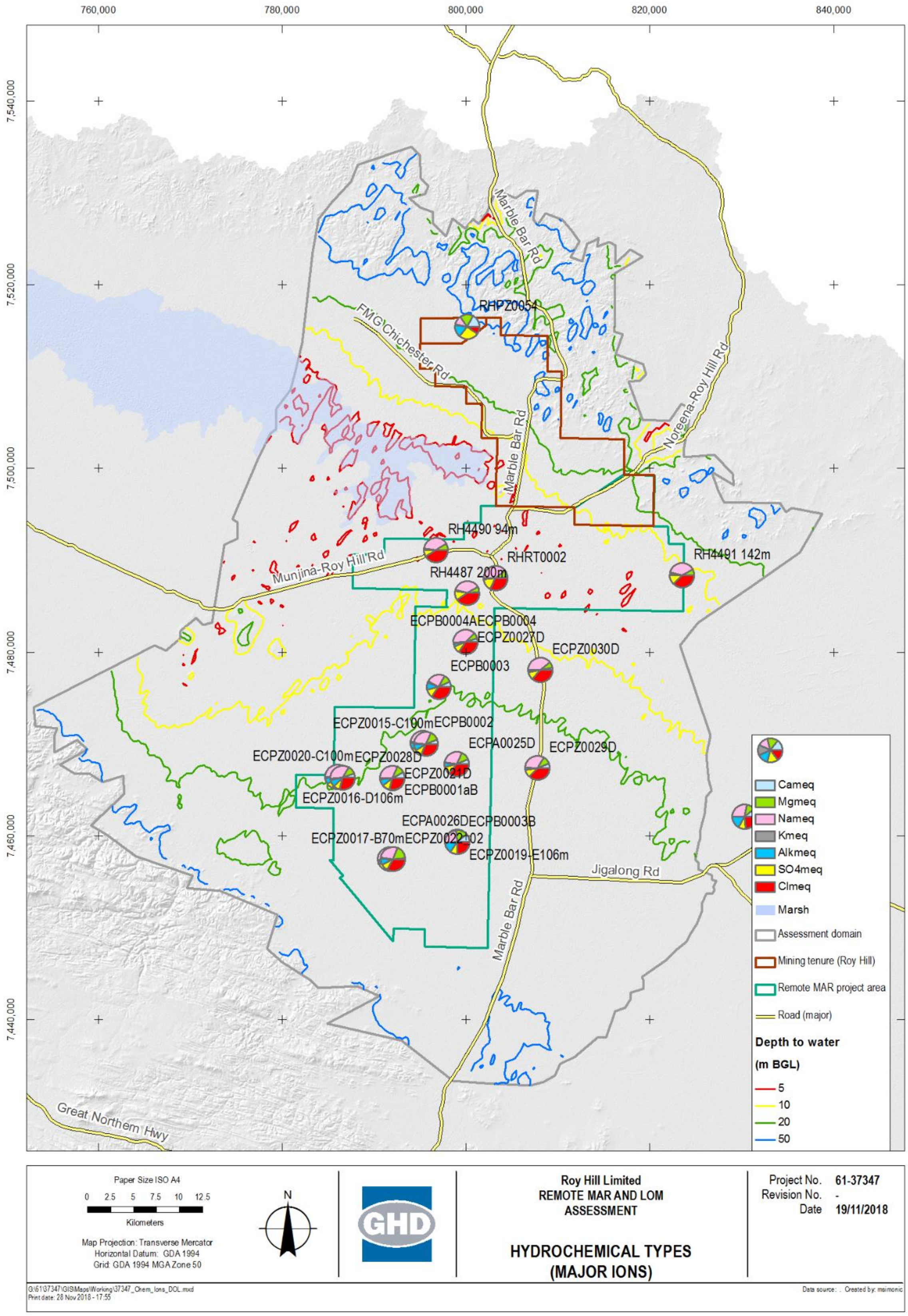


Figure 3-17: Hydrochemical signature (major ion composition), Wittenoom Formation

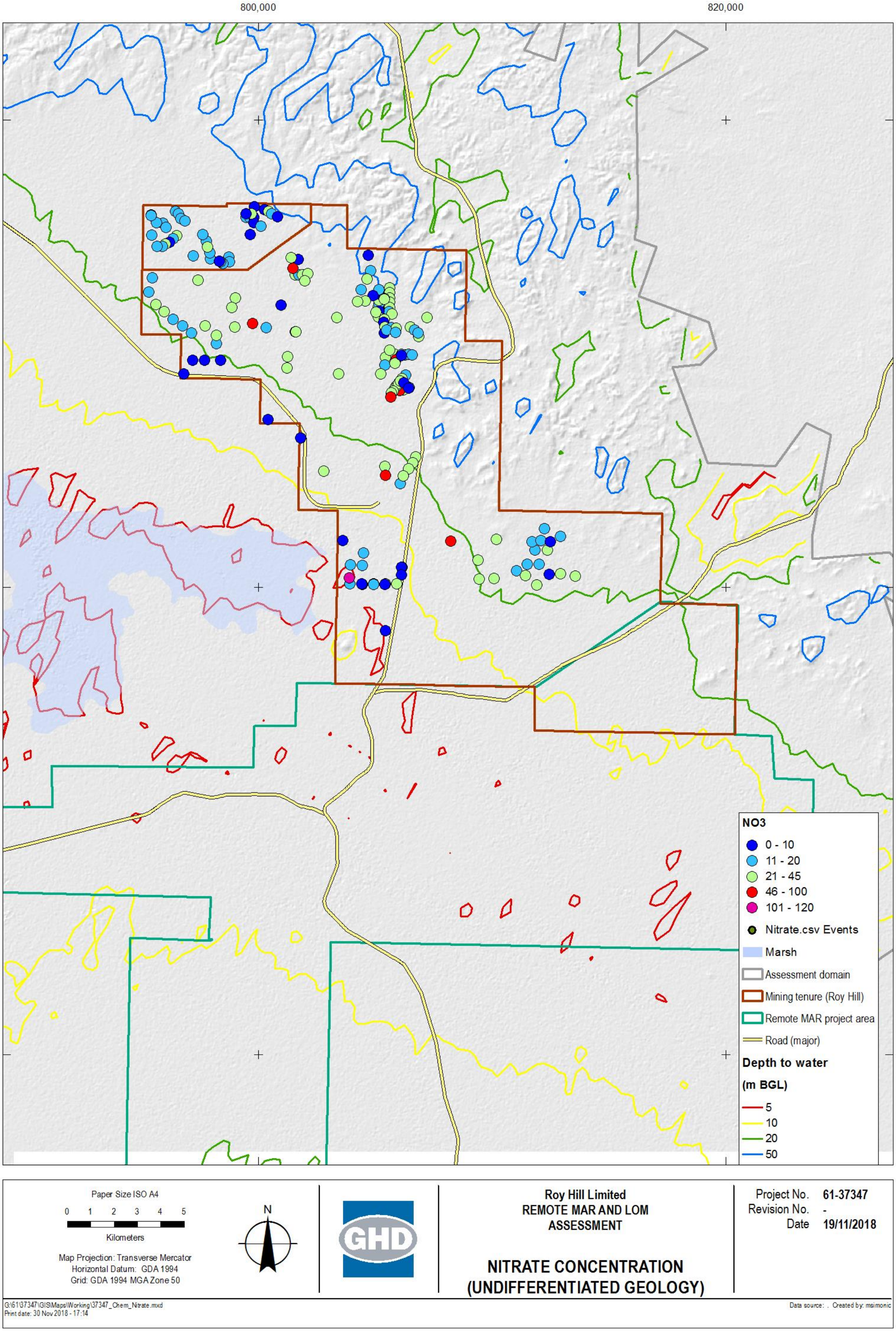


Figure 3-18: Groundwater nitrate concentrations

3.2.9 Environmental assets

The vegetation of the Hamersley and Chichester Ranges is typically open and dominated by spinifex, acacia small trees and shrubs, and occasional eucalypts. On the flats of the Fortescue Valley surrounding the Marsh, the vegetation is a mosaic of spinifex grasslands and Acacia woodlands and shrublands. This includes areas of groved Mulga and Snakewood formations. The major drainages are fringed by eucalypt woodlands and tussock grassland communities.

The marsh hosts sparsely vegetated, clay flats fringed by samphire vegetation communities. It is the largest ephemeral wetland in the Pilbara and has multiple conservation values. The marsh is classified as a wetland of national importance within the Directory of Important Wetlands in Australia and contains a number of Priority Ecological Communities (PEC).

In July 2013, the EPA defined a Fortescue Marsh Management Area consisting of seven sub-zones partitioned into three conservation significance categories (EPA Report 1484; EPA 2013). The study area encompasses the management zones identified in the Fortescue Marsh Management Area. Portions of the Marsh have been identified for transition into conservation tenure and management, in relation to the expiry of pastoral leases in 2015.

BHP Billiton commissioned a study (Simonic et al, 2015) which focused on ecohydrological assessment of the Fortescue Marsh catchment. One of the outcomes included a map of ecohydrological units (EHUs) which are characterised by differing levels of groundwater surface water interaction and the associated vegetation communities (Figure 3-19).

It identified the Marsh as an area of ecological importance with connectivity mechanism between surface water and groundwater and associated flora communities, in particular samphire and halophytic vegetation. The degree of connectivity is unclear due to uncertainty associated with the permeability of the Marsh's bed sediments.

Due to the presence of a relatively thick unsaturated zone outside of the Fortescue Marsh the associated risks would include effects from potential mounding on vegetation communities which are not groundwater dependent based on the current status. This includes Calcrete Flats (EHU 7), and Marillana Plains (EHU 6), while Fortescue River Coolibah (EHU8) may have possible dependence or interaction with groundwater systems.

3.2.10 Regional groundwater development

Mining dominates water use across the study area, with primary use being mine dewatering and discharge of surplus water.

Pastoral

Pastoral stations require water for livestock. Water is obtained from bores and permanent pools within ephemeral watercourses. The volume of water used for stock watering is negligible, when compared with abstraction for mining and town water supplies.

The pastoral industry has traditionally been a minor water user; however, access to water resources is crucial to its function. Shallow bores and hand-dug wells were initially constructed to meet the pastoral requirements for stock watering. Most pastoral bores and wells tend to be concentrated in the low-lying areas in alluvial aquifers. Most are less than 30 m deep and are typically equipped with a windmill, with yields of up to 10 m^3/day.

It is difficult to determine the number of functioning bores and wells for pastoral use with most abandoned or poorly maintained. Water licensing for stock and domestic use is not required under the Rights in Water and Irrigation Act 1914 unless the water is from an artesian source (DoW, Pilbara Regional Water Plan 2010-2030, 2008).

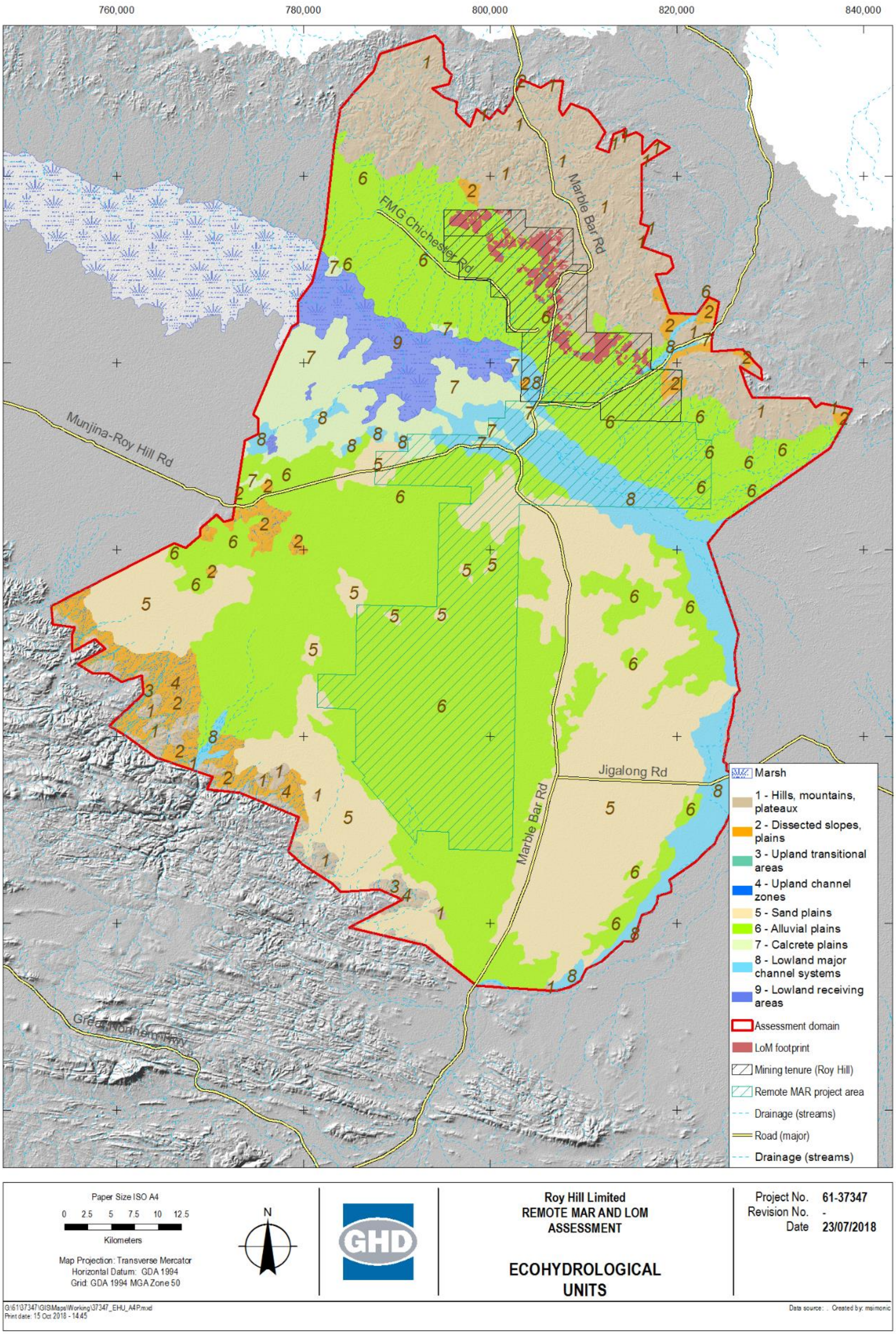


Figure 3-19: Ecohydrological classification (after Simonic et al., 2015)

Mining

The mining industry is the major groundwater user in the study area. Mining operations generally abstract several GL/yr (common rates are more than 10 GL/yr), from mine dewatering and borefields. Abstracted water is used for dust suppression, mineral processing and ore beneficiation, but a significant part is also returned to the aquifer system.

Mine dewatering borefields are designed to lower the watertable in advance of mining to facilitate safe mining conditions. In order to achieve dewatering, pumping rates must exceed the groundwater throughflow, resulting in localised storage depletion. In cases where dewatering exceeds the mine water demand, the discharge has to be responsibly managed in accordance with permit requirements. On completion of mining and cessation of dewatering, groundwater levels are expected to recover to near pre-pumping levels. The largest user in the study area is Roy Hill Iron Ore Mine.

3.3 Hydrogeological conceptual model

3.3.1 Key hydrogeological processes and flows

The hydrogeological conceptual model forms the basis of the numerical modelling. The conceptual model is based on the following key flow processes:

- Gradient-driven groundwater flow oriented from the ranges towards the Fortescue Marsh, with two components of flow present in the Cainozoic sediments and the underlying weathered and fractured basement aquifers (ore part of Marra Mamba Formation; Wittenoom dolomite)
- Groundwater flow in the Fortescue Valley is influenced by the dense brine mound regionally extending beneath and on the periphery of the Fortescue Marsh. The density contrasts are likely to drive fresher groundwater upward along the saline interface to be eventually removed by evapotranspiration.
- The overall throughflow is considered low due to high total pressure in the discharge area (exerted by hypersaline groundwater), low gradient and low permeability of shallow alluvial/claypan cover.
- Diffuse groundwater recharge is occasionally supplemented by short-term duration high-intensity flooding following the cyclonic events
- Groundwater removal (dewatering) associated with mining (Roy Hill area) has commenced and will continue to 2031. This may be complemented, when necessary, with groundwater extraction for Stage 1 or Stage 2 Borefields
- Excess groundwater discharge, generated at a rate of up to 205 ML/d (on average 87 ML/d) is planned to be returned to the aquifer system at various sites, including the resource area (into Tertiary detrital units and Nammuldi Member, up to 109 ML/d, on average 67 ML/d) at SWIB and in mining area generally; and remote (Stage 2) borefield into weathered dolomite (up to 96 ML/d, on average 20 ML/d)
- Under natural conditions the groundwater system terminates in the Fortescue Marsh area.
- The study area is considered an effectively closed system in that fluxes between the study area and the surrounding areas are considered negligible and as a consequence would be considered zero-flux boundaries. An exception is a section of the eastern boundary formed by the Fortescue River, which will be considered to be a constant head boundary or a prescribed flux boundary with recharge flux maintaining water levels in this area.

The important features of hydrogeological conceptualisation are summarised in Table 3-3 and presented in Figure 3-20 and Figure 3-21:

Table 3-3: Hydrogeological conceptual model

Element/feature	Description
Assessment domain	4,622 km
Aquifer units	See Section 3.2.7
Aquifer hydraulic properties	See Section 3.2.7
Groundwater recharge	Chichester, Hamersley outcrops: 3 mm/yr Large alluvial fans (e.g. Coondiner Creek, Christmas Creek), break of slopes: 11 mm/yr Fortescue Marsh – no recharge assumed under prevailing conditions 'steady state' Quaternary/Tertiary cover in the Fortescue Valley: 0 to 2 mm/yr (only active during cyclonic events?)
Groundwater discharge	Evaporation and evapotranspiration in the Fortescue Marsh. The rate of potential evaporation (approximately 1,550 mm/yr) can be applied at the surface, with rate decreasing with and up to extinction depth (2 to 5 m below ground level).
Groundwater salinity	Groundwater salinity ranges between less than 500 mg/L to more than 100,000 mg/L, however in the RMAR area the range of values indicates slightly to moderately brackish conditions,
Groundwater flow	Generally concentric towards the Fortescue Marsh. The majority of throughflow from the ranges will be equivalent to mean groundwater recharge. The aquifer system underneath the marsh represents a large storage of groundwater. In the RMAR, groundwater flows from the Hamersley Range through the Coondiner Creek alluvial fan.
Surface water groundwater interaction	Surface water flows dominate the water regime of the Fortescue Marsh. Groundwater / surface water interaction is also episodically expressed alongside key drainage lines.
Groundwater abstractions	Groundwater use in the area traditionally low, the major component has now been dewatering of mining pits which is estimated to be on average 132 ML/d (but up to 225 ML/d) during the assessed period of 2018 to 2031
Water injections	Reinjection is the proposed management measure to address excess dewater issues. On average 87 ML/d is planned to reinjected

3.3.2 Groundwater volumetric balance (study area)

The conceptual water balance represents broad average recharge and discharge conditions representative of a quasi-steady state, with negligible changes in aquifer storage.

Flooding events following the cyclonic rainfall represent a significant but relatively short-term deviation from the study area's water balance. It was shown that water levels within the RMAR area are remarkably stable suggesting well balanced groundwater flow conditions.

The recharge from the ranges is estimated to amount up to 6.8 GL/yr in total from the Chichester and Hamersley Ranges. The potential groundwater inflow from the Fortescue River catchment has been previously estimated at up to 8 to 10 GL/yr (Simonic et al., 2015), however under prevailing conditions (absence of flow in the Fortescue River) this component of inflow is considered to be minor.

Combined with potential diffuse recharge in the valley area and assuming no effective recharge in the marsh the overall average recharge to the study area is 6.7 GL/yr.

Groundwater flow in the study area eventually terminates via the process of evaporation and evapotranspiration in and around the marsh and in other smaller areas where groundwater may be close to the groundwater surface. Groundwater may occur generally within one or two metre from the ground in the marsh area, in approximately 40 km^2 of the study area groundwater could be two metre deep or less.

Removing 6.7 GL over that footprint during an average year would require an evapotranspiration rate of 168 mm/yr, which is well within the evaporative capacity of the area. In addition, approximately 10% of the study area which includes the marsh and its fringes contains groundwater occurring less than 6 m deep, within the range of phreatophytic vegetation which has additional transpiration potential to remove groundwater.

The key components of the water balance are summarised in Table 3-4:

Table 3-4: Study area groundwater balance summary (under natural prevailing conditions)

	Input (GL/yr)	Output (GL/yr)
Average year condition		
Inflow from Chichester Range	3.7	
Inflow from Hamersley Range	3.1	
Diffuse recharge, Cainozoic cover of Fortescue Valley	0	
Contribution from Fortescue River catchment	Ephemeral, considered minor	
Fortescue Marsh and fringes	0	>60 (potential ET)
Net	**6.8**	**Evapotranspiration capacity is in excess inputs**
Fortescue Marsh flood condition (not considered in the model) in addition to fluxed above		
Contribution to storage underneath the marsh	Potentially 2 to 4 GL (short duration)	Evapotranspiration capacity exceeds inputs

	Input (GL/yr)	Output (GL/yr)
Cainozoic cover in the Fortescue Valley (‘diffuse’ infiltration)	Potentially 5.6 GL	Evapotranspiration capacity exceeds inputs

Under (infrequent) flood conditions during which the full extent of the marsh footprint is flooded (a once in one thousand year event) the groundwater temporary groundwater storage attributable to the flood in the marsh is estimated at 2 to 4 GL/yr (assuming 1 to 2 m increase in water level and specific yield of 0.05 to 0.1).

That contribution is considered short-lived as it is promptly removed by evapotranspiration, and hence not material for the wider domain of the project. Within the study area the component of temporary groundwater storage associated with marsh ponding is estimated to be between 2 to 4 GL - per event, that is able to flood the entire footprint.

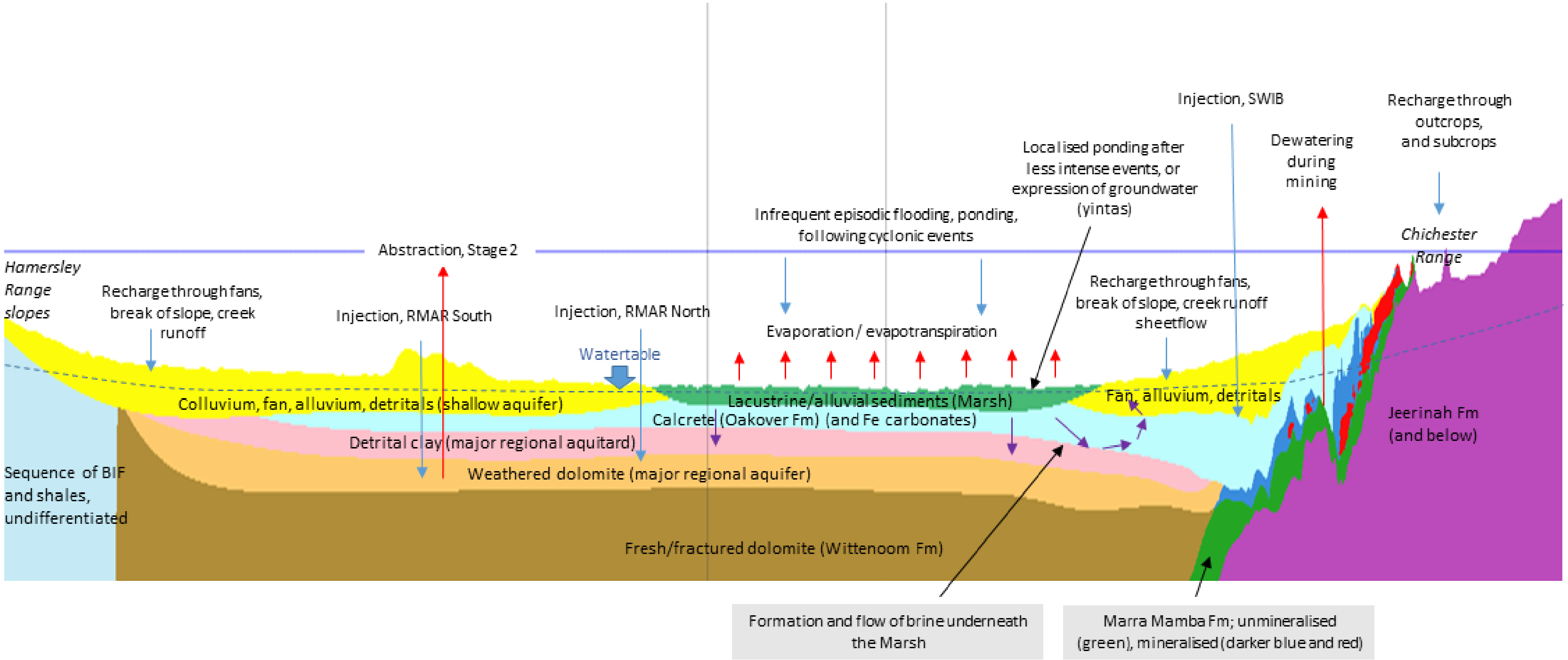


Figure 3-20: Conceptual understanding of hydrogeology of the study area – section view

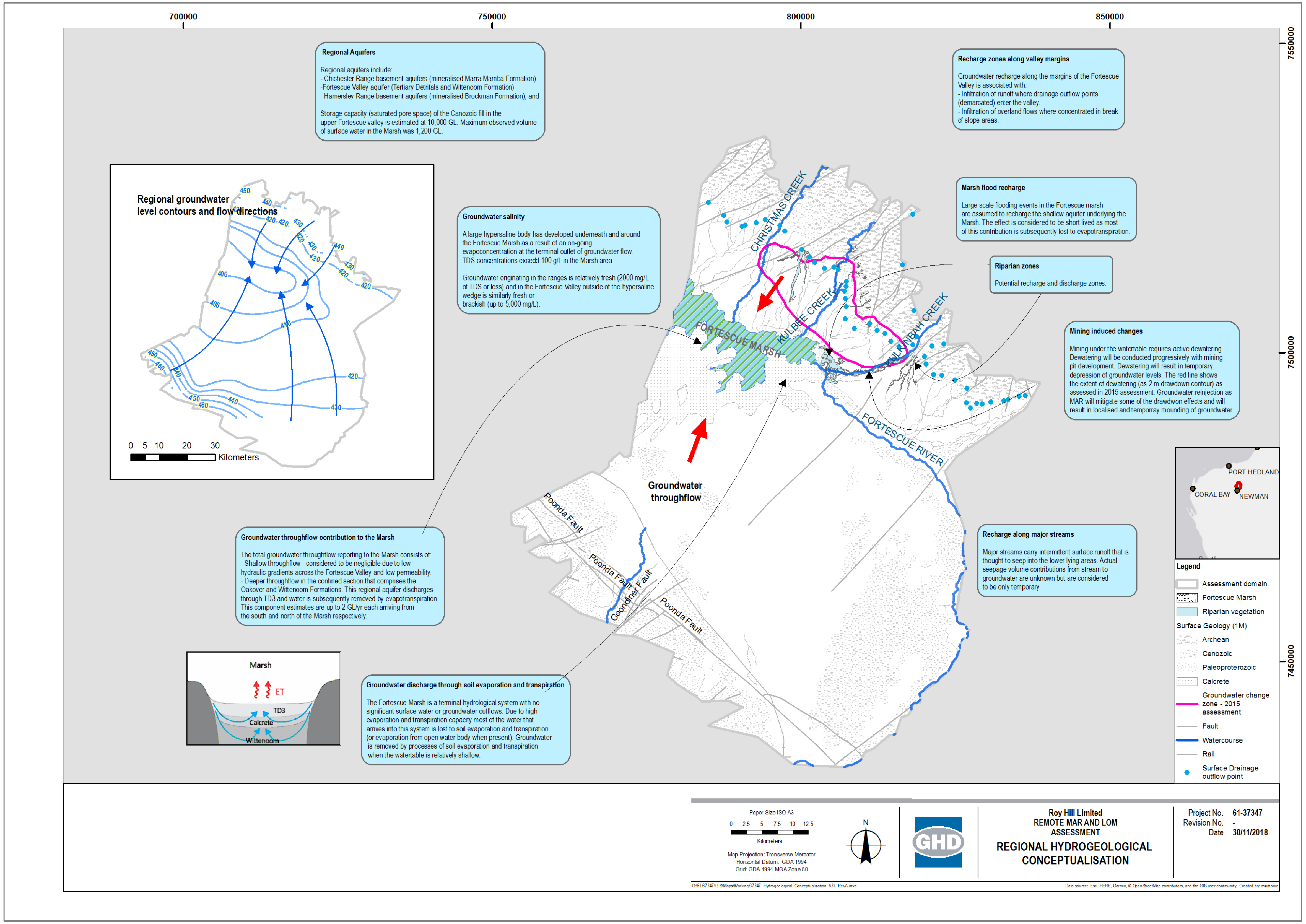


Figure 3-21: Regional hydrogeological conceptualisation

3.4 Numerical model development

3.4.1 Approach to numerical representation of conceptual model

Conceptual understanding of key groundwater flows and processes informed the development of a numerical groundwater flow model. In addition to the presented information the following was considered:

- Extension and update of the geological 3D model, developed in Leapfrog 3D as part of this study.
- Existing groundwater dewatering model developed in FEFLOW by Roy Hill (June 2018 version), and provided by Roy Hill to this study
- Description of the regional groundwater flow model developed for BFS (MWH, 2009)
- MAR considerations discussed in Managed Recharge (2018)
- Groundwater levels and pumping rates collected as part of Roy Hill monitoring program

The Leapfrog 3D model was used to develop a finite difference grid in MODFLOW-NWT and to populate parameter zones based on the principal hydrostratigraphical units. Due to its regional scale and extent the finite difference grid is inevitably coarser that the finite element mesh focused on the mining area. The mining area forms the northern section of the newly developed MODFLOW model which extends to the southern flanks of the Fortescue Valley.

The new model domain allows for integrated assessment of the effects of dewatering, local MAR, remote MAR and remote groundwater abstraction on groundwater levels.

The model's accuracy is suitable for regional impact assessment level (Class 2 model). The new model honours the exploration data interpretation in the mining area with some changes in southern flanks of the mining area the structure of which were corrected with assumed dolomite penetration.

The Fortescue Valley structure was based on interpretation of available (interpreted) geological information from regional bores and supplemented by extrapolation of the base elevations of the key aquifer units, such as weathered dolomite and Tertiary clay.

3.4.2 Model structure and parameterisation

The numerical model was constructed on the MODFLOW-NWT platform, using the Groundwater Vistas v7 interface.

The model consists of 360 rows, 296 columns and 15 layers and contains 1,109,685 active cells. The active area of the model covers 4,624 km^2. The finite different grid is offset by 30 degrees.

The grid reference of the bottom left corner of the model is 746,192 m and 7,461,494 m MGA94 Zone 50. Uniform cell spacing was applied with cell dimensions of 250 m by 250 m.

The elevations, thicknesses and parameter distribution of individual model layers were transferred from the Leapfrog model. Validation of Leapfrog-derived layers in the numerical model was examined by comparing of the selected cross sections in the mining and Fortescue Marsh areas between Leapfrog, and FEFLOW and MODFLOW models. The validation examples are presented in **Appendix C**.

This validation showed a good correlation between the new Leapfrog and MODFLOW models with some differences in comparison to the FEFLOW model due the new conceptualisation of dolomite and detrital layers in the southern perimeter of the mining area.

A broadly uniform thickness of approximately 10 m applied to the model layers extends over the majority of the model domain with the exception of the hilly areas of the ranges in which thicknesses are larger. The top elevation of the model domain (ground elevation) was interpreted from the 1 second (30 m) DEM. On comparison between the 30 m DEM and the 30 m DEM and a more precise LiDAR DEM examined for a small part of the Fortescue Valley area it was established that the 30 m DEM overrepresents elevations in the Fortescue Valley area on average by 2.5 m. The model's top elevations were adjusted by 2.5 in areas where the original elevations were 430 m RL or less. This led to better representation of elevations within and around the footprint of the Fortescue Marsh.

Aquifer properties (hydraulic conductivity and storativity) were selected from the existing data sources and models available for the study area which were tabulated in the previous section (Table 3-1).

3.4.3 Boundary conditions

A flux specified boundary with the topographic surface of the model combines the effects of recharge and evapotranspiration flux boundary driven by their respective rates and, in the case of evapotranspiration, also ground elevation in relation to the groundwater levels.

Recharge

Recharge is nominally active only in parts of the model and assumed effectively zero in large parts of the domain under prevailing conditions. This is consistent with the climatic factors and observed water levels in the area.

The distribution of active recharge zones is shown in Figure 3-22. It reflects the conceptual understanding in which recharge takes place in the ranges (outcrops/subcrops, drainage channels), at the break of slope areas at the foot of the ranges and along the major alluvial fans (Coondiner, Christmas Creeks).

The applied rates are 3 mm/yr in the ranges' outcrop areas and 11 mm/yr in the break of slope and alluvial fan areas (Figure 3-22).

Evapotranspiration

The Fortescue Marsh and the lower reaches of the Fortescue River function as a net outlet from the groundwater system through evapotranspiration. The rate of potential evapotranspiration is sufficient enough to remove any groundwater inflows under normal flow conditions. The rate of evapotranspiration applied in the model is 5 mm/d over extinction depth of 1 m in the Marsh footprint and 5 m in the fringing areas. While evapotranspiration is nominally implemented over the entire model area, the extinction depth parameter ensures it is only active in areas with relatively shallow watertable as would be expected.

Recharge and evapotranspiration were set identical for both steady state and transient calibration as well as for predictive simulations, i.e. the model does not have any significant climatic variability. This is consistent with the majority of groundwater hydrographs which show flat, unchanging trends for the calibration period.

Dewatering and injection

Dewatering in transient calibration model was implemented at the locations of the existing dewatering bores, which were represented using the WEL package in MODFLOW. The actual measured rates for 2014 to 2018 were applied on a monthly basis. In total, 125 dewatering bore locations were active during the calibration run (or part of it). Injection was active in 6 locations towards the end of the calibration run. The locations of dewatering and injection bores are presented in Figure 3-23.

For predictive simulations dewatering was modelled using a multi node well package (MNW2) which follow the mining plan in the development area termed Bravo to Zulu (Figure 3-24). The MNW2 package simulated abstraction via the vertical well screens extending over multiple layers. The pumping rates applied to the MNW2 package were compiled from the predictive results of the RHIO's FEFLOW model (Willis-Jones, 2018).

Dewatering rates in the FEFLOW model were derived using the 'drain' approach rather than actual bores. The estimated dewatering rates computed for FEFLOW finite elements representing the dewatering locations. These rates were then aggregated for the respective locations of finite difference cells of the MODFLOW model, based on their spatial coordinates. This approach introduces potential discrepancies which are due to potential minor differences in applied hydrostratigraphical units and discretisation. Due to its regional scale the MODFLOW model has a coarser discretisation then the dewatering-focused FEFLOW model.

The MNW2 locations in the MODFLOW represent 'dummy' bore locations simulating the effect of the 'drain' approach used in the FEFLOW model. There are in total 850 MNW2 locations implemented in the model (Figure 3-25).

Injection in calibration and predictive runs was modelled using the WEL package. Injection locations (Figure 3-23 and Figure 3-25) were categorised into three areas, the mining area which includes SWIB (34 locations) and Stage 1 Borefield (18 location), and RMAR North (11 locations) and South (20 locations).

3.4.4 Hydraulic parameter zones

Hydraulic parameter zones were brought in from the Leapfrog model and are reflective of major groundwater units. Each unit uses a lump parameter value, i.e there has been no further sub-division of groundwater unit zoning following the principle of parsimony.

The parameter zone spatial delineation per model layer as well as layer base elevations are presented in **Appendix D**.

The initial values of hydraulic parameters, at the start of calibration, were implemented as per Table 3-1.

3.5 Numerical model calibration

3.5.1 Approach

The numerical model is based on the pre-existing models developed for the area for various stages of development, with previously used and calibrated ranges of parameters and conceptual approaches (e.g. Willis-Jones, 2018; MWH, 2009). As the conceptualisation developed in this project is largely consistent the calibration presented in this document essentially represents a check or validation against the previously used calibrated parameters for defined aquifer units and boundary conditions.

Where necessary, minor adjustments to the parameter values were made, however the MODFLOW-NWT numerical model is broadly consistent with the previously used values and conceptual approaches.

The presented water levels (**Appendix E**) for the evaluated calibrated period (2014 to 2018) do not show any significant variations unless affected by dewatering in the vicinity of the monitoring bores. This suggests that the groundwater system is regionally balanced with respect to inflows and outflows to and from the system, approximating steady state conditions.

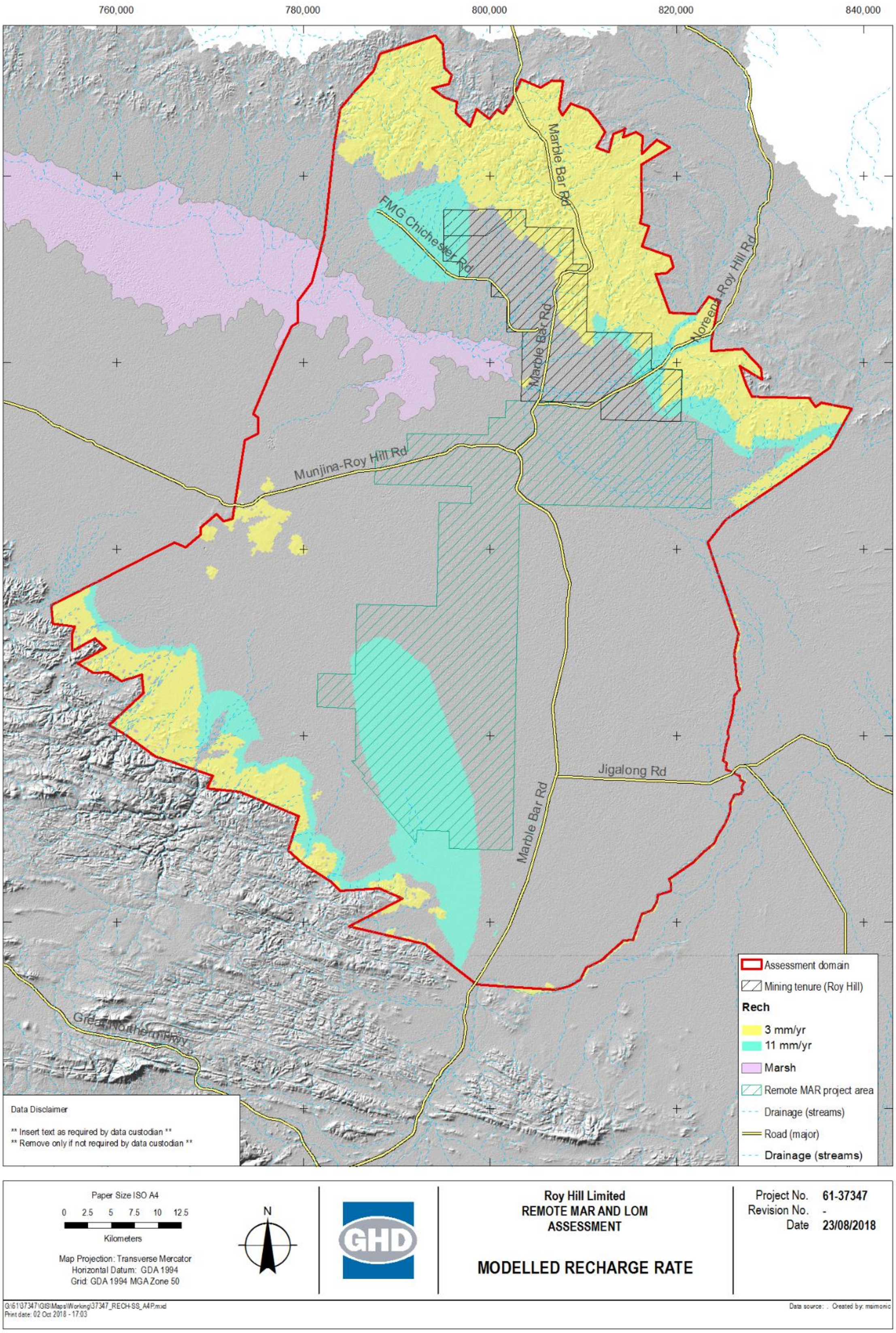


Figure 3-22: Delineation of recharge zones

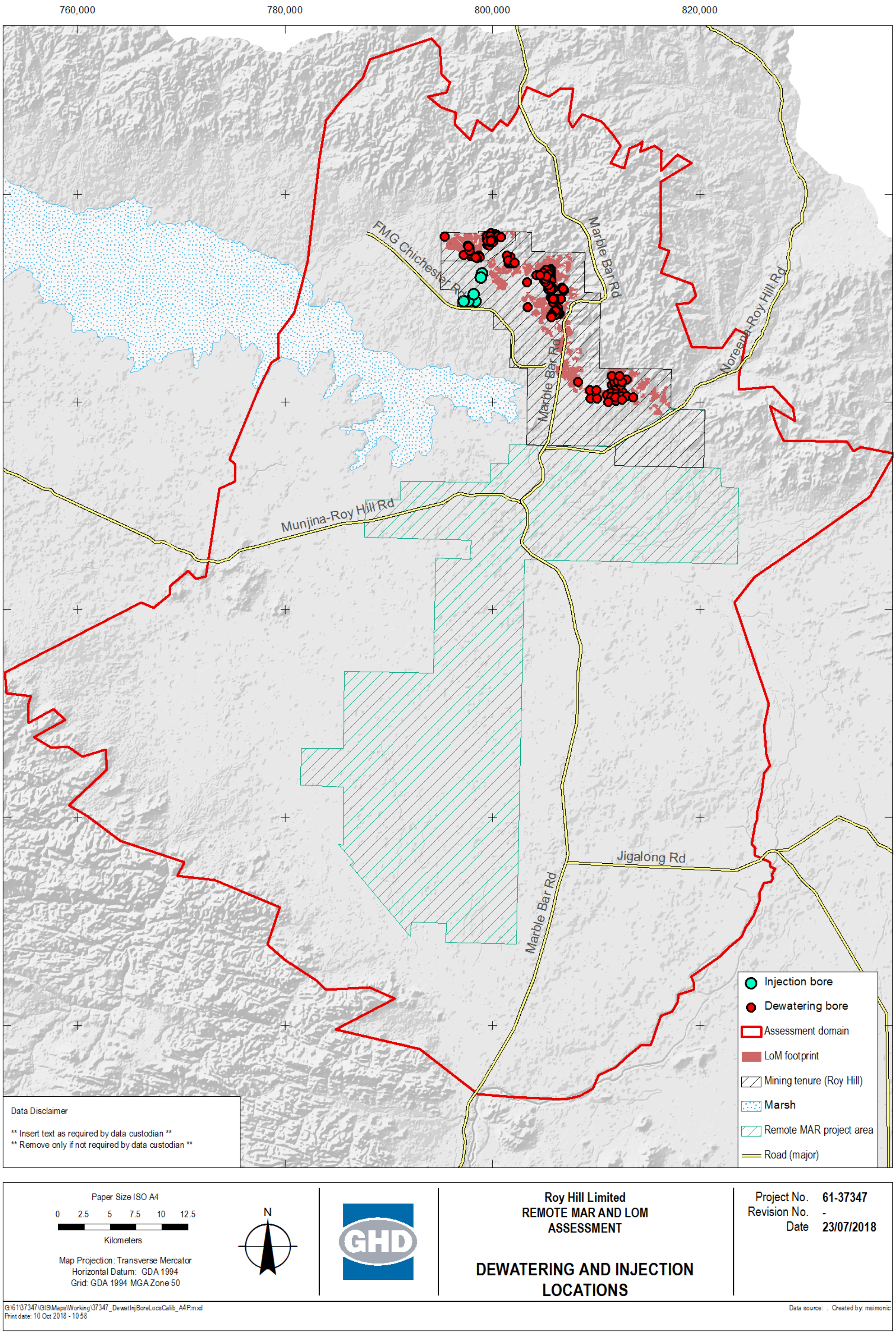


Figure 3-23: Dewatering and injection bores, calibration run

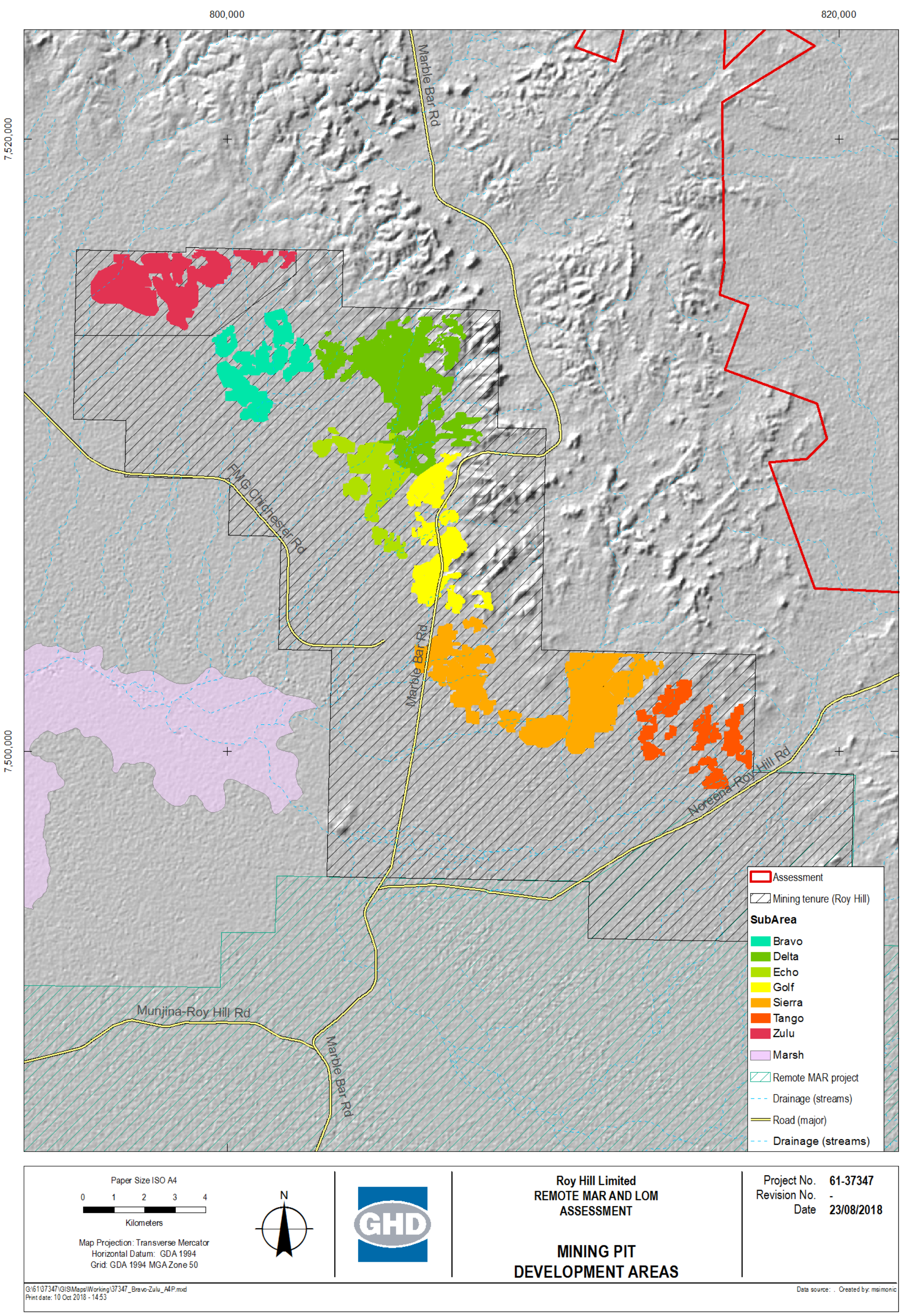


Figure 3-24: Mining pit development areas

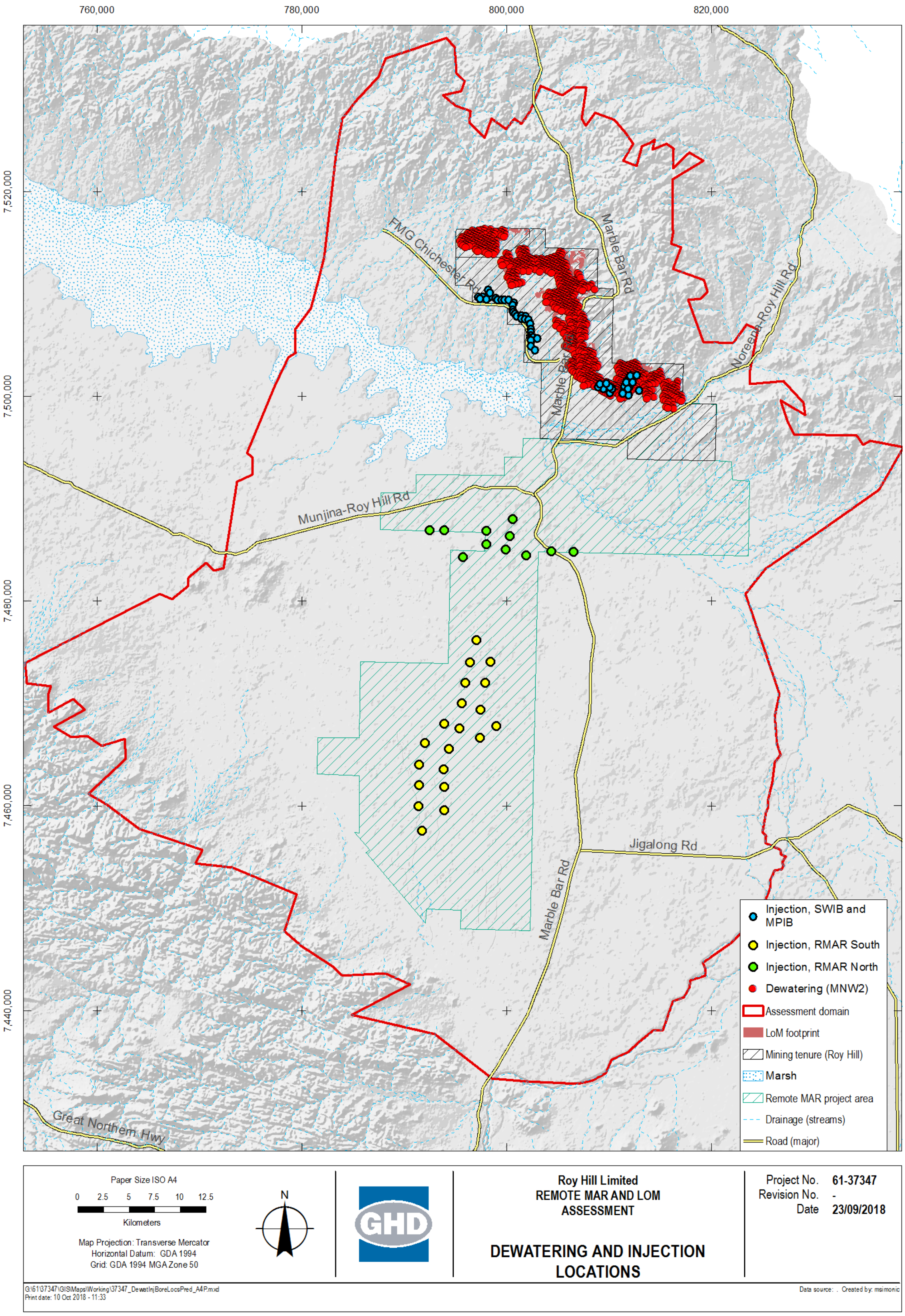


Figure 3-25: Dewatering and injection bores in predictive simulation runs

Variations in climatic factors (e.g. seasonality, large rainfall events) during the evaluated period did not have apparent influence on observed groundwater levels. The lack of surface flow records did not allow for evaluation of the near- or in-stream infiltration, however even monitoring locations close to the Fortescue River did not show any variations attributable to interaction with the river.

The groundwater system was consequently modelled with effectively unchanging climate inputs (expressed in groundwater recharge and evapotranspiration). In absence of climatic input variations, the transient-related parameters (storativity) were examined through artificial stresses such as dewatering and injection. The dewatering rates applied in the calibration period amount to over 37 GL (monthly volumes shown in Figure 3-26).

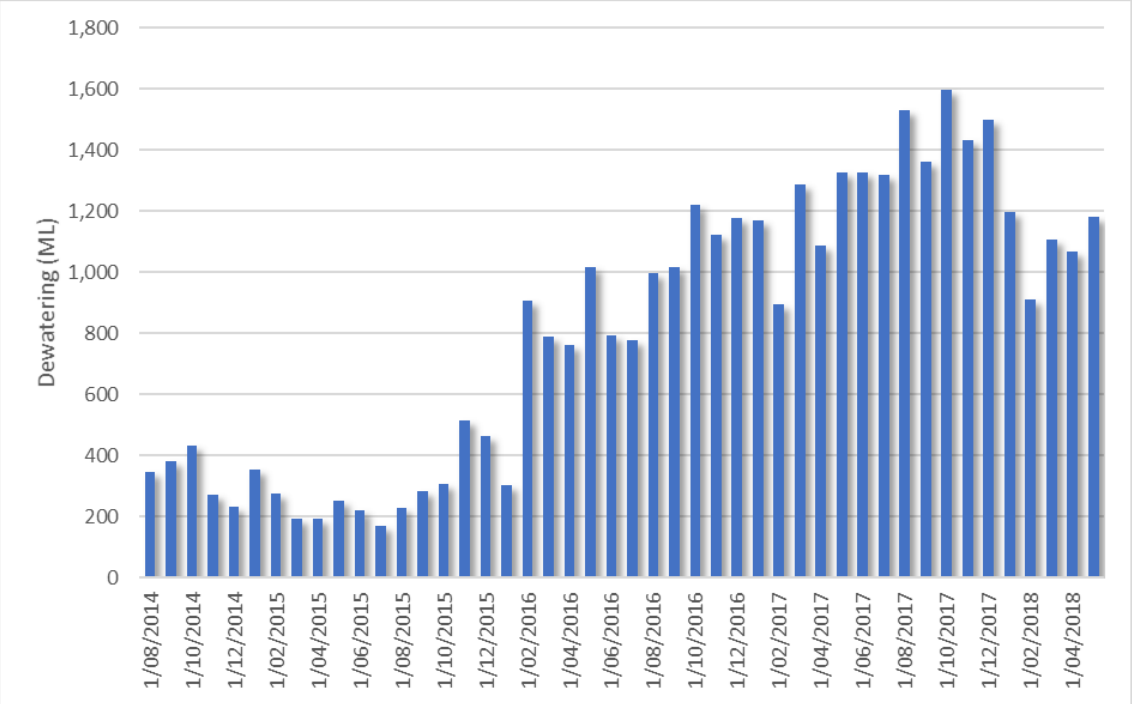


Figure 3-26: Actual monthly dewatering volumes during 2014 to 2018

3.5.2 Calibration targets

Calibration targets were selected from available (and reliable) bore water level records and with consideration of potentially sensitive environmental receptors (such as areas close to Fortescue Marsh, or riparian zones). The spatial distribution of calibration targets is shown in **Appendix E**. It also includes the 'validation' locations which were selected to confirm the calibration results.

In total 65 calibration targets span different aquifer units and areas. Calibration targets are not available along the southern perimeter of the model representing the foothills of the Hamersley Range, however this area is of minor relevance to this impact assessment.

The calibration run was set up to start with a steady state stress period, followed by monthly transient stress periods divided between 2014 and 2018. The choice of this period for calibration was driven by the availability and spatial representivity of reliable water level observation data.

It also includes the start of dewatering and injection operations, which allowed for checking the response of the model to large-scale artificial stresses and its transient nature.

3.5.3 Parameter adjustment and sensitivity

Although the model is based on knowledge from previous modelling projects undertaken for parts of this model domain, parameters and concepts were adjusted to achieve a model that represents the groundwater system by minimising the differences between simulated and observed water levels while still approximating estimated water budget components.

Adjustments to geological structure at the southern part of the mining tenement (incorporation of dolomite) did not significantly change the hydraulic function that part of the model since the weathered dolomite zone partly replaced the high permeability zones previously assigned to mineralised Marra Mamba and/or detrital sections.

Sensitivity of model parameters was monitored during the manual calibration with the following notable outcomes:

- While parameter values between this model and previous models are similar the RHIO's model (Willis-Jones, 2018, with update in August 2018) has more extensive areas of higher permeability associated with mineralised BIF. The lateral extent of mineralised BIF in MODFLOW model is limited to mapping from the Leapfrog model which is based on exploration data compiled for the mining area. The RHIO's model recent versions and learnings suggest that mineralised Marra Mamba Fm (or its hydraulic equivalent) extends more generally along the slopes of the Chichester Range which could be expected since it is also commercially used in FMG mining projects to the west of Roy Hill. The area extent in the FEFLOW model is estimated to be approximately 20% larger than in the MODFLOW model used for this study. This effect was partly mitigated in the MODFLOW model by introducing a higher permeability zone to the west of the Zulu area representing a substantial alluvial fan with high hydraulic conductivity at the outlet of the Christmas Creek
- Preliminary testing was applied with regards to assessing the response or sensitivity of the model to flooding in the Fortescue Marsh. This was attempted by imposing a general head boundary in the Marsh footprint for on to three months with its head set at up to 410 m RL. In a similar fashion, the effect of flows in the Fortescue River was represented using general head boundaries to establish whether these have a potential to impose changes on groundwater flows. Neither the Marsh nor the Fortescue River introduced significant changes to groundwater flow patterns and directions, these were only limited to the immediate perimeter. On the basis of their negligible flow effects on the regional groundwater flow system these boundaries were removed from the model and excluded from further consideration.
- Water levels in the Fortescue Valley area are more sensitive to hydraulic parameters of alluvial/detrital deposits
- Hydraulic properties of the Detrital clay value affect the degree of connectivity and hydraulic response between the weathered dolomite and the over-lying shallow aquifer.
- Small-scale variations of parameter values may be required to fine-tune the dewatering behaviour of the individual mining pits, however this is not deemed important for the regional scale assessment.
- Fortescue Marsh area (parameter zone 5, **Appendix D**, Table 3-5) was initially considered to be hardpan with low hydraulic conductivity, however better calibration results were obtained in the RMAR area when this unit was made more permeable. No hydraulic testing is available for this unit to improve the parameter estimate in this part of the model.

- Recharge rates were not extensively modified. A zone of higher recharge was implemented at the outflow from the Hamersley Range which is thought to maintain the refreshing effect on groundwater salinity in this area. A similar zone of higher recharge was implemented in the alluvial fan of the Christmas Creek.

3.5.4 Calibration results

Steady state calibration

Flow model calibration is commonly evaluated by comparing simulated water level elevations with observed groundwater elevations from monitoring bores. The average errors between observed and simulated groundwater elevations should be relatively small and unbiased. Groundwater levels measured in 2014 and the conceptual water mass balance were compared to simulated values to determine if the model adequately simulates the aquifer system as it was at that time.

The computed values from 65 locations and/or screen intervals match the observed values within 2 m differences for the majority of target locations, indicating reasonable agreement between the observed and computed values. This is also reflected in the calibration statistics which is a global measure of the degree of simulated water level deviation from observed values.

The following calibrations statistical outputs were obtained:

- residual mean is 0.26 m;
- residual means square error is 1.58 m and
- scaled residual mean square error is 2.1%.

These results indicate that the presented calibration result is adequate with no major bias. This is also indicated by the plot of observed and simulated values (Figure 3-27) which shows values closely centred onto the 45 degree (unity) line suggesting that the calibration results is unbiased and with minimum residual errors.

The differences between computed and observed water levels ('residuals') for steady state flow are presented spatially in Figure 3-29.

The example map of simulated groundwater elevations (water levels) obtained from the steady state model is shown in Figure 3-30. Modelled groundwater levels (Figure 3-30) are reasonably consistent with interpreted water level contour trends and confirm the overall spatial trends. In alignment with the conceptual understanding, the water level contours indicate concentric flow directions towards the Fortescue Marsh, which functions as the groundwater terminus in this modelled system with groundwater flow originating in the ranges on both, the northern and southern sides of the model domain.

Model performance in the RMAR area (in the Fortescue Valley) is considered good with minor differences between the model and observed data.

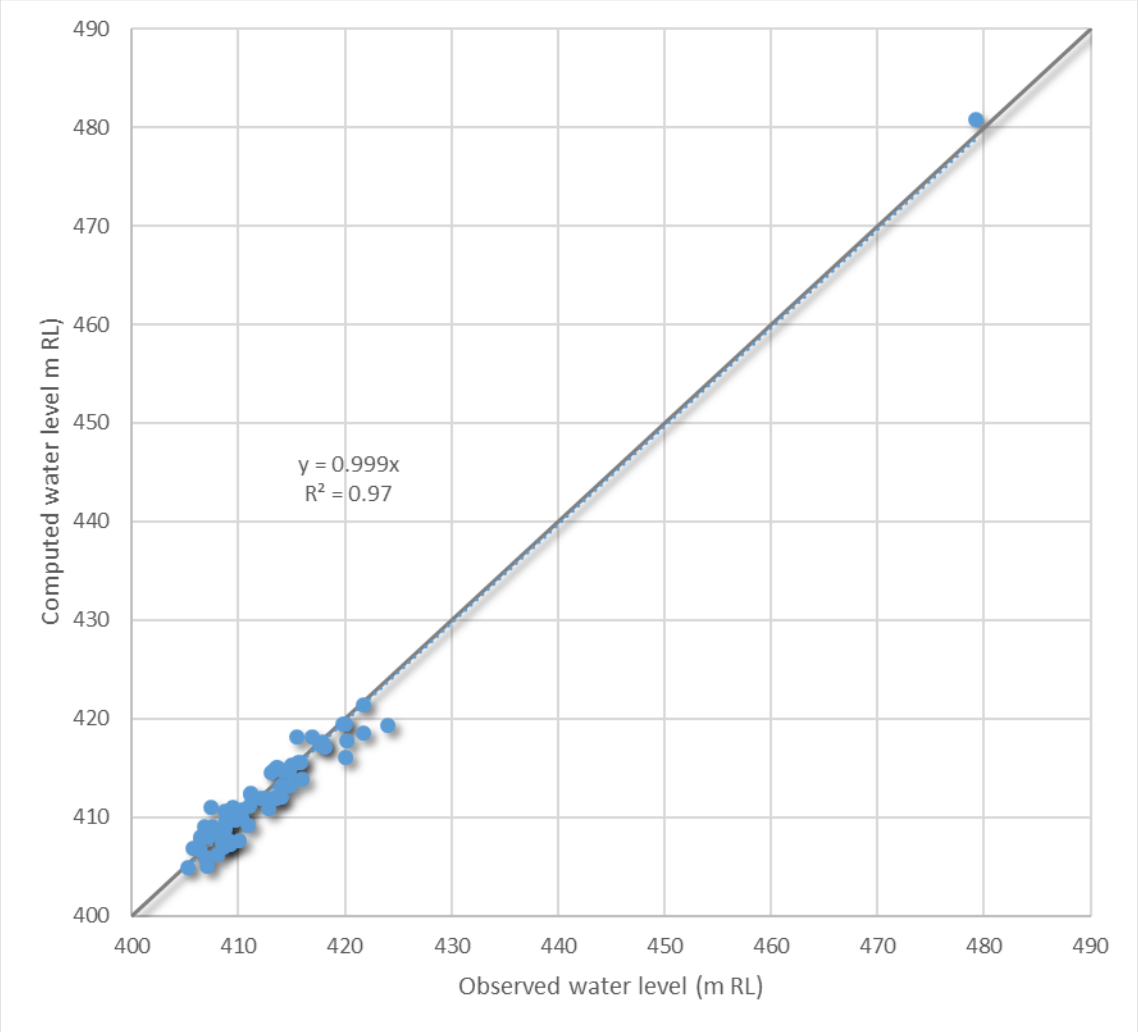


Figure 3-27: Computed and observed groundwater elevations (steady state)

The values, confirmed by current calibration for the parameter zones delineated in **Appendix D**, are presented in Table 3-5:

Table 3-5: Parameter values confirmed by calibration

Zone	Groundwater unit	Kh (Kv) [m/d]	Ss	Sy
5	Fortescue Marsh (calcrete top)	5 (1)	$1x10^{-5}$	0.1
2	Christmas Creek alluvial fan	30 (15)	$1x10^{-5}$	0.2
11	Alluvium, colluvium, TD cover	5 (0.5)	$1x10^{-5}$	0.1
12	Calcrete	3 (0.3)	$1x10^{-5}$	0.05
3	Detrital clay	0.001 (0.0001)	$1x10^{-5}$	0.05
10	Dolomite (weathered)	20 (10)	$5x10^{-5}$	0.05
4	Dolomite (fresh)	0.01 (0.01)	$1x10^{-6}$	0.01
7	Marra Mamba mineralised	35 (35)	$5x10^{-5}$	0.05
14	Marra Mamba (mineralised)	25 (25)	$1x10^{-5}$	0.1

Zone	Groundwater unit	Kh (Kv) [m/d]	Ss	Sy
16	Marra Mamba (unmineralised)	1.7 (0.17)	$1x10^{-5}$	0.03
15	Jeerinah Fm	0.045 (0.0045)	$1x10^{-6}$	0.01
1	Hamersley Range, undifferentiated	0.1 (0.01)	$1x10^{-5}$	0.02

The groundwater balance for the steady state model indicates that recharge represents 7.9 GL/yr which is eliminated by the equivalent rate of evapotranspiration. This is consistent with the conceptual model balance, noting that is a 16% increase on the value previously estimated.

Table 3-6: Comparison of conceptual and steady state model budgets

Element	Conceptual model (GL/yr)	Steady state model (GL/yr)
Recharge	7.9	6.8
Evapotranspiration	potential for 60 GL/yr	6.8

The steady state budget error is small, at 0.004% of model budget.

Transient calibration

The transient calibration performance was assessed by comparing hydrographs of observed and computed water levels which are presented in **Appendix E**. The emphasis of the transient calibration was to adjust the model to more accurately simulate water level fluctuations in the areas where groundwater stresses were applied (dewatering and injection), absolute water levels and transient trends. Due to the zonal approach to parameterisation, some deviations at pit level were expected.

Similar to the steady state model the calibration statistics are considered adequate for a regional scale model. The results for 190 observations are as follows:

- residual mean is 0.22 m;
- absolute residual mean is 1.62 m
- residual means square error is 1.62 m and
- scaled residual mean square error is 2.1%.

Comparison between observed and computed data is also presented in Figure 3-28.

Measured water levels generally do not fluctuate in response to annual changes in rainfall, rather they respond to large groundwater withdrawals. Simulated water levels maintain the generally stable water levels in areas outside of mining, and fluctuate in response to dewatering and in most cases the magnitude and timing of these fluctuations reasonably match the changes in measured water levels.

In some areas, simulated water levels do not match the magnitude of short term measured water level fluctuations. The examples of this are monitoring bores RHPZ0093D, RHPZ0140D and TSFMW04 in which variations are due to local flux changes (for example mounding from TSF in TSFMW04), which are dealt with in the regional model.

These results also indicate that there are finer variations in hydraulic properties in individual mining areas which are cannot be adequately reflected by global parameter values. This explains some of the deviations between observed and modelled values. For example, improvement in performance in the Zulu area leads to deterioration of fit in the Delta area and vice versa suggesting that there are detailed scale variations at a pit level as would be expected in areas affected by enhanced mineralisation.

No water level fluctuations were observed or simulated by calibration runs in the Fortescue Valley and the match for the majority of the observation bores outside of the mining area is considered good.

Despite these differences the model is considered suitably representative of the groundwater system for the impact assessment purposes at a regional scale.

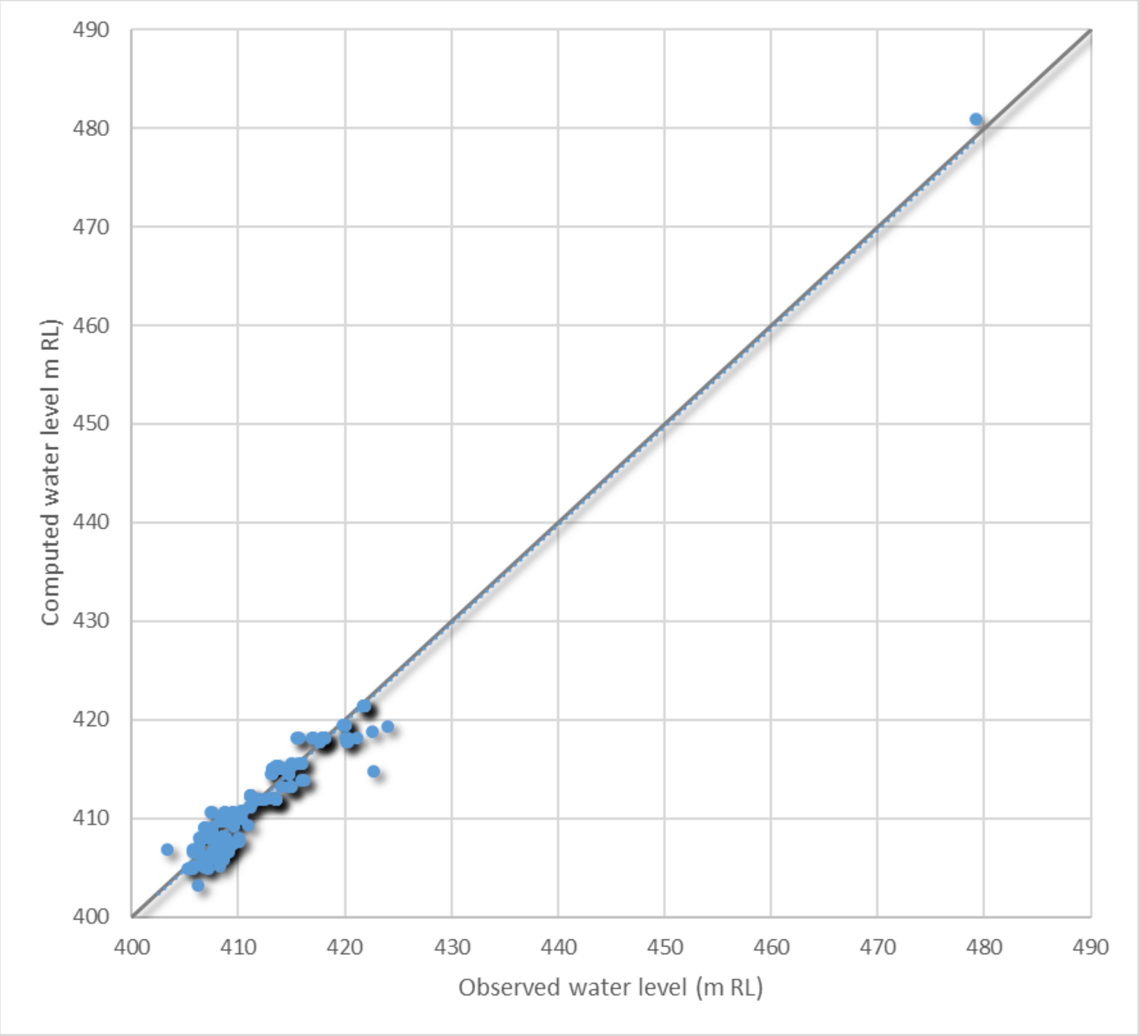


Figure 3-28: Computed and observed water levels (transient)

In the transient calibration model the dewatering volumes are balanced by changes in groundwater storage resulting in the propagation of the cone of depression which changes as dewatering progresses from one area to the other and as dewatering rates vary. During the calibration period the model reported 37.2 GL of dewatered and 2.3 GL injected groundwater.

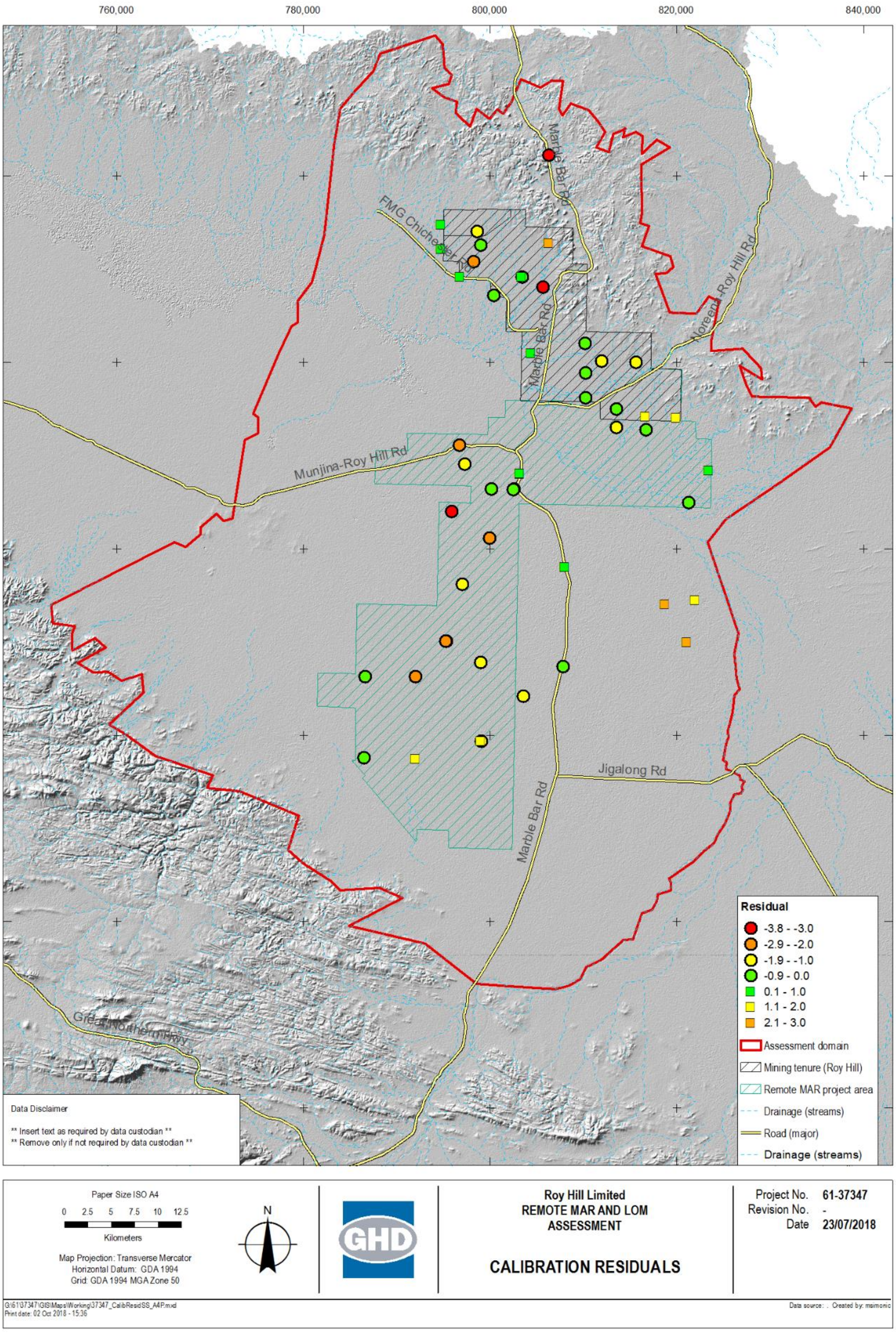


Figure 3-29: Calibration residuals (steady state)

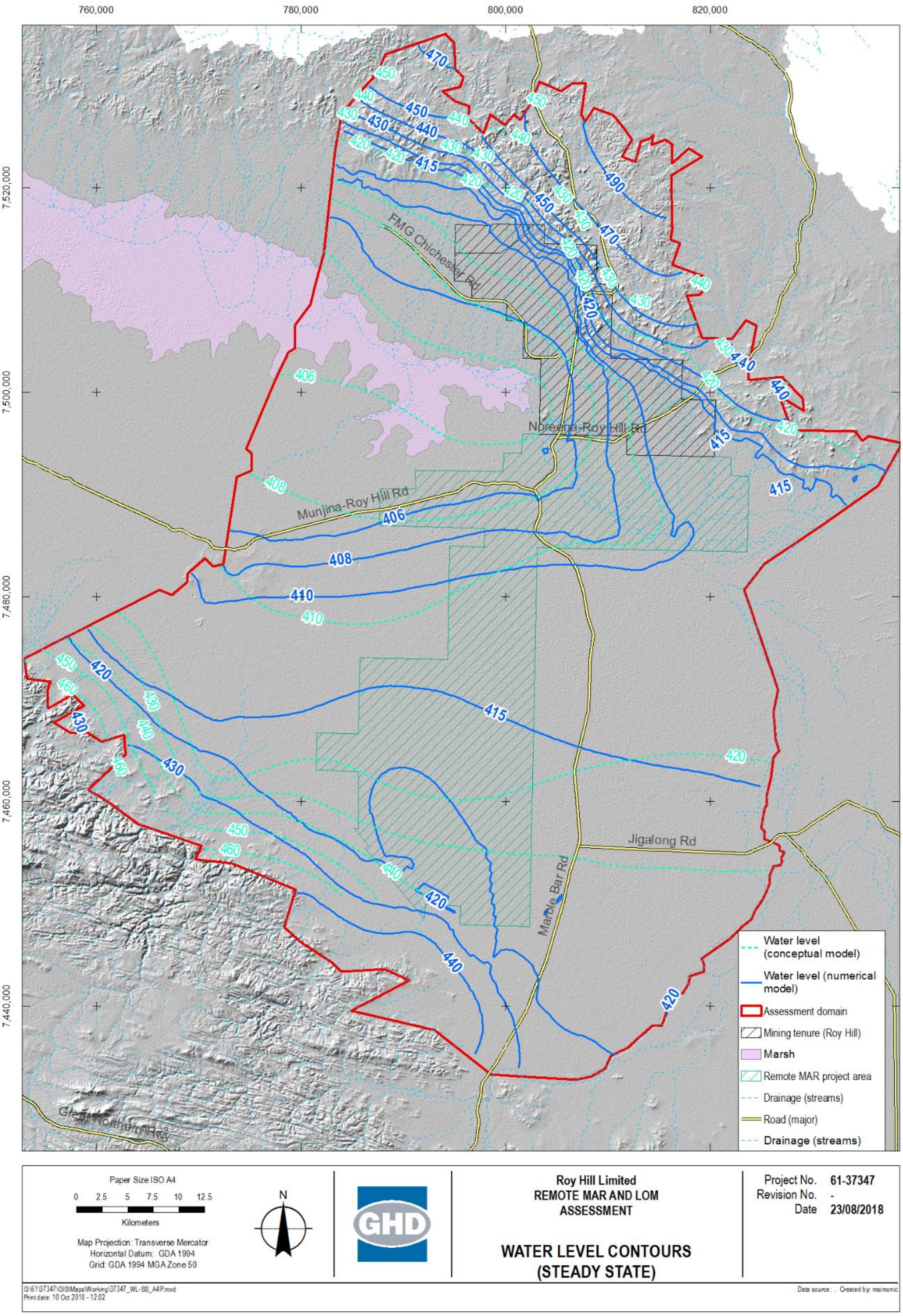


Figure 3-30: Computed water levels (steady state)

At the same time 30.3 GL entered the groundwater system as recharge and the equivalent volume was lost to evapotranspiration. The volume of recharge divided by the model domain area (although recharge is only active in parts of the domain) yields a net recharge rate of 5 mm/yr which is well within the range of estimates for the Pilbara region.

The net change in groundwater storage during the modelled period was 34.9 GL (Table 3-7).

Table 3-7: Groundwater flow budget, transient model

Element	Total volume (GL/yr)	Average rate (ML/d)
Recharge	30.4	21.7
Injection	2.3	1.6
Storage in	38.3	27.3
Evapotranspiration	-30.3	-21.6
Dewatering	-37.2	-26.5
Storage out	-3.5	-2.5
Total	0	0
Error (%)	0	0

3.5.5 Summary of calibration

Model calibration demonstrates that the model performs reasonably well for the regional impact assessment purposes. This applies to both steady state and transient conditions. Various improvements may be made for more detailed examination of the model performance at a pit level, however the regional monitoring locations indicate that stresses imposed by dewatering are correctly reflected at these locations.

Trial model runs which simulated inundation in the Fortescue Marsh did not result in the rise of water levels in the Fortescue Valley and were limited to the perimeter of inundation. This model therefore suggests that inundation on its own has a very limited impact on groundwater levels and the valley groundwater system is hydrologically stable in terms of groundwater flows.

The model's transient response in the Fortescue Valley will still require validation, however the parameterisation and conceptualisation is aligned with MWH (2009).

3.6 Predicted groundwater level change

3.6.1 Scenario description

Several injection and dewatering scenarios were run to inform the assessment of groundwater change due to the mining operations. The scenarios were set up as follows:

- The predictive simulation period for mining is from September 2018 to March 2031, however it also includes 100 years post mining, i.e. to March 2131.
- The dewatering rates were adopted from Roy Hill's dewatering FEFLOW model. The summary rates compiled and aggregated from the FEFLOW model for individual MODFLO model cells were set up as dummy dewatering wells using the MNW2 package in the MODFLOW model. The MNW2 package used the Thiem option with radius of 40 m and zero skin, to simulate dewatering of the modelled cell with prescribed dewatering rates.

- The injection well locations for the mining area were adopted from the FEFLOW model and assigned excess dewatering rates. Identical rates were assigned to individual injection wells but these vary on the monthly basis.
- The injection wells in the RMAR zone were divided into RMAR North and RMAR South. RMAR North is considered as more suitable for higher TDS injection while RMAR South is considered only for injection of water brackish water quality (i.e. less than 3,000 to 5,000 mg/L). In total 11 injection sites were examined in the RMAR North and up to 20 sites in the RMAR South. Injection rates assigned were uniformly applied either to RMAR North or RMAR South bores.
- Recharge and evapotranspiration rates were adopted from the calibration model and were unchanged for the duration of the predictive simulation run.

To demonstrate the impact of dewatering and injection options six scenarios are presented:

- **Scenario 1**: Dewatering and injection in the mining area only;
- **Scenario 2**: Dewatering and injection in the mining area plus injection in the RMAR North;
- **Scenario 2B**: Dewatering and injection in the mining area plus injection in the RMAR North, including 20 ML/d injection in RMAR South;
- **Scenario 3**: Dewatering and injection in the mining area plus injection in the RMAR South;
- **Scenario 3B**: Dewatering and injection in the mining area plus injection in the RMAR South, including 20 ML/d injection into RMAR North;
- **Scenario 4**: Dewatering and injection in the mining area, abstraction from Stage 2 Borefield (RMAR South area) and injection in RMAR North.

The applied dewatering and injection rates used in predictive simulations are shown in **Error! Reference source not found.**. A summary of peak and average rates applied for each scenario is presented in Table 3-8. The design of the scenarios enables assessment of drawdown and mounding related to dewatering, water supply and surplus water disposal.

The scenarios address requirements of probable future operating conditions. Scenario 2 considers disposal of brackish water quality in RMAR South, while scenario 3 considers disposal of saline water quality in RMAR North. Scenario 4 considers the abstraction requirement for remote water supply. All scenarios consider conditions where process water requires disposal.

Table 3-8: Summary of predictive scenarios

Scenario	Dewatering (ML/d)	Surplus disposal – SWIB & Mine Pit Area (ML/d)	Surplus disposal – RMAR South (ML/d)	Surplus disposal – RMAR North (ML/d)	Water supply (Remote borefield) (ML/d)
1	225 (peak 132 (mean)	109 (peak) 67 (mean)			
2	225 (peak) 132 (mean)	109 (peak) 67 (mean)		96 (peak) 20 (mean)	
2B	225 (peak) 132 (mean	109 (peak) 67 (mean) includes process water (20)	20	96 (peak) 20 (mean)	
3	225 (peak) 132 (mean)	109 (peak) 67 (mean)	96 (peak) 20 (mean)		
3B	225 (peak) 132 (mean)	109 (peak) 67 (mean) includes process water (20)	96 (peak) 20 (mean)	20	
4	225 (peak 132 (mean)	109 (peak) 67 (mean)		96 (peak) 20 (mean)	40 ML/d

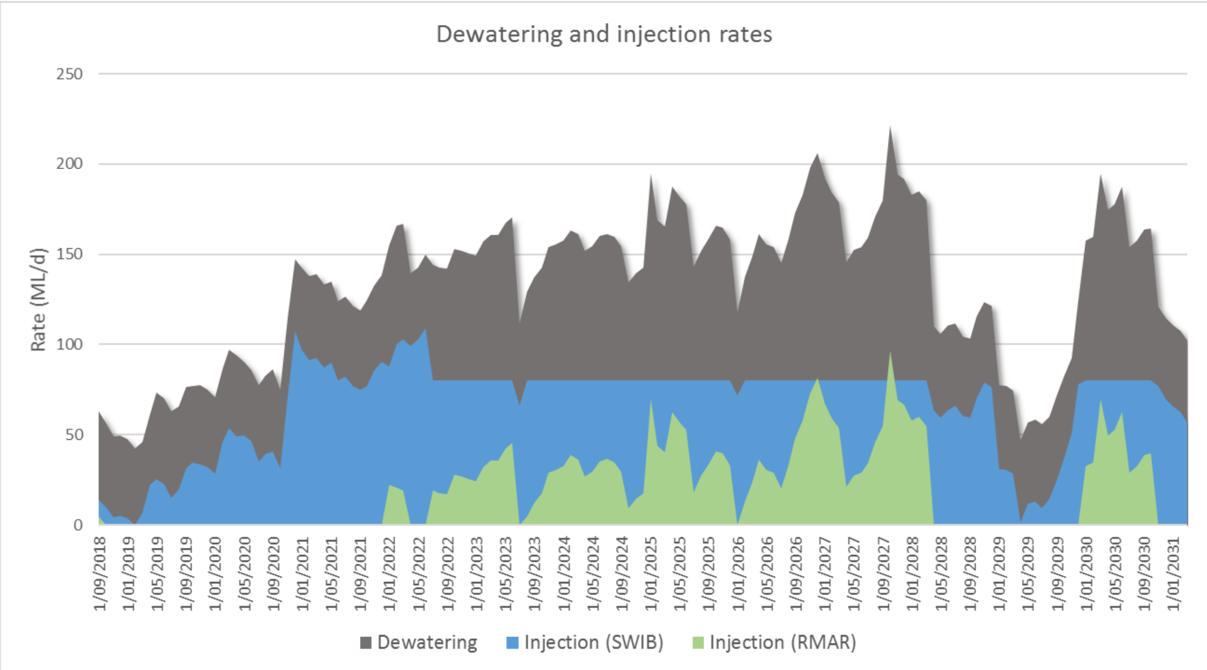


Figure 3-31: Dewatering and injection rates for LoM

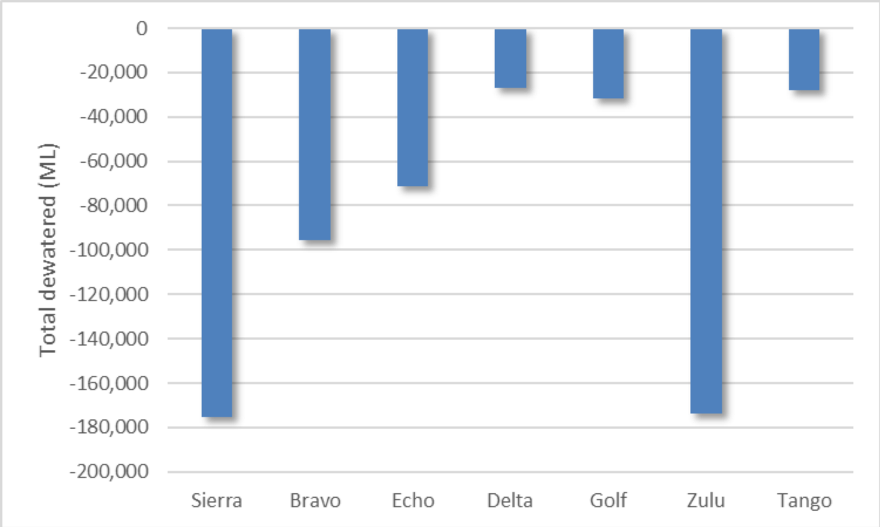


Figure 3-32: Total LoM dewatered volume per mining area

There are large differences in total dewatered volumes between the mined areas ranging between approximately 30,000 ML each for Delta, Golf and Tango areas, to more than 170,000 ML each in Sierra and Zulu areas (Figure 3-32).

The maps of depth to water and water level change were compiled for Scenario 1 for annually for March 2019 to March 2031 and are presented in **Appendix F**. The configuration of depth to water and water level change for other scenarios is similar to Scenario 1 and consequently the dates of the distinct peak rates are used for reporting of the predictive results of other scenarios since they would reflect conditions of maximum expected impacts on water level change. December 2026, one of such peak dates for example, was selected to present the results of water level change and contours of depth to groundwater. The maps, showing the water level change and depth to groundwater in December are also presented in **Appendix F**.

3.6.2 Proposed threshold

The threshold levels are considered to maintain the structure and composition of the vegetation health within the MAR Vegetation Monitoring Zones both within lease and off-lease.

This modelling aims to ensure a maximum water level rise of 5 m BGL, consistent with previously proposed (Willis-Jones, 2018) and agreed values.

Hydrographs of monitoring locations showing the response to dewatering and injection were also compiled to demonstrate compliance with the 5 m BGL threshold and to present water level changes over LoM and post closure (**Appendix F**).

3.6.3 Predicted groundwater response

The results of all scenarios suggest that groundwater changes, such as water level decrease due to dewatering or water level rise because of injection, would be largely effected within or in the vicinity of the mining and RMAR footprints. The predicted impact is evaluated against the maximum 5 m BGL rise to groundwater in the zone of influence.. The zone of influence is assumed to be an area in which the change of the groundwater level due to dewatering or injection is more than two metres, to exclude the influence of potential natural variations.

Maps of the predicted water level change and depth to groundwater at selected development stages during the predictive period are presented in **Appendix F**, with selection provided in Figure 3-33 to Figure 3-38 and discussed below:

Scenario 1: Dewatering and injection in mining area only

Groundwater is influenced by dewatering in an area up to 40 km long and 15 km wide. Depth to groundwater and water level change during one of the peak dewatering and injection periods, in December 2026, is shown in Figure 3-33.

Injection in SWIB is predicted to form a groundwater mound in an area of up 10 km long and 6 km wide. The bore injection rates in the SWIB were optimised for water level in the mound to not exceed the 5 m threshold during maximum injection. In general the maximum injection rates were applied to the west injection area of the SWIB.

Injection in Stage 1 borefield will induce the groundwater level change in a comparatively smaller area (6 km by 3 km at its largest), and depth to groundwater is predicted to be 10 m BGL or more (**Appendix F**).

Scenario 2: Dewatering and injection in mining area plus injection in RMAR North

Groundwater level changes in the mining area are predicted to be similar to Scenario 1.

Injection in RMAR North is predicted to not induce watertable changes in excess of 2 m in the shallow aquifer (Figure 3-34). Depth to watertable in the shallow aquifer is predicted to remain below 5m BGL (**Appendix F**).

Similar with other RMAR scenarios (2B, 3, 3B, 4), the piezometric head in the weathered dolomite aquifer is predicted to increase by up to 20 m in response to injection. This piezometric head increase would not propagate into the overlying Tertiary detrital aquifer due to the presence of the thick confining layer (basal Tertiary clay) for the majority of in MAR lifespan. The latter was shown to eliminate or dampen the response of shallow aquifer to injection or pumping in the weathered dolomite (ManagedRecharge, 2018). Towards the end of mining a small mound in excess of 2 m is predicted to develop in the central part South (**Appendix F**). The depth to water in this area will be more than 20 m BGL.

The occurrence of the basal clay is ubiquitous within the Fortescue Valley and is thought to pinch out only at the southern limits of the valley, adjacent to Hamersley Range.

Scenario 2B: Dewatering and injection in mining area plus injection in RMAR North and RMAR South (20 ML/d)

Groundwater level changes in the mining area are predicted to be similar to Scenario 1.

Injection in RMAR North and into RMAR South is predicted to not induce watertable changes in excess of 2 m in the shallow aquifer (Figure 3-35) for the majority of MAR duration, except in small areas to the south of RMAR South, where Tertiary Clay is thought to be missing. Towards the end of mining a small mound in excess of 2 m is predicted to develop in the central part of RMAR South with depth to groundwater remaining 20 m BGL or more (**Appendix F**). Depth to watertable in the entire RMAR area is predicted to remain below 5 m BGL (**Appendix F**).

Scenario 3: Dewatering and injection in mining area plus injection in RMAR South

Groundwater level changes in the mining area are predicted to be similar to Scenario 1.

Injection in RMAR North and into RMAR South is predicted to not induce watertable changes in excess of 2 m in the shallow aquifer Figure 3-36), except in small areas to the south of RMAR South, where Tertiary Clay is thought to be missing. Towards the end of mining a small mound in excess of 2 m is predicted to develop in the central part RMAR South with depth to groundwater remaining 20 m BGL or more. Depth to watertable in the RMAR area is predicted to remain below 5m BGL (**Appendix F**).

Scenario 3B: Dewatering and injection in mining area plus injection in RMAR South and RMAR North (20 ML/d)

Groundwater level changes in the mining area are predicted to be similar to Scenario 1.

Injection in RMAR North and into RMAR South is predicted to not induce watertable changes in excess of 2 m in the shallow aquifer Figure 3-37), except in small areas to the south of RMAR South, where Tertiary Clay is thought to be missing. Depth to watertable in the RMAR area is predicted to remain below 5 m BGL (**Appendix F**).

Scenario 4: Dewatering and injection in mining area, abstraction from Stage 2 borefield plus injection in RMAR North

Groundwater level changes in the mining area are predicted to be similar to Scenario 1.

Injection in RMAR North and into RMAR South is predicted to not induce watertable changes in excess of 2 m in the shallow aquifer (Figure 3-38). Depth to watertable in the RMAR area is predicted to remain below 5 m BGL (**Appendix F**).

Comparison with 2015 impact assessment

The area of groundwater change due to mining has increased in comparison with previous assessment. This is due to the change of the mining plan, and consequently larger dewatering rates and volumes removed and injected during the life of mine:

The Amendment to mine dewatering and saline water disposal (Ministerial Statement 824 and 829) specified proposed changes for mine dewatering, saline dewater disposal and saline dewater reuse for dust suppression. Total dewater for life for mine in this statement was specified to 286 GL (average 46 ML). The current assessment covered in this report predicts total dewater for life of mine to be 602 GL (80 ML/d brackish and 52 ML/d saline).

The increase in the dewater volume will result in a larger footprint – the comparison between the previously considered footprint and the drawdown at the end of mining in March 2013 predicted by the current assessment approach is shown in Figure 3-41.

The 2 m drawdown is predicted to move to the west, by approximately 5 km, to the north of the previous footprint by 2 to 4 km. The extended fooprint will partly move to the south in places of up to 4 km.

While the dewatering footprint is predicted to increase it is not likely to reach the area of the Fortescue Marsh. Re-injection of dewater into SWIB will partly assist in keeping the drawdown footprint largely contained within the mining tenement.

It is possible that groundwater level change of FMG Christmas Creek operation, to the west of Roy Hill's mining tenement will combine with the potential water level change from Roy Hill. These changes will be cumulative but are considered to be relatively minor since this potential combination of changes will take change on margins of the change envelope of both operations.

Post mining groundwater rebound

The large footprint of dewatering and the volume of water removed (in excess of 600 GL) over the LoM combined with the generally slow rate of groundwater recharge in the Pilbara will contribute to a relatively slow rebound of groundwater levels to the pre-mining level. The difference between the pre-mining and post-closure levels after 5 years (Figure 3-39) clearly define the mining footprint. Even 20 years after closure (in 2051), the drawdown footprint created by previous dewatering is still in place with maximum residual drawdown in the mining tenement between 5 to 10 m (Figure 3-40).

Predictive simulations suggest that it would take up to 100 years post closure to achieve the groundwater rebound close to the pre-mining levels (see also hydrograph plots in **Appendix F**).

This estimated time of rebound is expected for average climate conditions, the presence of a sequence of high recharge events may speed up or enhance the recovery of groundwater levels.

Within the Fortescue Valley, the water level impacts associated with mining or MAR are predicted to be negligible, hence they would remain close to the pre-mining levels at all times. The groundwater mound created by injection into the SWIB is predicted to dissipate quickly, within the first few years of closure since it will be redistributed into the groundwater drawdown area created by dewatering. The area previously occupied by the mound will become part of the drawdown footprint which will rebound slowly to pre-mining levels. During the rebound the groundwater flow from the mining area to the Fortescue Marsh will be minor until groundwater gradients reverse to their natural state.

3.6.4 Summary of predicted groundwater change from dewatering and MAR

The following can be drawn from the simulations results:

- The area of water level change due to dewatering is predicted to be up to 40 km long and 15 km wide. In this area the predicted change to pre-mining groundwater level will be two metres or more.
- Injection in the SWIB is predicted to create a noticeable mound which will be present during mining but will disappear after closure and will be absorbed by the still existing drawdown area of dewatering before it rebounds completely.
- The footprint of dewatering in the mined area will increase compared to 2015 assessment (expressed as an area of 2 m drawdown). The increase will represent extension of the 2 m drawdown by up to 5 km in some areas, specifically to the west, with extensions also to the north and south of the previously assessed footprint. The extent of the 2 m drawdown footprint derived from the current assessment is predicted to not reach the Fortescue Marsh area.
- Water level change in the shallow aquifer is minor in RMAR borefields and generally less than 2 m. There may be small areas to the south of RMAR South where water levels change is in excess of 2 m, however depth to groundwater in these area remains high.
- Depth to groundwater for all scenarios is predicted to remain at least 5 m BGL. This however required optimisation of injection rates in the SWIB (generally higher injection rates in the northwest situated bores of the SWIB borefield and decreased rates in the central and southern part of this borefield). The future injection rates will have to be monitored against the observed water levels and adjusted where necessary to maintain the desired depth to groundwater threshold.
- The expression of piezometric head in the weathered dolomite aquifer can result up to 20 m rise. While this is predicted to not propagate into the overlying Quaternary and Tertiary sediments the extent of mounding in the weathered dolomite can be large, up to 20 km in diameter. The piezometric head control is exerted by the presence of the clay layer at the base of the detrital sequence.

3.7 Groundwater quality change assessment

Baseline groundwater quality in the project area including RMAR is presented in Section 3.2.8. This section outlines the likely changes in groundwater quality due to the project.

MAR areas, including Mine MAR (areas), SWIB, RMAR North and RMAR South are proposed to receive excess dewater (and process water in case of SWIB). Brackish dewater (less than 5,000 mg/L) is planned for the Mine Pit MAR areas and RMAR South which is similar to the existing groundwater quality in this area. Groundwater quality change up to 5,000 mg/L TDS may occur in these areas.

Saline surplus dewater of up to 50,000 mg/L TSD will be directed into the SWIB and RMAR North. The existing hypersaline groundwater (more than 100,000 mg/L) exceeds these injection concentrations in the SWIB, however there may be an increase in groundwater concentrations when water of this salinity range is injected into RMAR North in which the salinity in some parts, in particular east, is not as high as in the SWIB. Groundwater salinities on the western side of RMAR North, presumably close or at the hypersaline wedge extending in the subsurface from the Fortescue Marsh are however of similar salinity - or higher, to saline surplus dewater.

The saline dewater will be injected at depth, into the hypersaline body of groundwater in the SWIB. Mixing will likely reduce the overall salinity and associated concentrations of the hypersaline body in the zone of influence. The saline injected water is likely to partly migrate vertically. Groundwater quality change at the water table not exceeding 5,000 mg/L in areas where baseline is below 5,000 mg/L is expected to be minor due to physical and density controls on upward migration and mixing.

In the SWIB, a large part of injected volume will flow north. This is due to the hydraulic gradient to the north set up by the low hydraulic head in the area of dewatering and higher hydraulic head in the injection area.

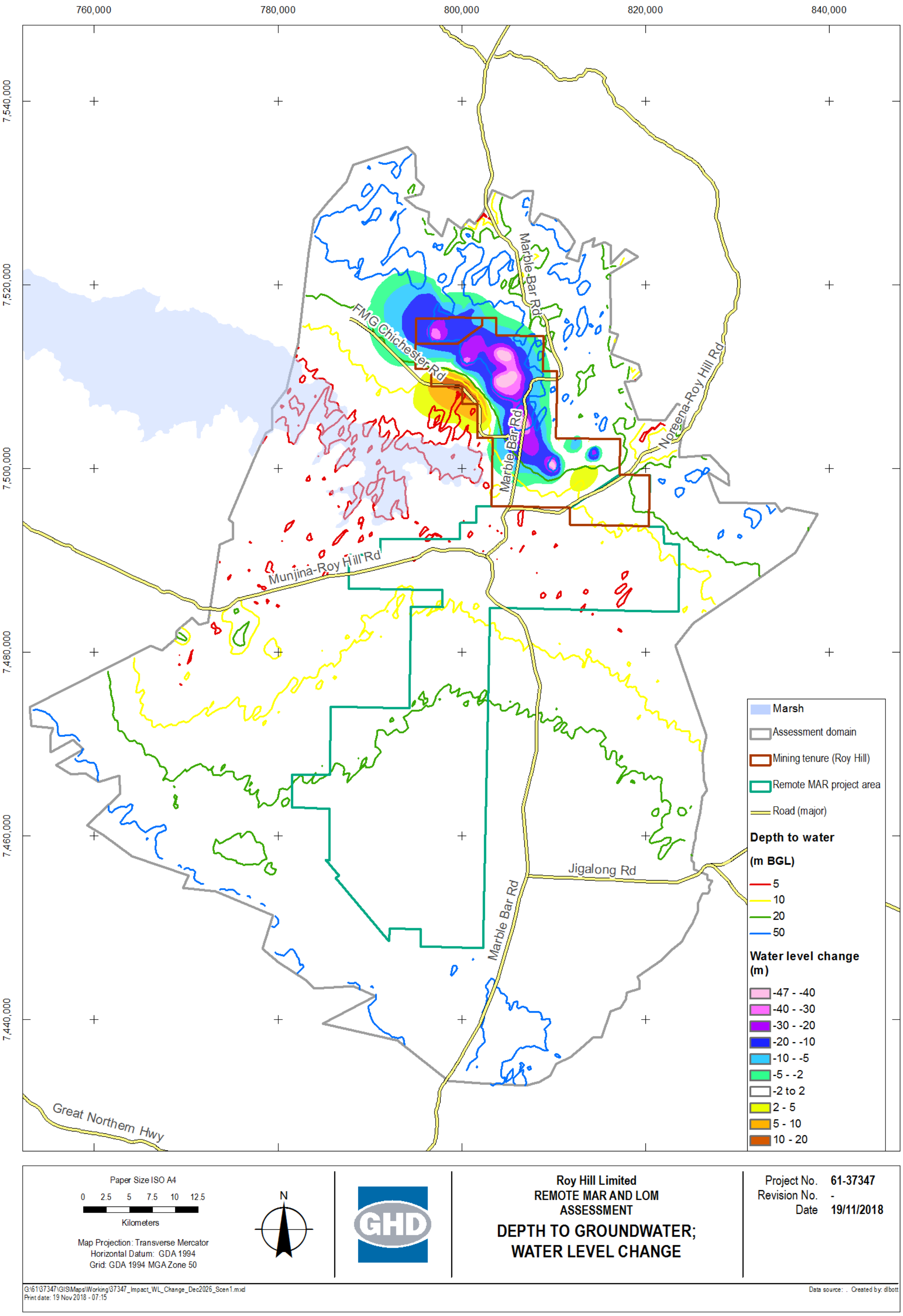


Figure 3-33: Predicted change in water level and depth to groundwater, Scenario 1 (dewatering and injection in mining area only), December 2026

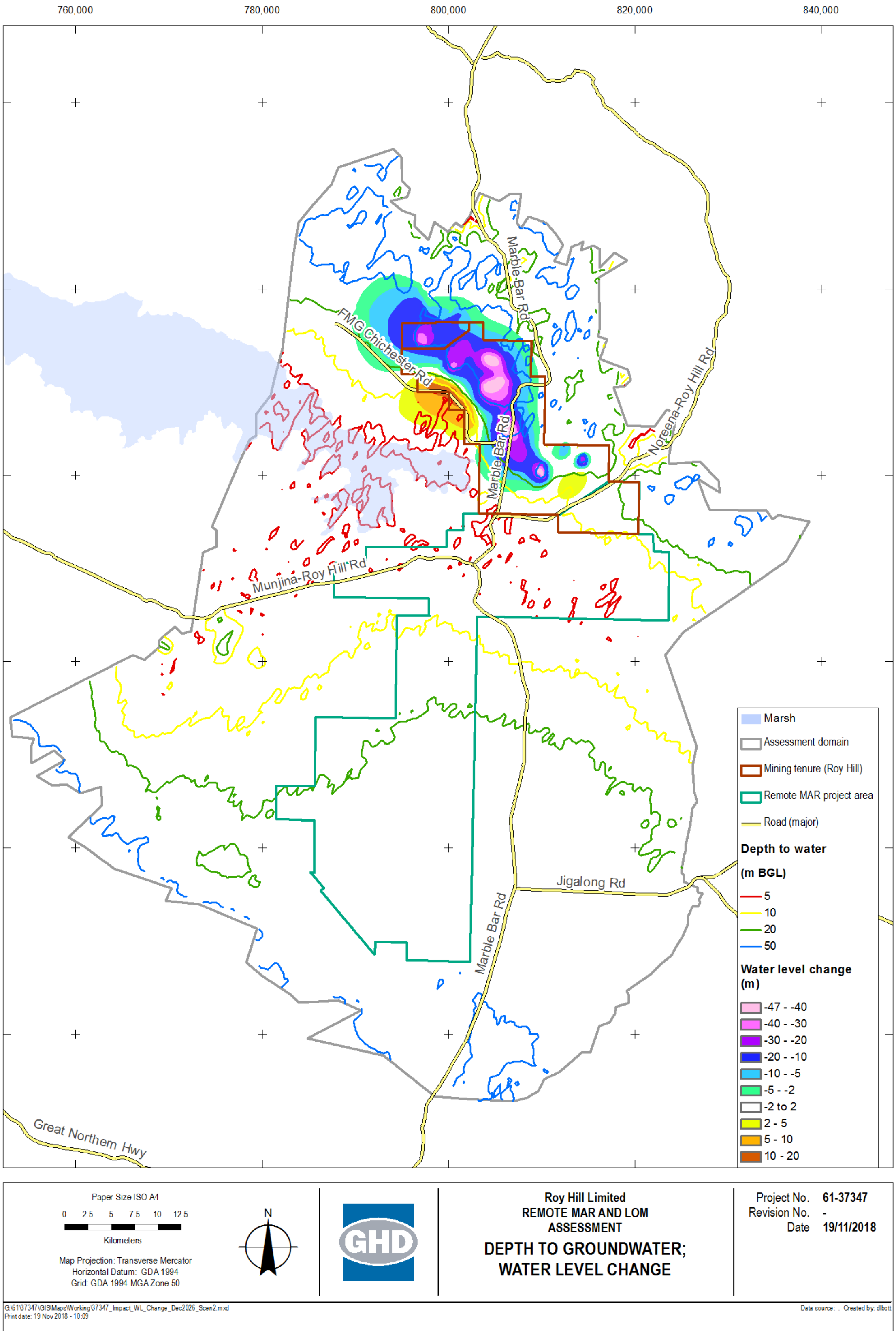


Figure 3-34: Predicted change in water level and depth to groundwater, Scenario 2 (dewatering and injection in mining area plus injection in RMAR North), December 2026

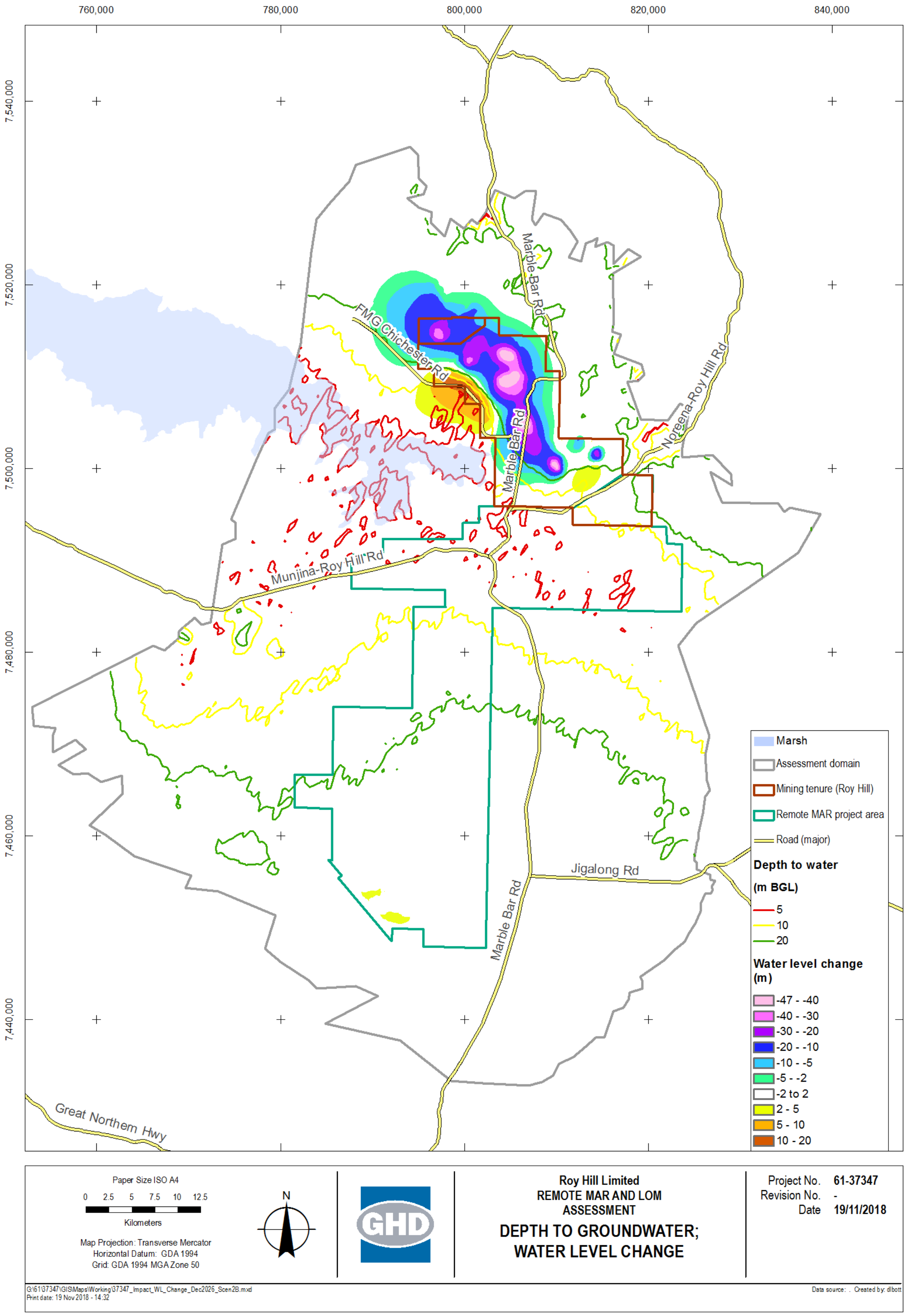


Figure 3-35: Predicted change in water level and depth to groundwater, Scenario 2B (dewatering and injection in mining area plus injection in RMAR North and 20 ML/d in RMAR South), December 2026

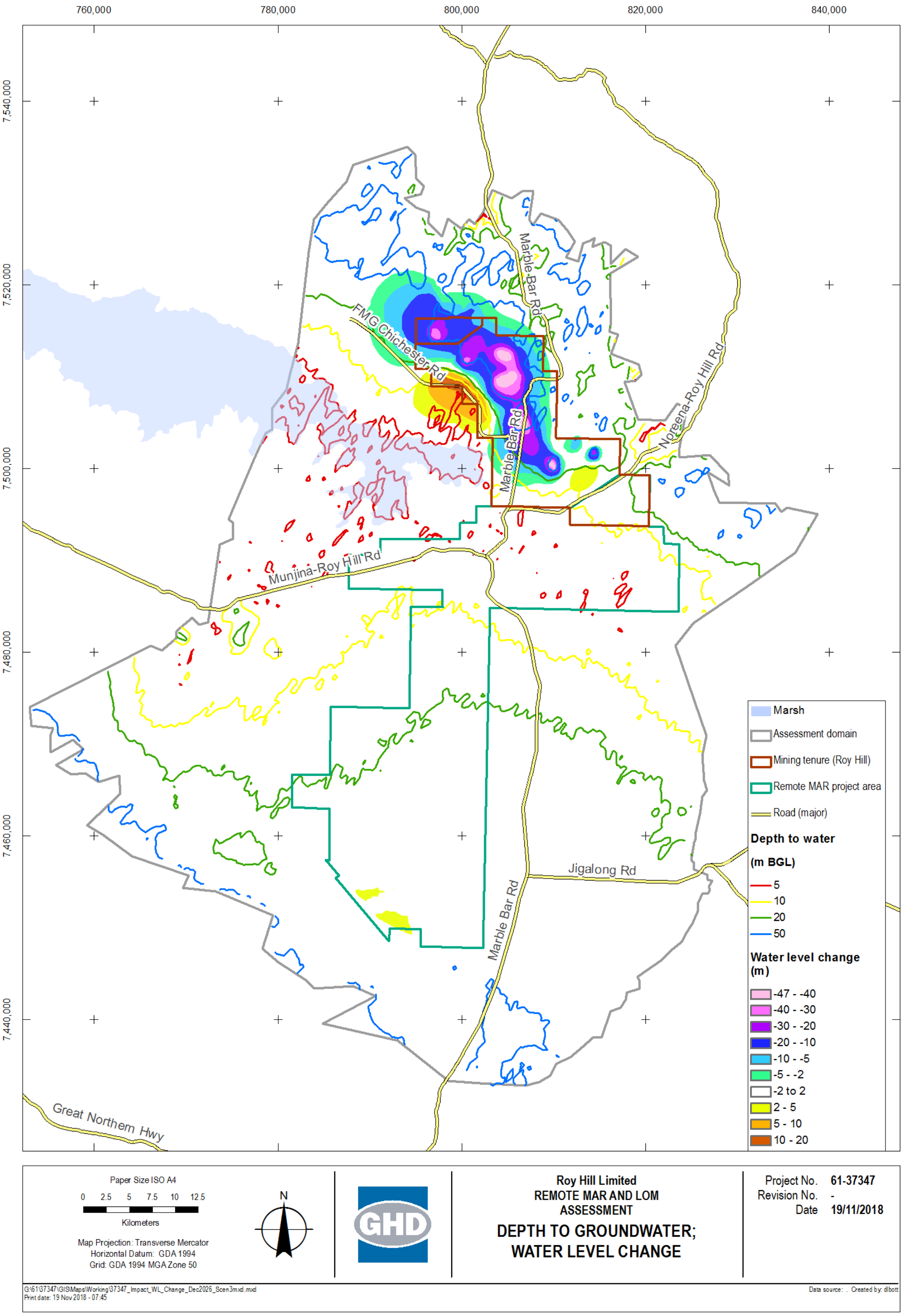


Figure 3-36: Predicted change in water level and depth to groundwater, Scenario 3 (dewatering and injection in mining area plus injection in RMAR South), December 2026

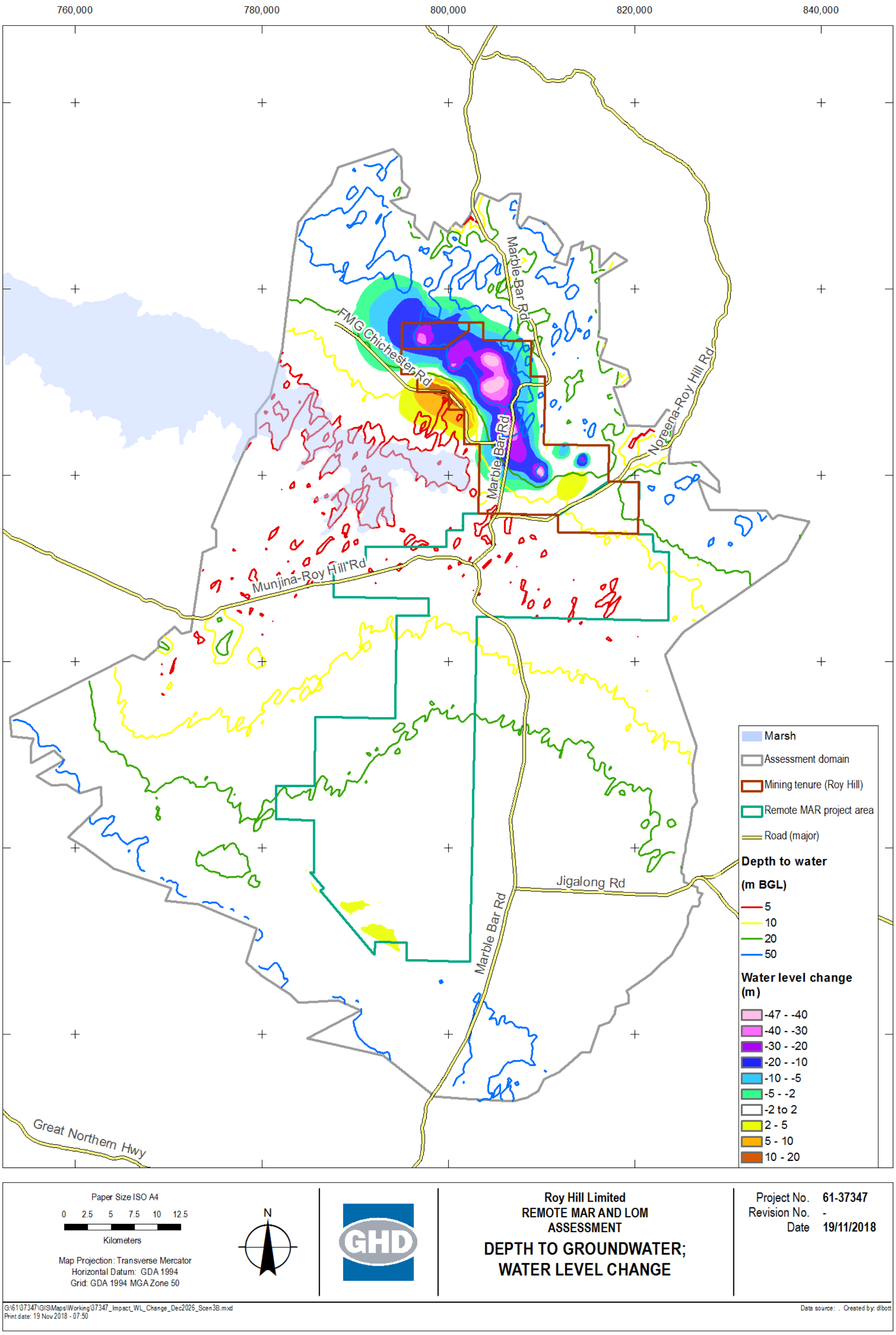


Figure 3-37: Predicted change in water level and depth to groundwater, Scenario 3B (dewatering and injection in mining area plus injection in RMAR South and 20 ML/d in RMAR North), December 2026

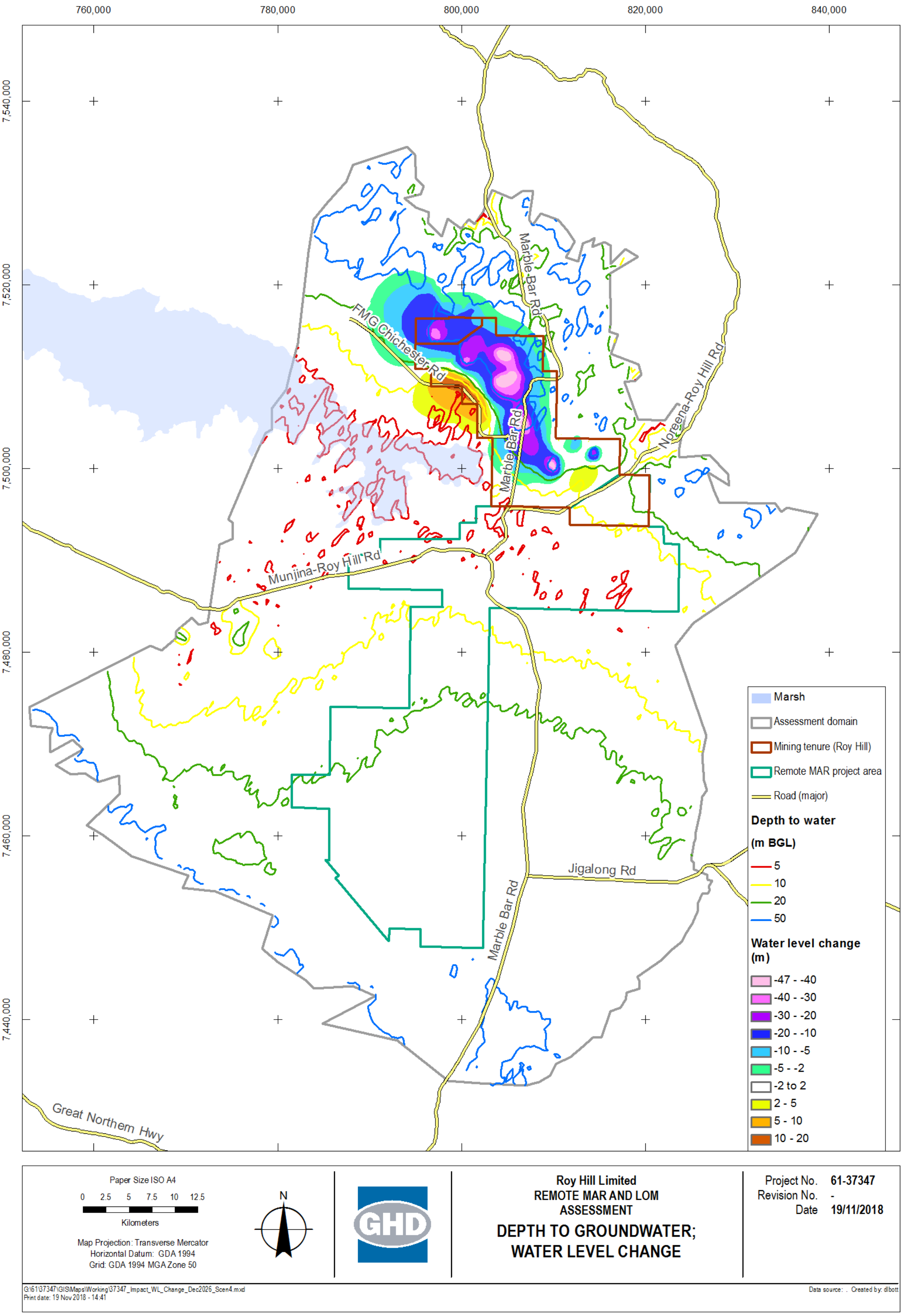


Figure 3-38: Predicted change in water level and depth to groundwater, Scenario 4 (dewatering and injection in mining area), abstraction in Stage 2 borefield plus injection in RMAR North, December 2026

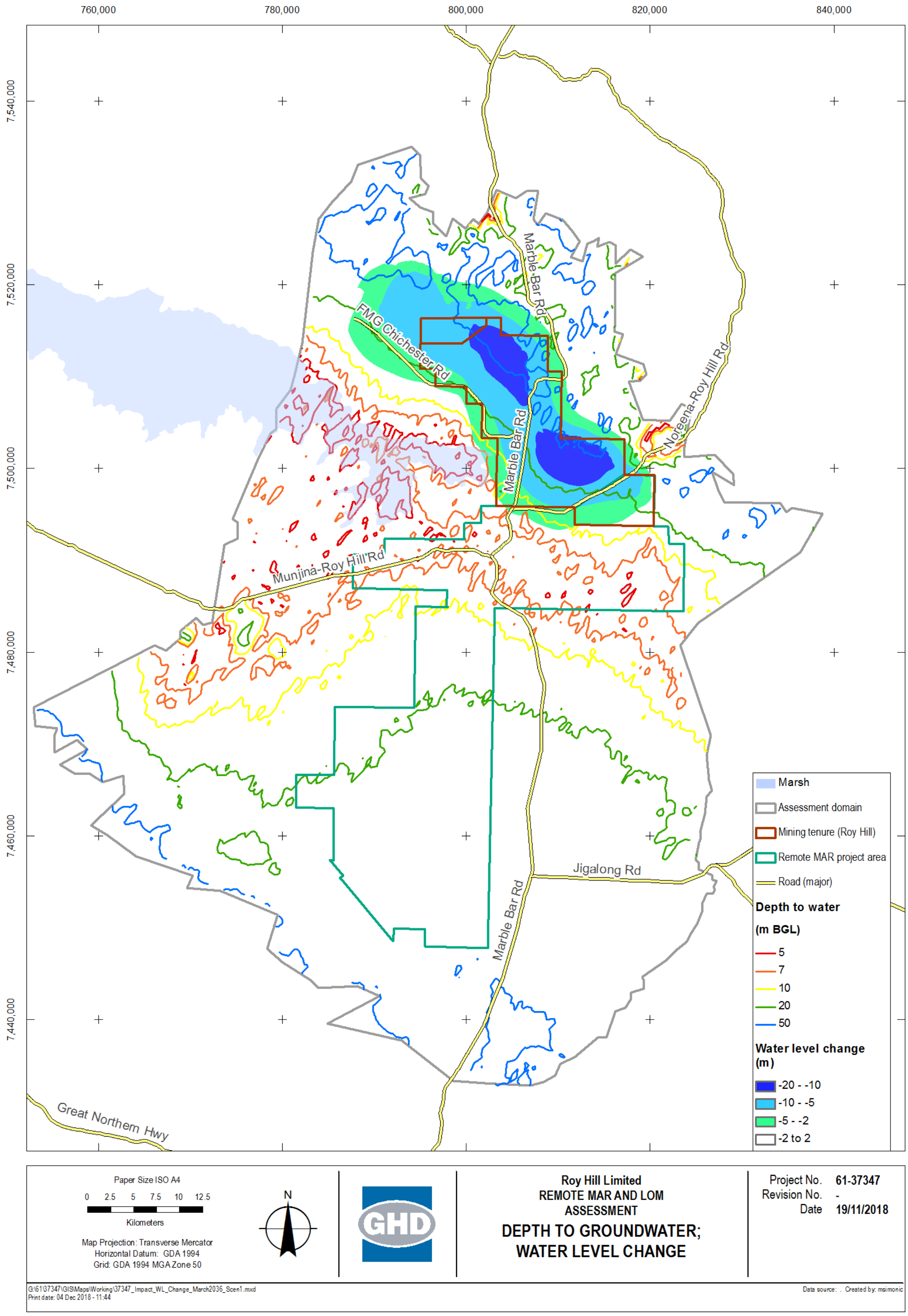


Figure 3-39: Depth to groundwater and residual drawdown 5 years after closure (Year 2036)

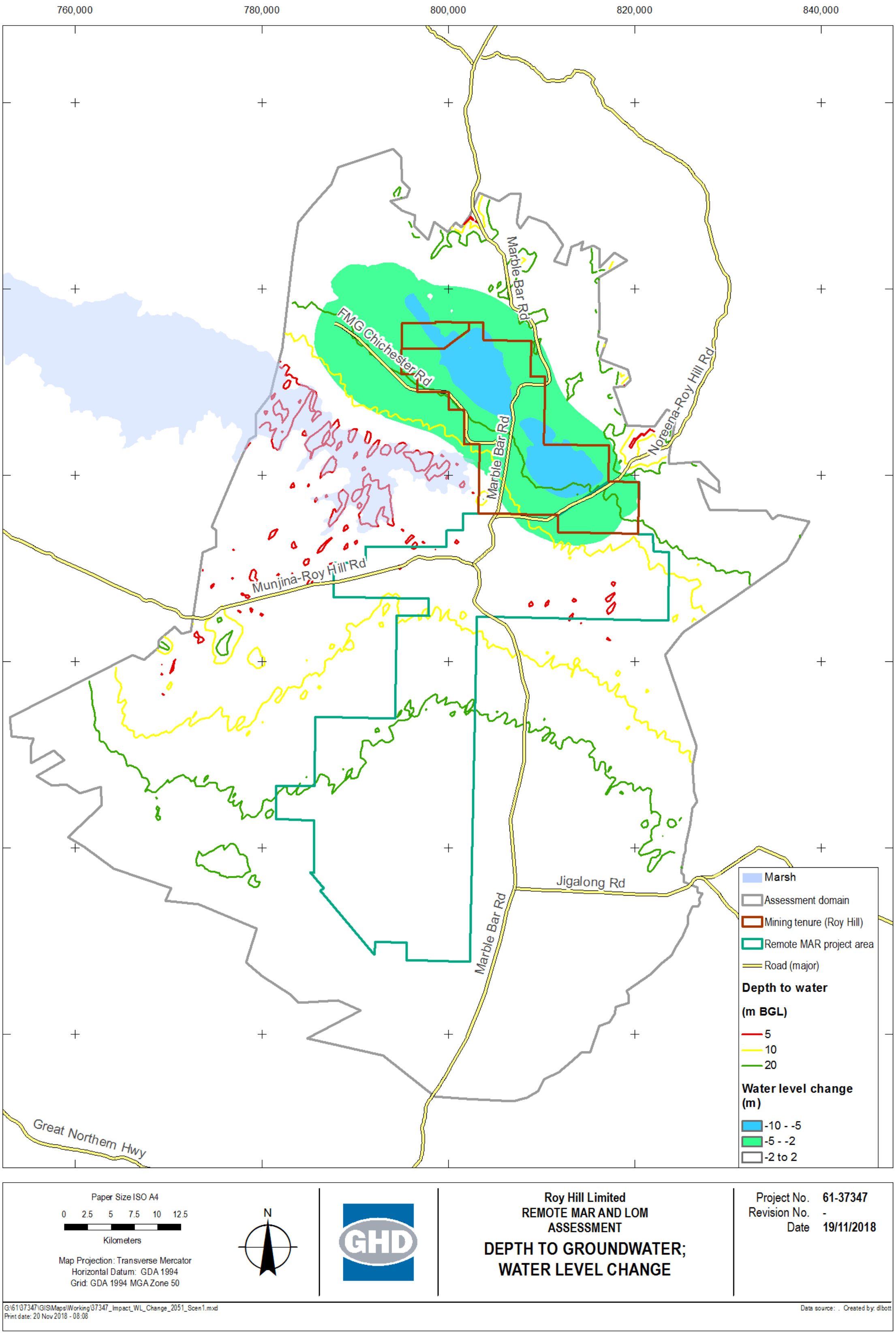


Figure 3-40: Depth to groundwater and residual drawdown 20 years after closure (Year 2051)

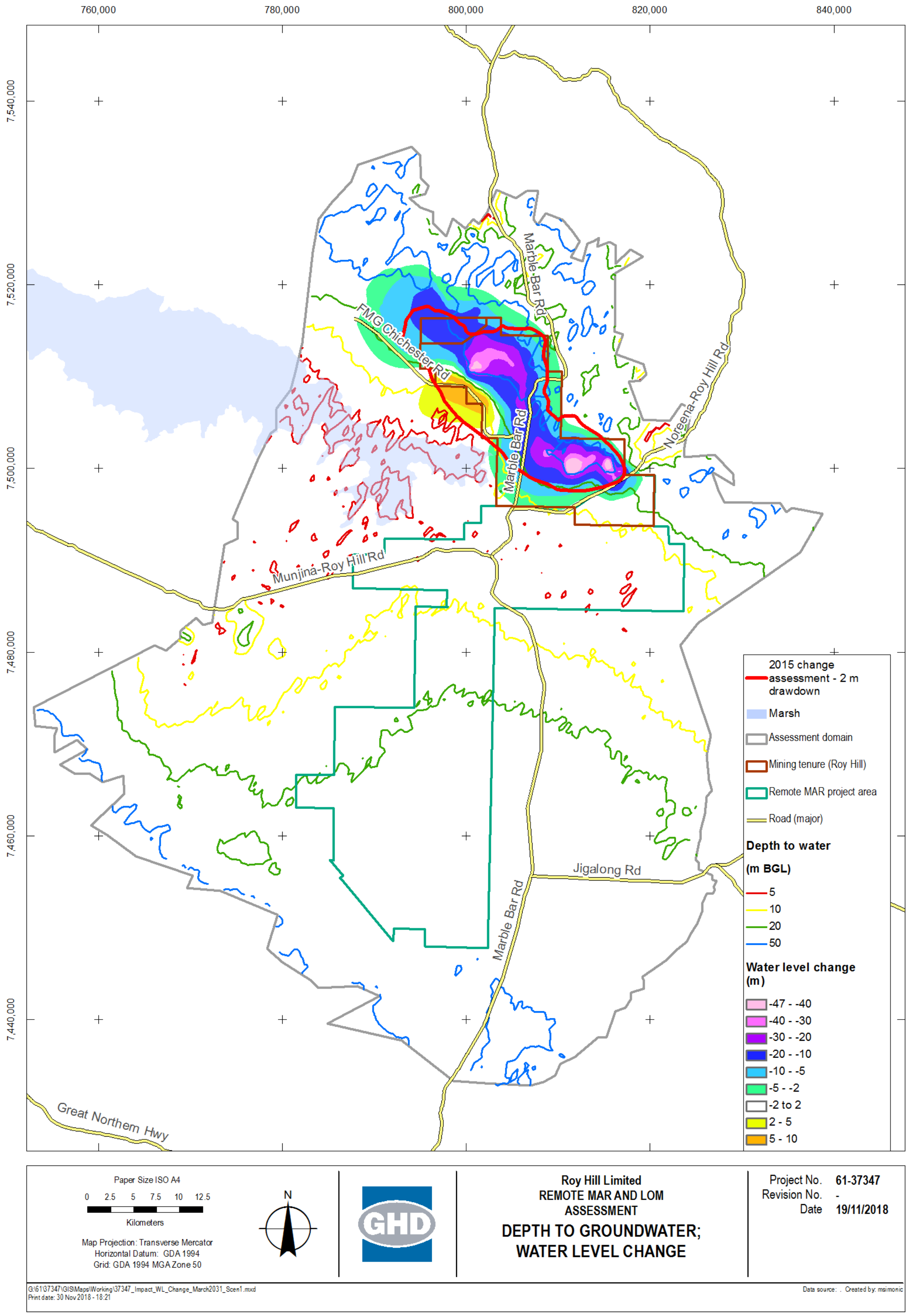


Figure 3-41: Comparison of the mining-induced change footprint, 2015 assessment and this study

4. Management approach for RHWMS

RH are committed to implementing robust planning systems to ensure business, environment and stakeholder objectives are satisfied. The planning system underpinning the RHWMS is founded on a philosophy of continuous improvement and adaptive management.

The RHWMS planning approach will consist of:

- Periodic review of RHWMS assumptions (business requirements);
- definition of near and long term water balances and operating conditions;
- Periodic maintenance (validation and calibration) of groundwater models and other predictive tools;
- Periodic simulation of proposed operating conditions and identification of potential groundwater impacts;
- Business approvals for operating plans, including forecast groundwater impacts; and
- groundwater monitoring.

Roy Hill operate monitoring systems to gauge the degree of impact of mining on the receiving environment. These include a network of monitoring bores which are designed to monitor various parts of the aquifer system, selection of trigger levels for depth to watertable and operational plan with trigger action response plans.

Several potential scenarios were evaluated in this study and selection or adoption of any of these scenarios is likely to result in the need of updating the monitoring systems and operational plans.

Willis-Jones (2018) presented a conceptual network of groundwater monitoring bores in areas of potential impact. The findings of this study support this conceptual network with the added need to re-evaluate the monitoring network in the RMAR area in addition to the existing monitoring bores and the associated trigger levels.

The natural response to the exceedance of a trigger level requires a redistribution of injection through available elements of the MAR system and its injection borefields. RH will carefully optimise and monitor injection rates in the SWIB and redistribute water through the MAR system where necessary.

These ecosystems are mainly part of the alluvial plain ecohydrological unit (EHU 6) with the potential effects to be monitored in the SWIB injection borefield and potentially, depending on injected rates in the RMAR North.

The trigger levels and limits will be also applied to ecohydrological receptors which are currently predicted to be as not affected, specifically calcrete flats and Fortesue Marsh units.

5. Conclusions

Roy Hill Water Management Strategy (RHWMS) addresses the requirements of mine dewatering, water supply and surplus water disposal. To ensure resilience the strategy considers multiple realistic operating conditions that will occur during the life of mine.

The impact assessment presented in this report is based on several iterations of data acquisition and related groundwater system conceptualisation starting with BFS in 2009 through dewatering and MAR assessments into 2018. On this basis a numerical modelling tool was developed for the purposes of this study to predict the groundwater response to the proposed RHWMS which addresses requirements for dewatering, water supply and surplus water disposal for the Roy Hill operation.

The numerical model, developed in MODFLOW-NWT is presented to be a Class 2 model, capable of addressing the needs of a regional impact assessment. The level of confidence is based on:

- Maximisation of the knowledge gained through a succession of previous numerical models;
- Current understanding of hydrogeological interpretation of geological data and learnings from existing dewatering and injection;
- Interpretation of a large monitoring dataset (water levels, abstraction and injection rates);
- The calibration period includes periods with applied groundwater stresses (both dewatering and injection) in the mining area, while the monitoring data indicates near steady-state conditions in the Fortescue Valley

This assessment is considered preliminary and subject to future updates, however it is robust enough to provide carefully considered predictive results with understanding of uncertainty attached to them. The duration of prediction exceeds the period of calibration which is a function of the monitoring data availability. With the mining operation entering the Operational Phase 2 there will be opportunities to extend and improve the monitoring dataset and verify the existing calibration and confirm confidence in predictive results.

The dewatering, water supply and surplus water disposal requirements assessed in this study are presented in Table 5-1. The capacity of the proposed MAR study areas are considered suitable to manage surplus water including surplus process water.

Table 5-1: Summary of predictive scenarios

Scenario	Dewatering (ML/d)	Surplus disposal – SWIB & Mine Pit Area (ML/d)	Surplus disposal – RMAR South (ML/d)	Surplus disposal – RMAR North (ML/d)	Water supply (Remote borefield) (ML/d)
1	225 (peak 132 (mean)	109 (peak) 67 (mean)			
2	225 (peak) 132 (mean)	109 (peak) 67 (mean)		96 (peak) 20 (mean)	
2B	225 (peak) 132 (mean	109 (peak) 67 (mean) includes process water (20)	20	96 (peak) 20 (mean)	
3	225 (peak) 132 (mean)	109 (peak) 67 (mean)	96 (peak) 20 (mean)		
3B	225 (peak) 132 (mean)	109 (peak) 67 (mean) includes process water (20)	96 (peak) 20 (mean)	20	
4	225 (peak 132 (mean)	109 (peak) 67 (mean)		96 (peak) 20 (mean)	40 ML/d

The predictive results indicate that groundwater levels change will be the largest within the mining area with drawdowns in excess of 50 m below the pre-mining water levels. MAR will result in limited groundwater mounding which will be more noticeable in the mining area (notably SWIB) and predicted to be minor in the remote MAR area.

The planning system underpinning the RHWMS is founded on a philosophy of continuous improvement and adaptive management.

The RHWMS planning approach will consist of:

- Periodic review of RHWMS assumptions (business requirements);
- definition of near and long term water balances and operating conditions;
- Periodic maintenance (validation and calibration) of groundwater models and other predictive tools;
- Periodic simulation of proposed operating conditions and identification of potential groundwater impacts;
- Business approvals for operating plans, including forecast groundwater impacts; and
- Groundwater monitoring & trigger level review.

6. List of references

Brandes de Roos, I, Youngs, J, 2010: hydrogeological assessment for the Christmas Creek water management scheme. FMG report CC-RP-HY-0004

Johnston, K, Hamilton, R, 2018: Roy Hill remote MAR project – Phase 1. ManagedAquifer report prepared for Roy Hill Iron Ore

MWH, 2009: Roy Hill Remote Borefield, Preliminary Modelling of Impacts of Abstraction. MWH technical report prepared for HPPL (Sep 2009)

Rouillard, A, Skrzypek, G, Dogramaci, S, Turney, C, and PF Grierson, 2015: Impacts of high inter-annual variability of rainfall on a century of extreme hydrologic regime of northwest Australia. Hydrol. Earth Syst. Sci. 19, 2057-2078

Simonic, M, van Rensburg, Huxtable, D, Clark, G, 2015: Ecohydrological conceptualisation of the Fortescue Marsh. MWH technical report prepared for BHP Billiton Iron Ore

Surrette, M, 2018: Roy Hill Mine groundwater operating strategy. Roy Hill report OP-REP00512

Surrette, M, Clark, G, 2009: Hydrogeological assessment of the Roy Hill remote borefield. MWH technical report prepared for Hancock Prospecting Pty Ltd

Willis-Jones, B, 2018: Hydrogeological assessment for Roy Hill managed aquifer recharge system report. Roy Hill report OP-REP-00510

Appendix A Land systems, description

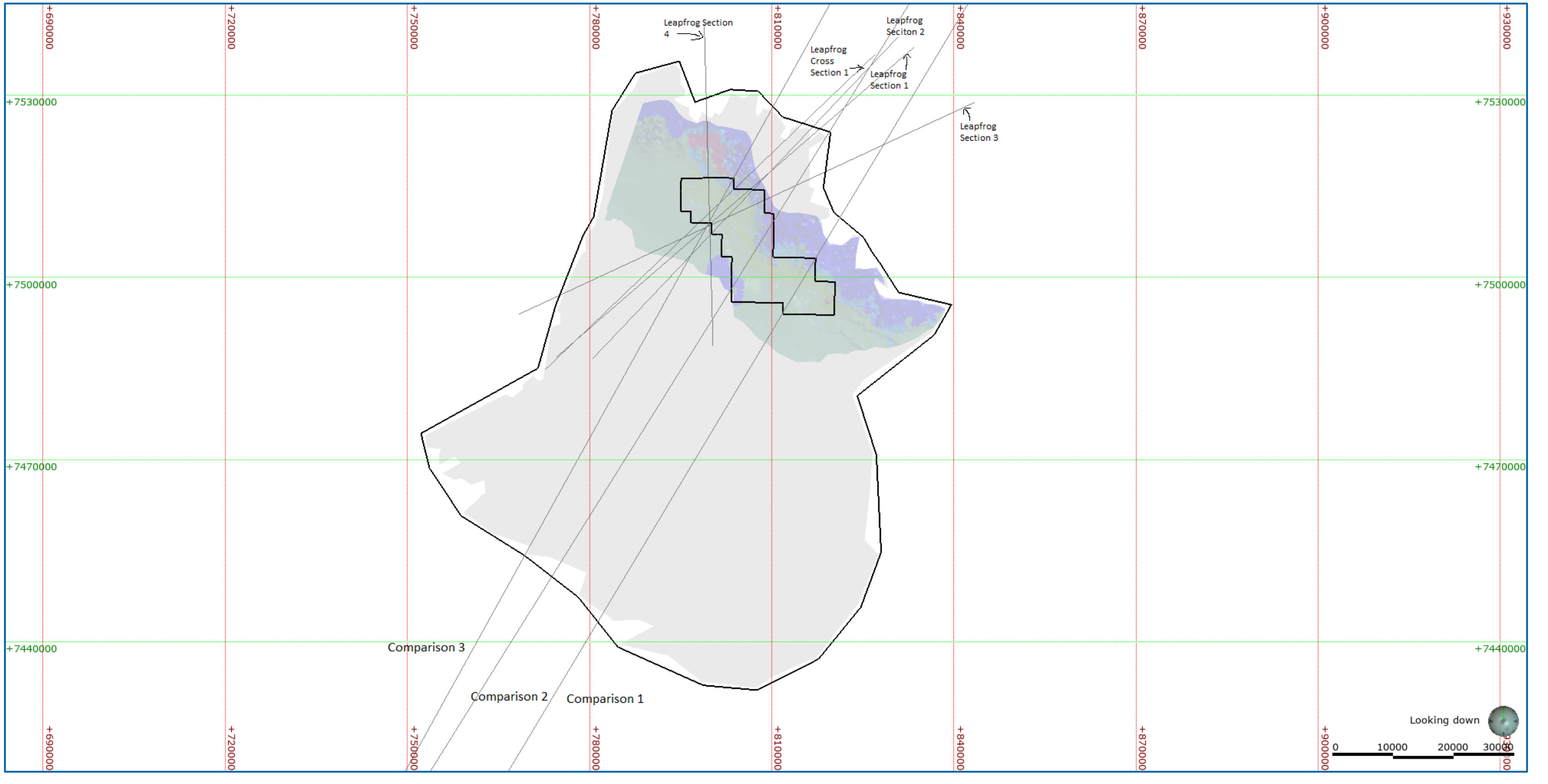
Land system	Type	Description
Adrian	6	Stony plains and low silcrete hills supporting hard spinifex grasslands: Erosional surfaces typified by rounded hills and rises. Short drainage lines with radial patterns away from rises. Soils are stony and shallow.
Billygoat	5	Dissected plains and slopes supporting hard spinifex grasslands: Erosional surfaces including extensive dissected gravelly/stony plains, minor plateaux and residual upper plains and occasional low breakaways. Narrow interfluves and slopes with dendritic drainage networks. Slopes marginal to drainage lines are often calcreted. Soils are shallow and stony/gravelly.
Bonney	6	Low rounded hills and undulating stony plains supporting soft spinifex grasslands : Erosional surfaces including low hills, undulating rises and gently undulating stony plains. Widely spaced drainage patterns of narrow drainage floors with minor channels. Upland soils are shallow and stony, with a mix of non-cracking clays, calcareous loamy earths and red loamy earths on rises and plains.
Boolgeeda	8	Stony lower slopes and plains below hill systems supporting hard and soft spinifex grasslands and Mulga shrublands: Quaternary colluvium parent materials. Closely spaced dendritic and sub-parallel drainage lines. Predominantly depositional surfaces characterised by red loamy soils of variable depth.
Brockman	14	Alluvial plains with cracking clay soils supporting tussock grasslands: Depositional surfaces derived from Quaternary alluvium. Non-saline alluvial plains with clay soils and gilgai micro-relief, flanked by slightly more elevated hardpan washplains. Sluggish internal drainage with occasional channels. Soils are mainly self-mulching cracking clays and red/brown non-cracking clays, with some red loamy earths on elevated washplains.
Calcrete	18	Low calcrete platforms and plains supporting shrubby hard spinifex grasslands: Tertiary calcrete formed in detrital deposits, with minor Quaternary alluvium. Drainage is generally indistinct. Soils are mainly shallow calcareous loams (<50 cm overlying calcrete), with minor calcareous loamy earths and red shallow loams.
Coolibah	17	Floodplains with weakly gilgaied clay soils supporting Coolibah woodlands with Tussock grass understorey: Depositional surfaces; active floodplains and alluvial plains associated with the Fortescue river (i.e. non-Fortescue Marsh sections). Soil types mainly include deep red/brown non-cracking clays, with some deep red loamy duplex soils.
Cowra	15	Plains fringing the Marsh land system and supporting Snakewood and Mulga shrublands with some halophytic undershrubs: Depositional surfaces; almost level plains of non-saline and weakly saline alluvium with gravelly surfaces. Drainage foci and tracts support denser vegetation, included banded formations in some places. Soils mainly include red loamy earths and duplex types; with abundant cobbles and stony mantles. Restricted to the Fortescue Valley and considered to have elevated conservation significance (EPA 2013).
Divide	11	Sandplains and occasional dunes supporting shrubby hard spinifex grasslands: Depositional surfaces reworked by Aeolian processes. Drainage is generally indistinct. Soils are mainly red deep sands and red sandy earths, with occasional shallower soils overlying gravel or rock.
Elimunna	10	Stony plains on basalt supporting sparse Acacia and Senna shrublands and patchy tussock grasses: Mainly depositional surfaces including level to gently undulating plains with a mosaic of surface types (e.g. stony, gilgai microrelief), Wide to very wide spaced tributary drainage floors, with sluggish internal drainage patterns on gilgai plains. Mostly heavy soil types (cracking and non-cracking clays).
Fan	12	Washplains and gilgai plains supporting groved Acacia shrublands (Mulga and Snakewood) and minor tussock grasslands: Flat depositional surfaces subject to overland flow and banded vegetation formations. Soils are generally deep red loamy earths.
Fortescue	17	Alluvial plains and floodplains supporting patchy grassy woodlands and shrublands and tussock grasslands: Depositional surfaces associated with river channels and commonly subject to fairly regular flooding. Soils are mainly deep red/brown non-cracking clays and self-mulching cracking clays.
Jamindie	12	Stony hardpan plains and rises supporting groved Mulga shrublands, occasionally with spinifex understorey: Depositional surfaces including non-saline plains with hardpan at shallow depth, stony upper plains and low rises on hardpan or rock. Very widely spaced tributary drainage tracts and channels. Minor stony gilgai plains, sandy banks and low rides and hills. Shallow loamy soils (often stony/gravelly) are predominant.
Laterite	4	Laterite mesas and gravelly rises supporting Mulga shrublands: Erosional surfaces formed by dissected parts of the old Tertiary plateaux. Mesas and breakaways, gravelly footslopes and lower plains. Drainage tracts and floors with sluggish

Land system	Type	Description
		drainage or sub-parallel braided creeks (frequently saline). Soils are generally shallow sands and gravels; with red/brown cracking and non-cracking clays in low-lying areas.
Marillana	15	Gravelly plains with large drainage foci and unchannelled drainage tracts supporting Snakewood shrublands and grassy Mulga shrublands: Depositional surfaces derived from Quaternary alluvium. Sheetflow areas occur and are associated with stony surface mantles. Broad, unchannelled drainage tracts can receive more concentrated through flow. Soils are generally deep red loamy earths, duplex soils or clays. Considered to have elevated conservation significance (EPA 2013).
Marsh	20	Lakebeds and floodplains subject to regular inundation, supporting samphire and halophytic shrublands: Depositional surfaces derived from Quaternary alluvium and lacustrine deposits. Soils include red/brown clays, often with high alkalinity and gypsum content. Soils can be underlain by siliceous or calcareous hardpans.
McKay	1	Hills, ridges, plateau remnants and breakaways of meta-sedimentary and sedimentary rocks supporting hard spinifex grasslands: Erosional surfaces with moderately spaced tributary drainage patterns incised in narrow valleys in upper parts, becoming broader and more widely spaced downstream. Soils are mainly shallow and stony.
Narbung	15	Alluvial washplains with prominent internal drainage foci supporting Snakewood and Mulga shrublands with halophytic low shrubs: Almost level alluvial plains receiving overland sheetflow. Localised internal drainage, with no defined channel features. Soil types generally include red deep sandy duplex and shallow sandy duplex soils.
Newman	1	Rugged jaspilite plateaux, ridges and mountains supporting hard spinifex grasslands. Widespread across the Pilbara region: Erosional surfaces, characterised by skeletal soils (with abundant pebbles, cobbles and stones) and frequent rock outcropping. Soils are shallow and stony.
River	17	Active floodplains and major rivers supporting grassy eucalypt woodlands, tussock grasslands and soft spinifex grasslands: Riverine environments subject to flooding, with generally deep soils of various texture classes.
Robe	3	Low limonite mesa and buttes supporting soft spinifex (and occasionally hard spinifex) grasslands: Erosional surfaces formed by partial dissection of old Tertiary surfaces. Closely to moderately spaced narrow tributary drainage floors. Soils are generally shallow and gravelly.
Rocklea	1	Basalt hills, plateaux, lower slopes and minor stony plains supporting hard spinifex (and occasionally soft spinifex) grasslands: Erosional surfaces including hills, ridges and plateaux remnants. Tributary drainage patterns grade into broader floors and channels downslope. Soils are generally shallow with abundant basalt cobbles.
Spearhole	12	Gently undulating hardpan plains supporting groved mulga shrublands and hard spinifex: Depositional surfaces including level to gently undulating plains on hardpan. Sparse patterns of tributary drainage with restricted areas of shallow valleys and finely dissected slopes. Soils are generally red brown shallow loams with hardpans, and red loamy earths.
Turee	14	Stony alluvial plains with gilgaied and non-gilgaied surfaces supporting tussock grasslands and grassy shrublands: Mosaic depositional surfaces of low relief (hardpan, stony and gilgai plains) inter-dispersed with few drainage channels. Localised sheetflow can occur. Soils include various earths, loams and clays often with abundant surface cobbles.
Warri	18	Low calcrete platforms and plains supporting Mulga and Senna shrublands: Depositional surfaces of low relief. Calcrete layers, with narrow inter-bedded areas. Soil types mainly include calcareous shallow loams and loamy earths. Surface mantles commonly include calcrete pebbles and fragments.
Washplain	12	Hardpan plains supporting groved mulga shrublands: Depositional surfaces including alluvial level hardpan plains. Discrete drainage foci associated with groved vegetation, with some drainage tracts receiving more concentrated flow. Soils are generally deep duplex types, and red loamy earths; commonly with hardpans at depth.

Appendix B Stratigraphy review

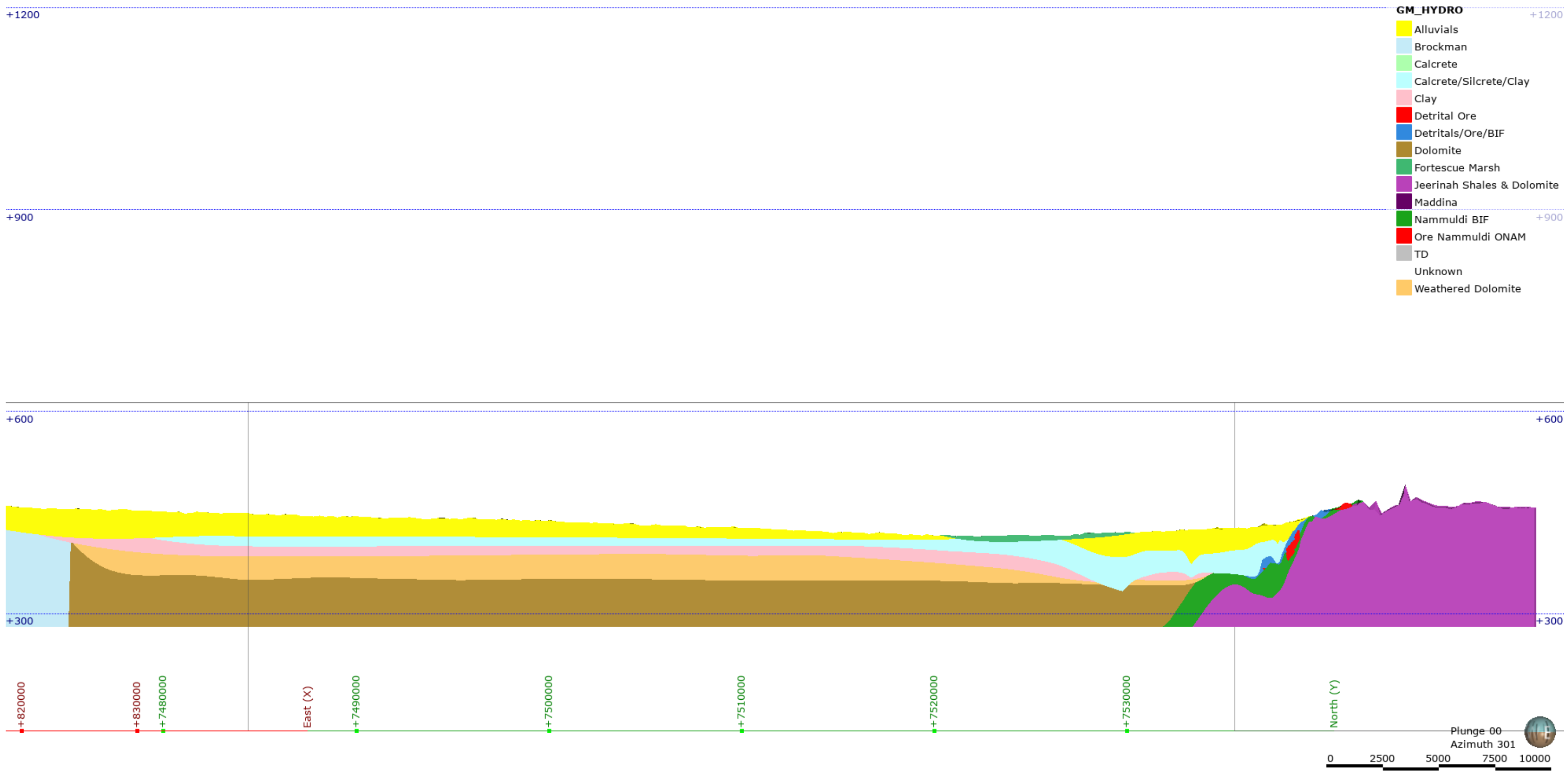
Age	Group	Formation	Member	Dominant lithology	Hydrogeology
Cainozoic	Quaternary	Eolian deposits (Qs)		Sand in sheets and longitudinal dunes	Generally unsaturated
		Alluvium (Qa, Ql, Qw)		Unconsolidated silt, sand, and gravel, in drainage channels and on adjacent floodplains	Often unsaturated, occasional aquifer, can be heterogeneous depending on texture
		Colluvium (Qc)		Unconsolidated quartz and rock fragments in soil	While unsaturated, may form localised, temporary, perched aquifers
	Tertiary Detritals (TD)	TD3		Valley-fill sandy silt (top) to clay (towards the base), calcretised in places	Generally aquitard
		Calcrete, silcrete, ferricrete		Lacustrine sediments including sheet carbonate (calcrete), Oakover Formation	Aquifer
		TD2		Channel iron deposits (CID), generally occurring at depth in palaeodrainages	Aquifer
Early Proterozoic - Archaean	Hamersley Group	Boolgeeda Iron Formation		Iron formation, pelite and chert	Low permeability material
		Woongara Rhyolite		Metamorphosed volcanicsand BIF	Low permeability material
		Weeli Wolli Formation		BIF, pelite, chert, dolerites, sills	Mostly unsaturated
		Brockman Iron Formation	Yandicoogina Shale Member	Interbedded chert and shale	Low permeability material
			Joffre Member	BIF with minor shale bands	Limited aquifer(s) in mineralised zones
			Whaleback Shale Member	Interbedded shale, chert and BIF	Low permeability
			Dales Gorge Member	Interbedded BIF and shale	Limited aquifer(s) in mineralised zones
		Mount McRae Shale		Shale and dolomitic shale with minor thinly bedded chert	Low permeability (in general), pockets of shale may form minor aquifers
		Mount Sylvia Formation		Shale, dolomitic shale, and BIF	Low permeability (in general), pockets of shale may form minor aquifers
		Wittenoom Formation	Bee Gorge Member	Graphitic shale with minor sequences of carbonate, chert, volcaniclastic rock, and BIF	Low permeability
			Paraburdoo Member	Dolomite with minor amounts of chert and shale - karstic in areas	Aquifer at regional scale, especially where karstified
			West Angela Member	Dolomite, dolomitic shale, and chert	Minor, localised aquifers
		Marra Mamba Iron Formation	Mount Newman Member	Chert, banded iron-formation, and shale	Aquifer in mineralised zones
			MacLeod Member	Well podded to laminar chert and chert BIF with shale macrobands	Low permeability
			Nammuldi Member	BIF with chert and shale	Aquifer in mineralised zones
Archaean	Fortescue Group	Jeerinah Formation	Roy Hill Shale Member	Dark-gray to black graphitic shale and chert; locally pyritic	Low permeability
			Warrie Mamber	Dolomite with inter-bedded chert (locally ferruginous), shale and mudstone	Low permeability

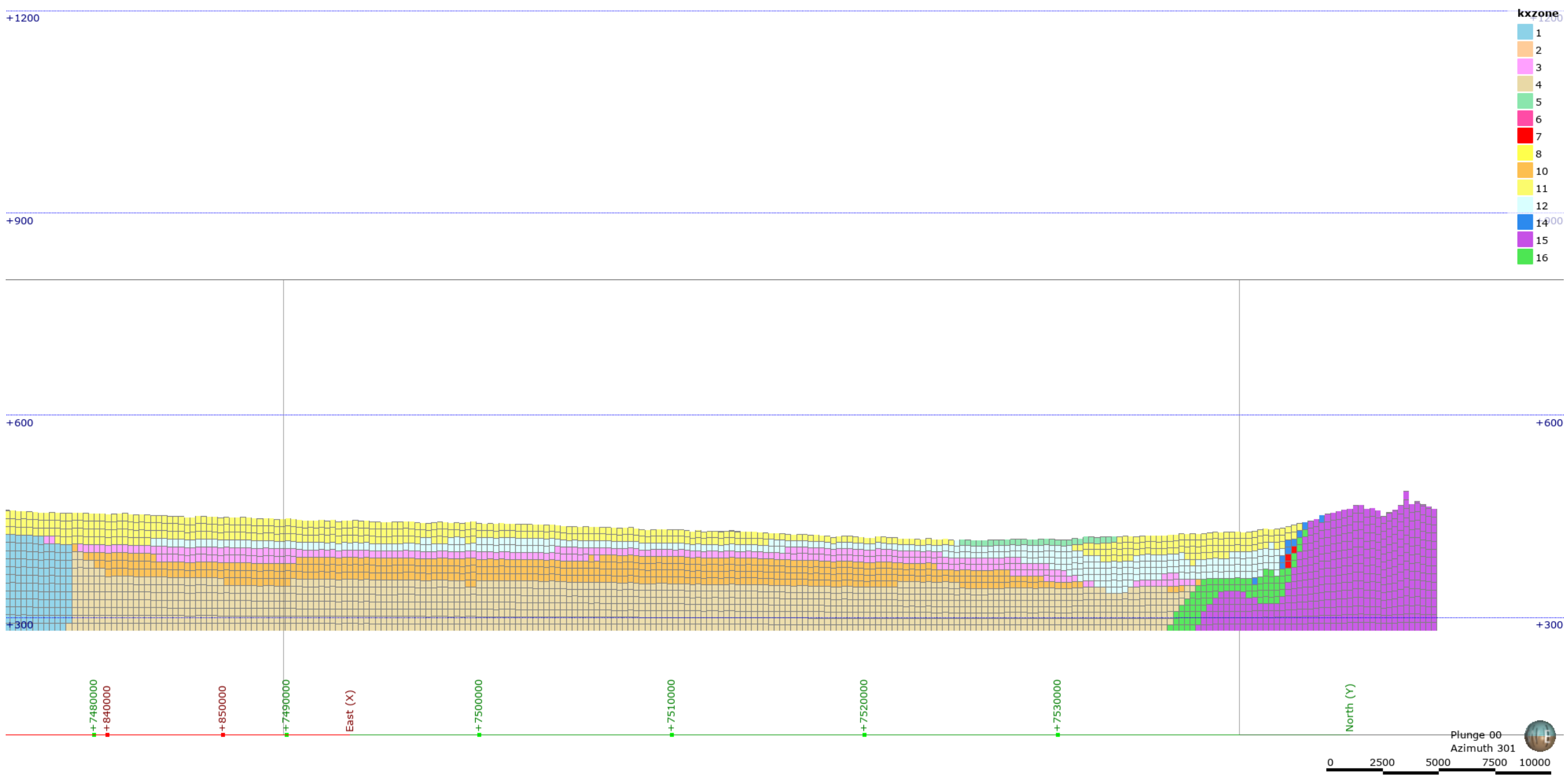
Appendix C Section views (Leapfrog, MODFLOW, FEFLOW)

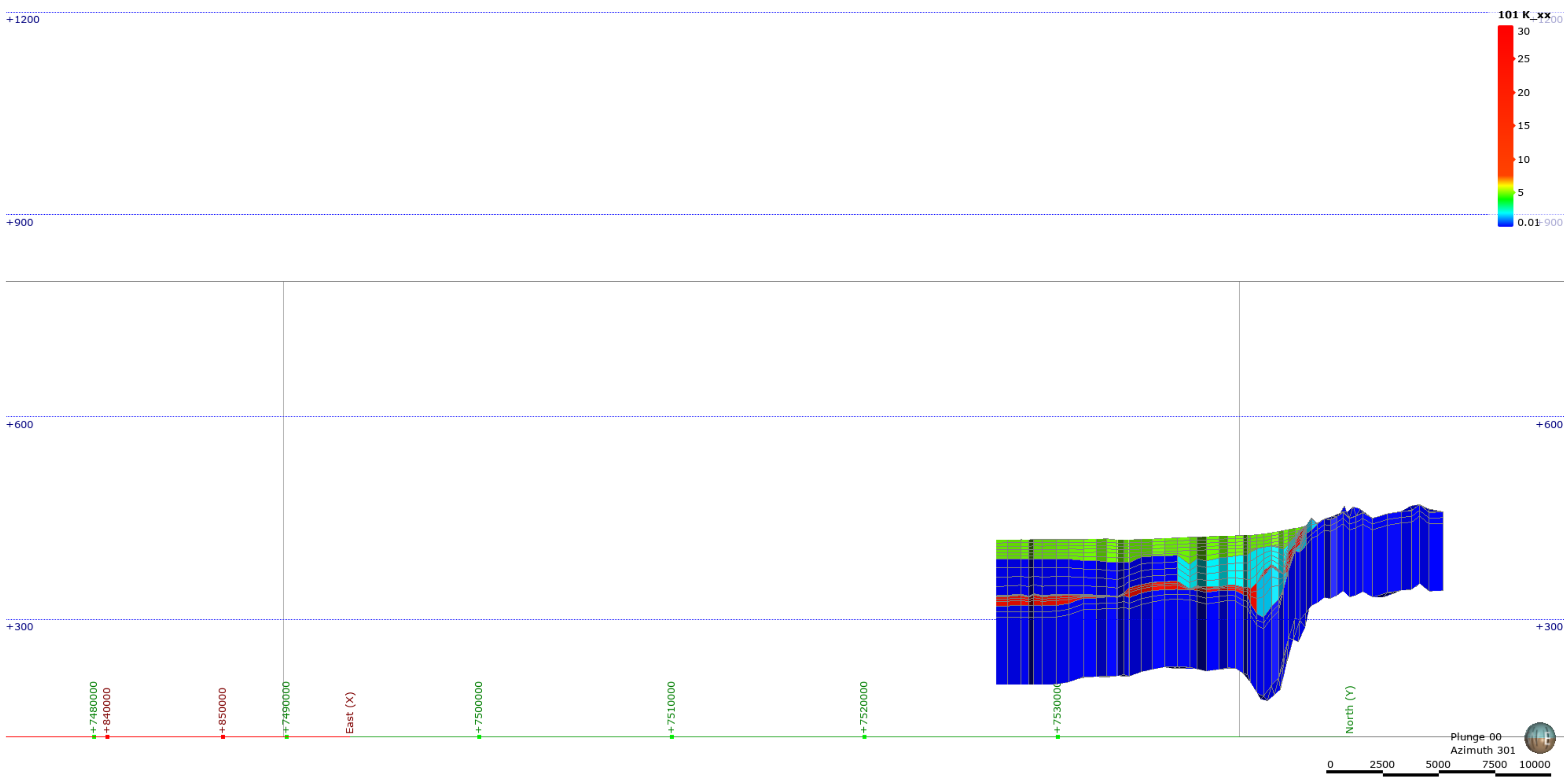


Locations of comparative sections

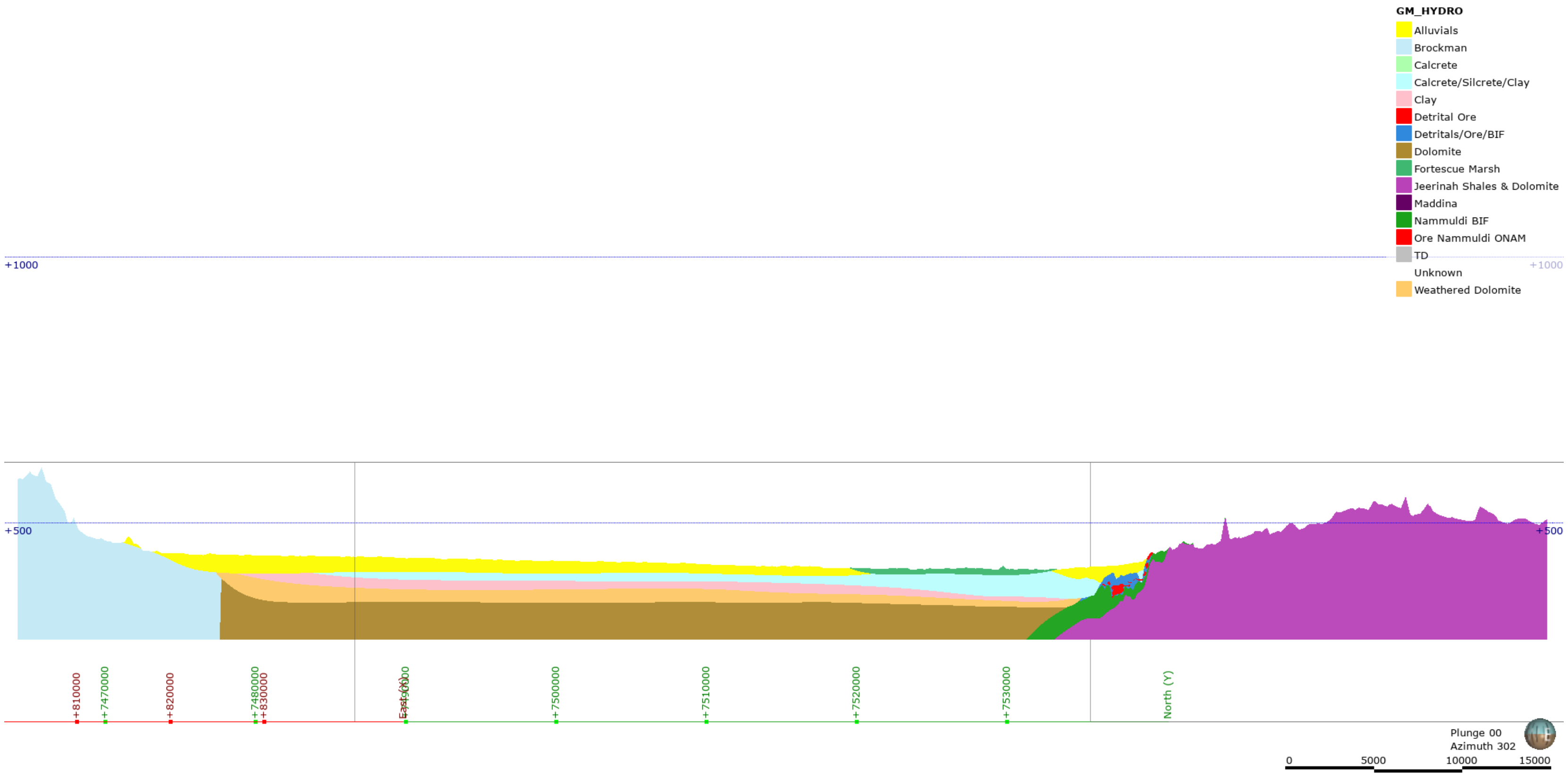
Comparison Section 1

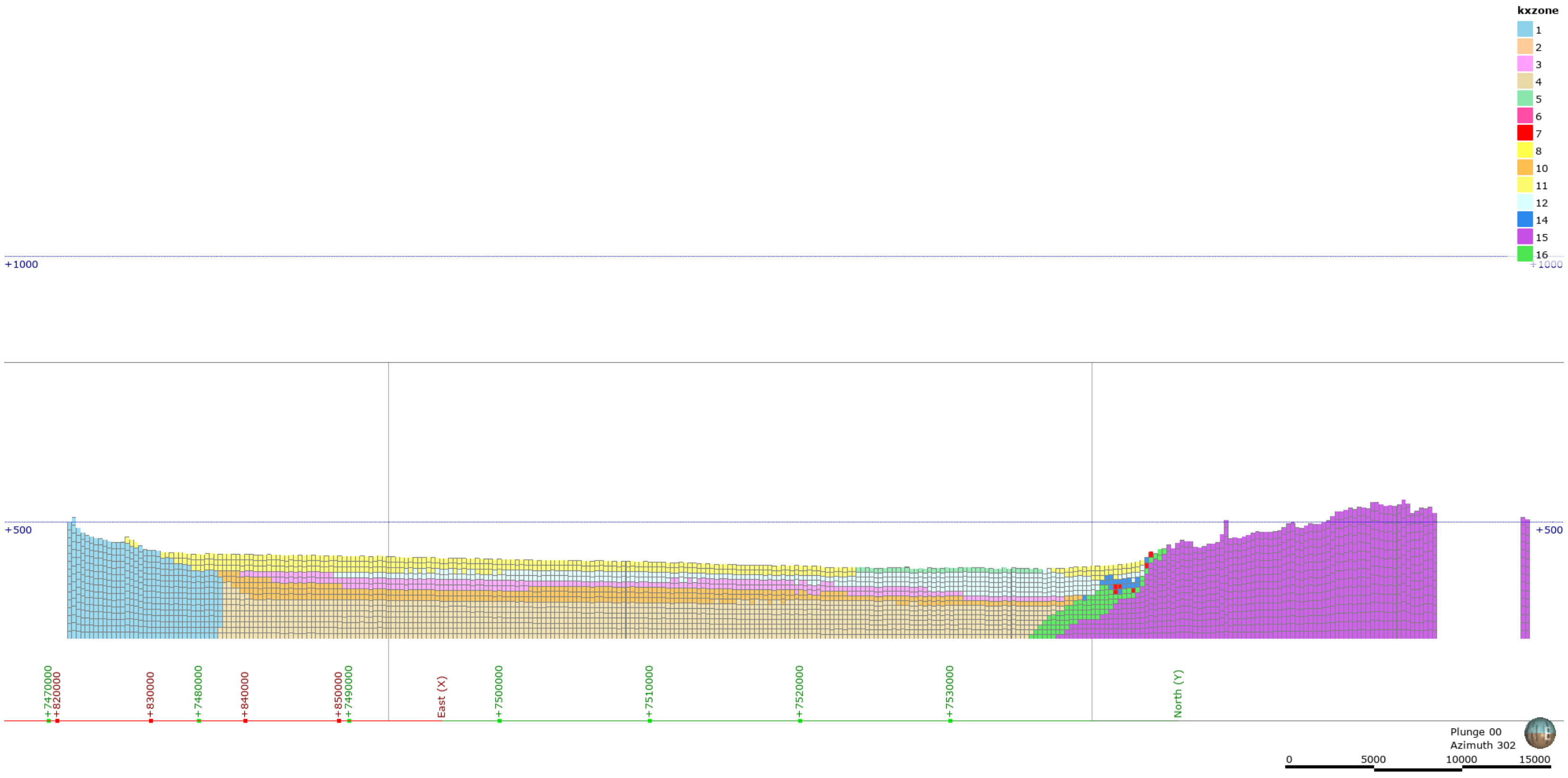


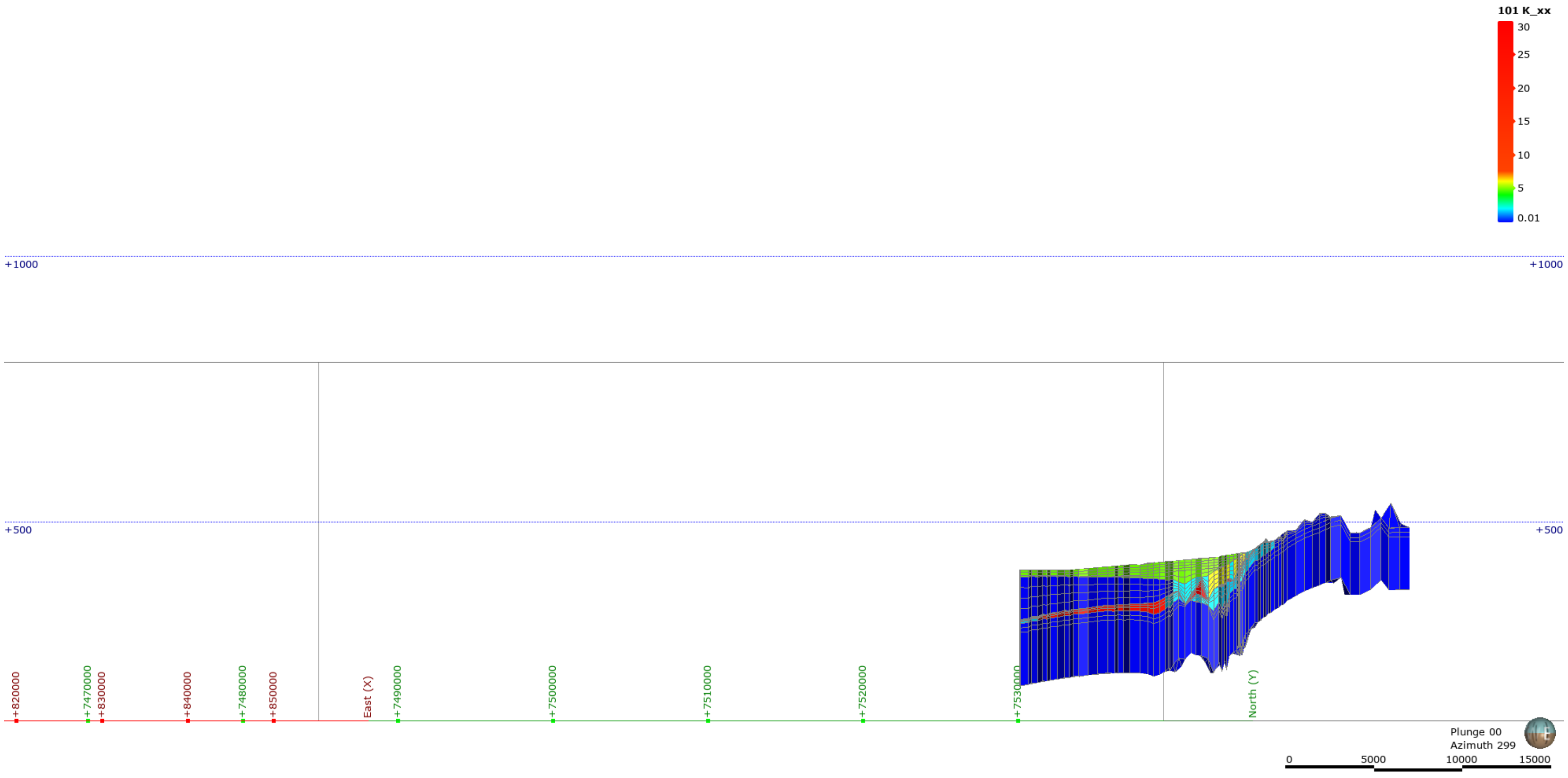




Comparison Section 2







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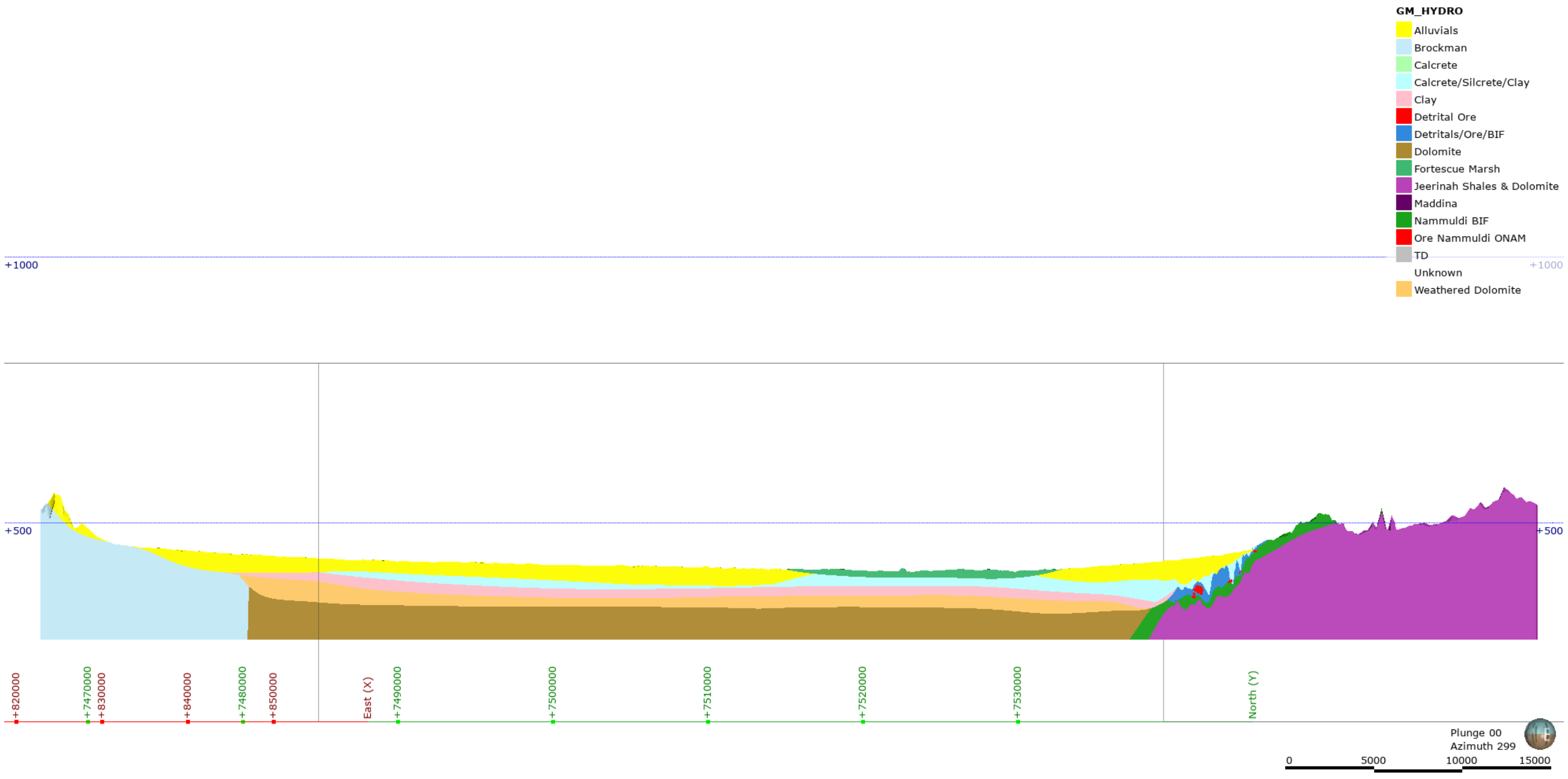
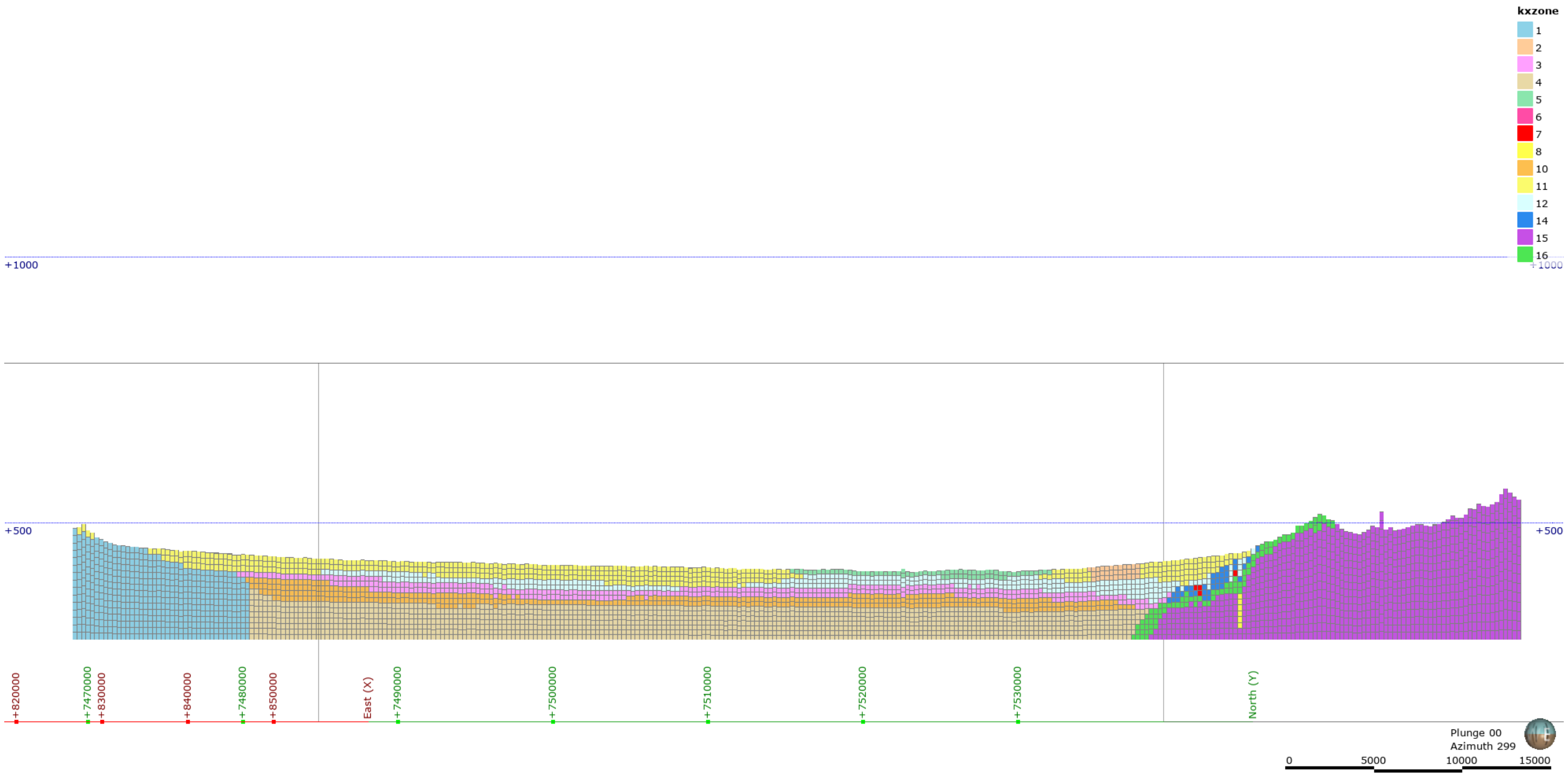
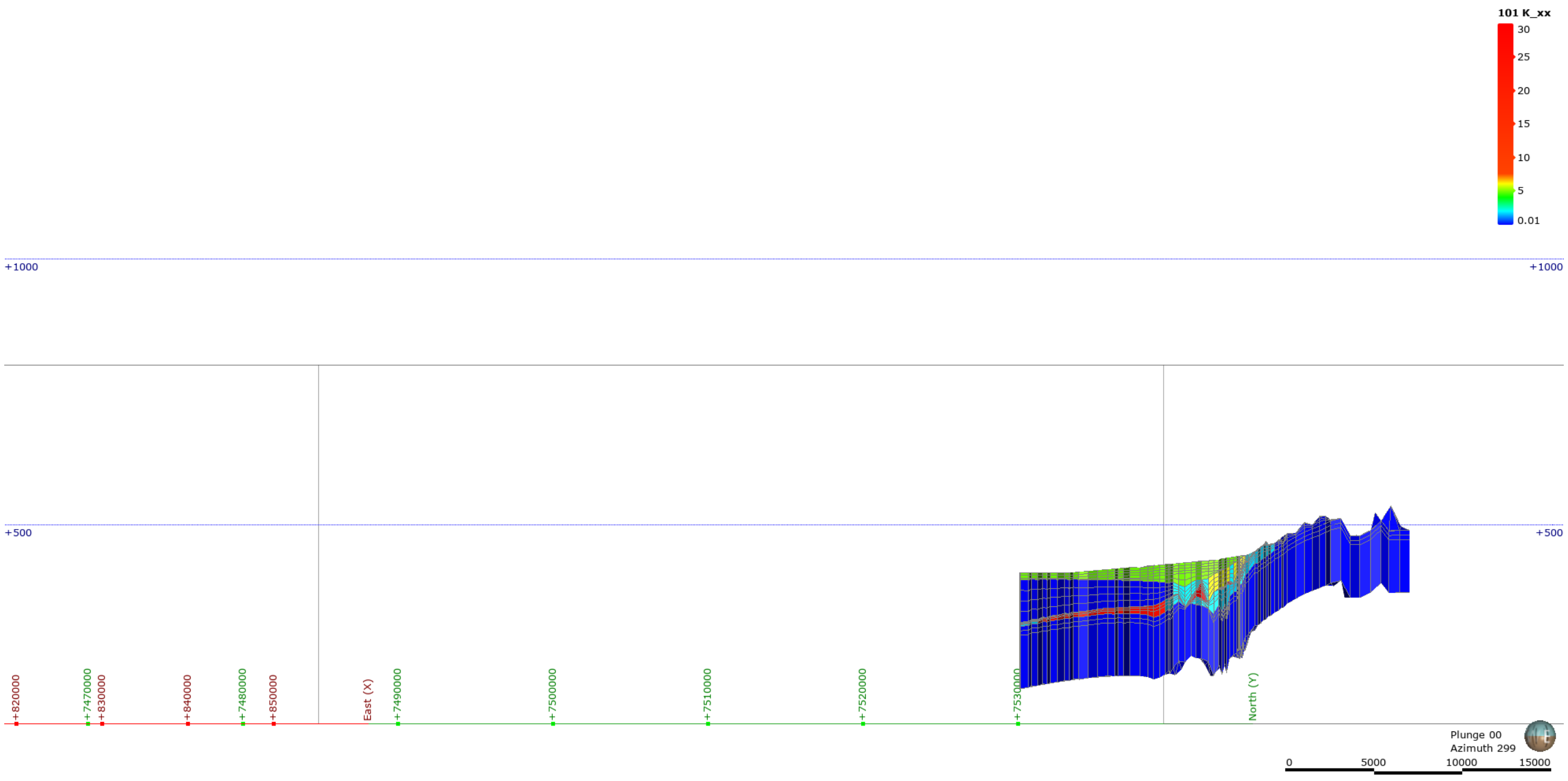
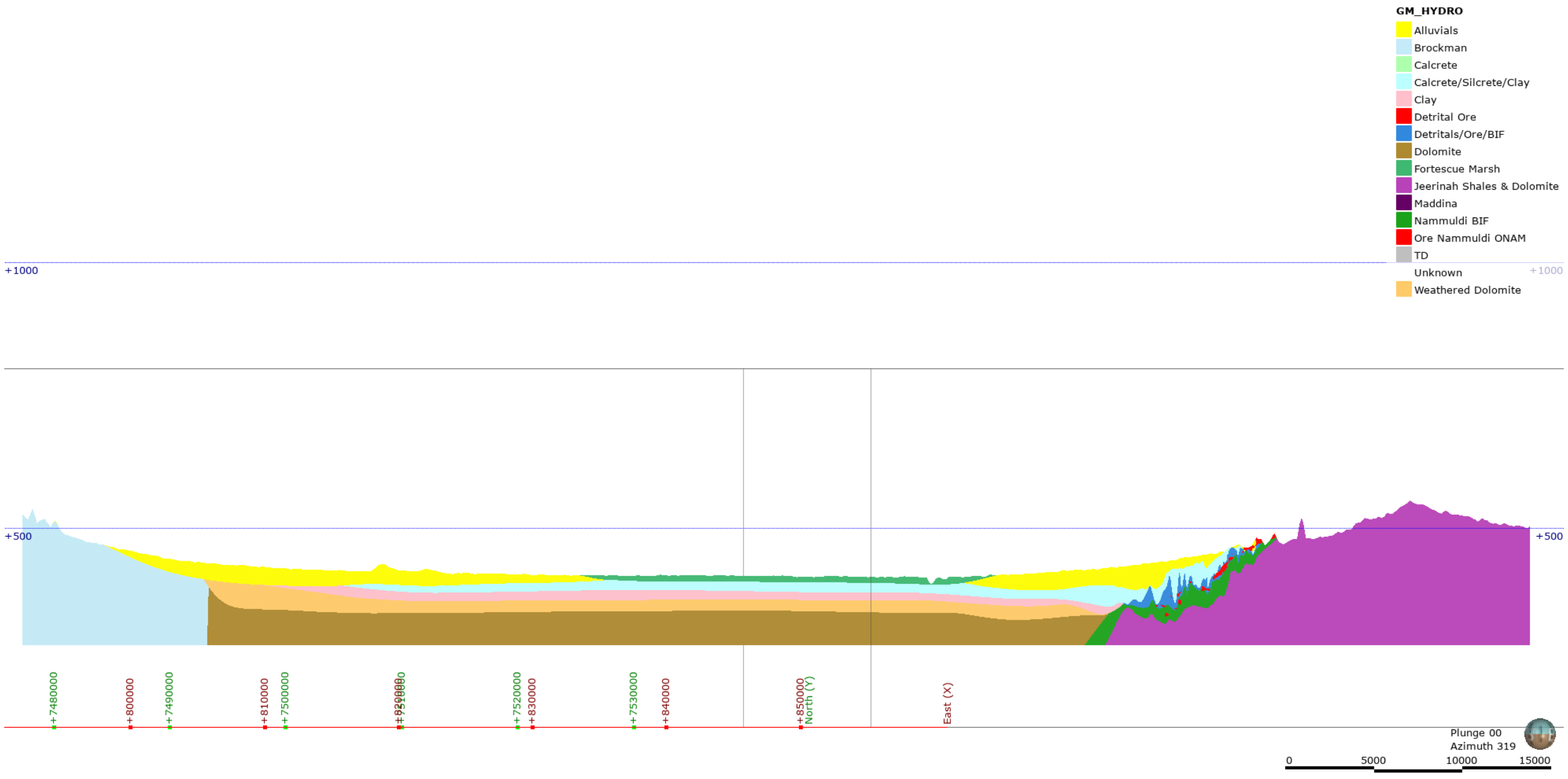
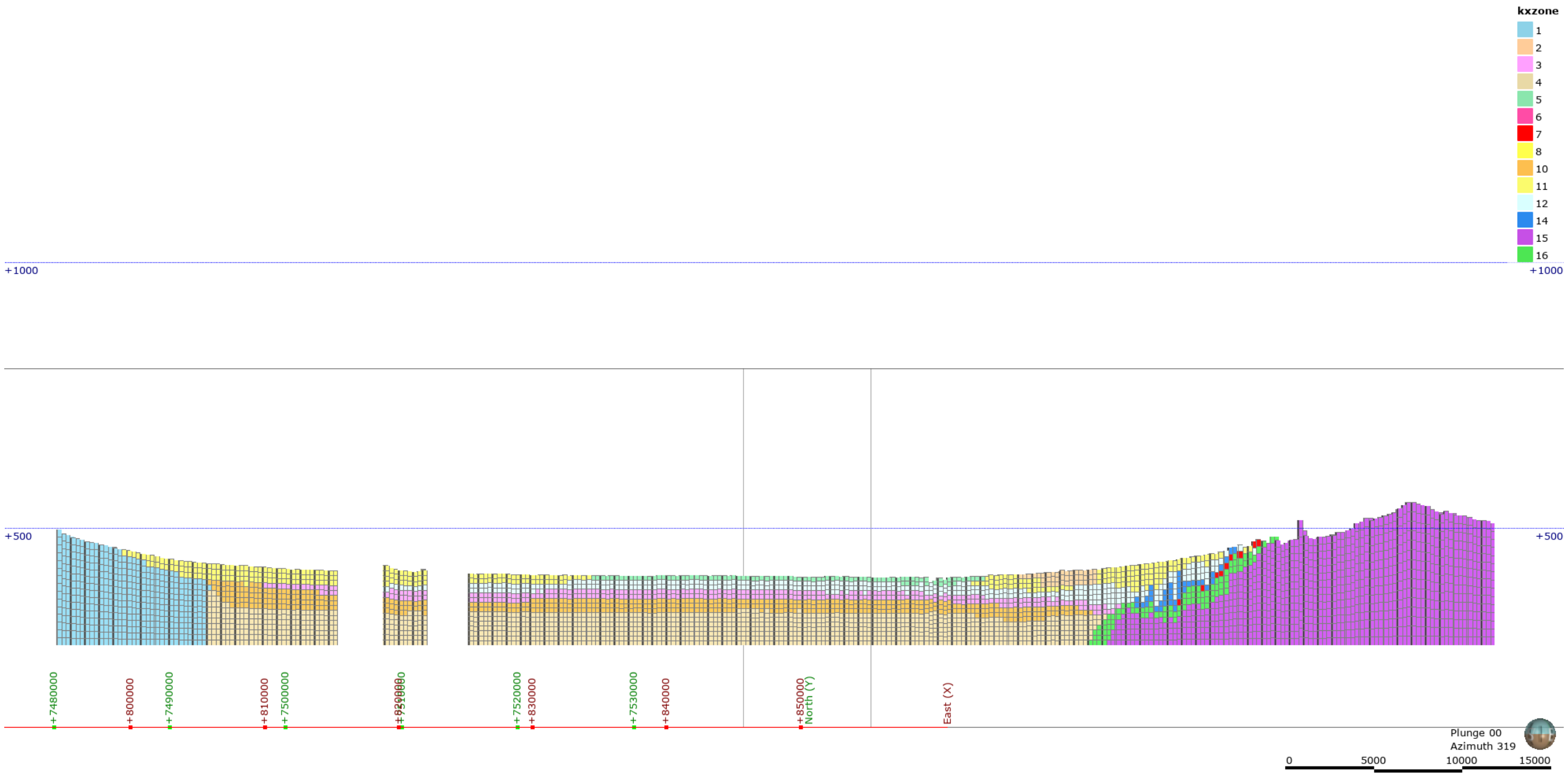


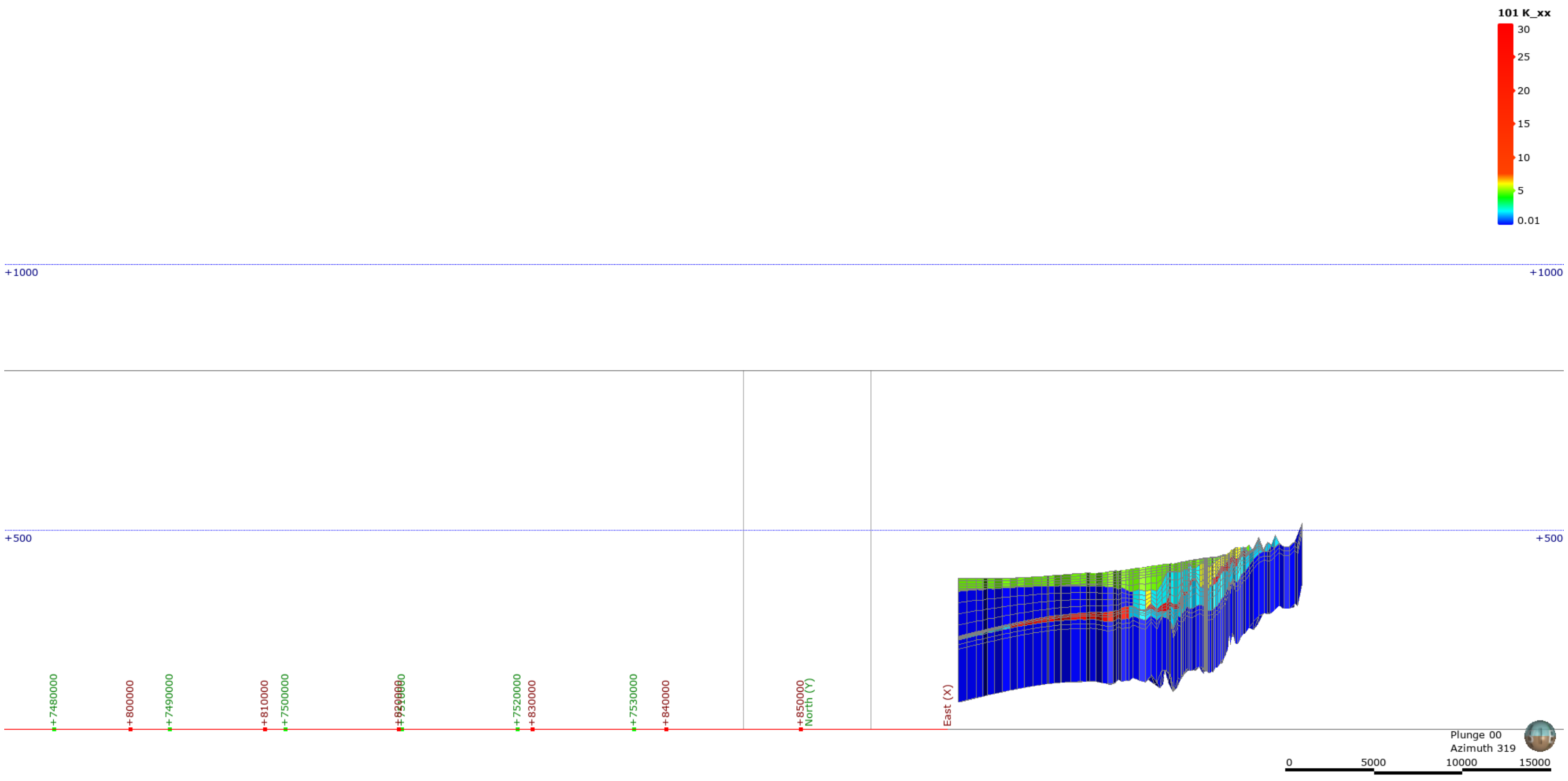




Leapfrog Section 1







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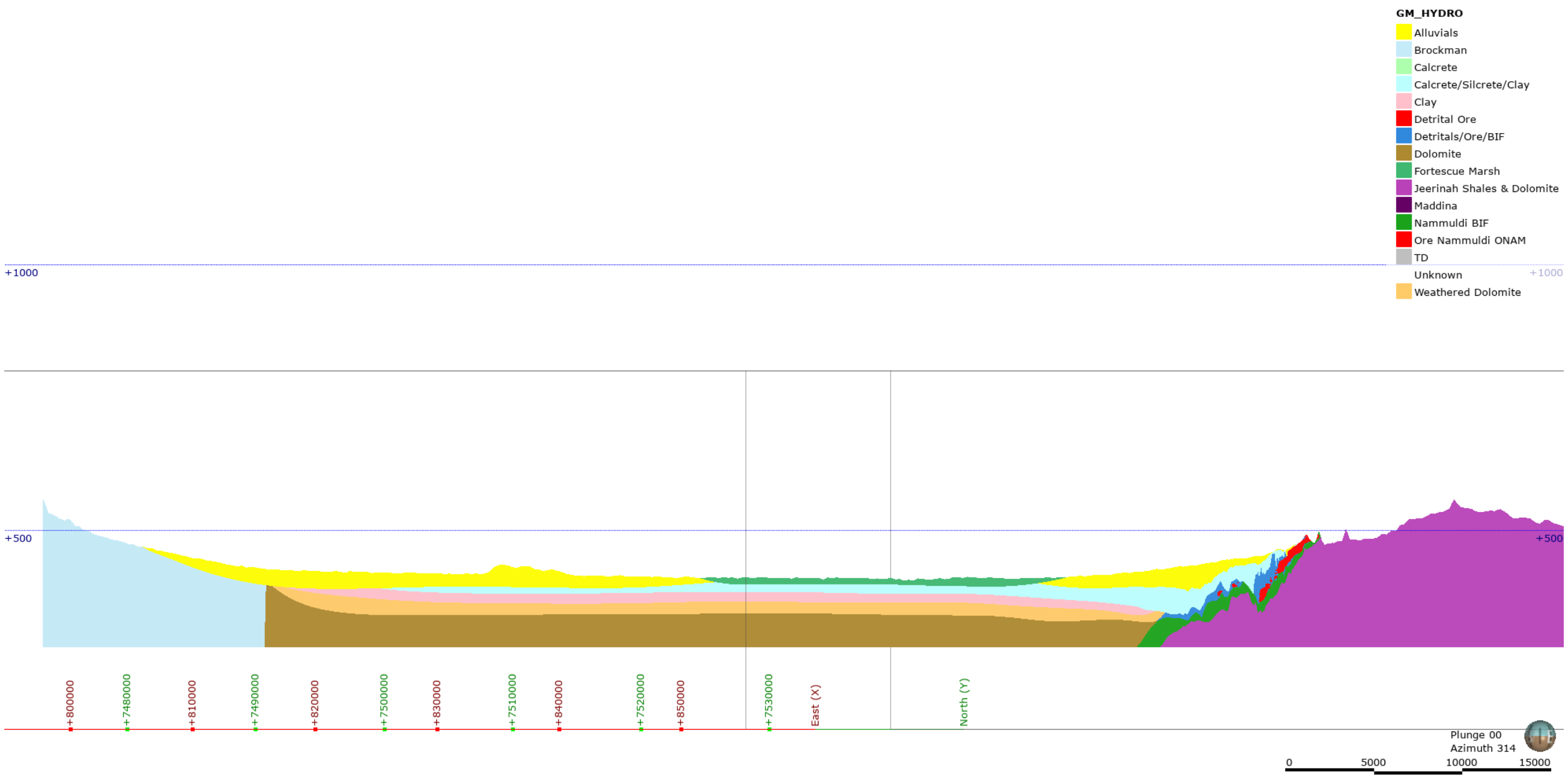
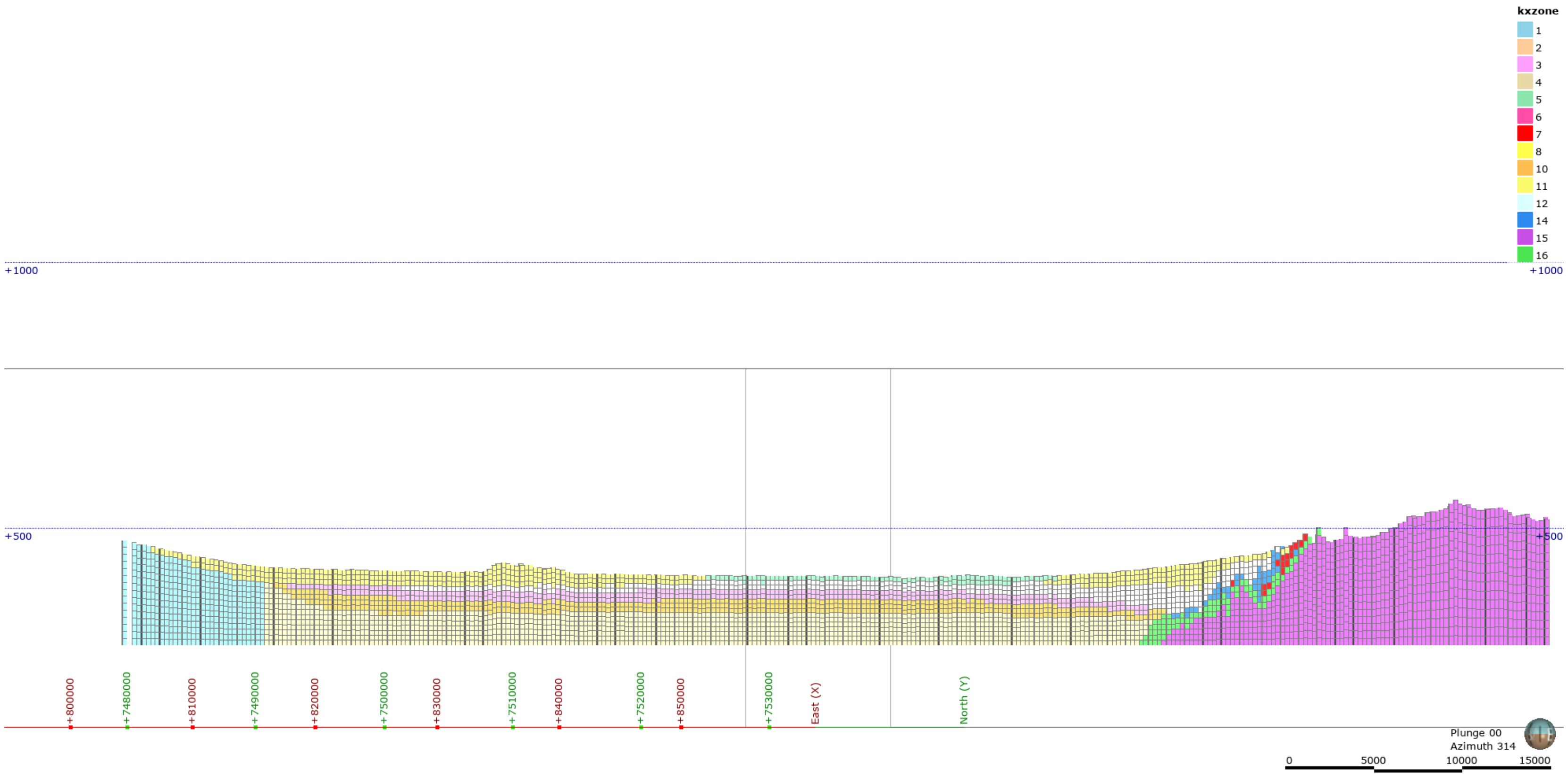
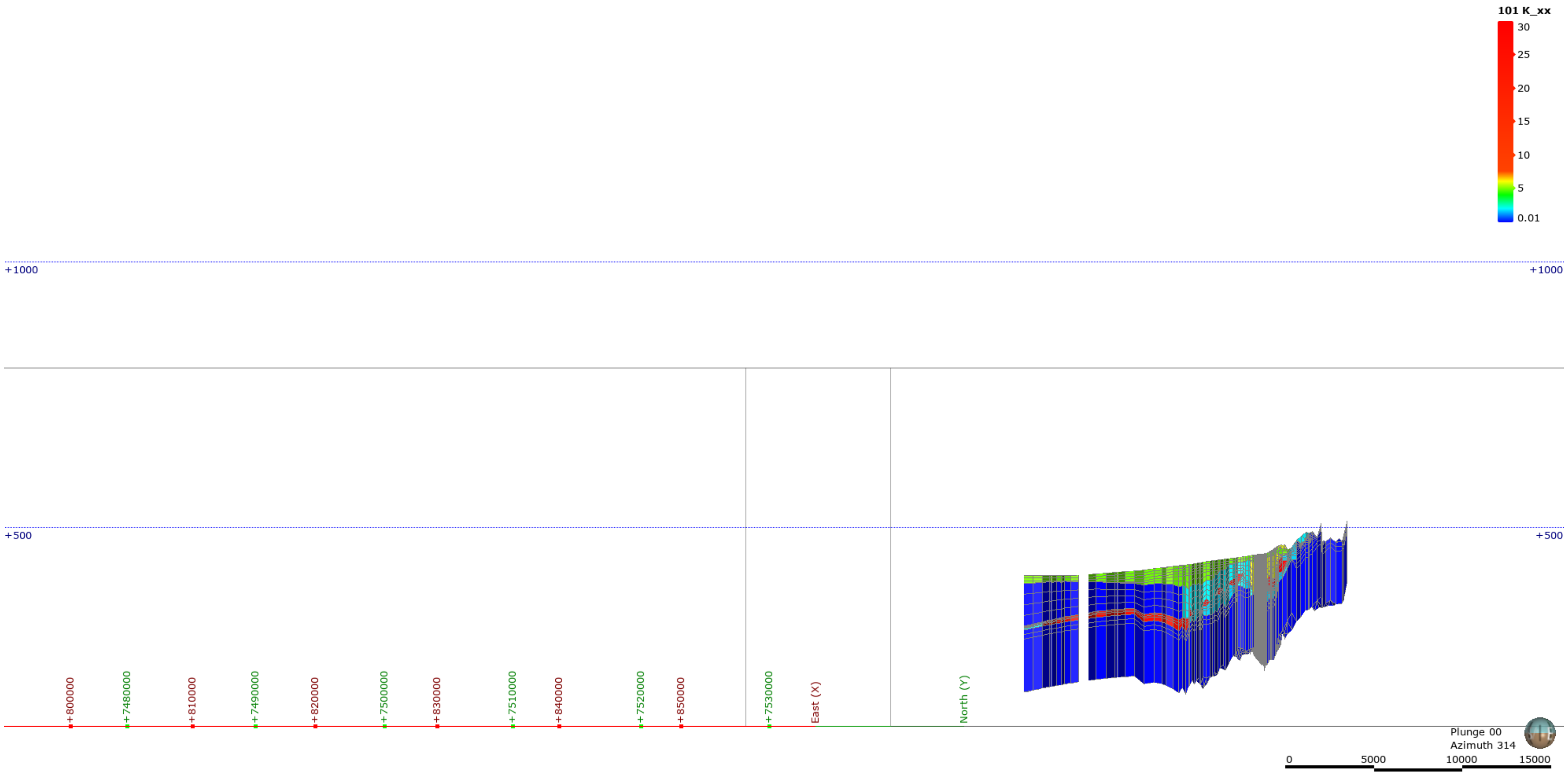
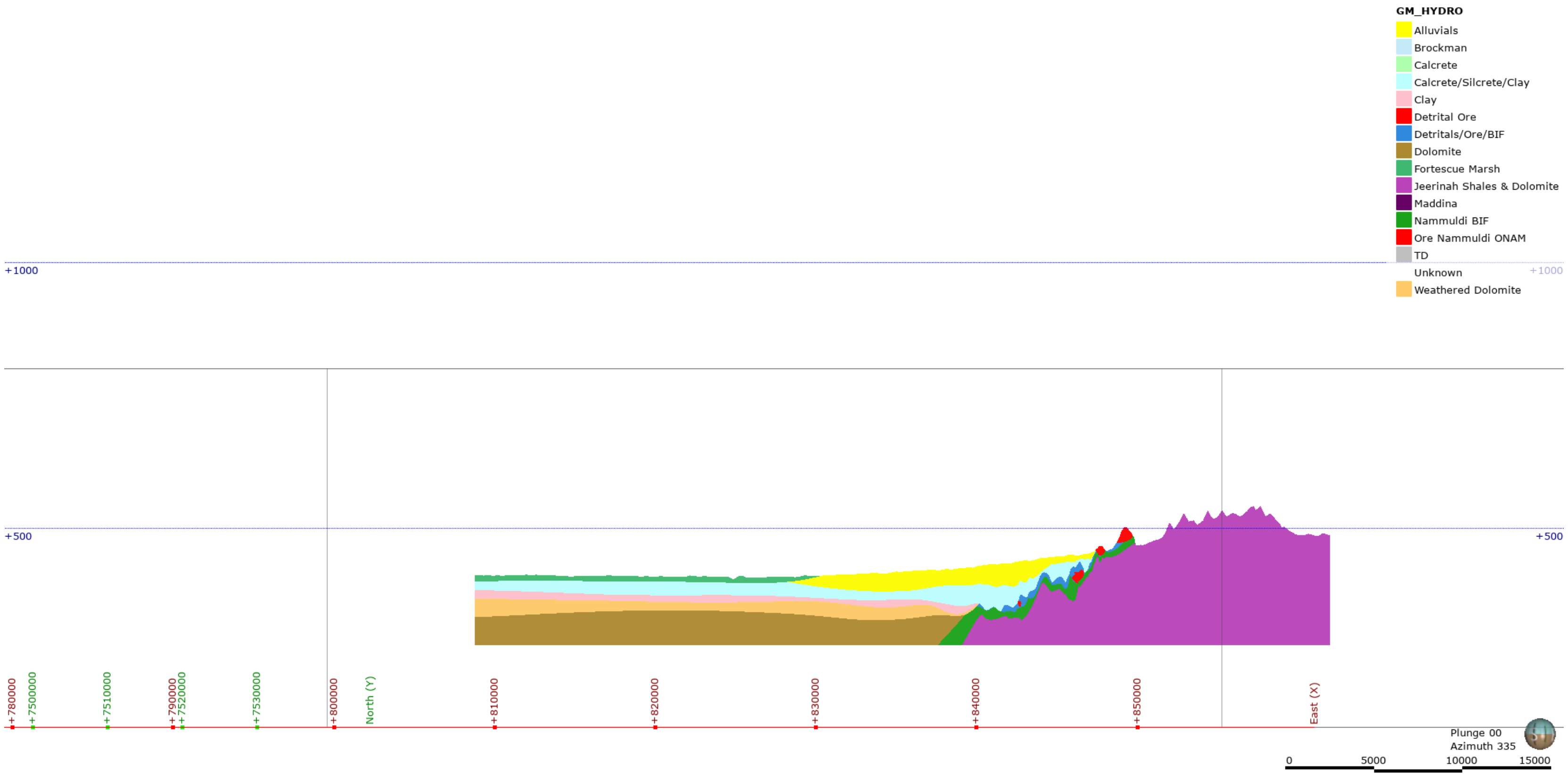
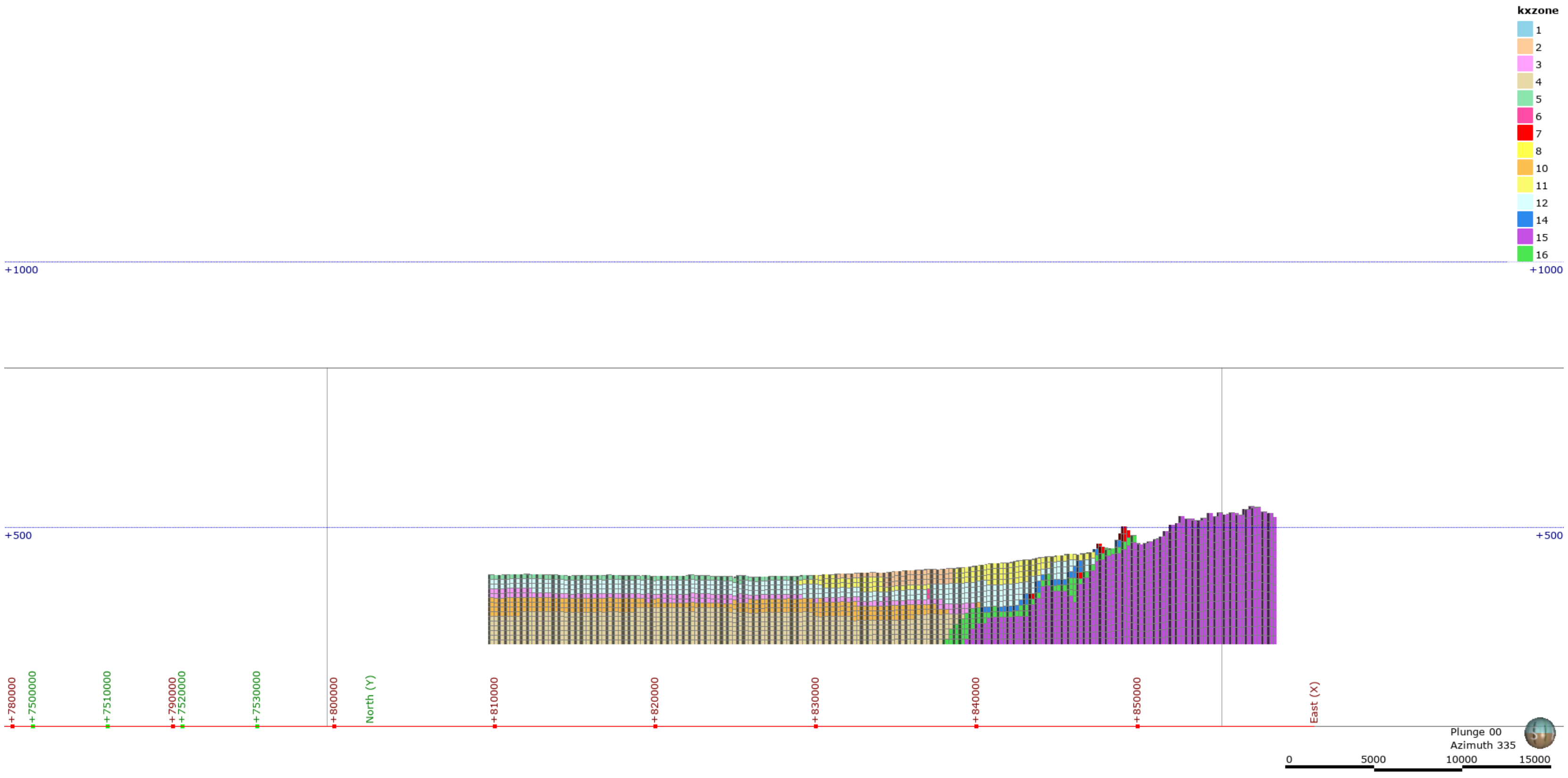


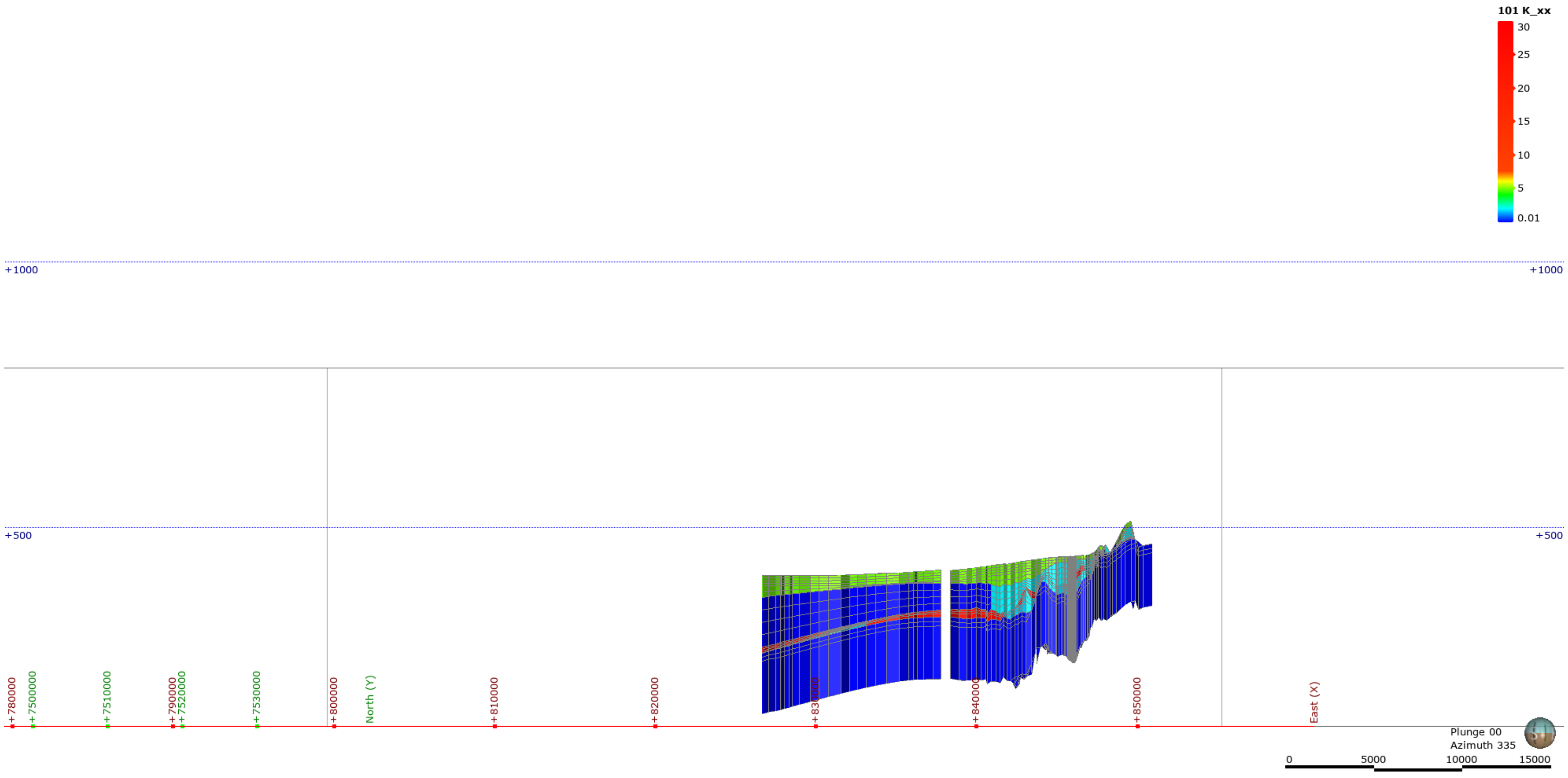




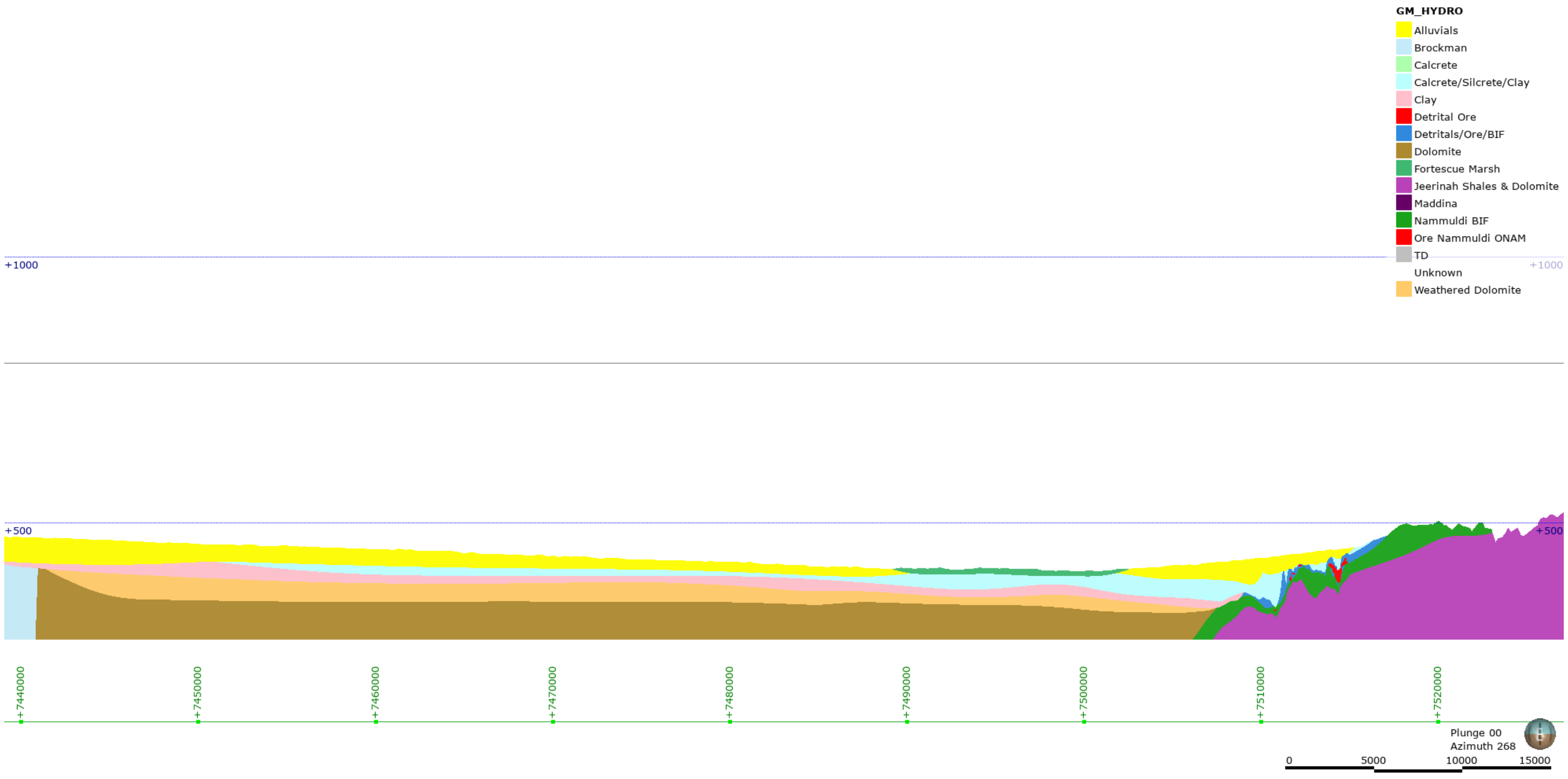
Leapfrog Section 3

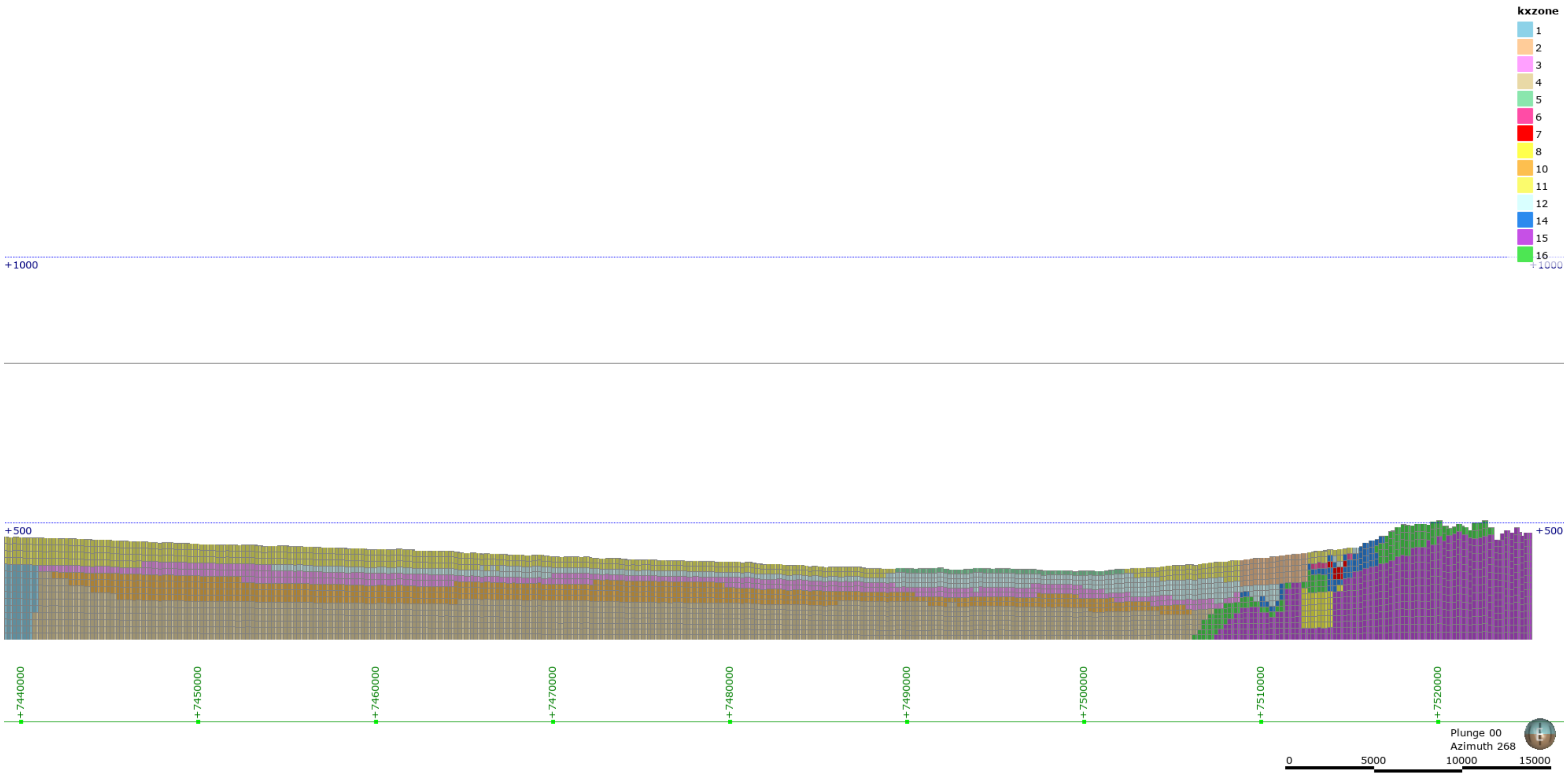


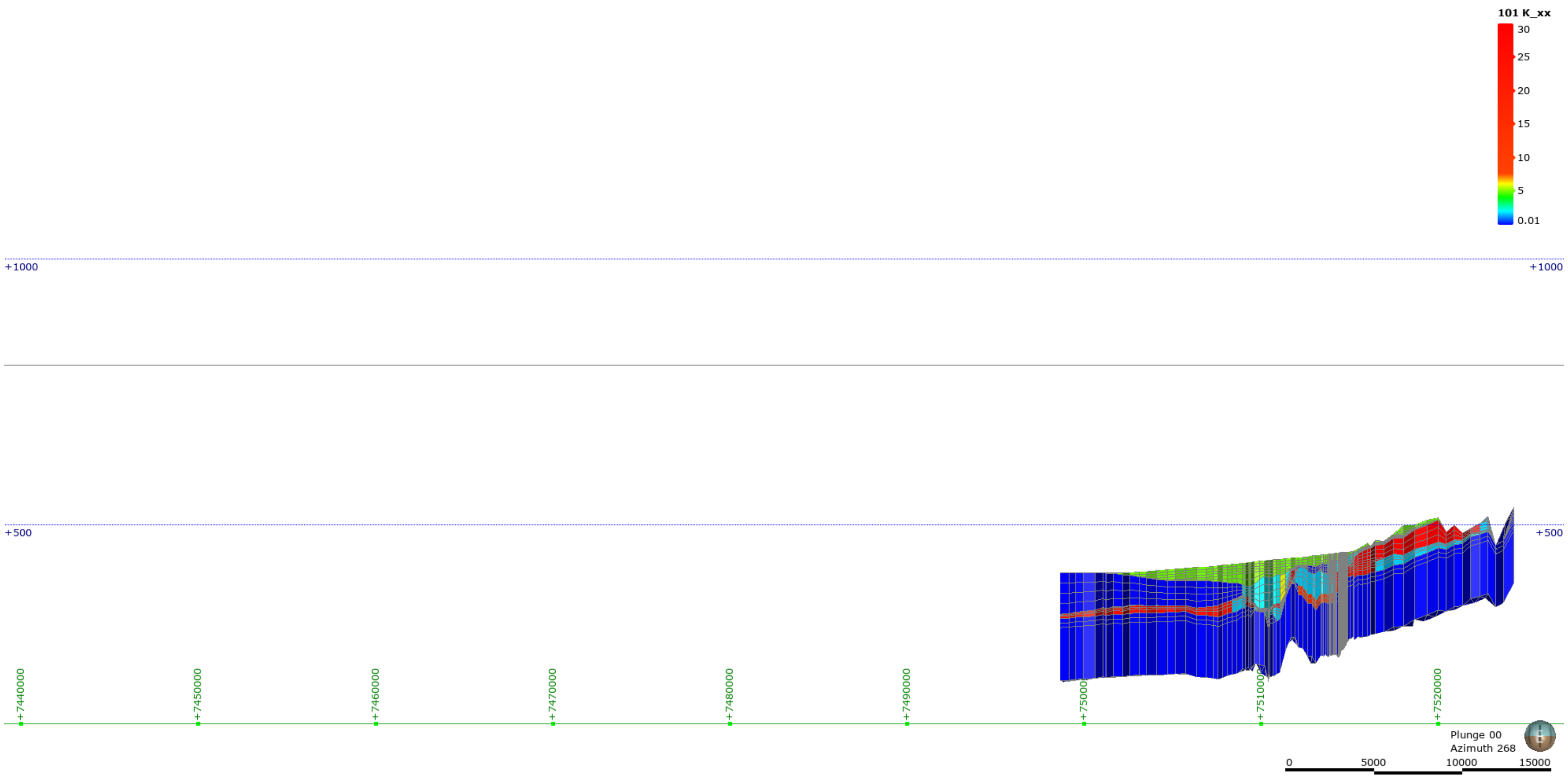




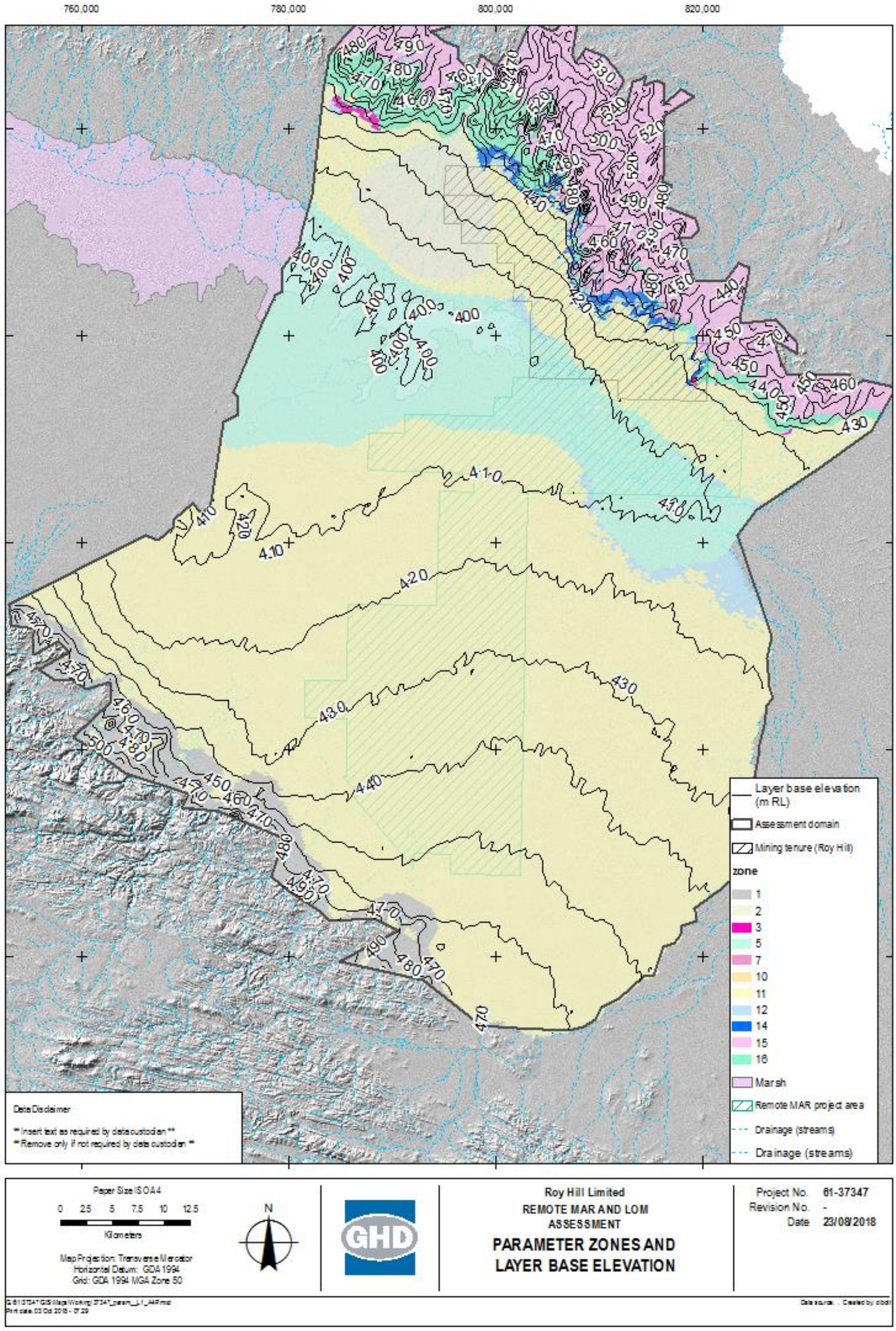
Leapfrog Section 4



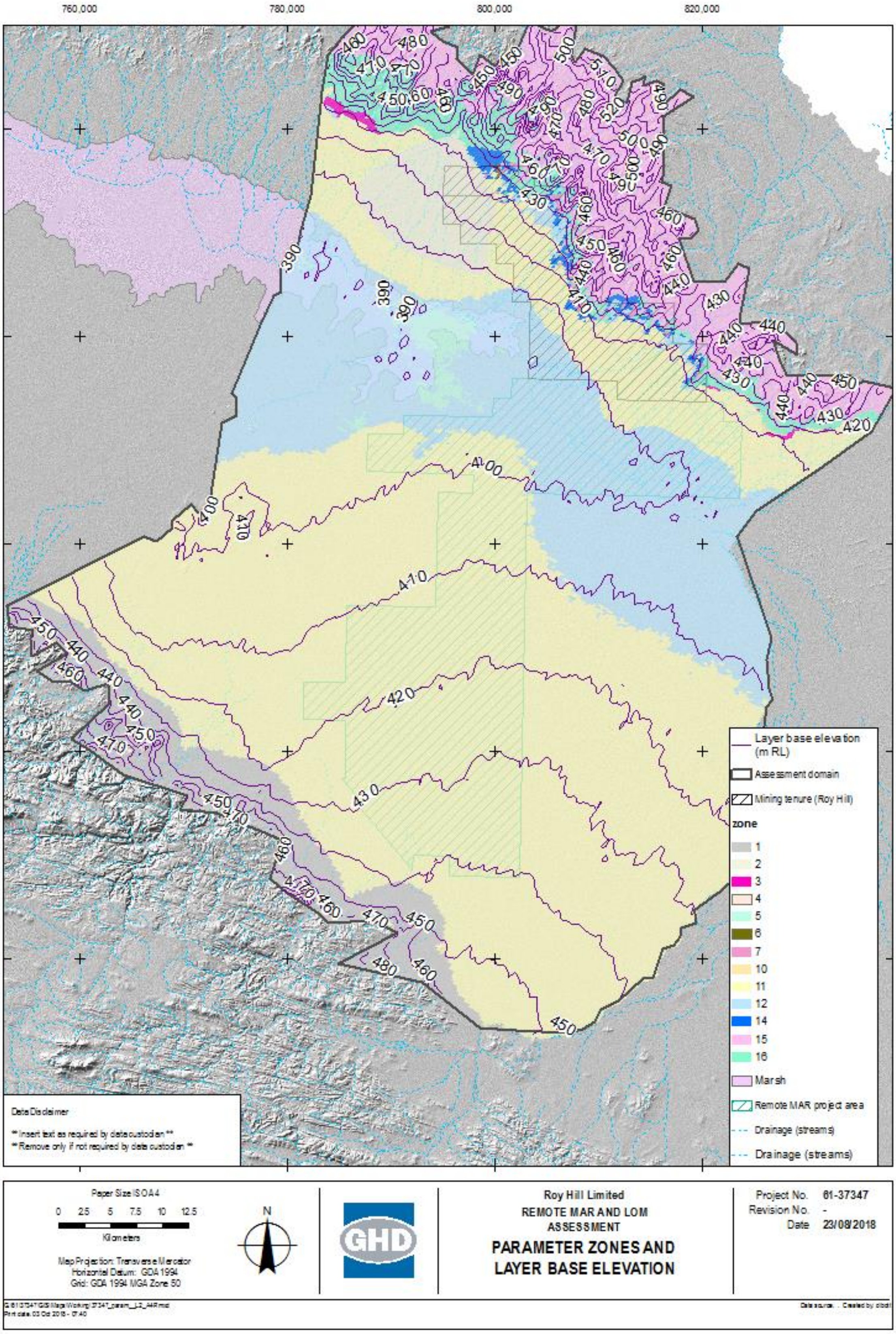




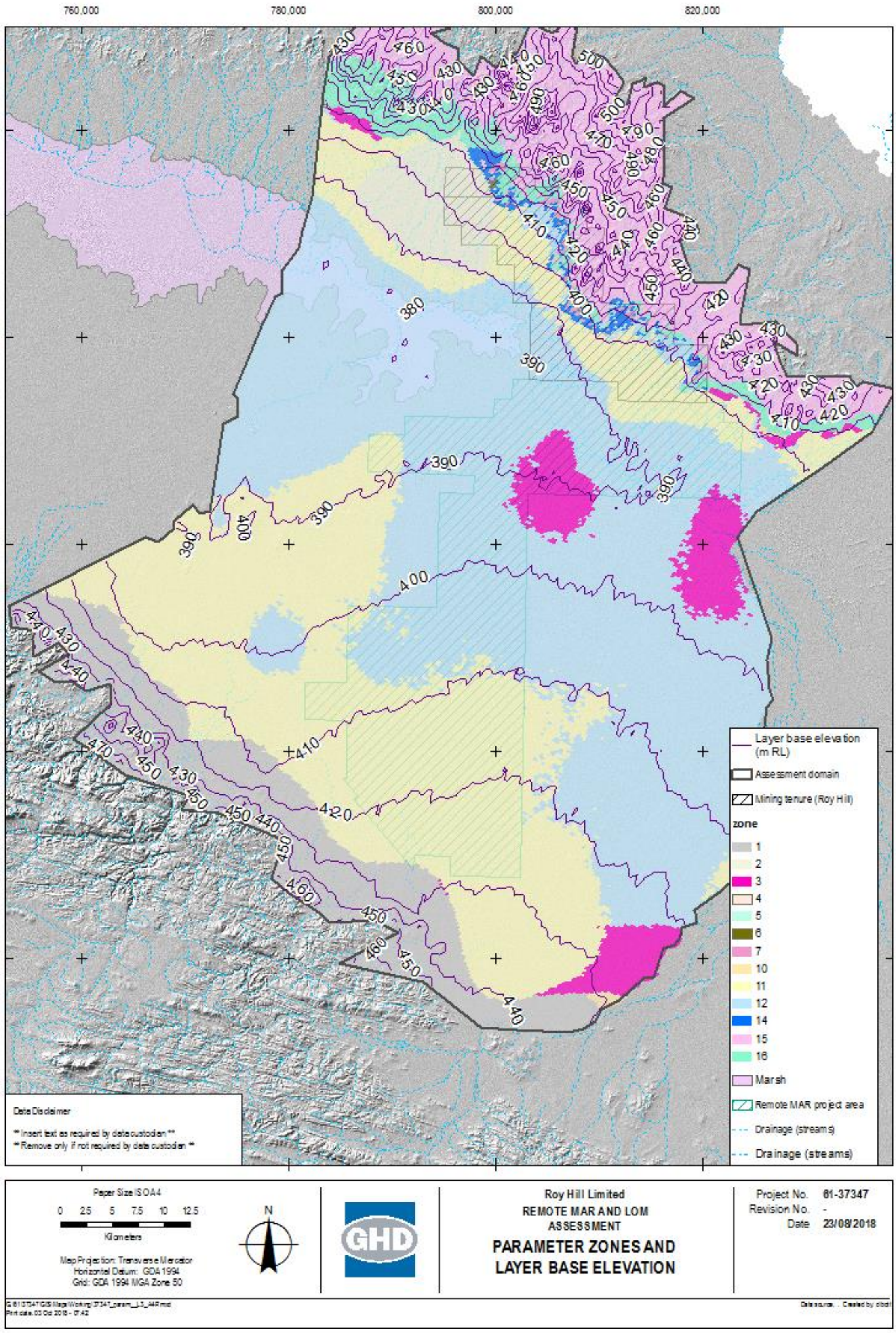
Appendix D Hydraulic property zone maps



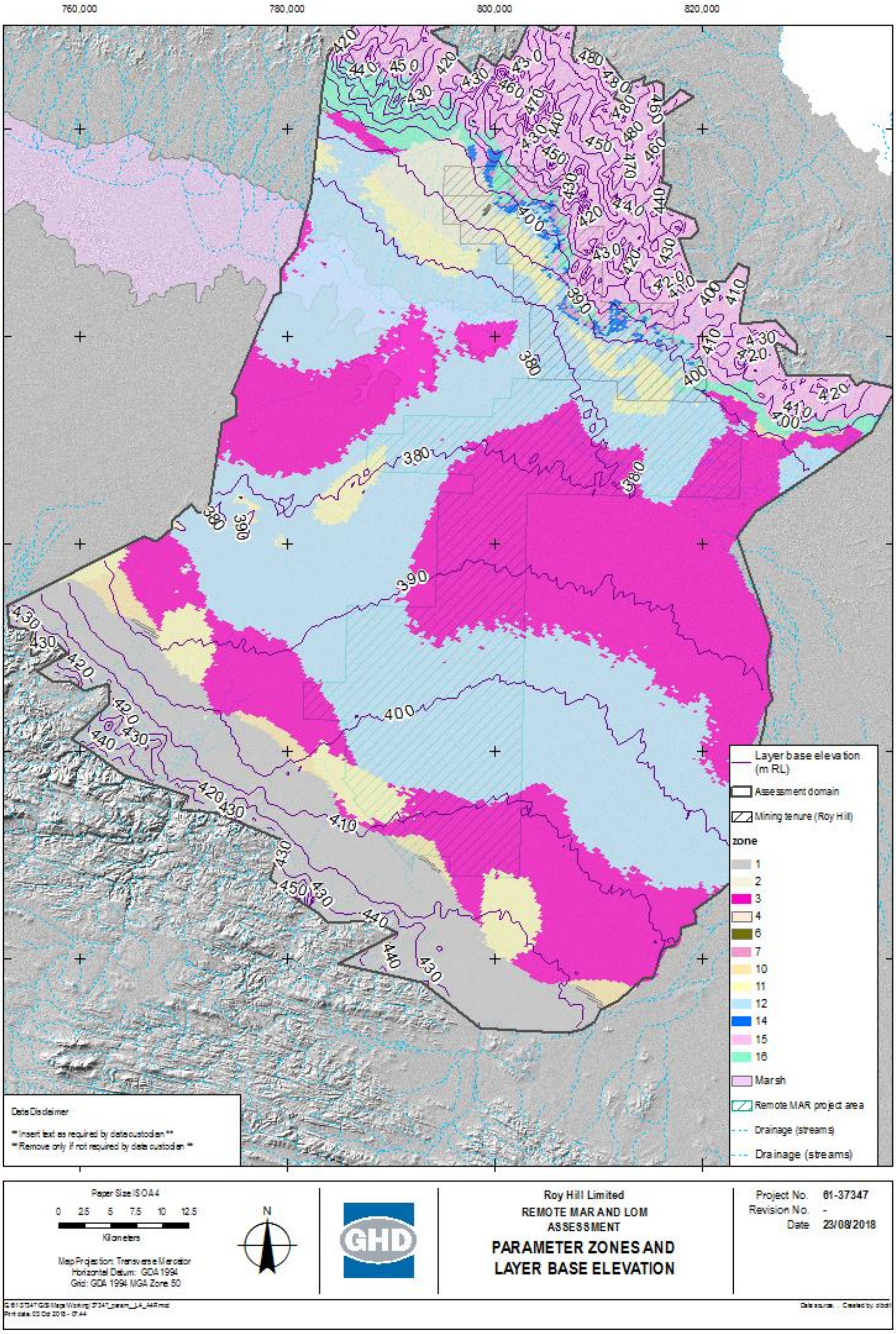
Parameter zone spatial delineation and base elevations, model layer 1



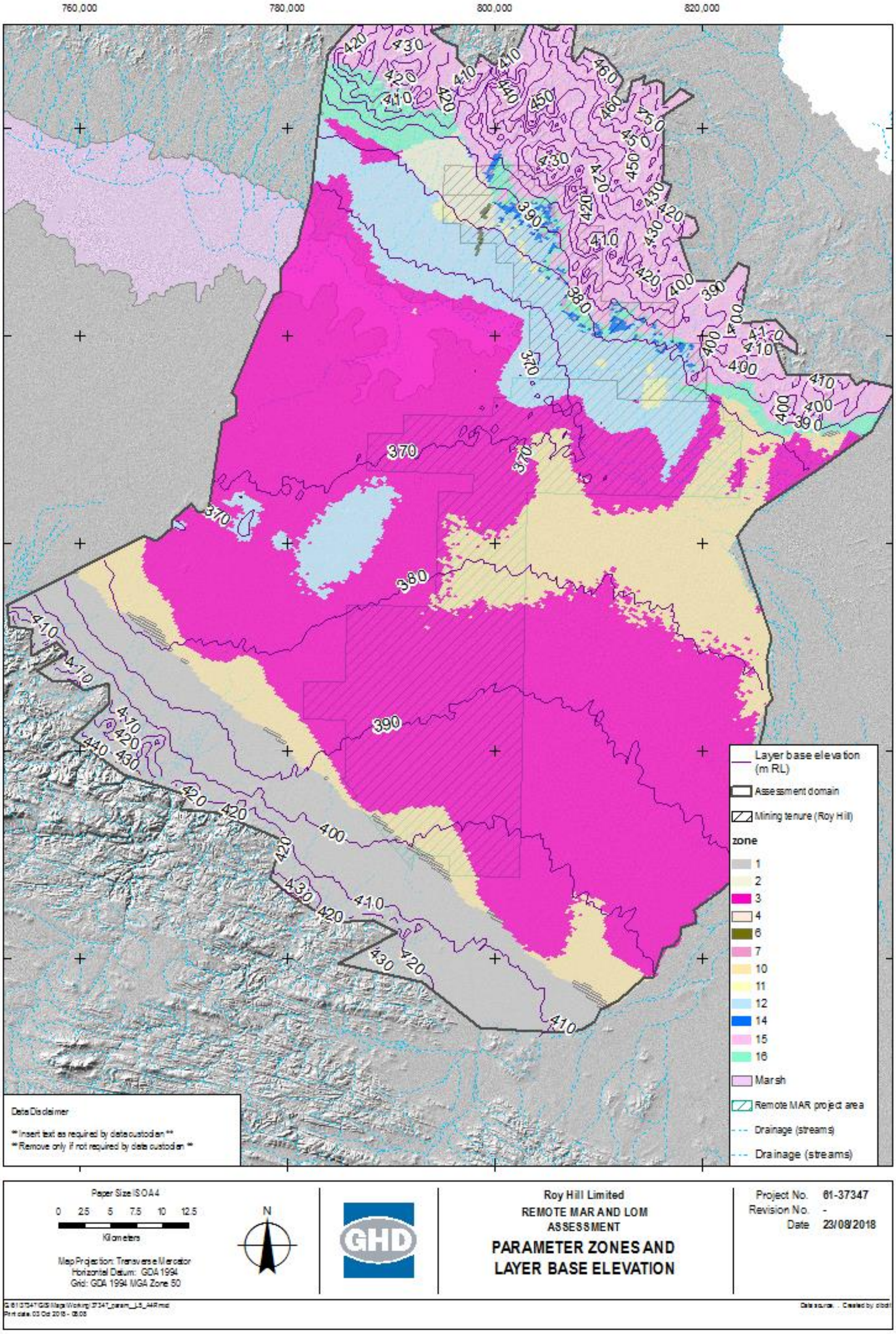
Parameter zone spatial delineation and base elevations, model layer 2



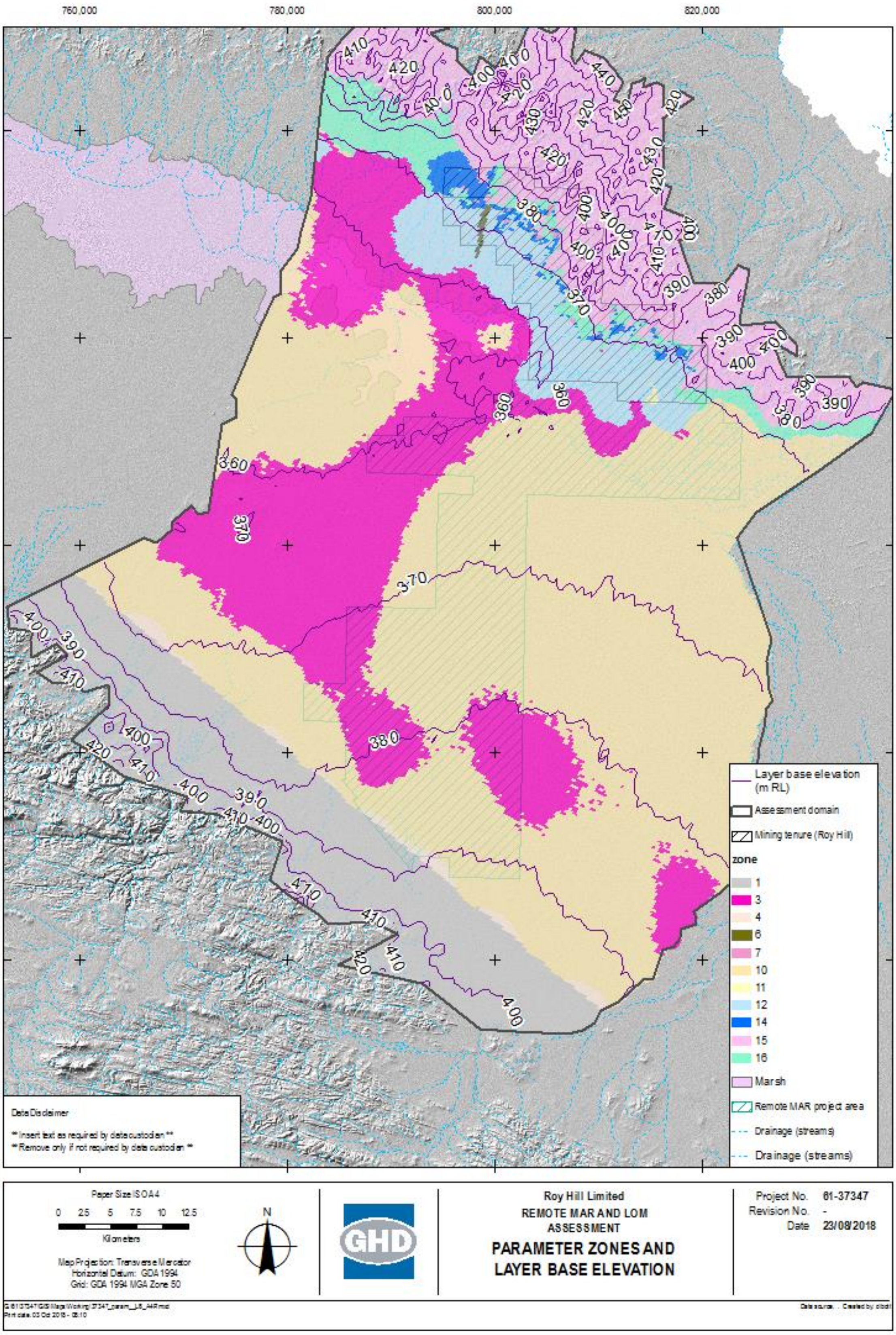
Parameter zone spatial delineation and base elevations, model layer 3



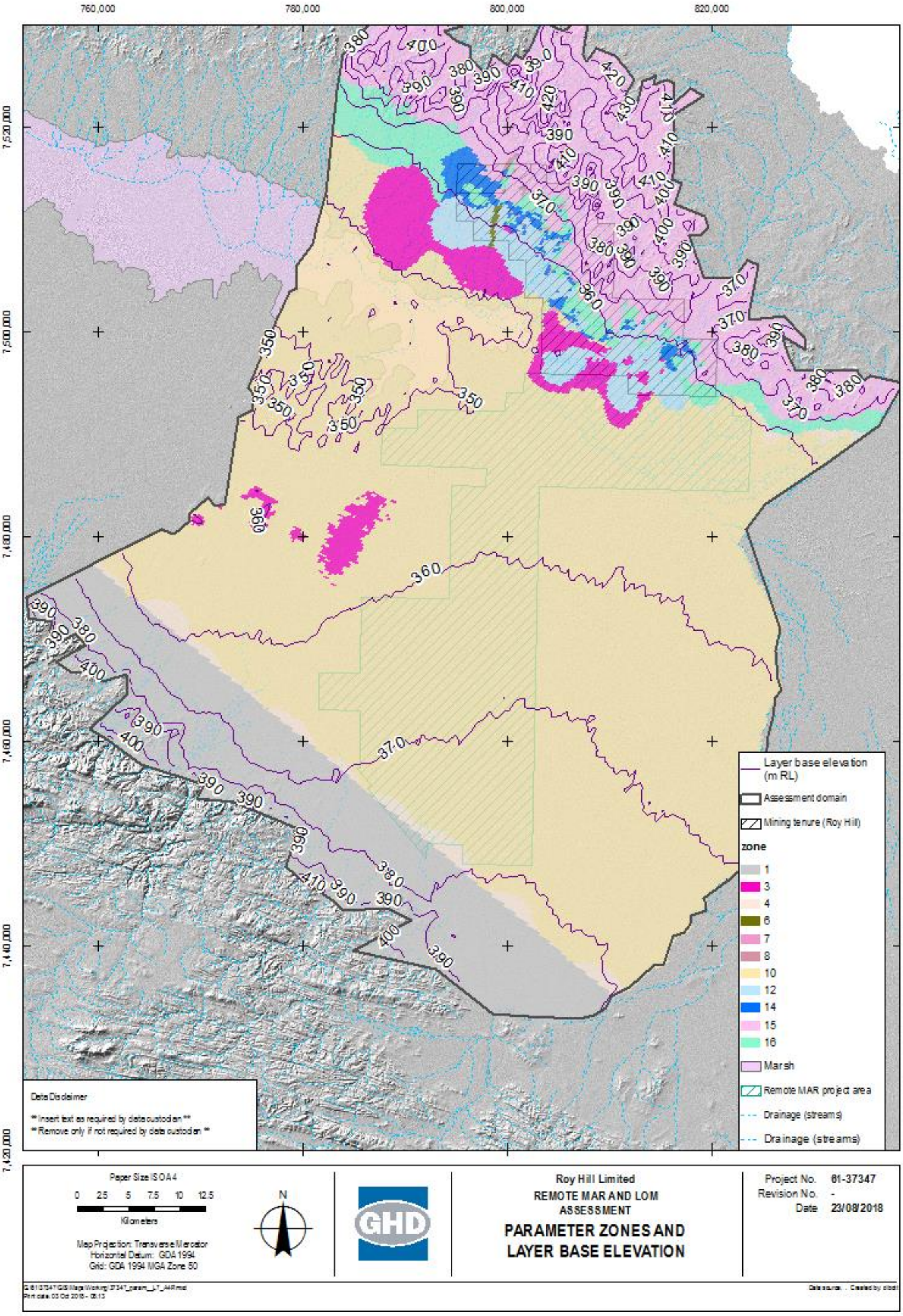
Parameter zone spatial delineation and base elevations, model layer 4



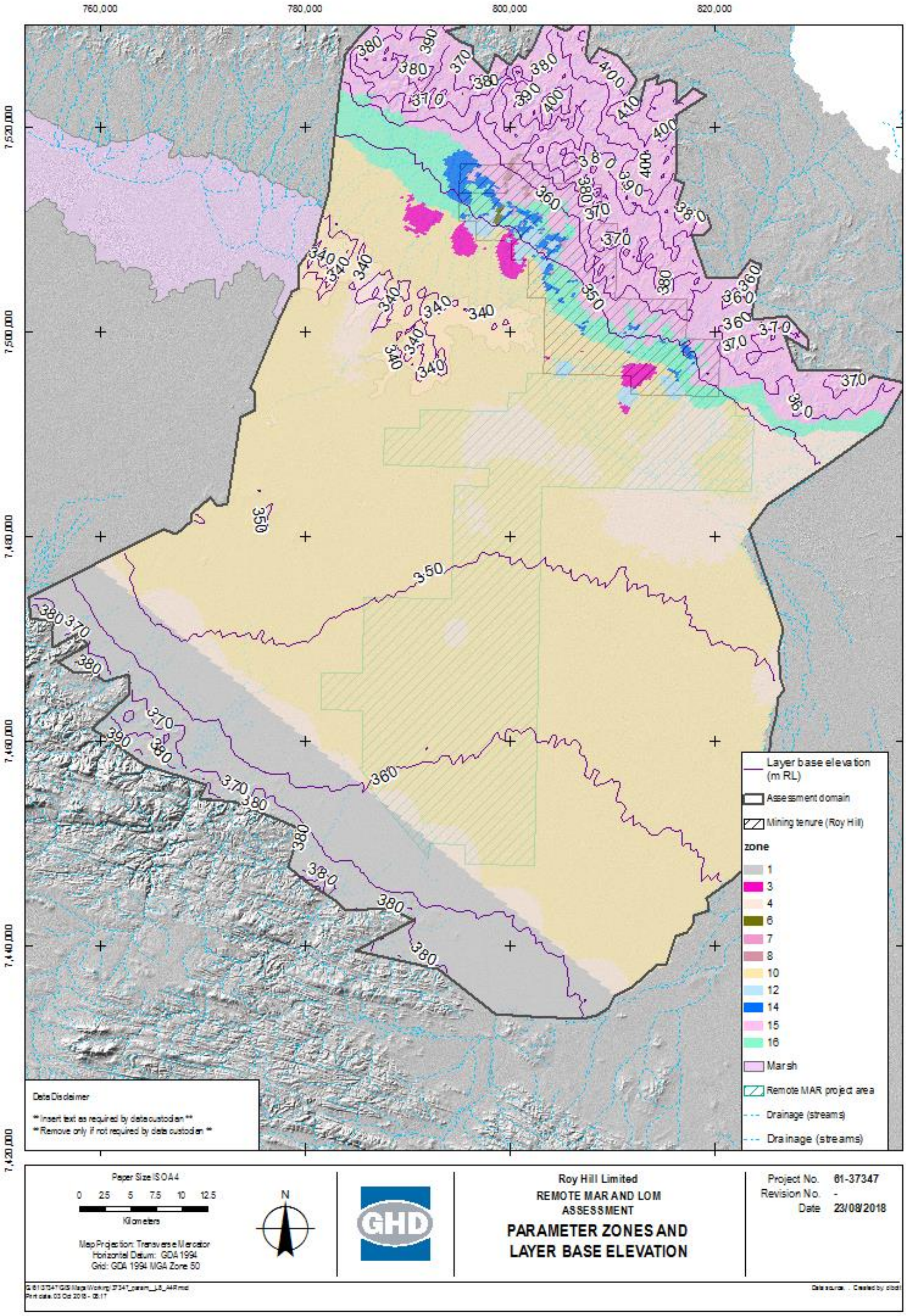
Parameter zone spatial delineation and base elevations, model layer 5



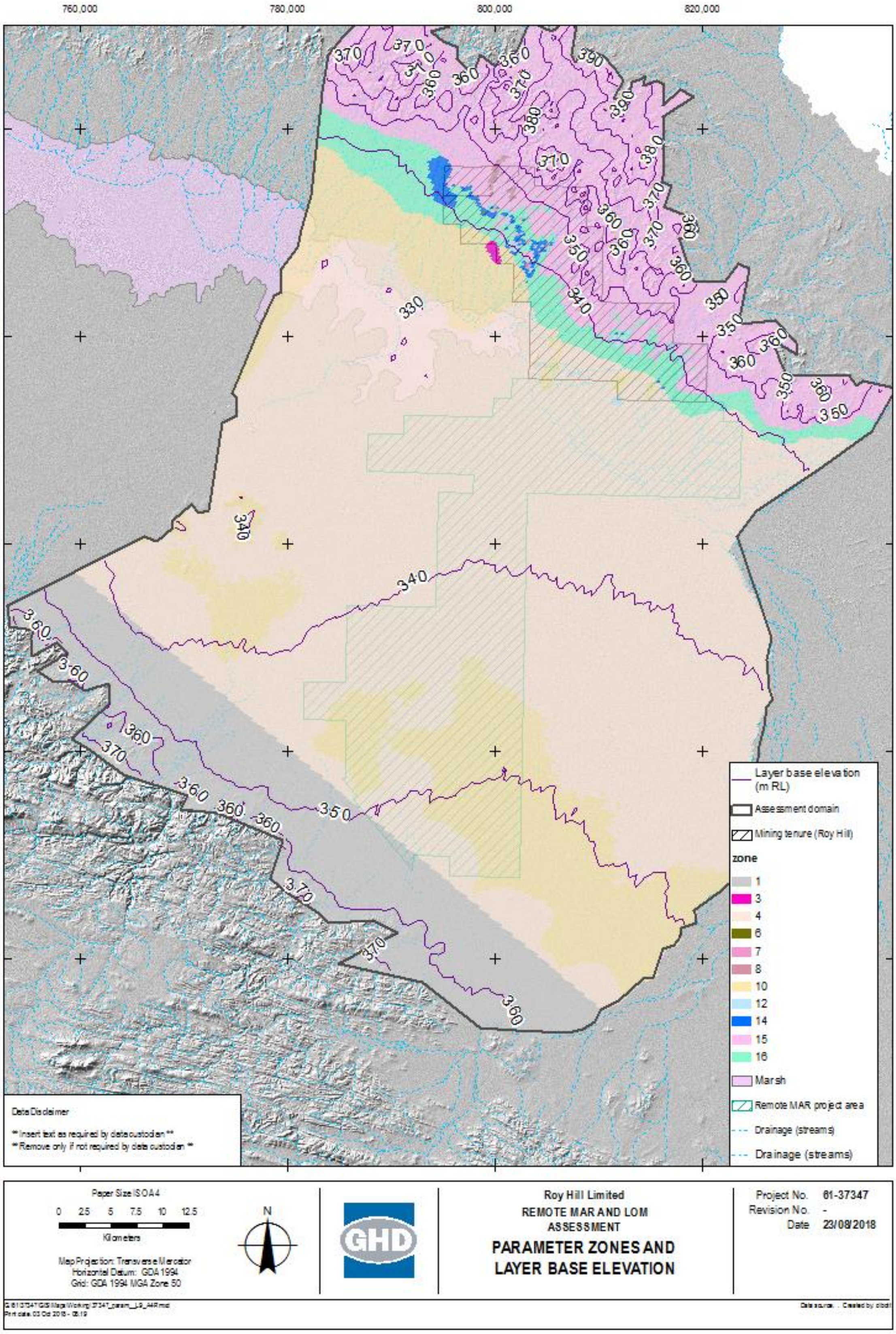
Parameter zone spatial delineation and base elevations, model layer 6



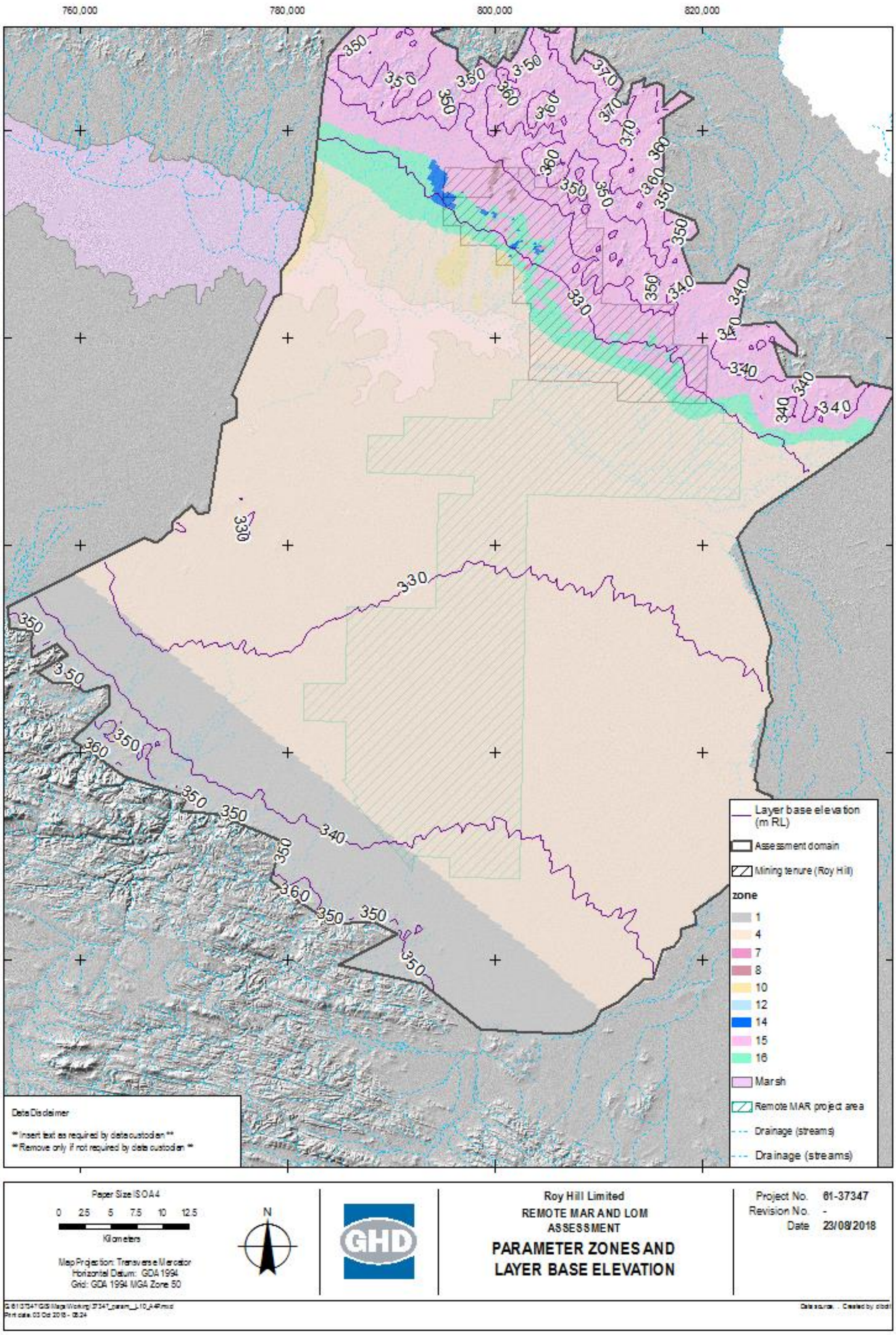
Parameter zone spatial delineation and base elevations, model layer 7



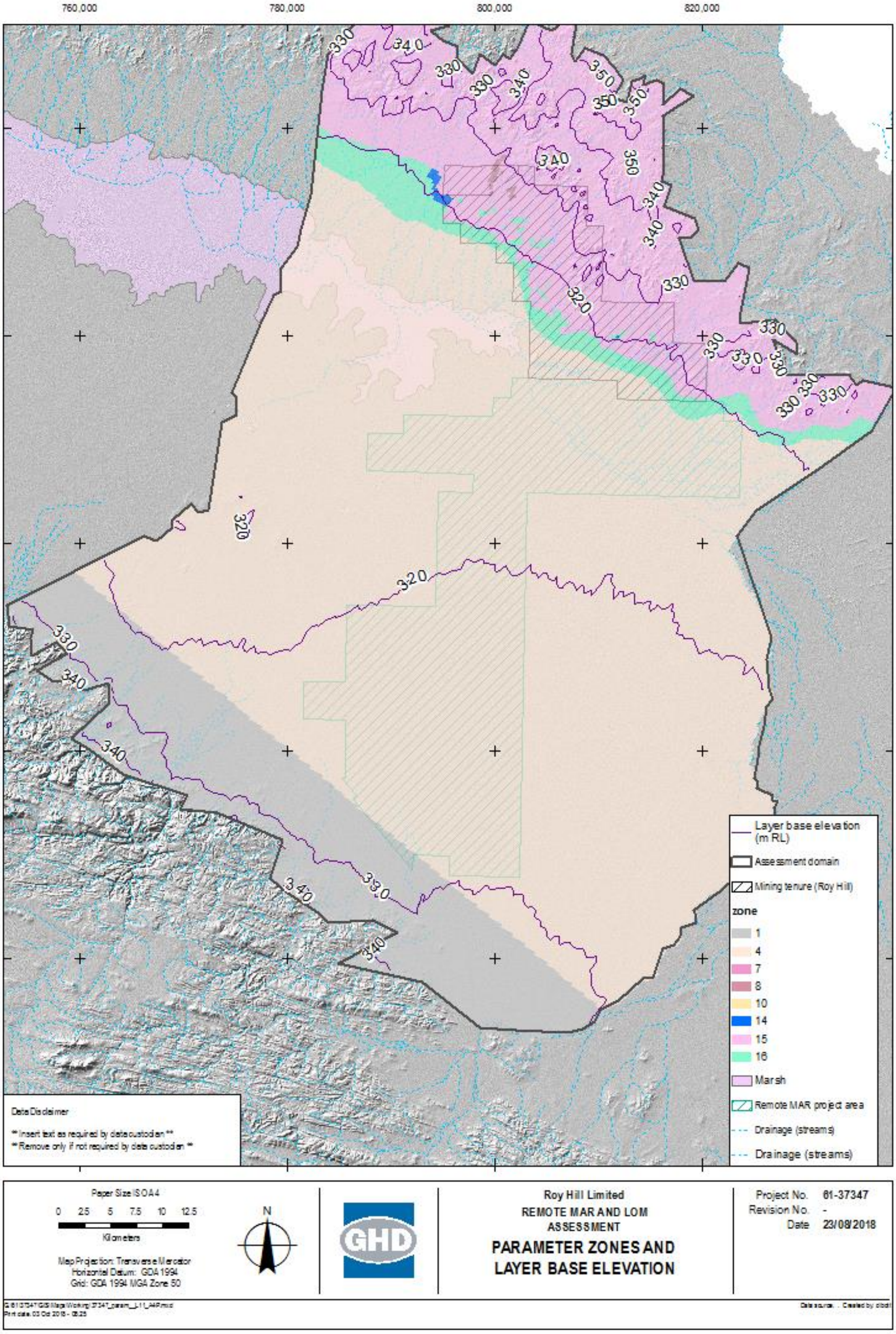
Parameter zone spatial delineation and base elevations, model layer



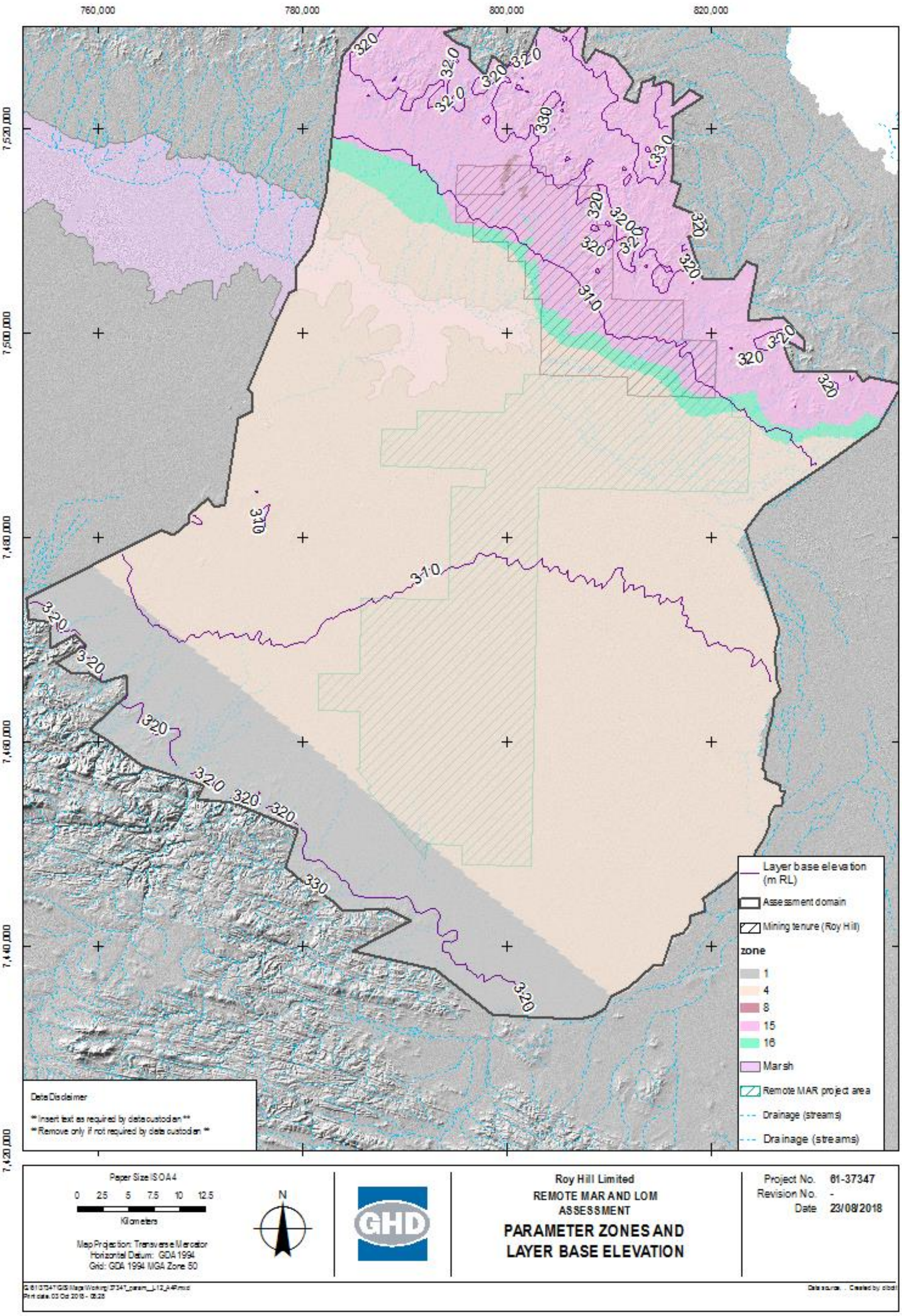
Parameter zone spatial delineation and base elevations, model layer 9



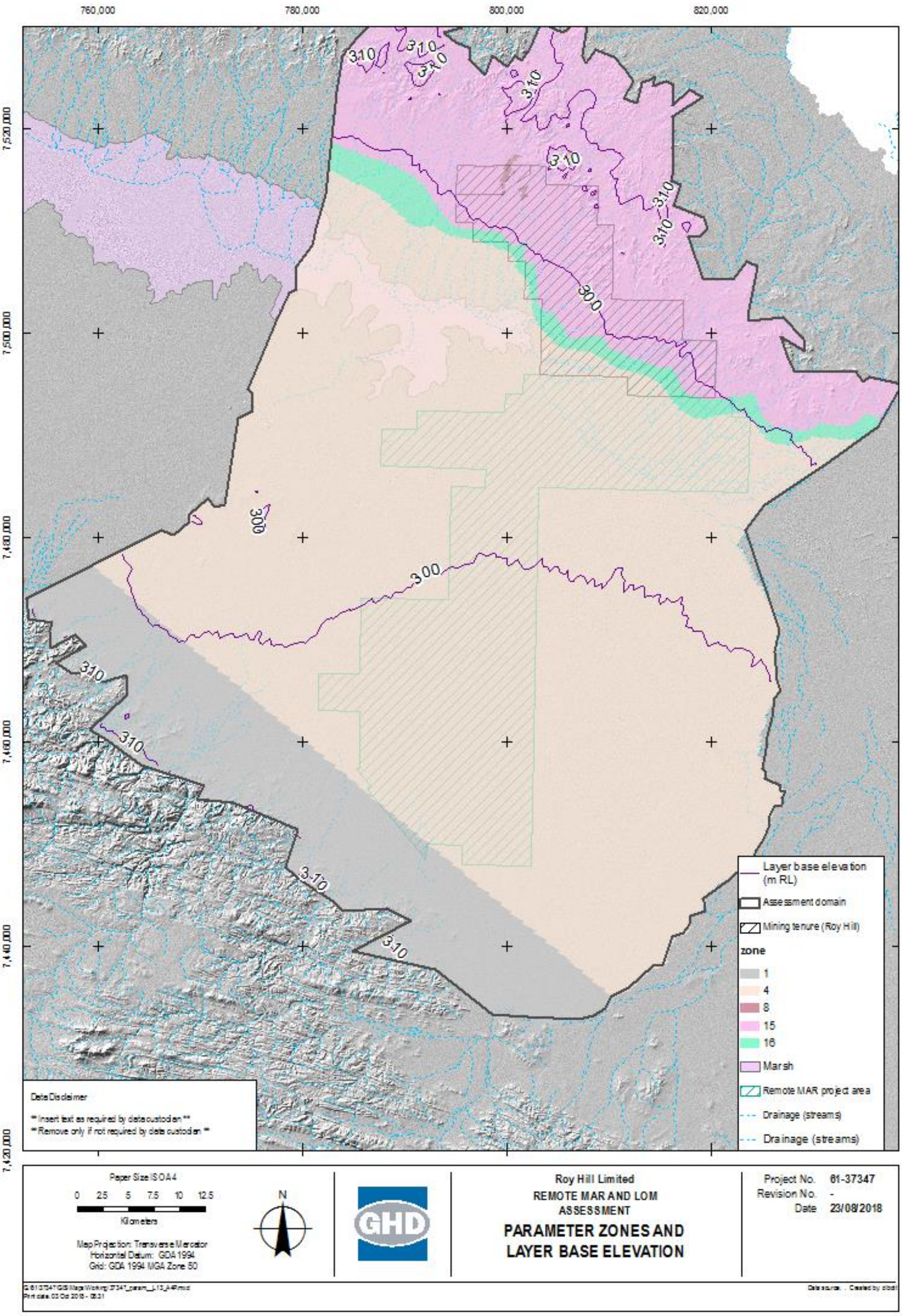
Parameter zone spatial delineation and base elevations, model layer 10



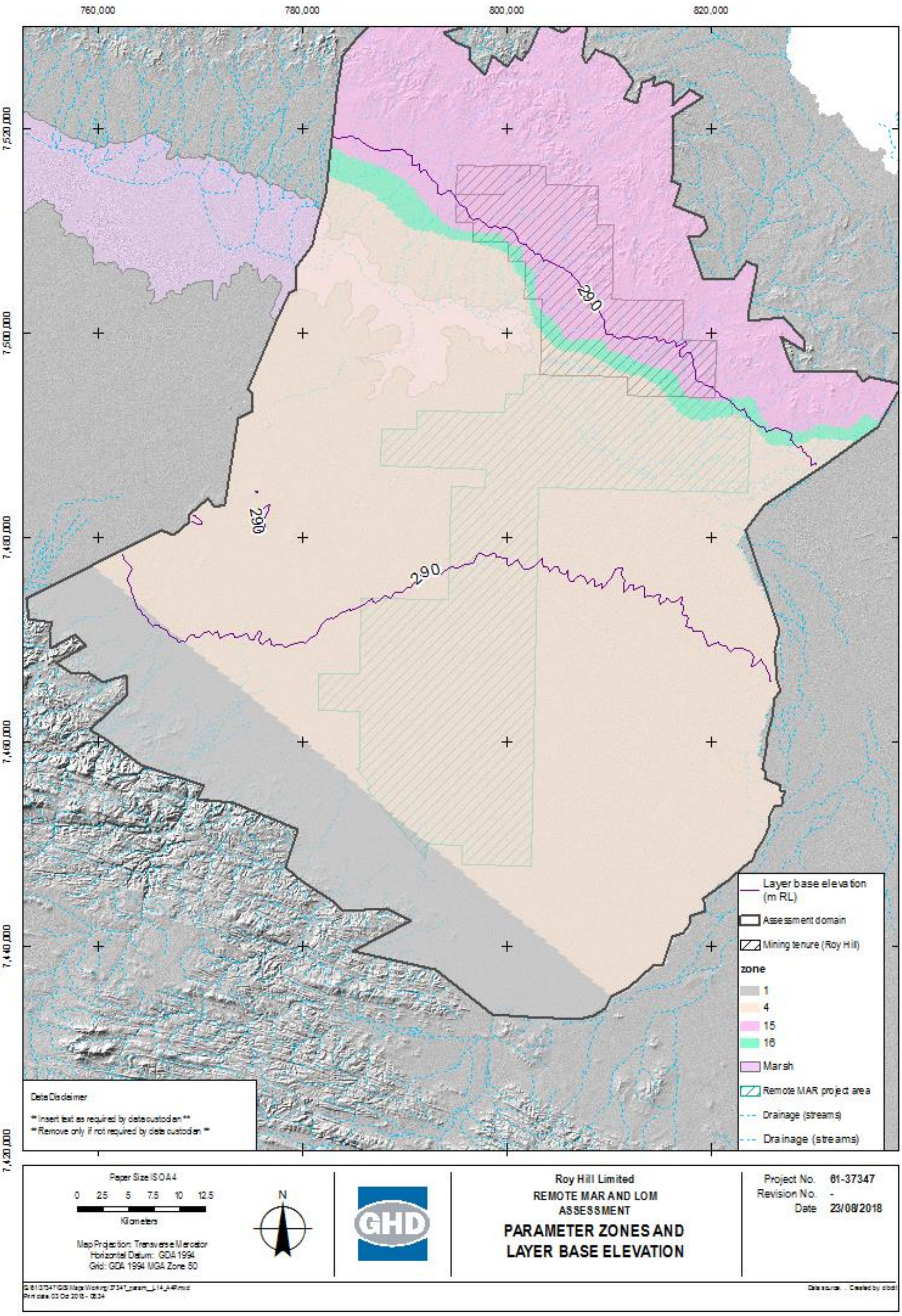
Parameter zone spatial delineation and base elevations, model layer 11



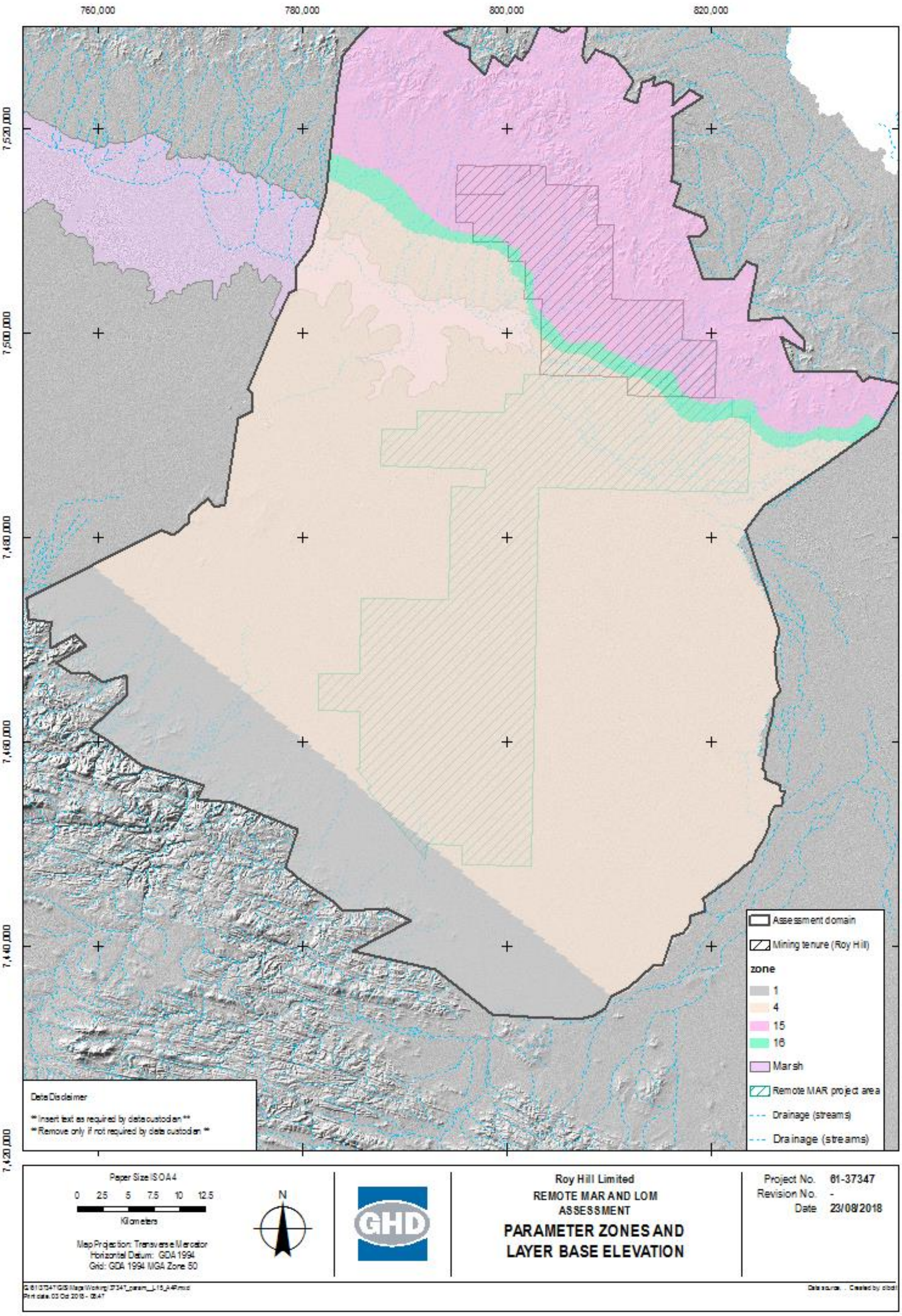
Parameter zone spatial delineation and base elevations, model layer 12



Parameter zone spatial delineation and base elevations, model layer 13

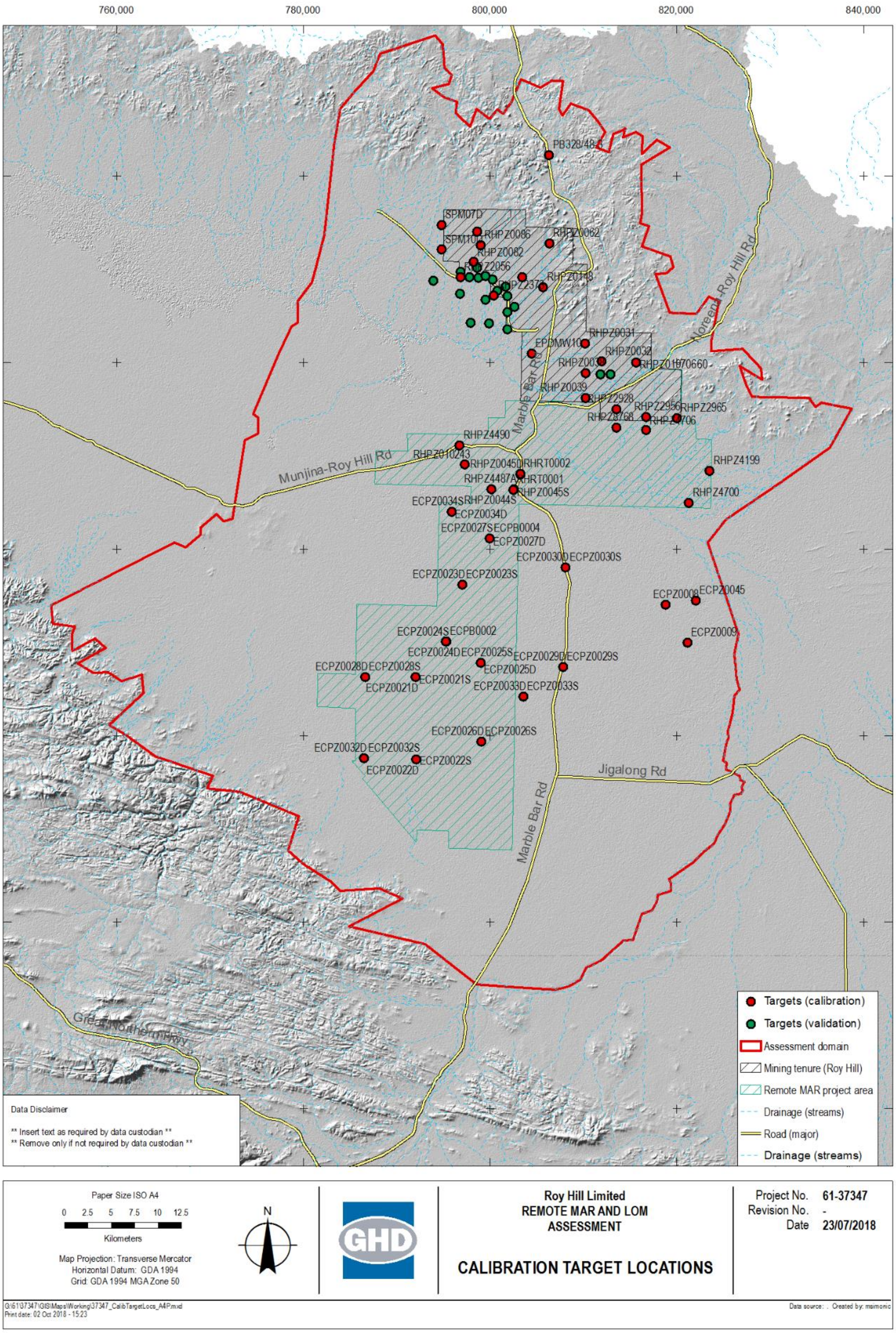


Parameter zone spatial delineation and base elevations, model layer 14



Parameter zone spatial delineation and base elevations, model layer 15

Appendix E Groundwater elevation calibration hydrographs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780,000
800,000
820,000
840,000
7,520,000
7,500,000
7,480,000
7,460,000
7,440,000
7,420,000
Munjina-Roy Hill Rd
Marble Bar Rd
Jigalong Rd
Great Northern Hwy
Noreena-Roy Hill Rd
Targets (calibration)
Targets (validation)
Assessment domain
Mining tenure (Roy Hill)
Remote MAR project area
Drainage (streams)
Road (major)
Drainage (streams)
Data Disclaimer
** Insert text as required by data custodian **
** Remove only if not required by data custodian **
Paper Size ISO A4
0 2.5 5 7.5 10 12.5
Kilometers
Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 50
N
GHD
Roy Hill Limited
REMOTE MAR AND LOM
ASSESSMENT
CALIBRATION TARGET LOCATIONS
Project No. 61-37347
Revision No. -
Date 23/07/2018
G:\61\37347\GIS\Maps\Working\37347_CalibTargetLocs_A4P.mxd
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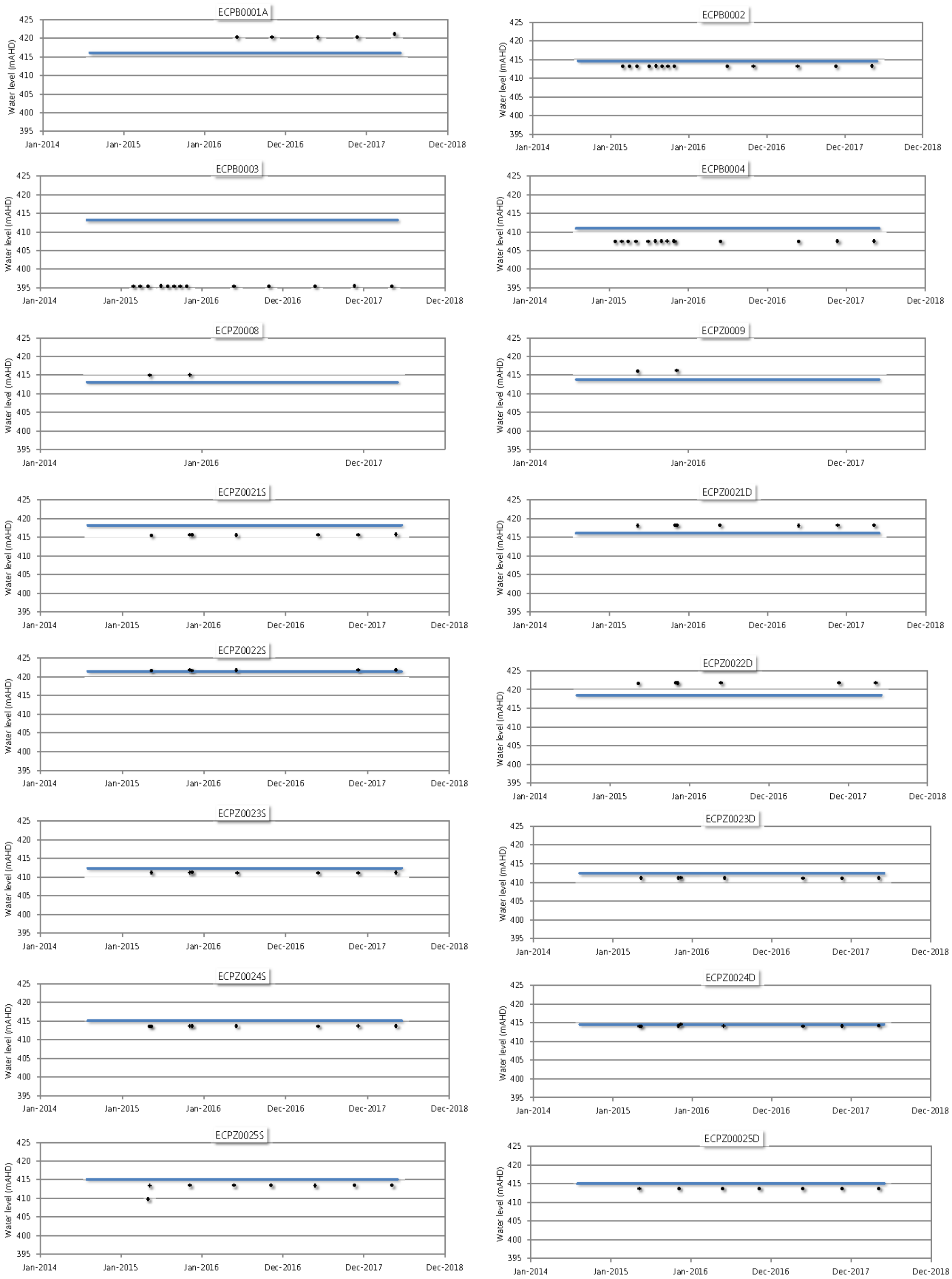
Groundwater Levels

Roy Hill - Remote MAR Study
Hydrograhps



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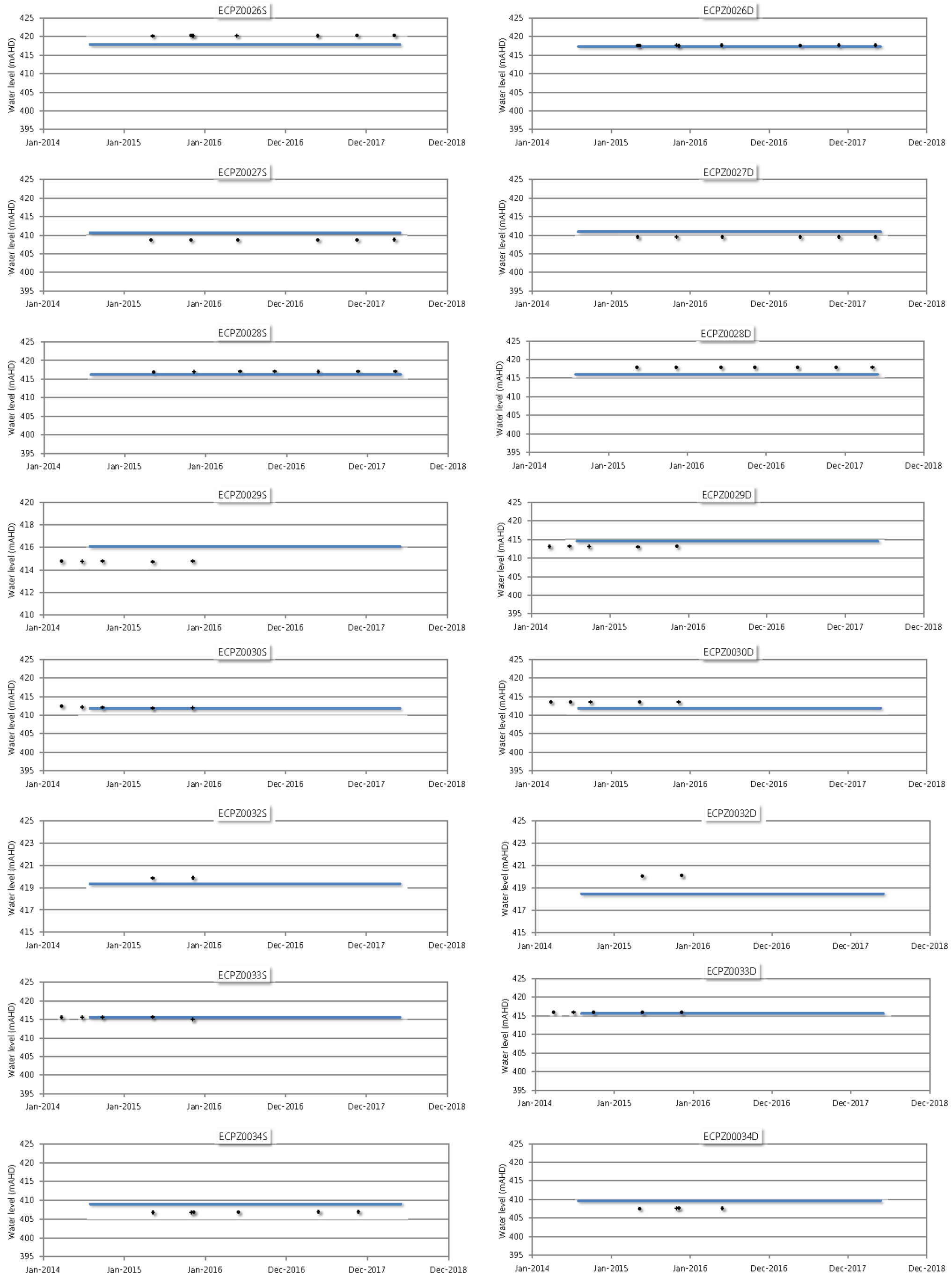
Groundwater Levels

Roy Hill - Remote MAR Study
Hydrographs



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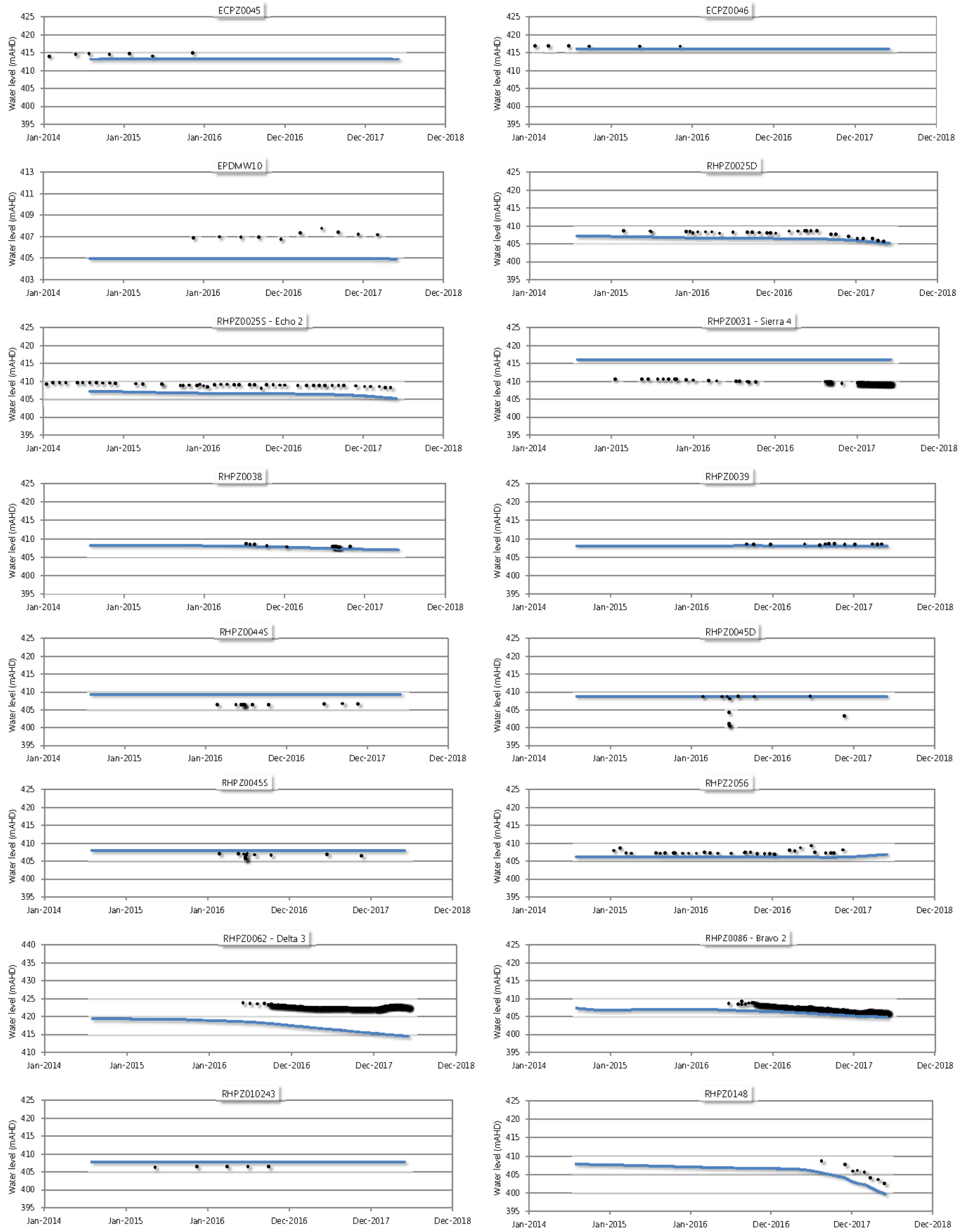

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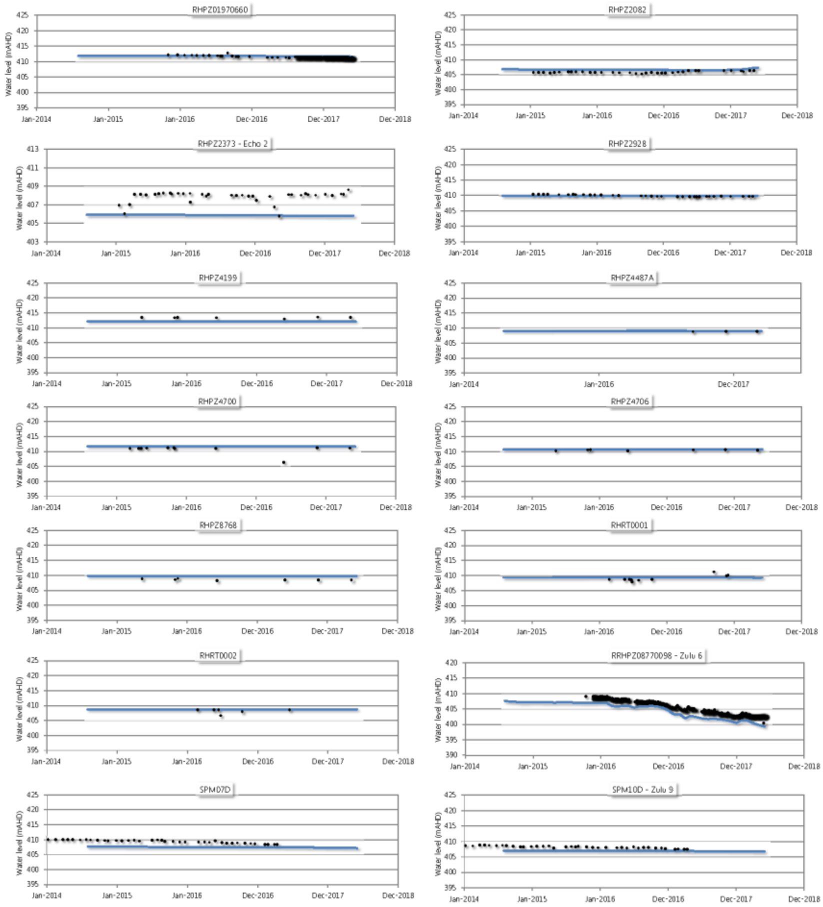

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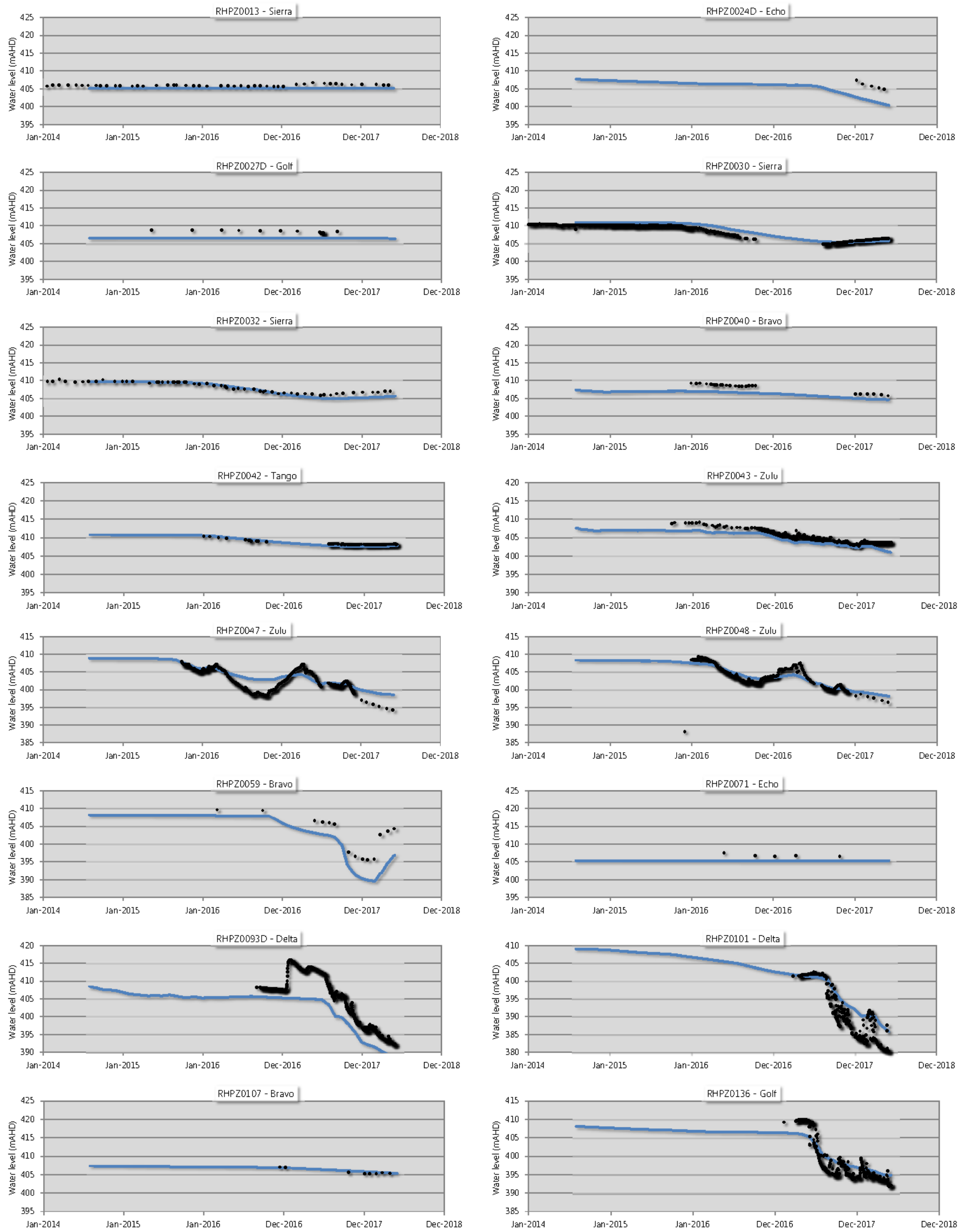
Groundwater Levels

Roy Hill - Remote MAR Study
Hydrographs



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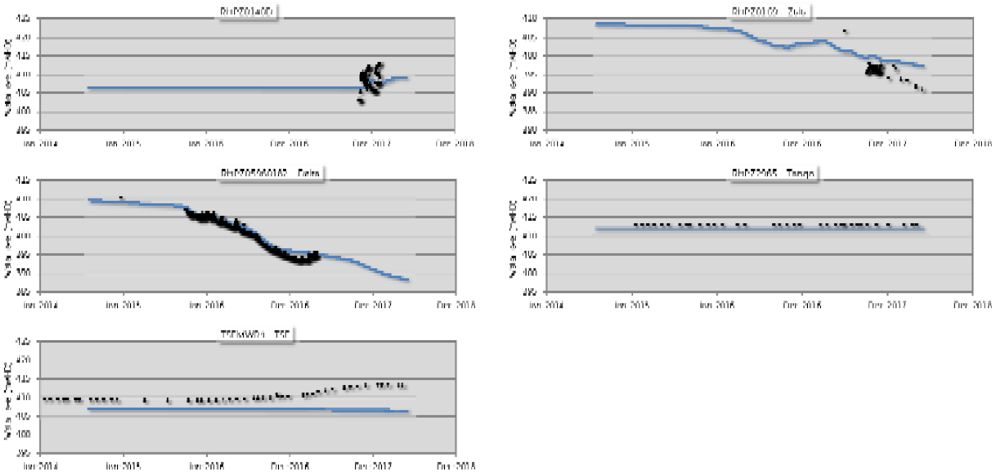
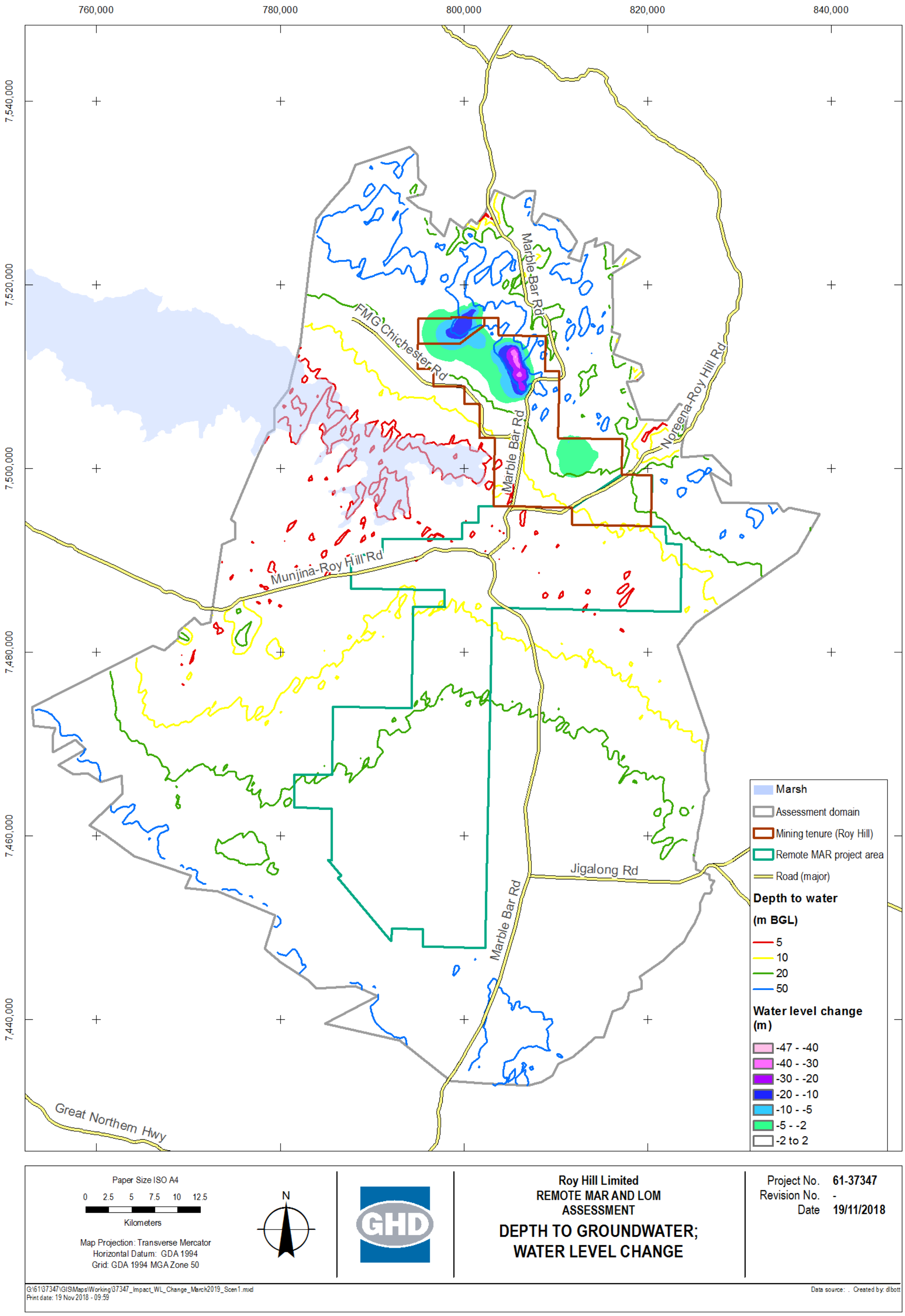
Groundwater Levels

Roy Hill - Remote MAR Study
Hydrographs



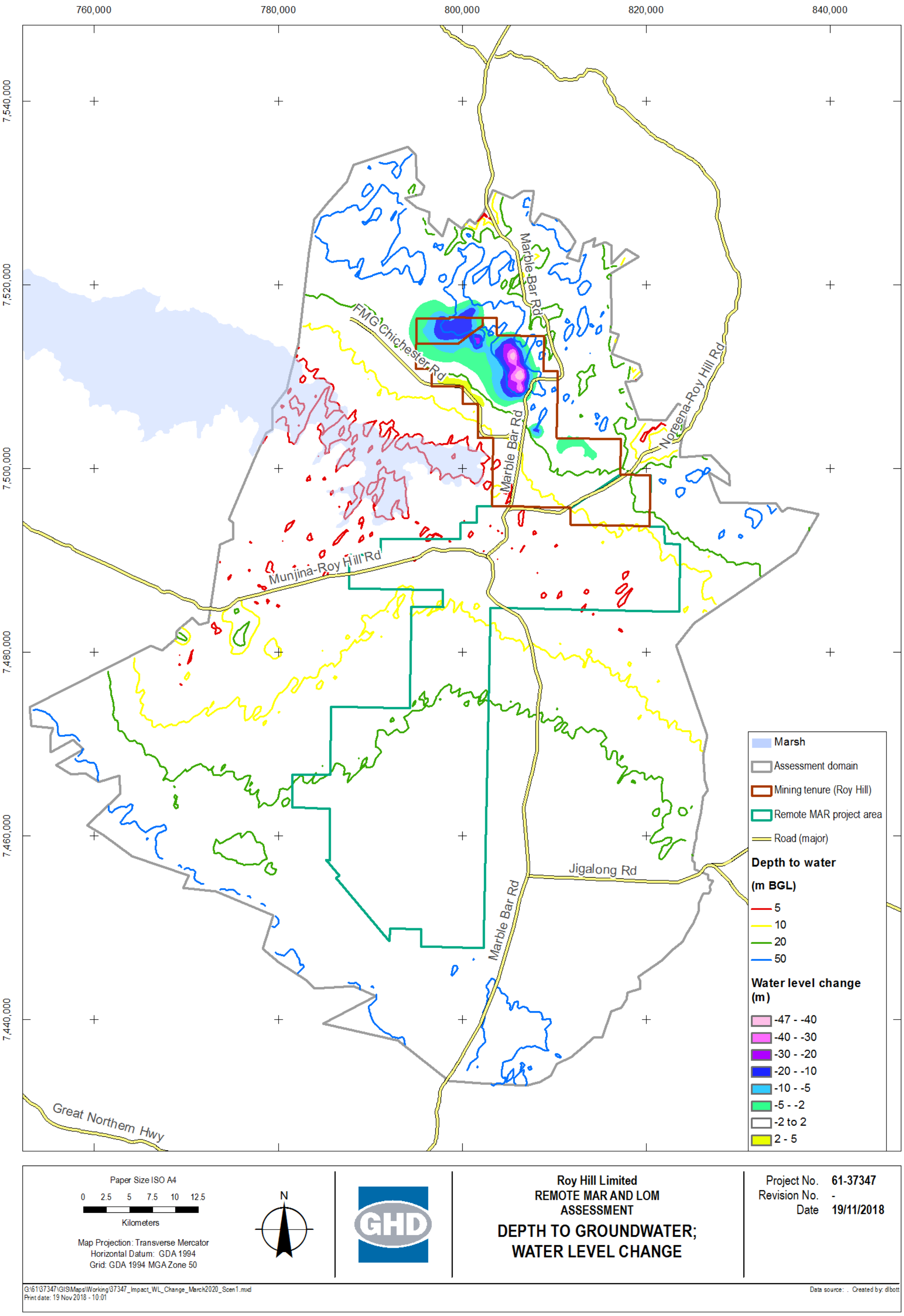
Appendix F Maps of predicted water level change and depth to groundwater for management simulations

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



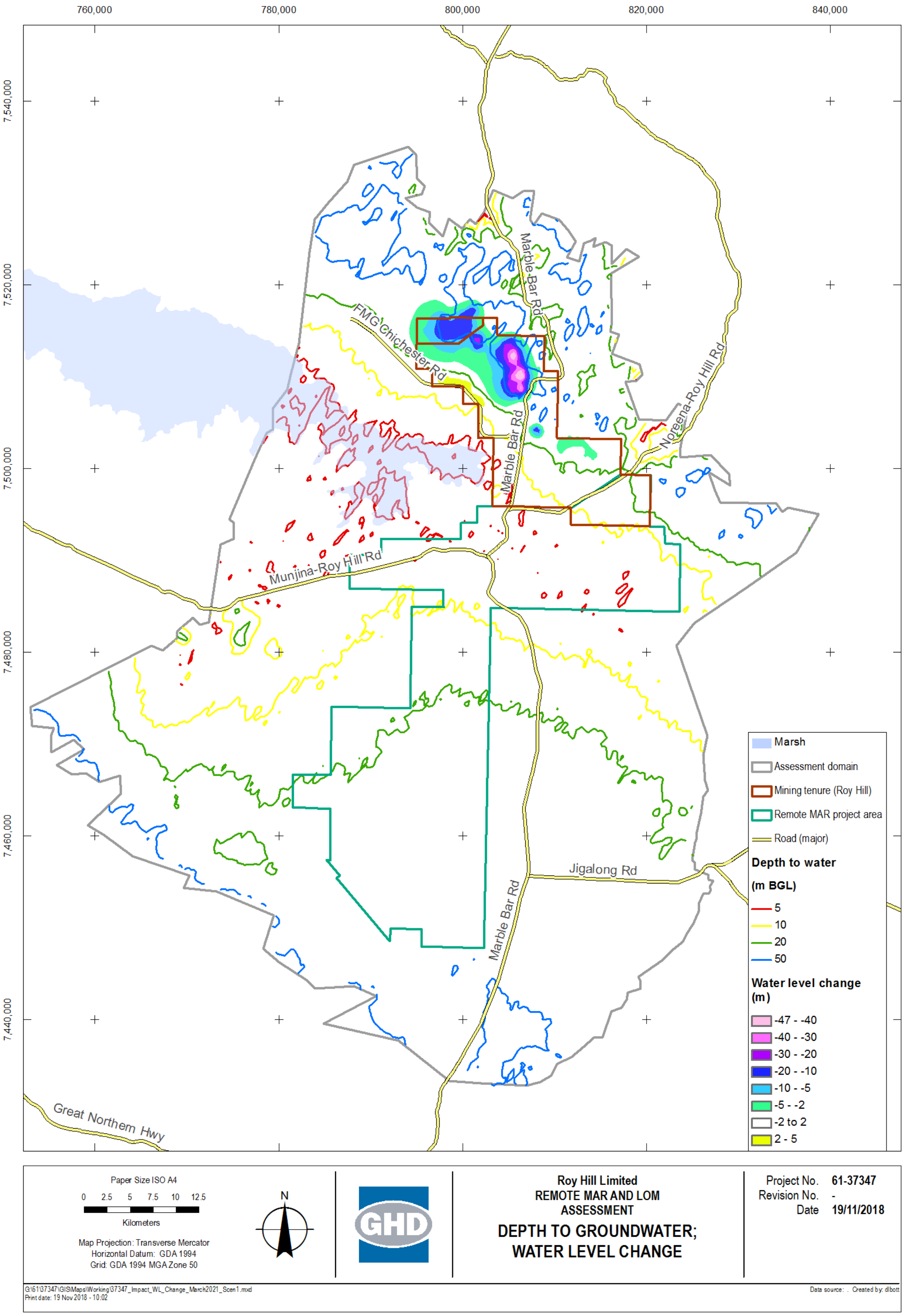
Depth to groundwater; water level change, March 2019

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



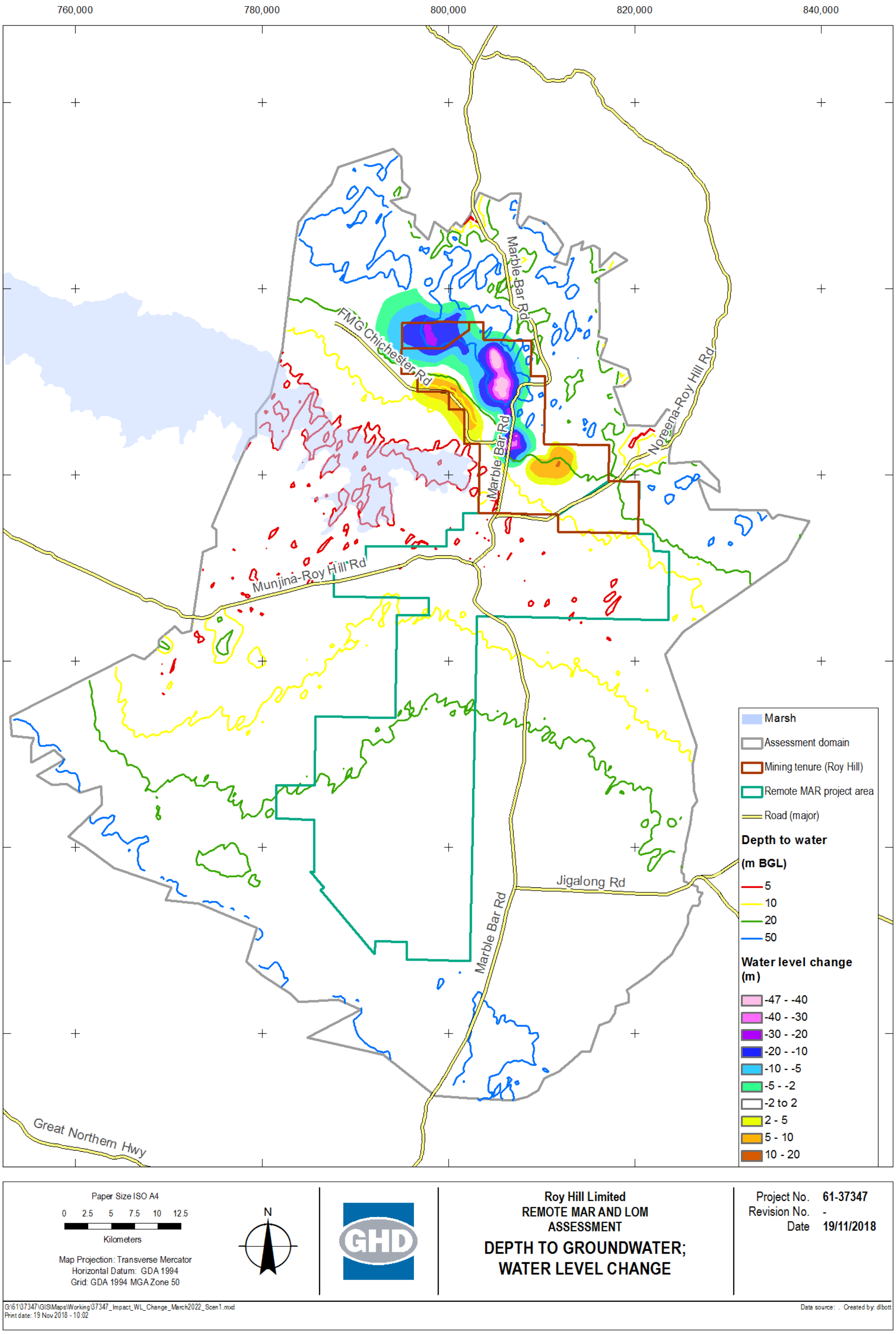
Depth to groundwater; water level change, March 2020

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



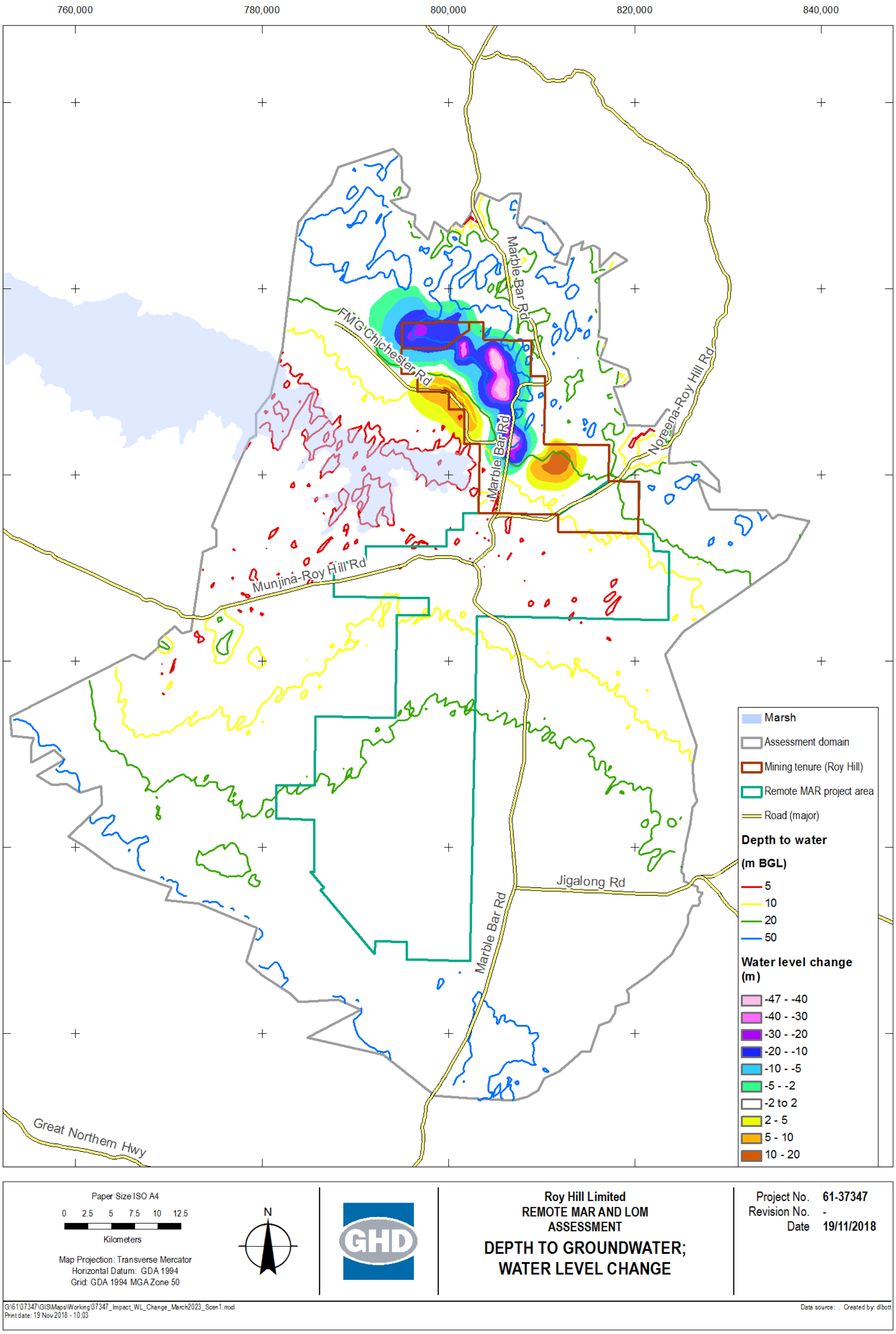
Depth to groundwater; water level change, March 2021

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



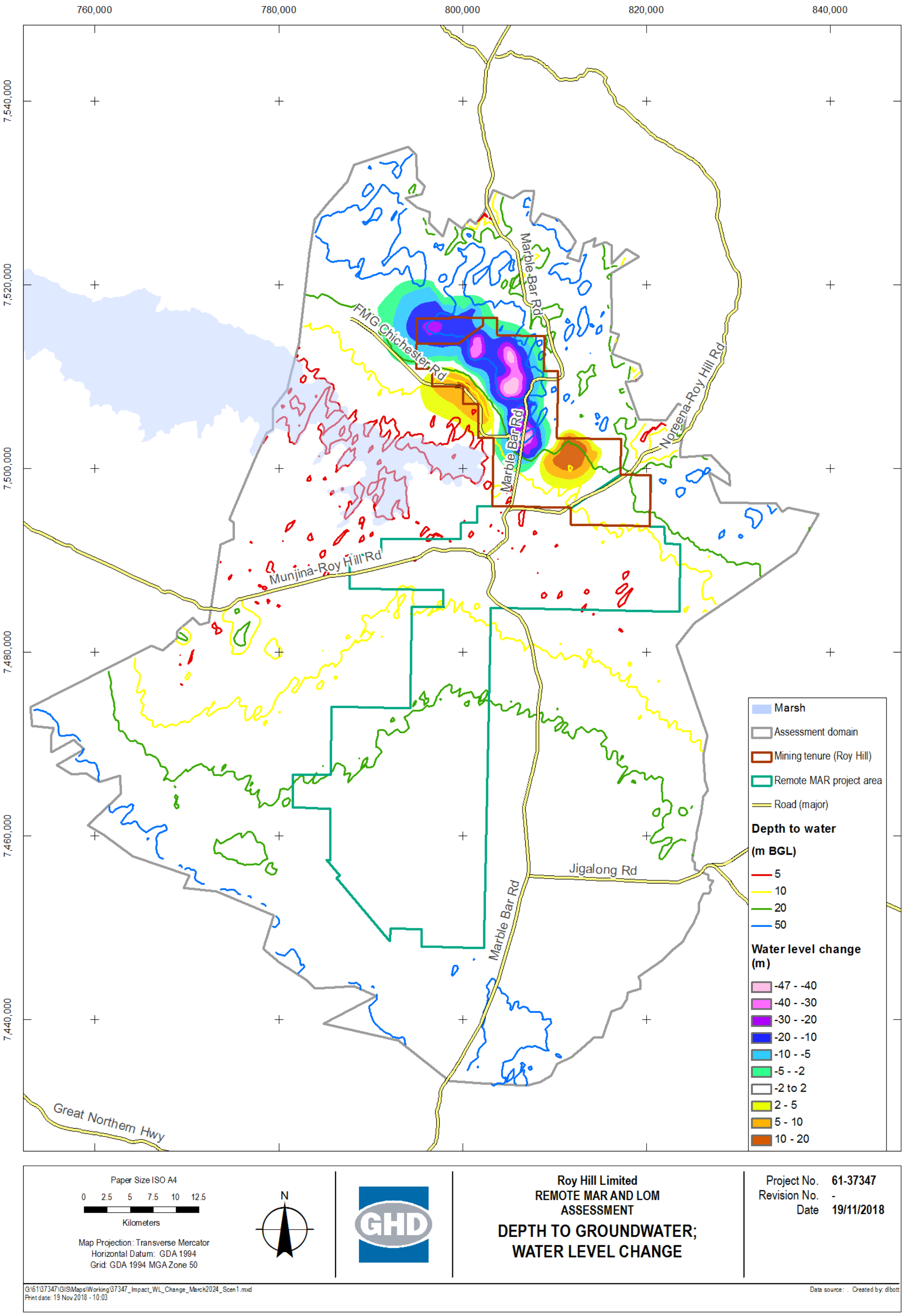
Depth to groundwater; water level change, March 2022

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



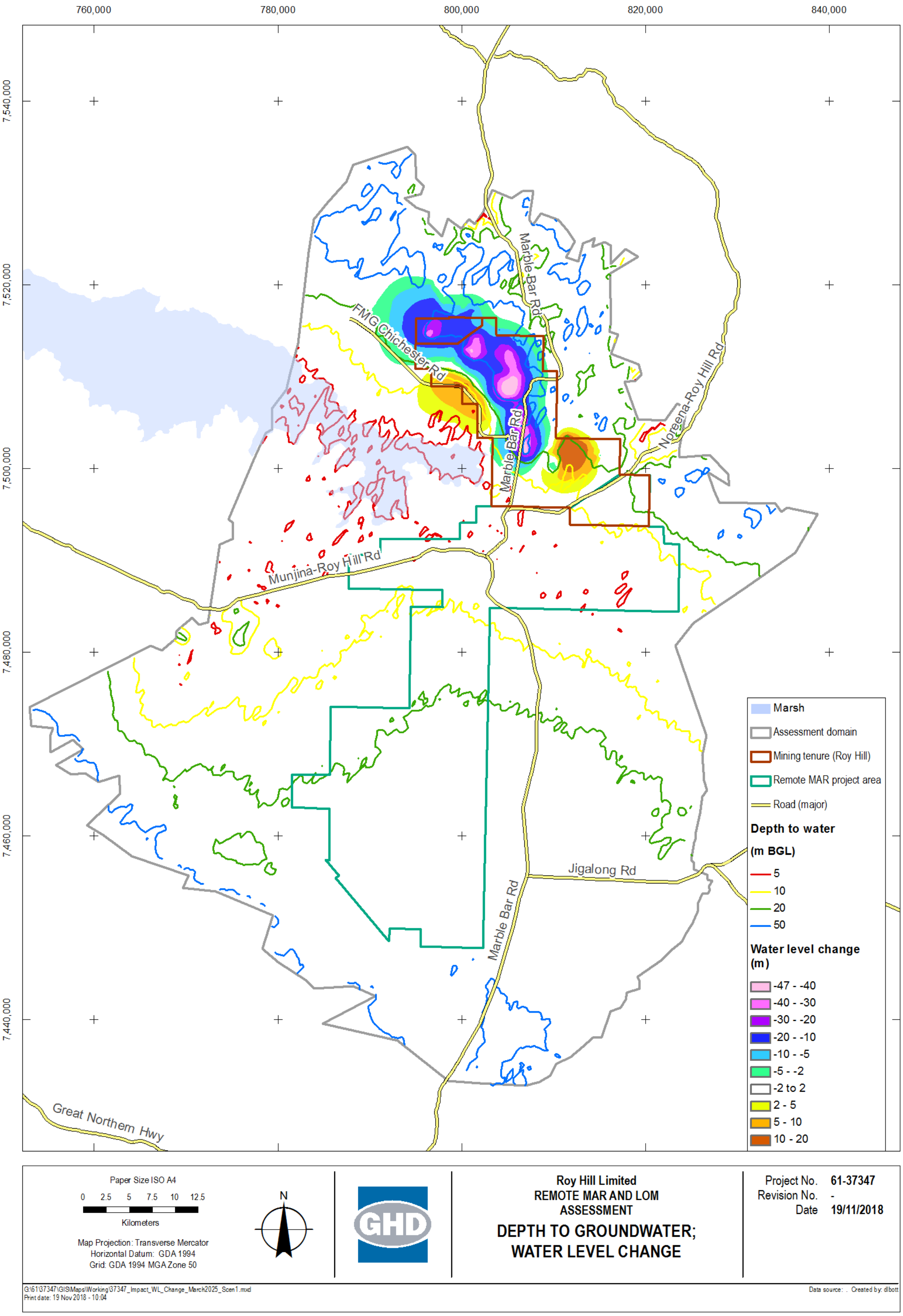
Depth to groundwater; water level change, March 2023

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



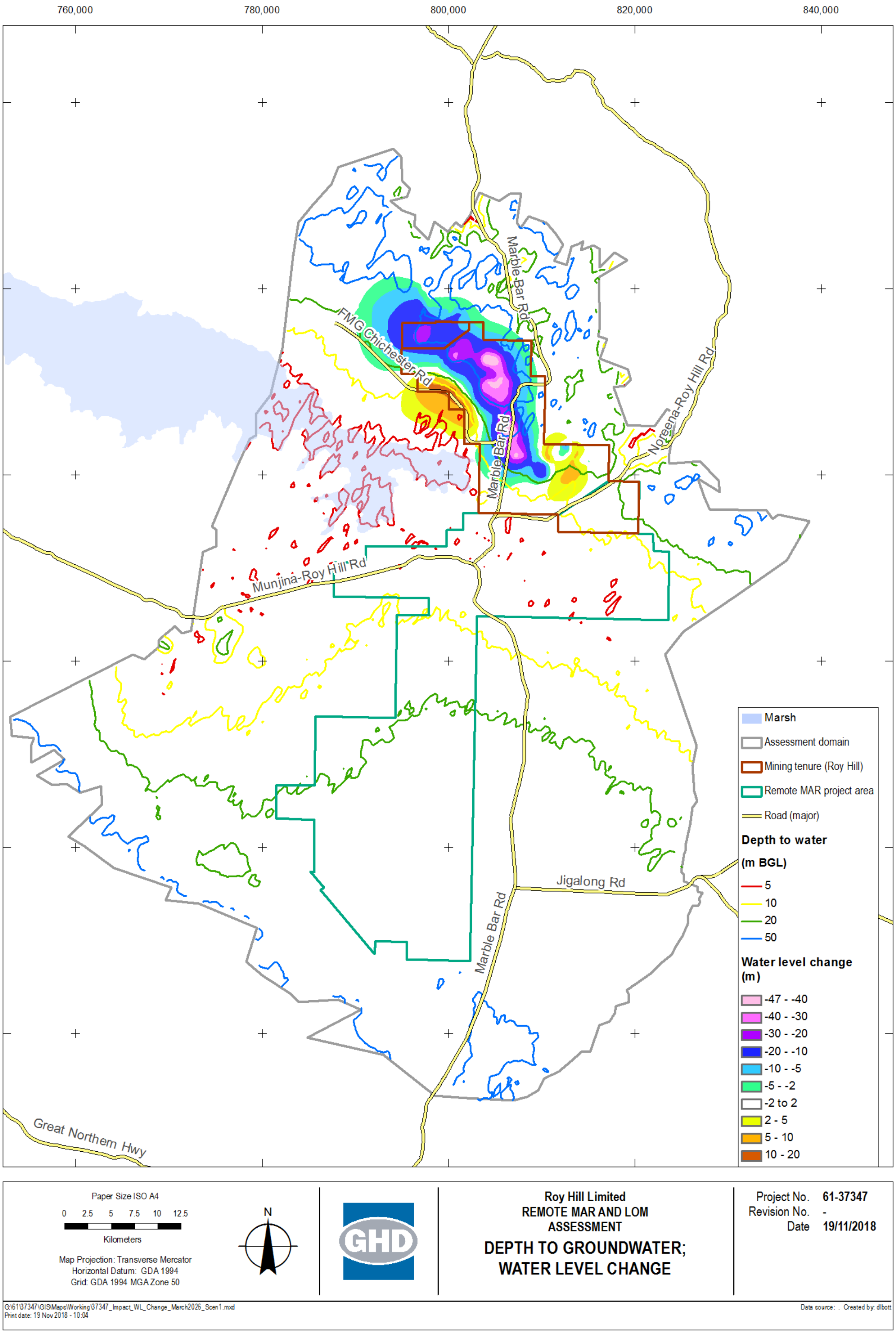
Depth to groundwater; water level change, March 2024

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



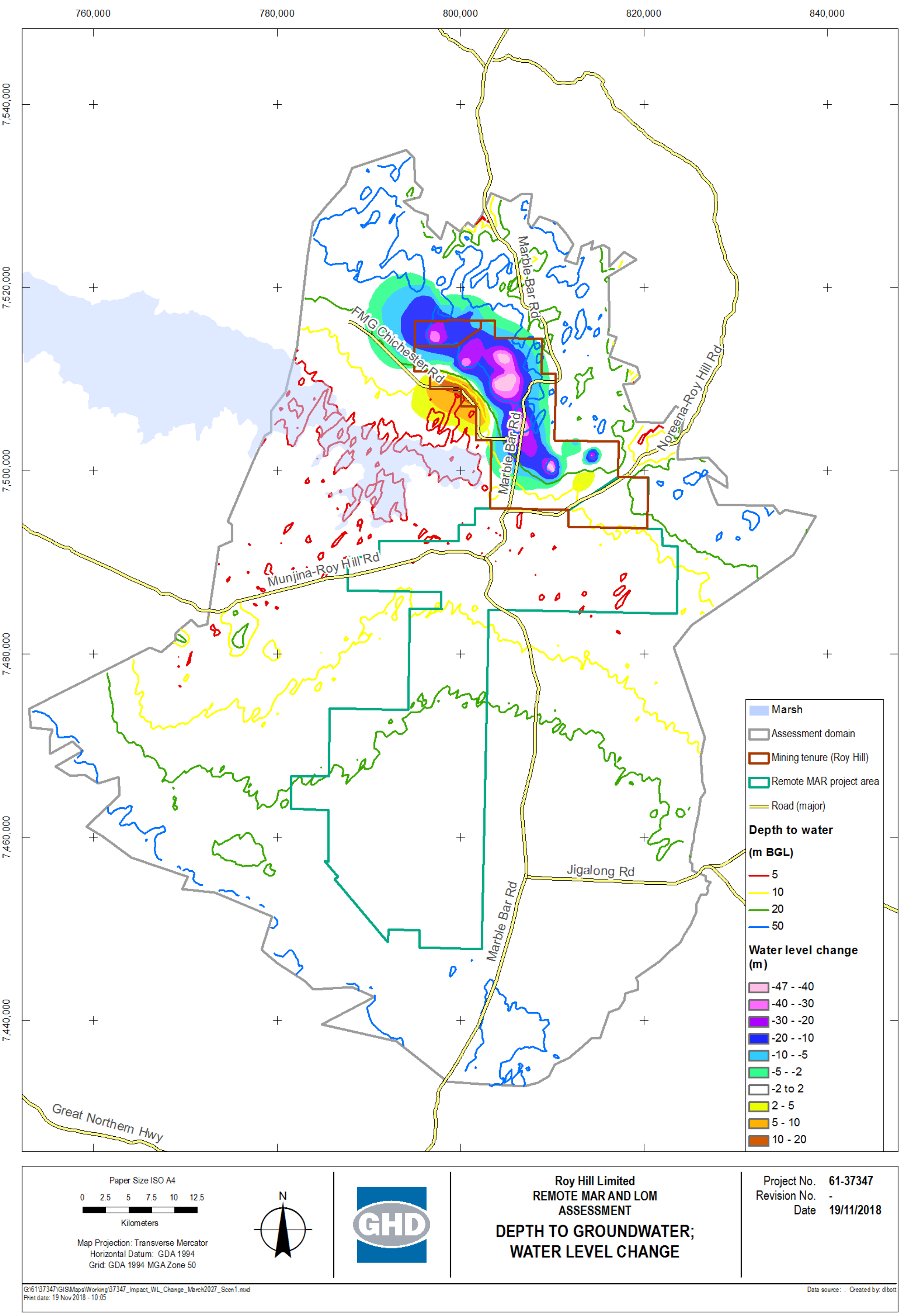
Depth to groundwater; water level change, March 2025

Scenario 1: Dewatering and injection in mining area and RMAR North (SWIB, MPIB)



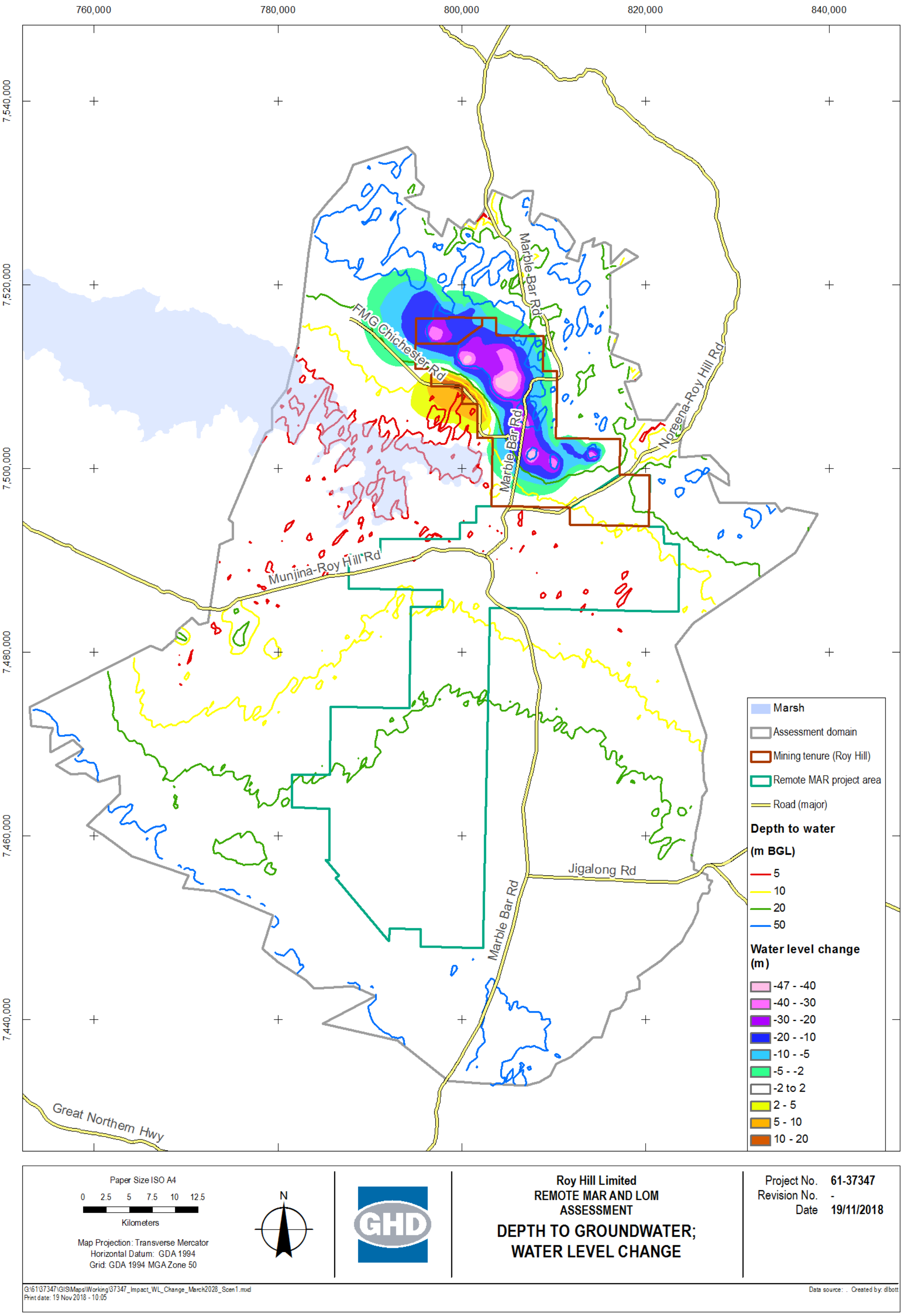
Depth to groundwater; water level change, March 2026

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



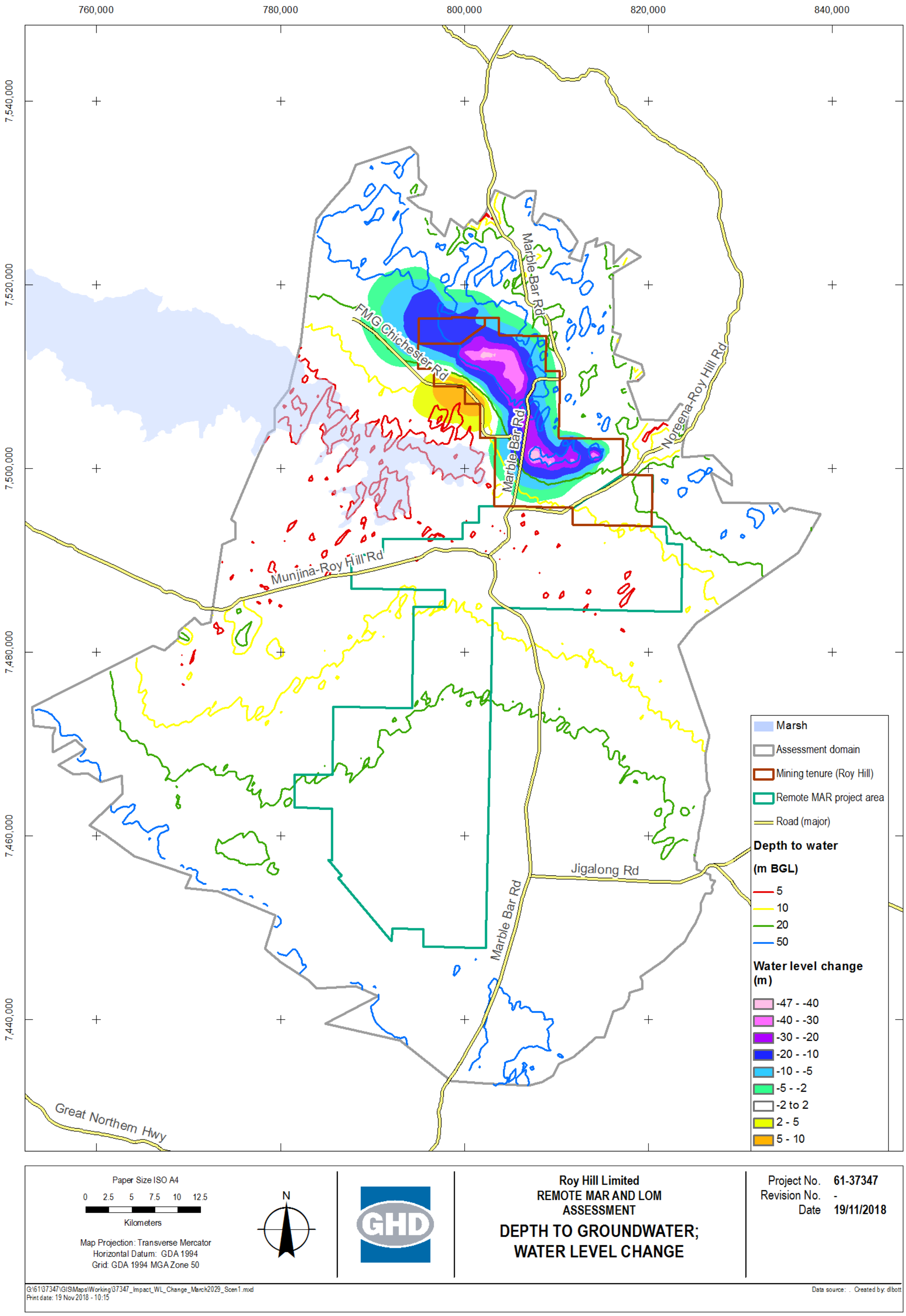
Depth to groundwater; water level change, March 2027

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



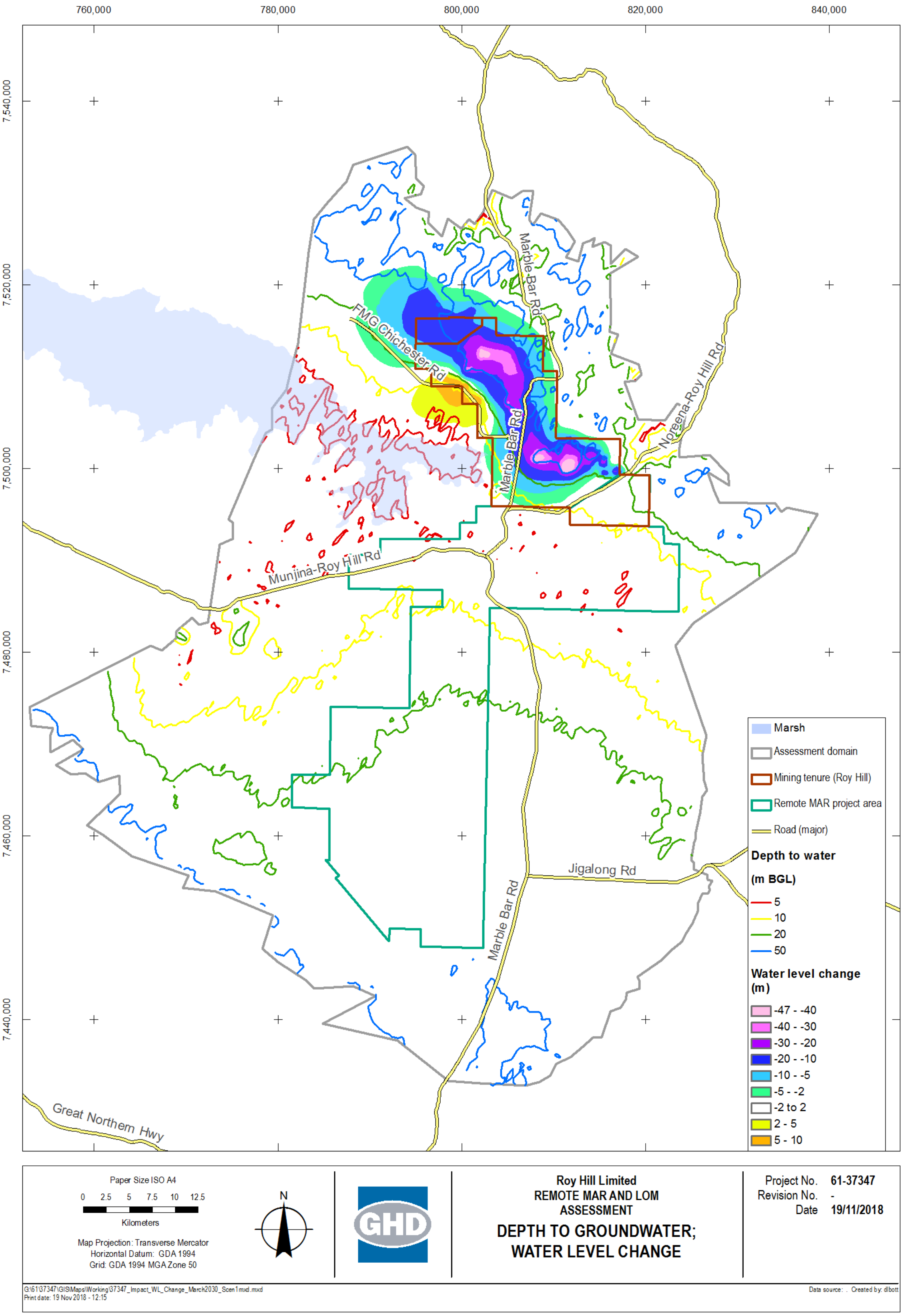
Depth to groundwater; water level change, March 2028

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



Depth to groundwater; water level change, March 2029

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



Depth to groundwater; water level change, March 2030

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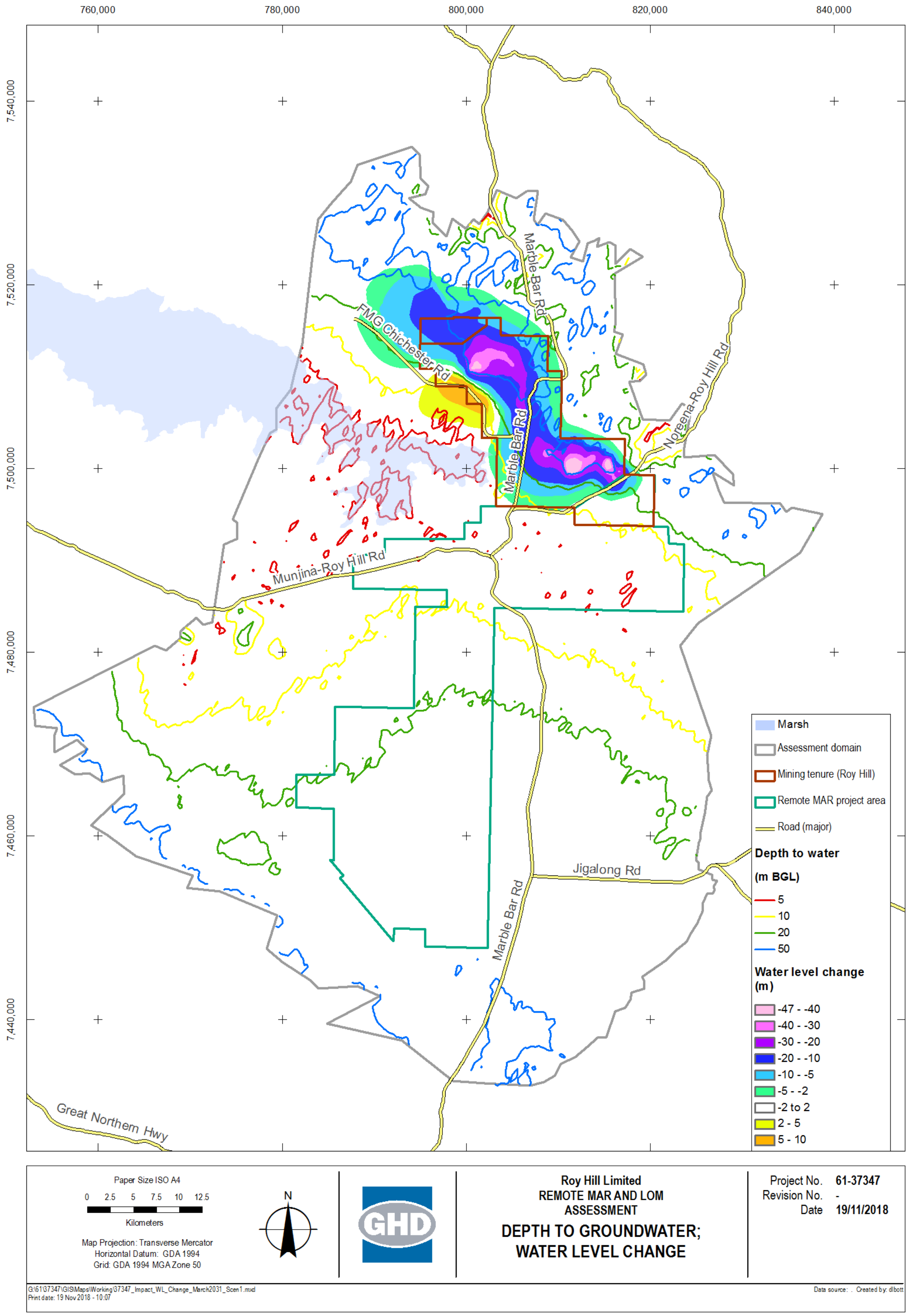
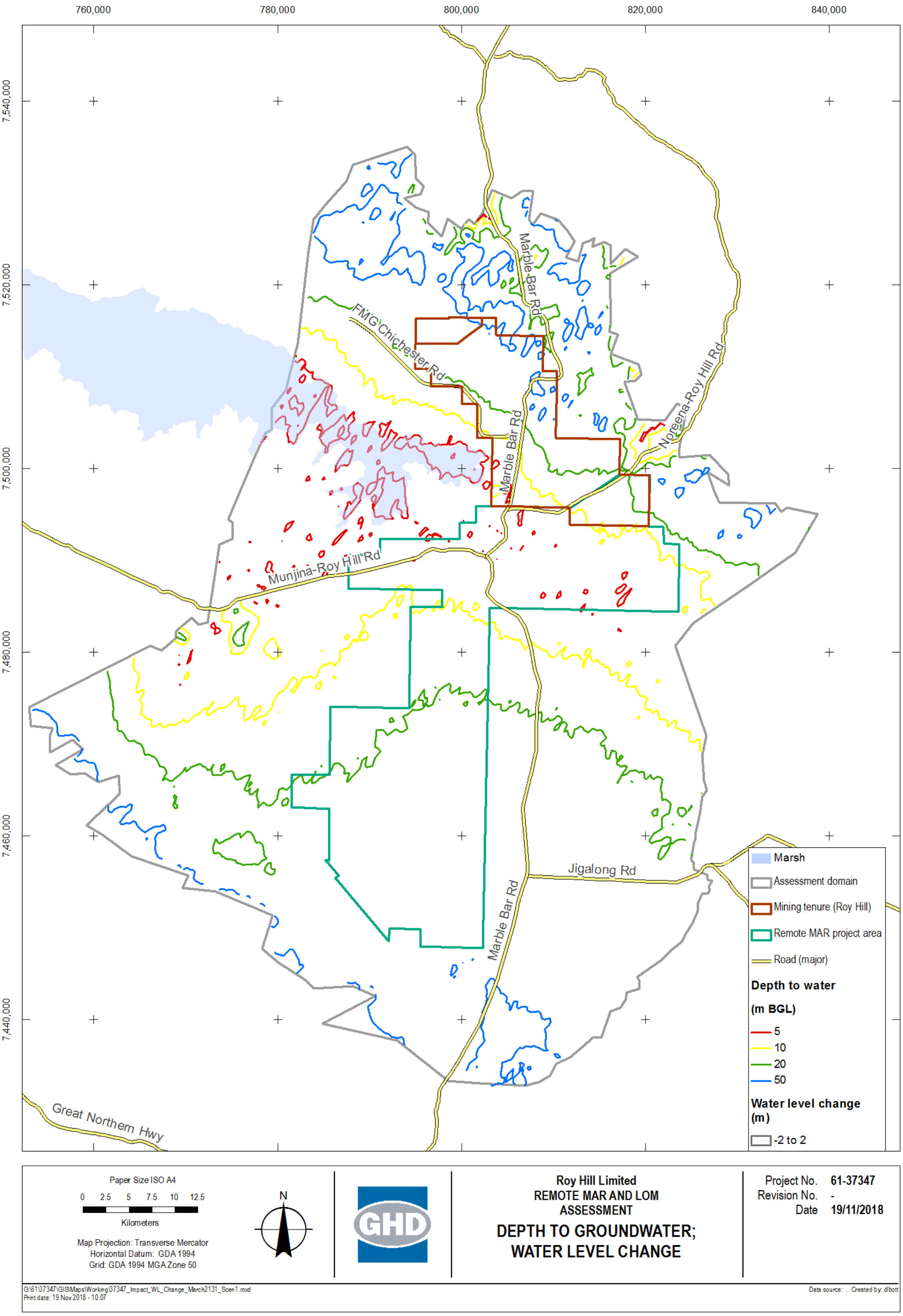


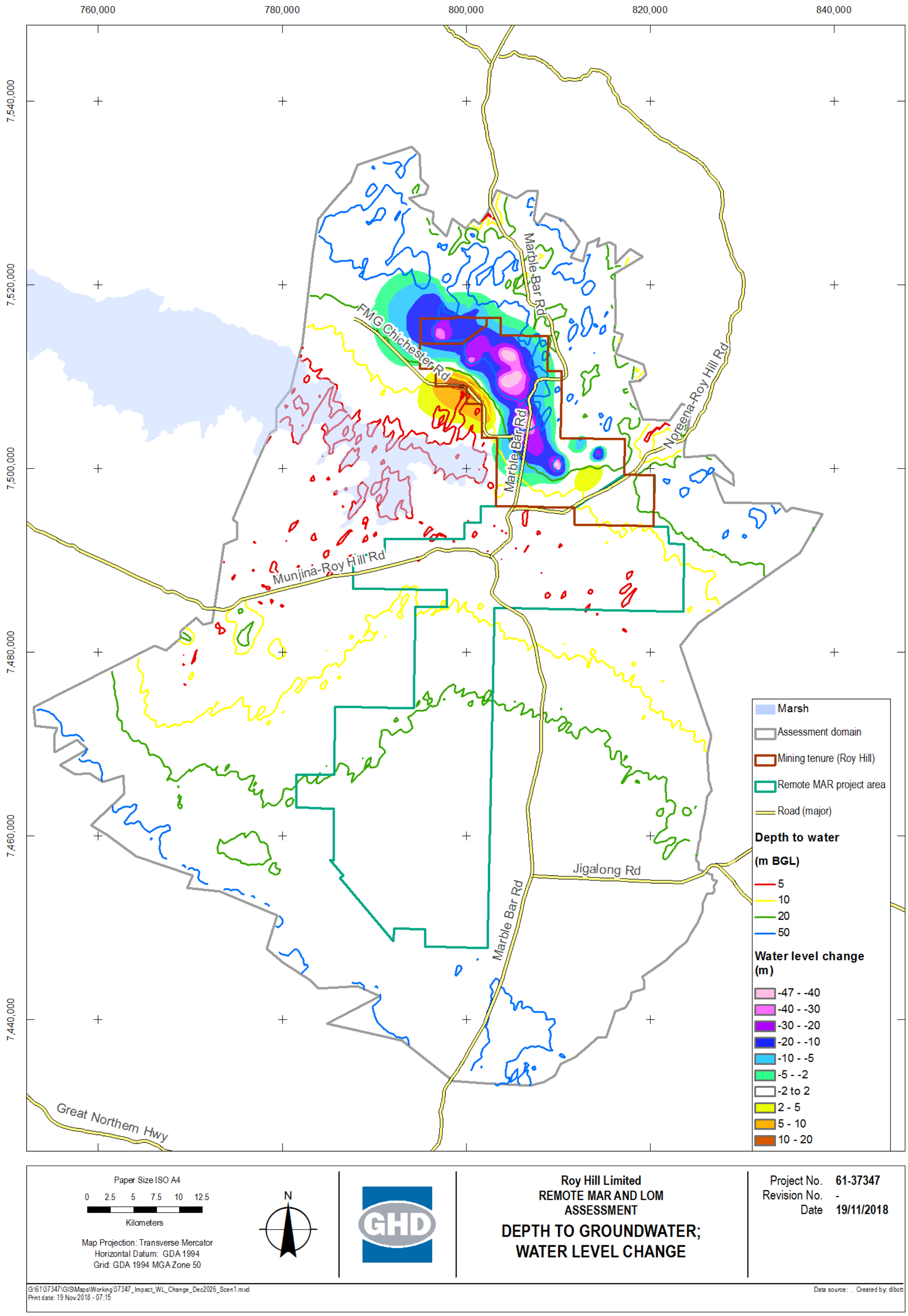
Depth to groundwater; water level change, March 2031

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



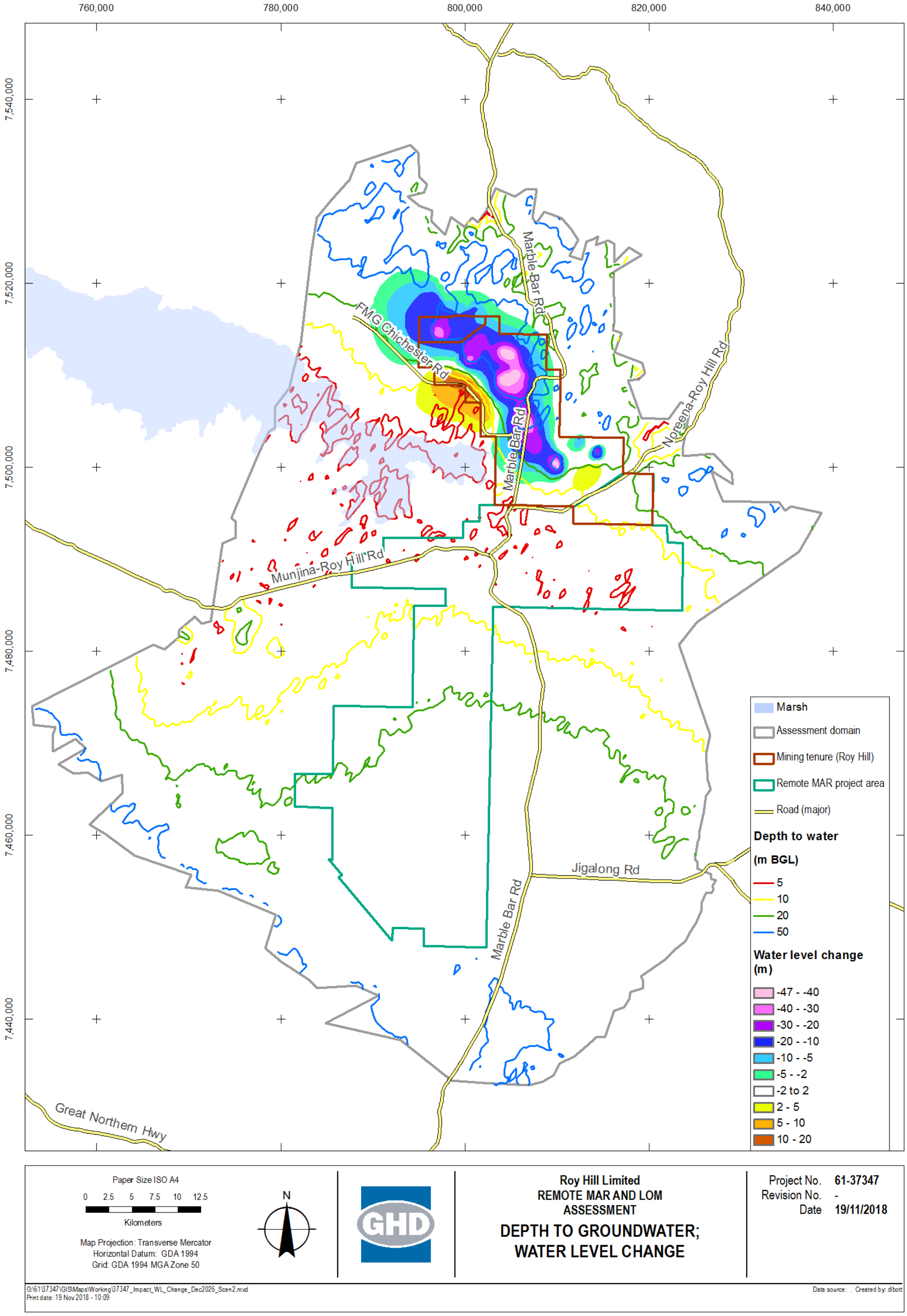
Depth to groundwater; water level change, March 2131 (100 years post closure)

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



Depth to groundwater; water level change, December 2026

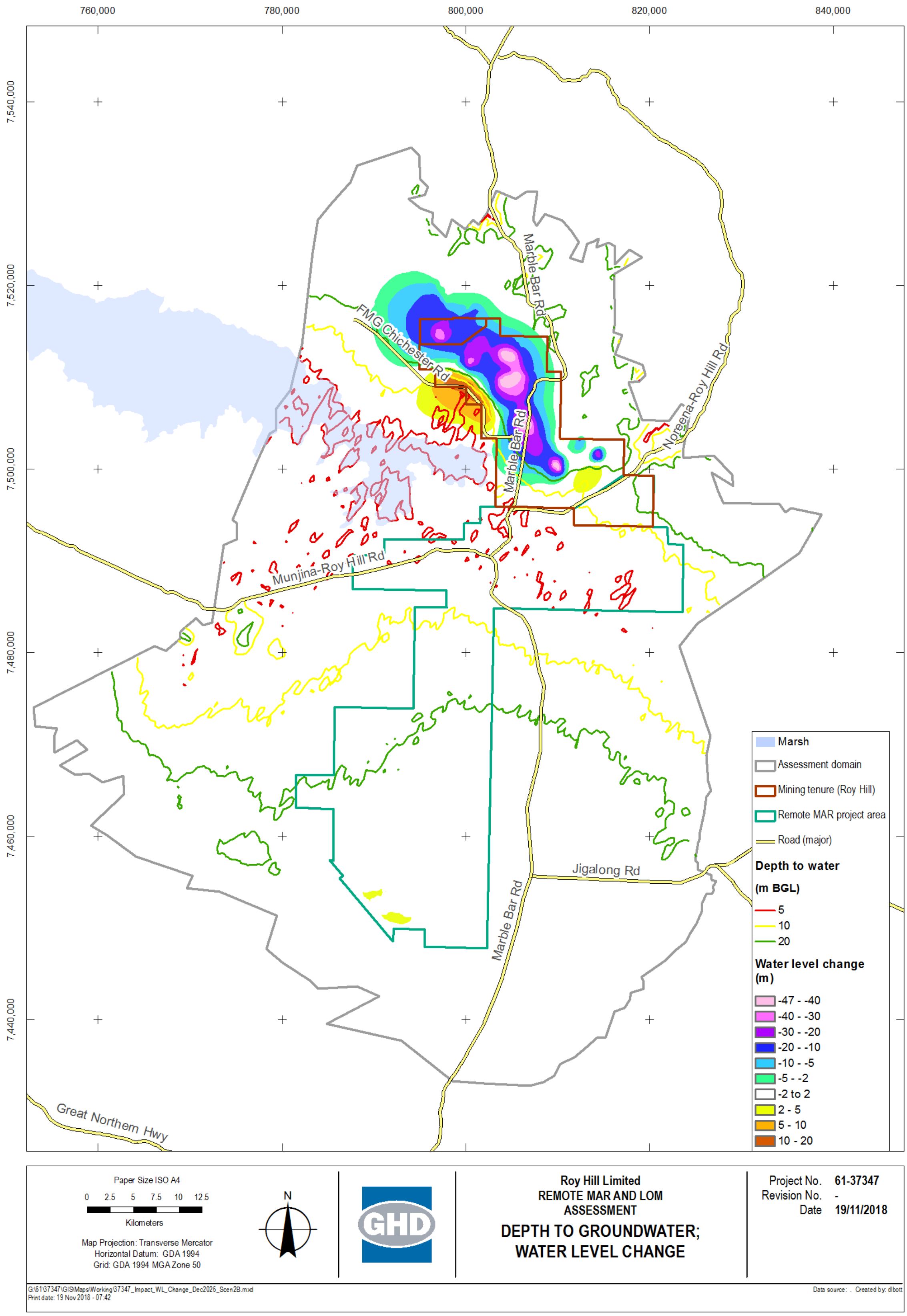
Scenario 2: Dewatering and injection in mining area (SWIB and MPIB), surplus disposal in RMAR North



Depth to groundwater; water level change, December 2026

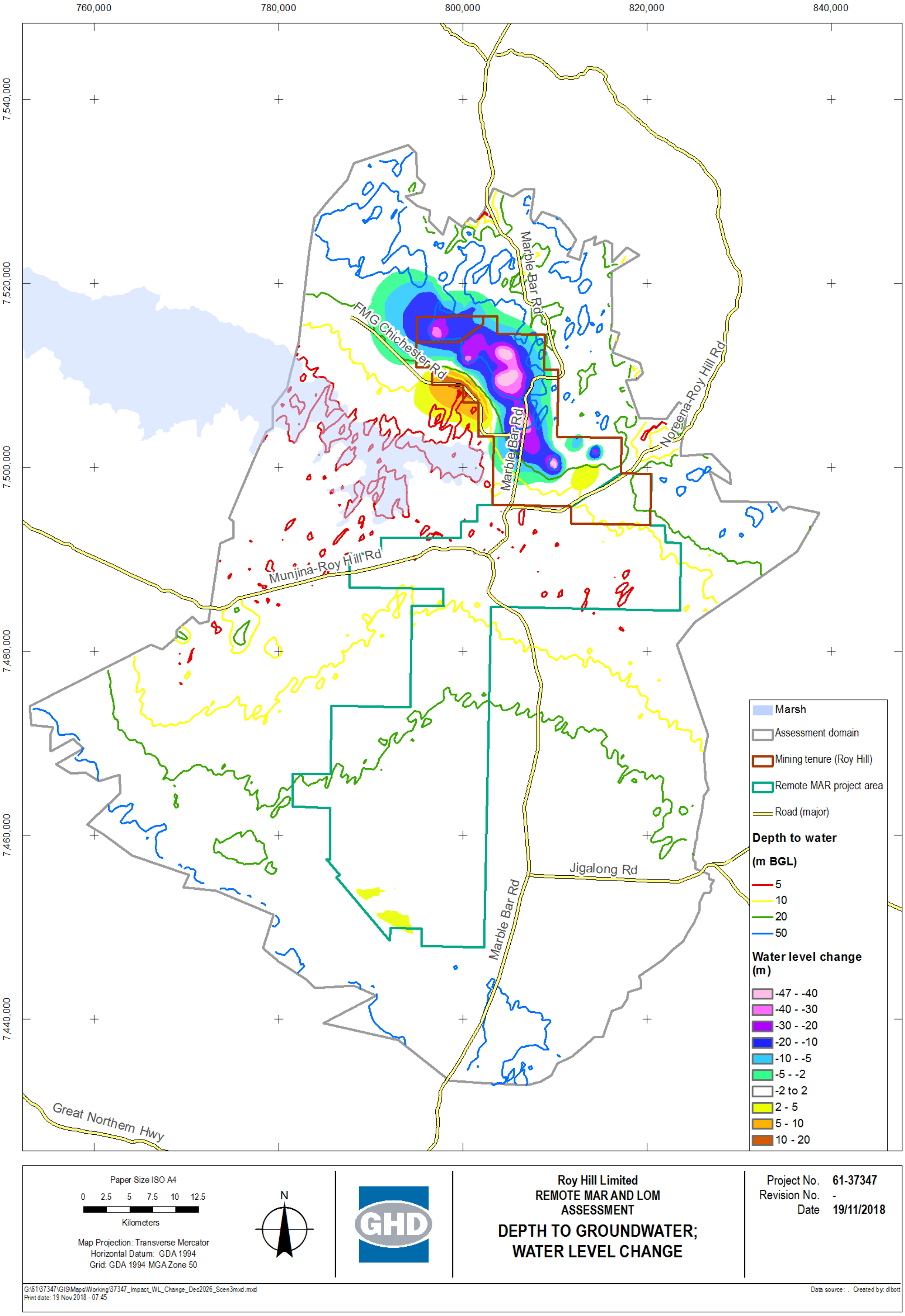
Scenario 2B: Dewatering and injection in mining area (SWIB and MPIB), surplus disposal in RMAR North and in RMAR South (20 ML/d)

,



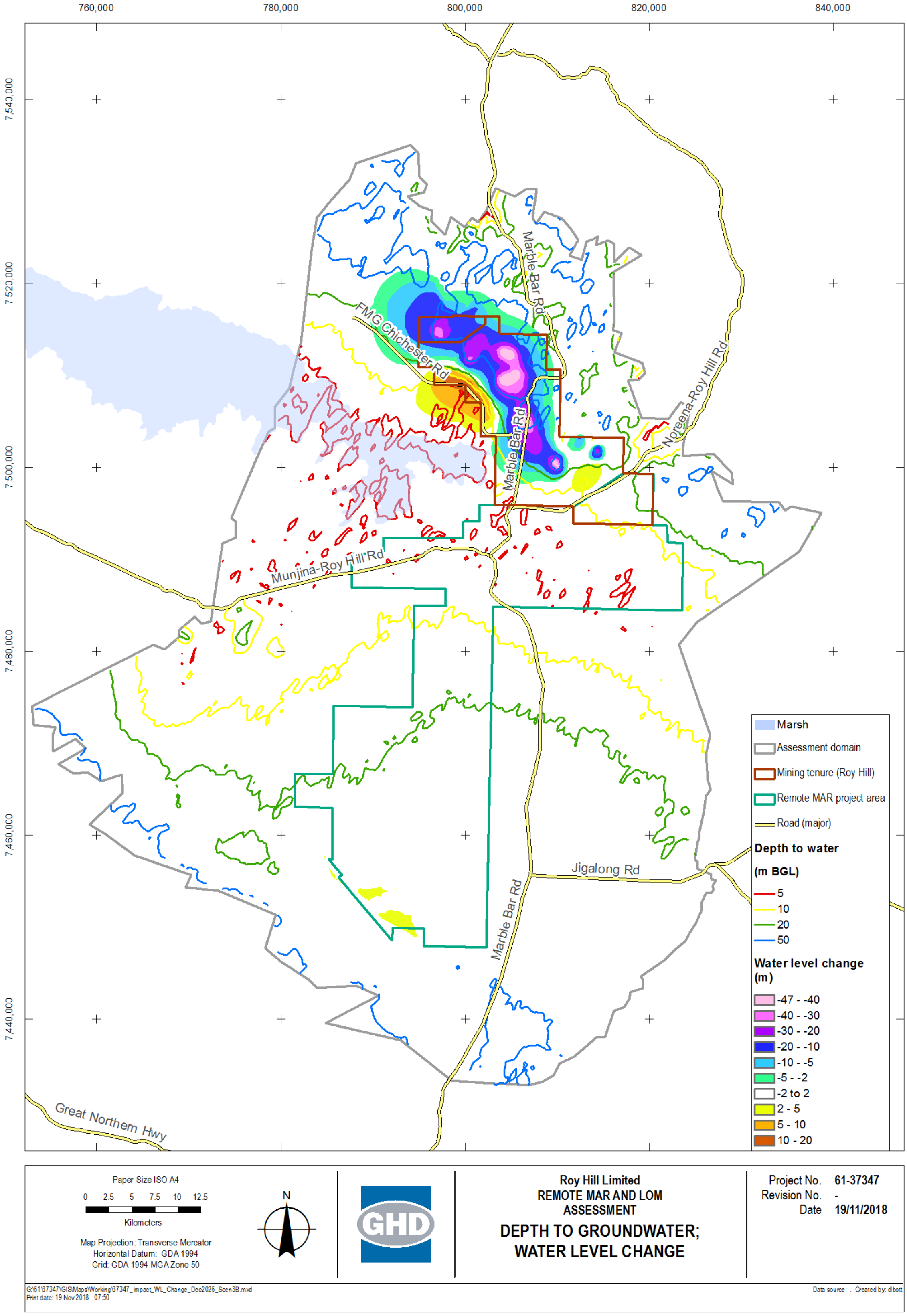
Depth to groundwater; water level change, December 2026

Scenario 3: Dewatering and injection in mining area (SWIB and MPIB), surplus disposal in RMAR South



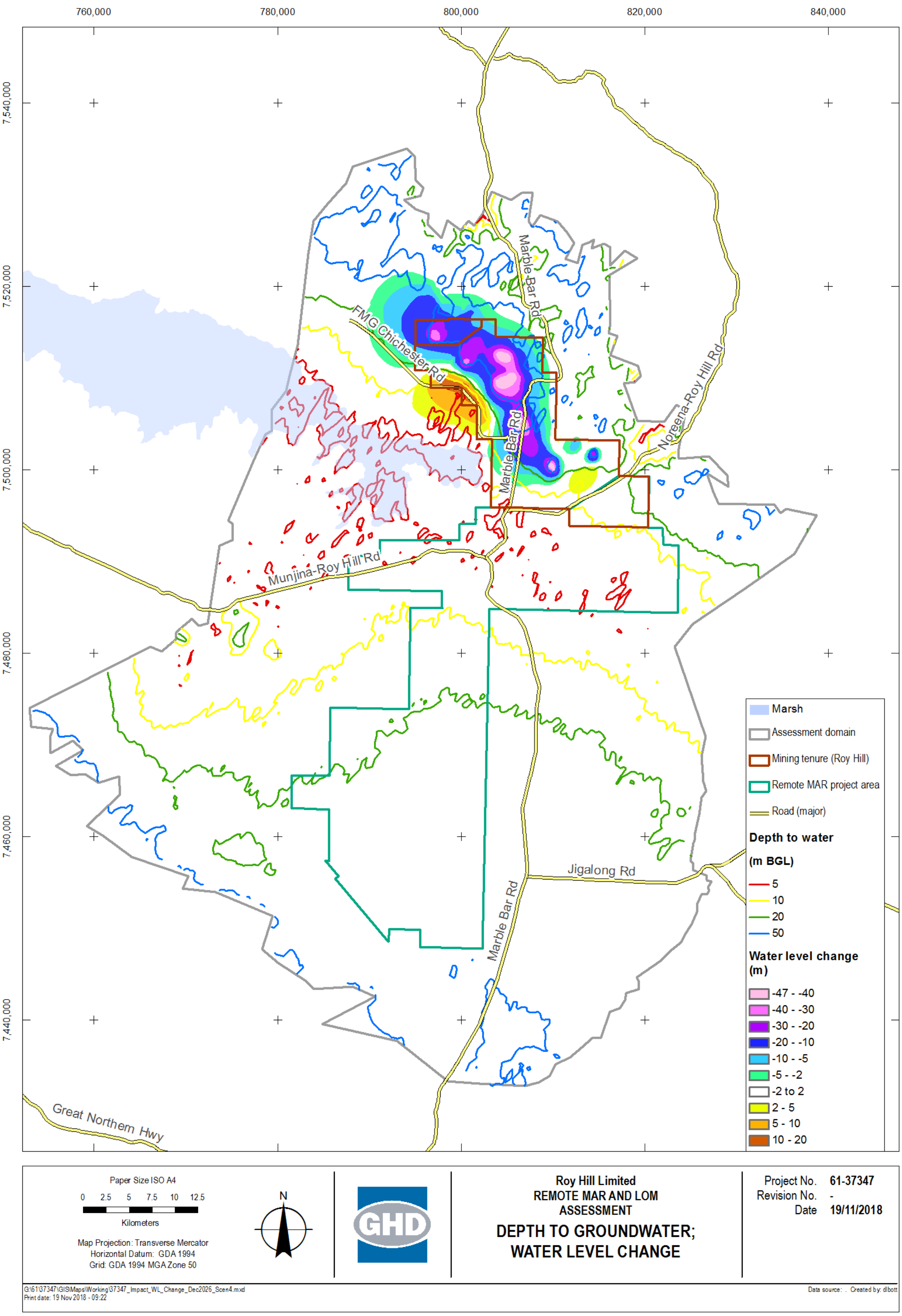
Depth to groundwater; water level change, December 2026

Scenario 3B: Dewatering and injection in mining area (SWIB and MPIB), surplus disposal in RMAR South and in RMAR North (20 ML/d)



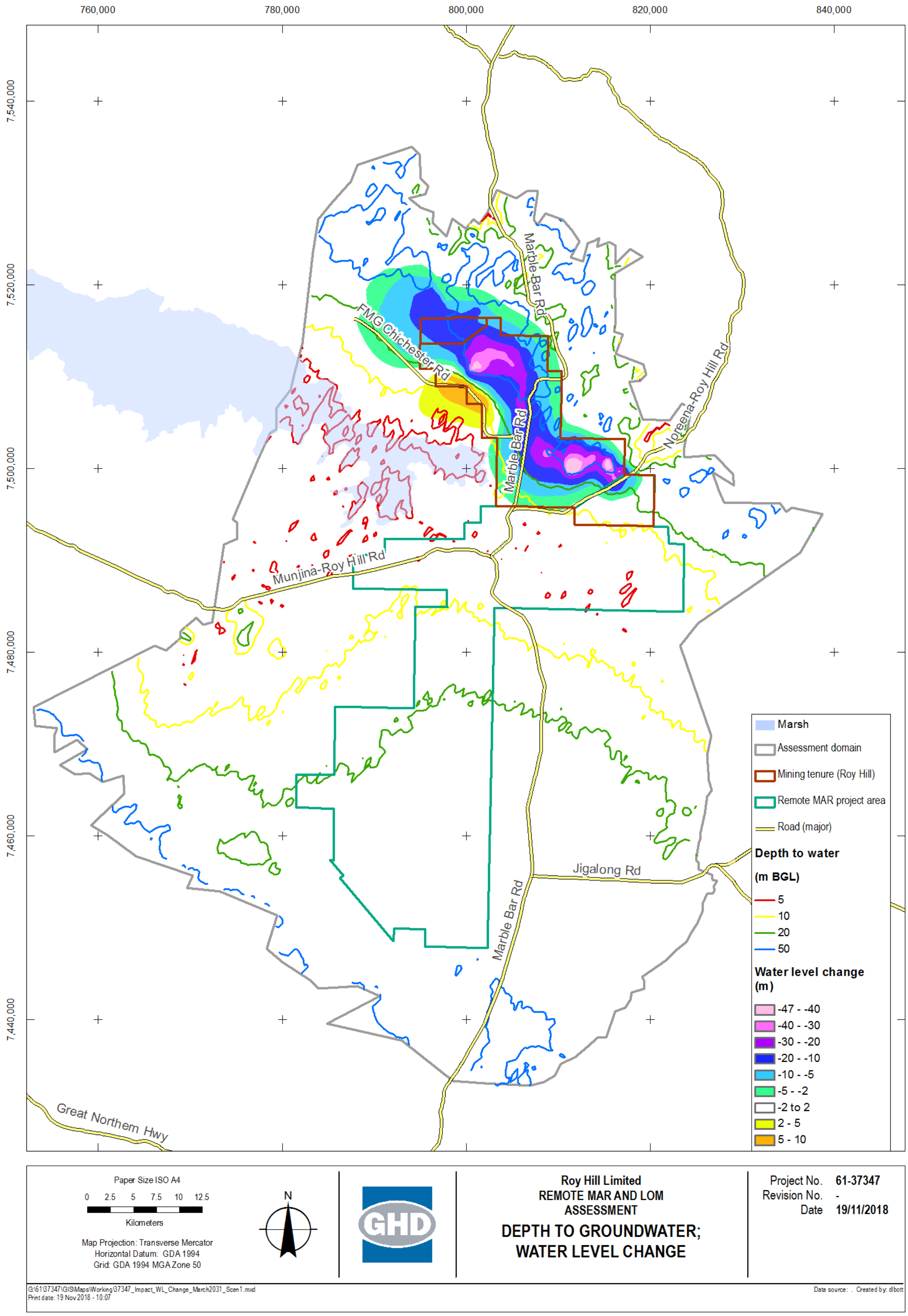
Depth to groundwater; water level change, December 2026

Scenario 4: Dewatering and injection in mining area (SWIB and MPIB), surplus disposal in RMAR North; abstraction from Stage 2 borefield (40 ML/d)



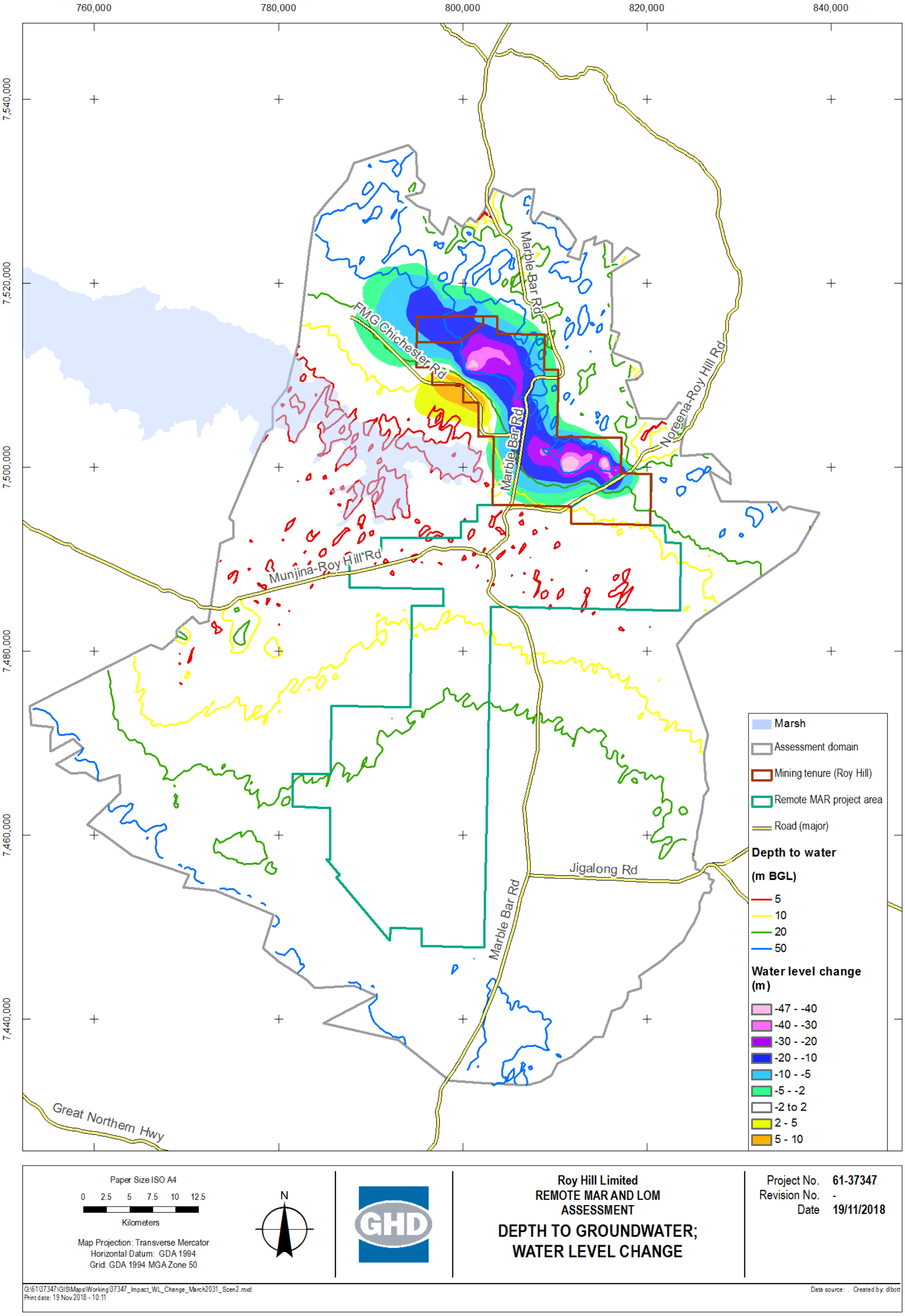
Depth to groundwater; water level change, December 2026

Scenario 1: Dewatering and injection in mining area (SWIB and MPIB)



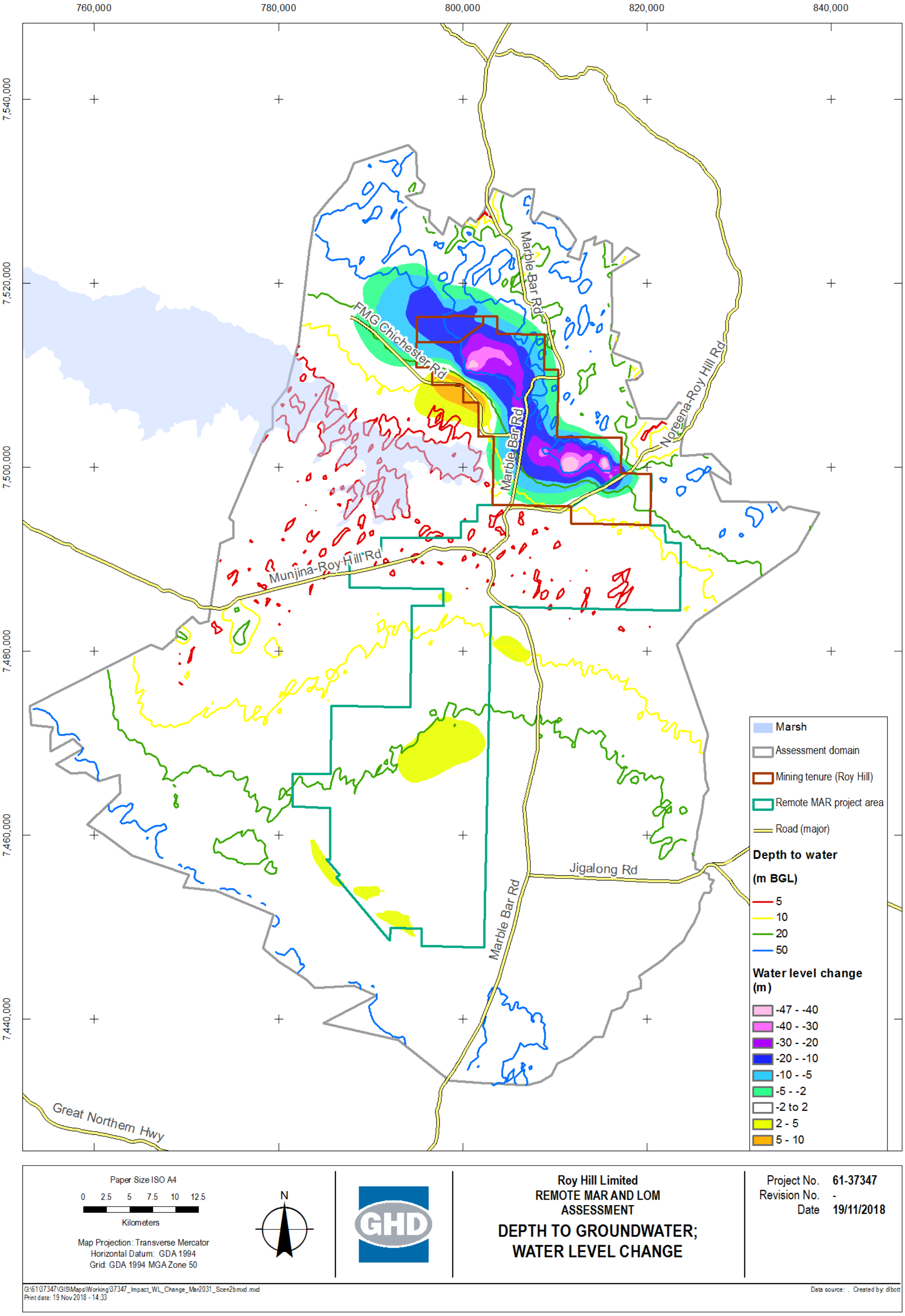
Depth to groundwater; water level change, March 2031

Scenario 2: Dewatering and injection in mining area (SWIB and MPIB), surplus disposal in RMAR North



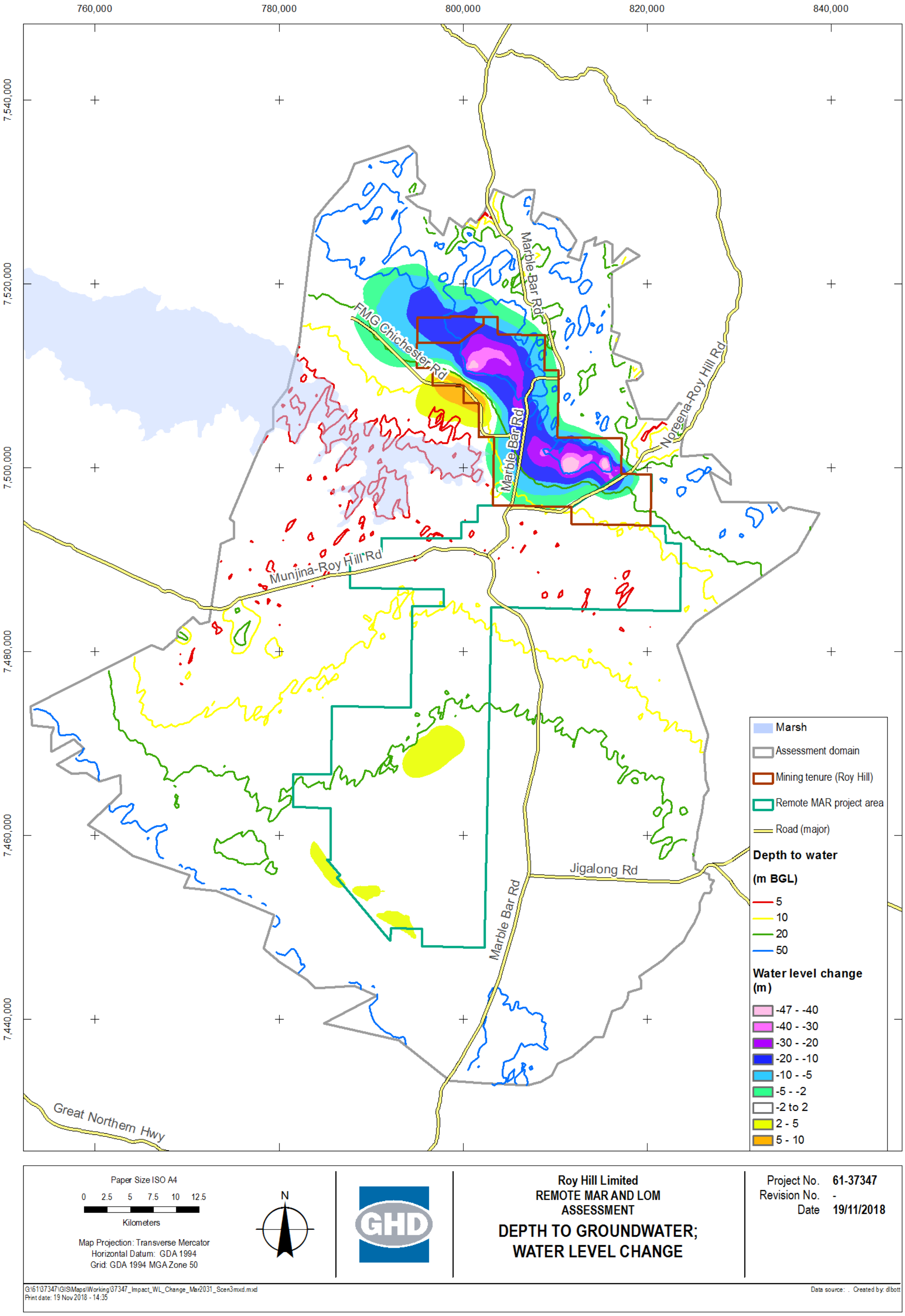
Depth to groundwater; water level change, March 2031

Scenario 2B: Dewatering and injection in mining area (SWIB and MPIB), surplus disposal in RMAR North and in RMAR South (20 ML/d)



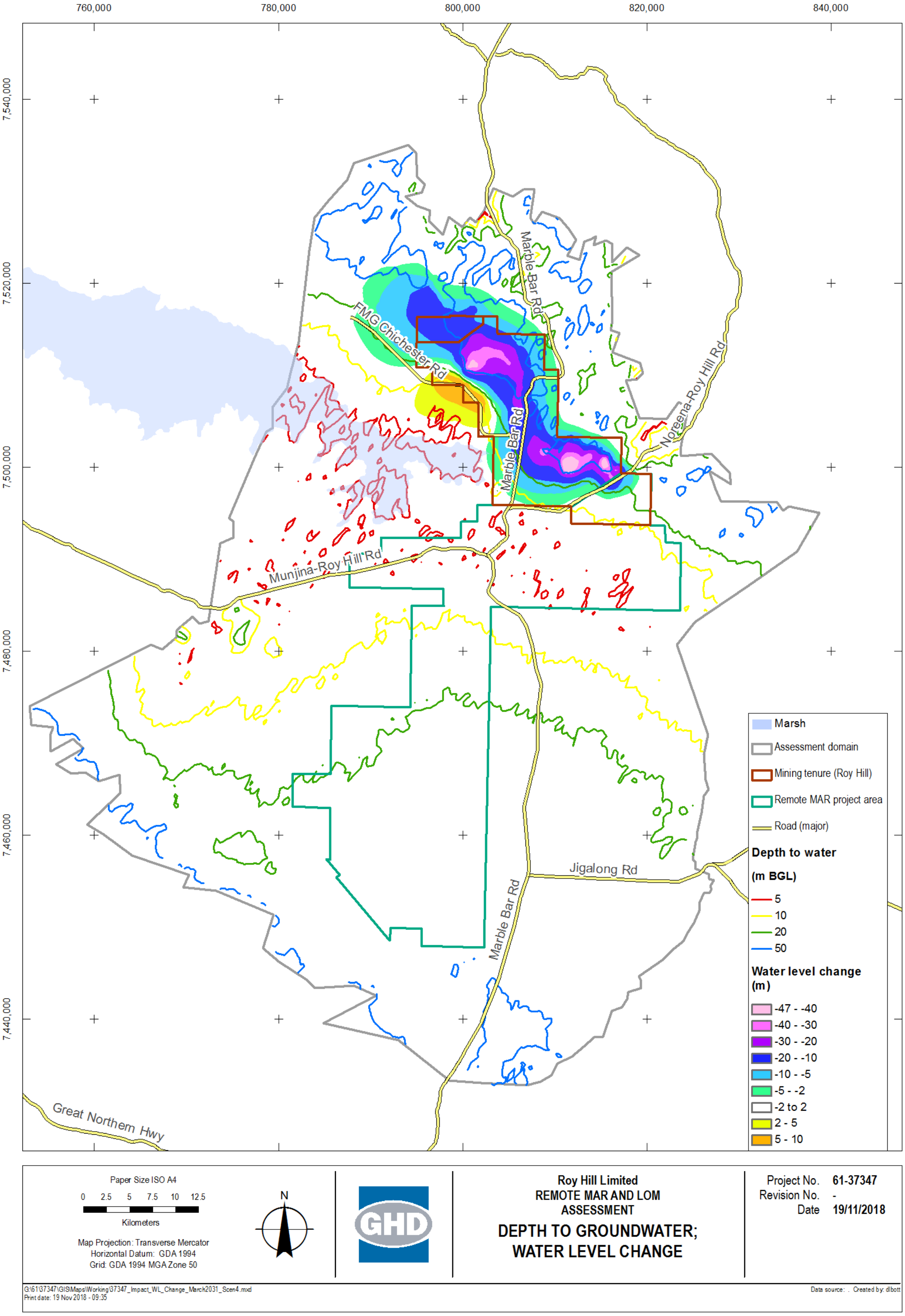
Depth to groundwater; water level change, March 2031

Scenario 3: Dewatering and injection in mining area (SWIB and MPIB), surplus disposal in RMAR South



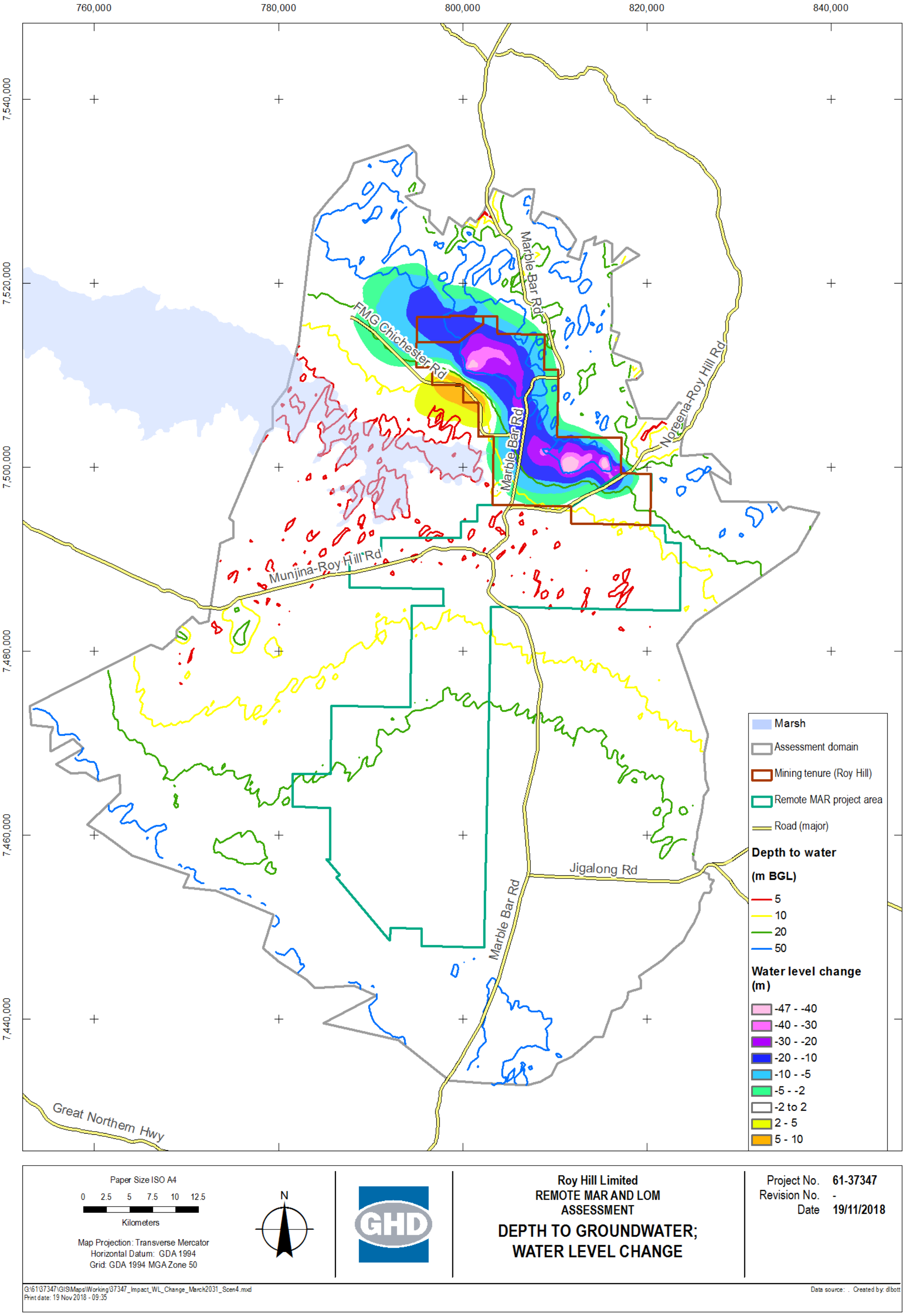
Depth to groundwater; water level change, March 2031

Scenario 3B: Dewatering and injection in mining area (SWIB and MPIB), surplus disposal in RMAR South and in RMAR North (20 ML/d)



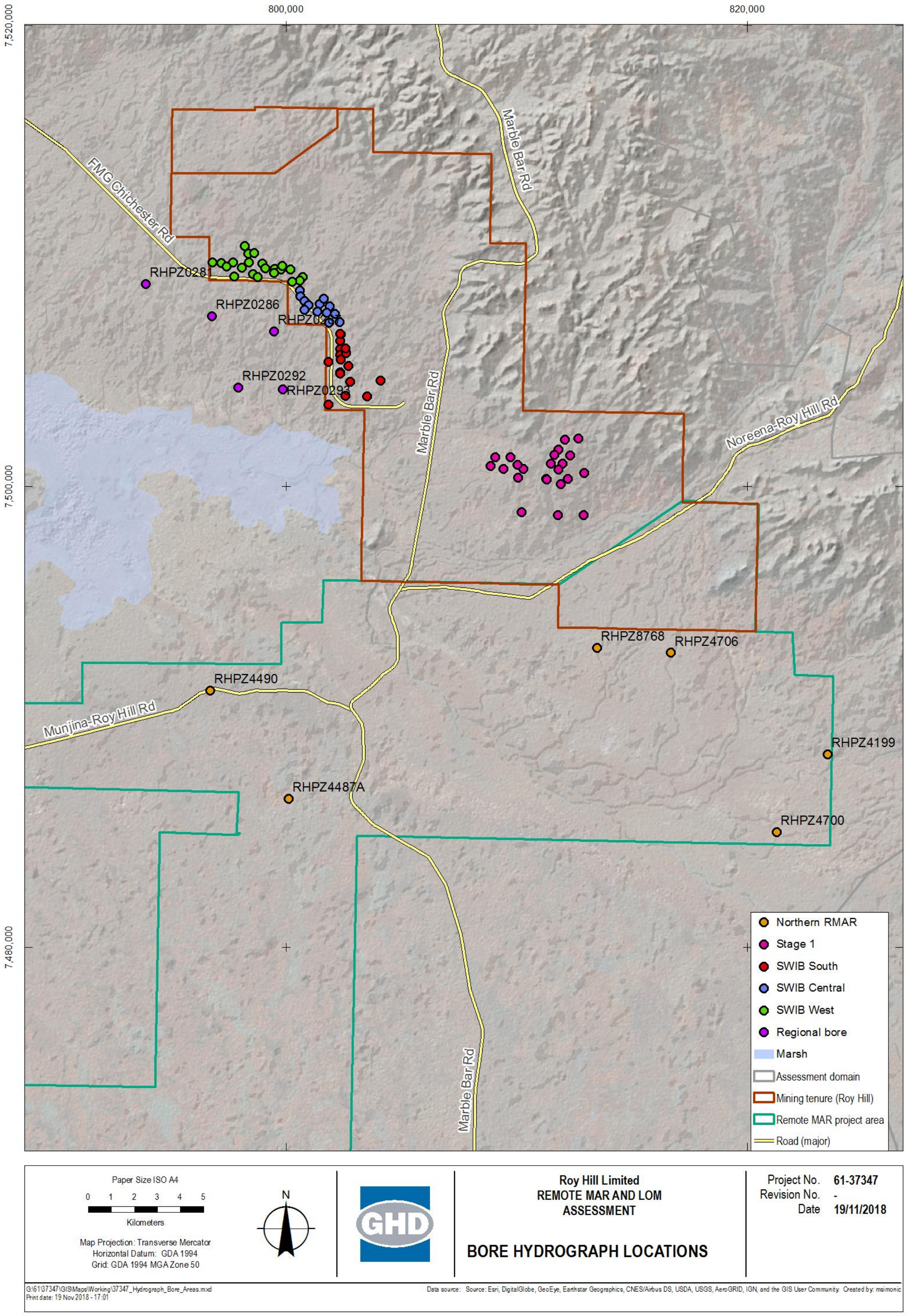
Depth to groundwater; water level change, March 2031

Scenario 4: Dewatering and injection in mining area (SWIB and MPIB), surplus disposal in RMAR North; abstraction from Stage 2 borefield (40 ML/d)



Depth to groundwater; water level change, March 2031

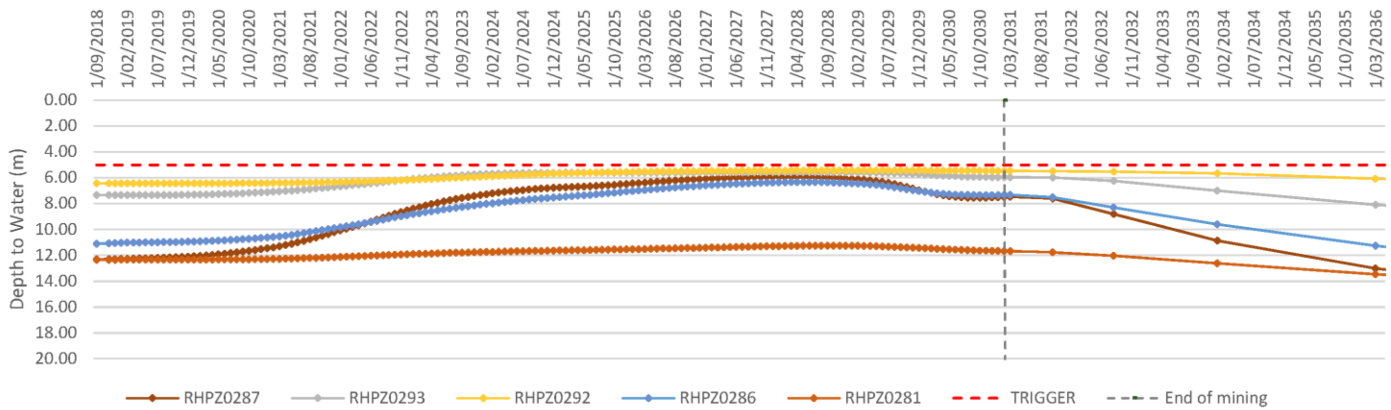
Maps of predicted water level change and depth to groundwater for management simulations



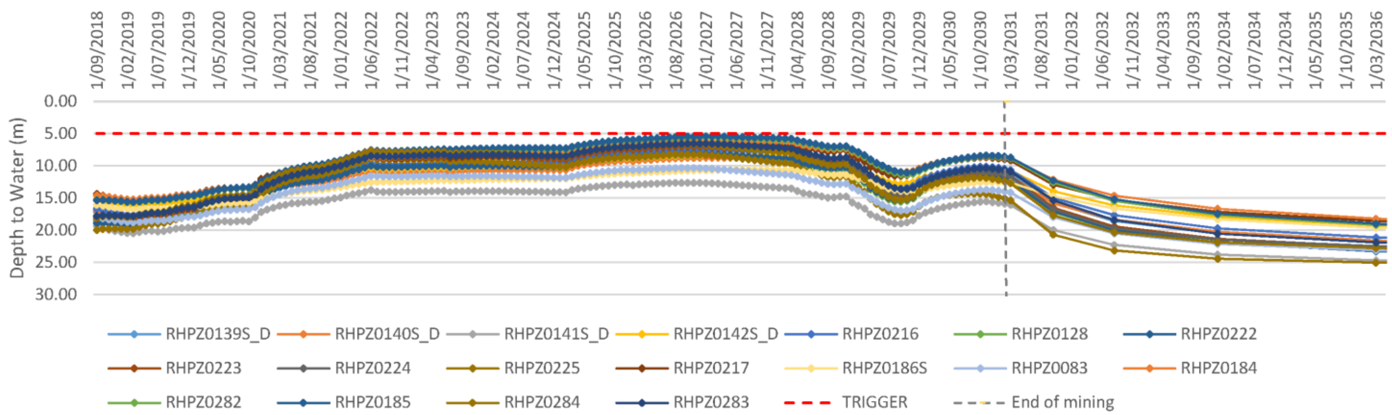
Predicted depth to water

Roy Hill - Remote MAR Study
Hydrographs

Scenario 1: Depth to Water: Outside Domain



Scenario 1: Depth to Water: West Injection Area



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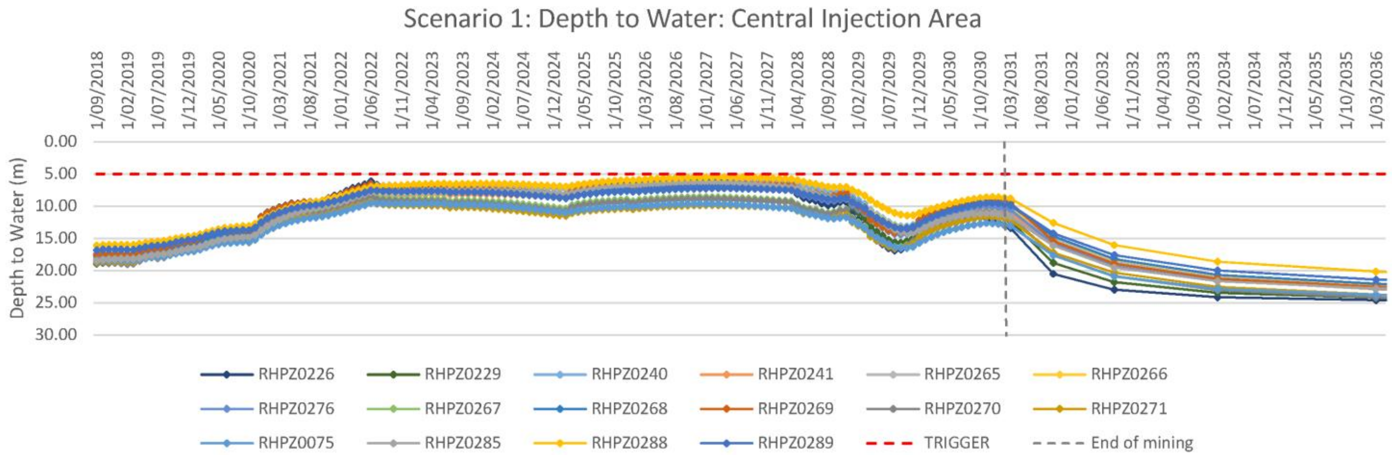
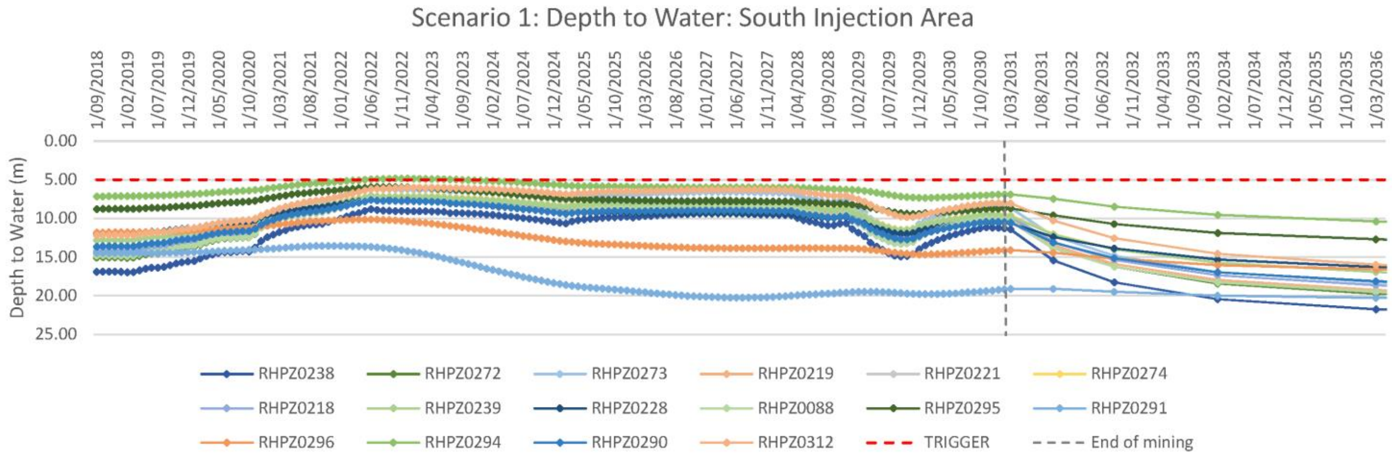
Predicted depth to water

Roy Hill - Remote MAR Study
Hydrographs





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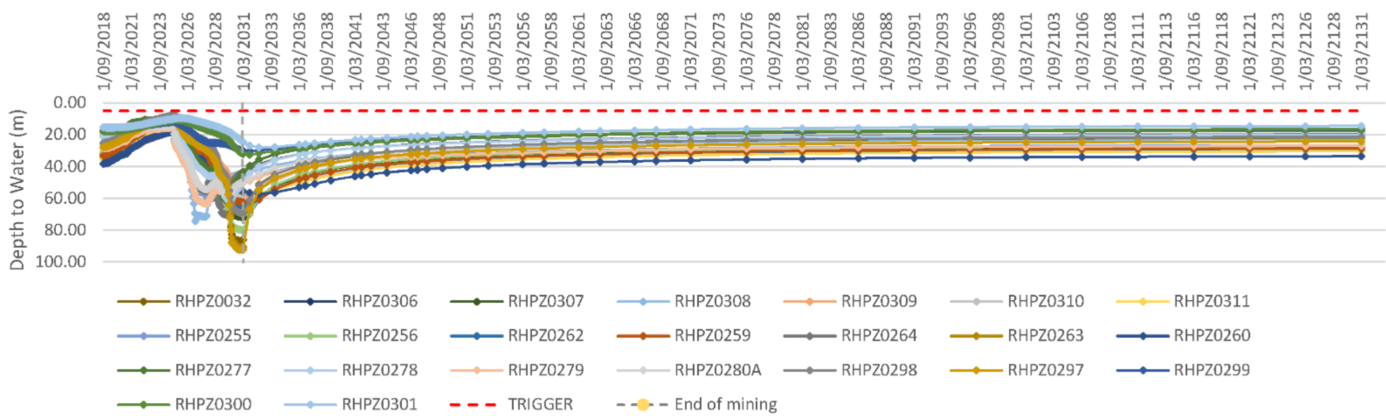

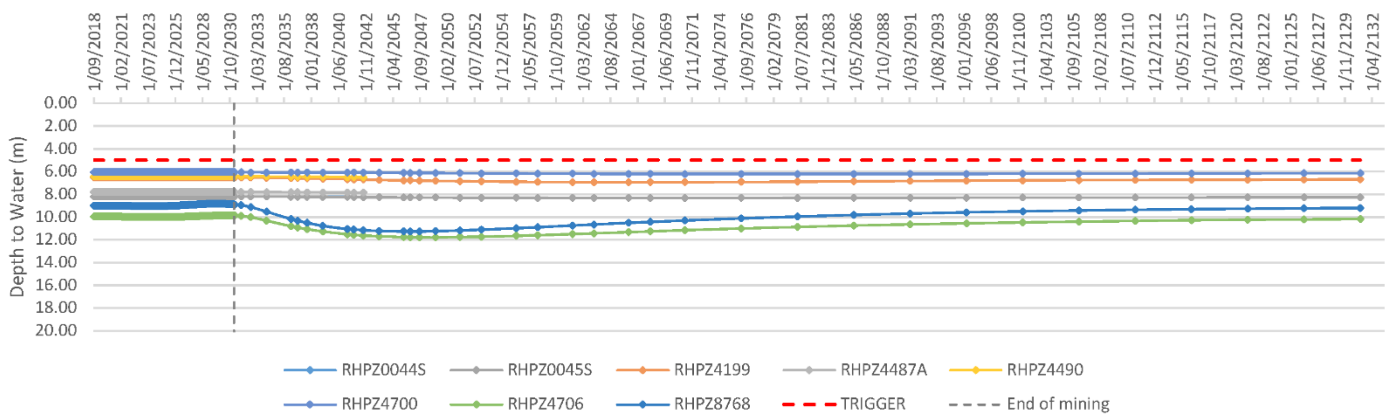

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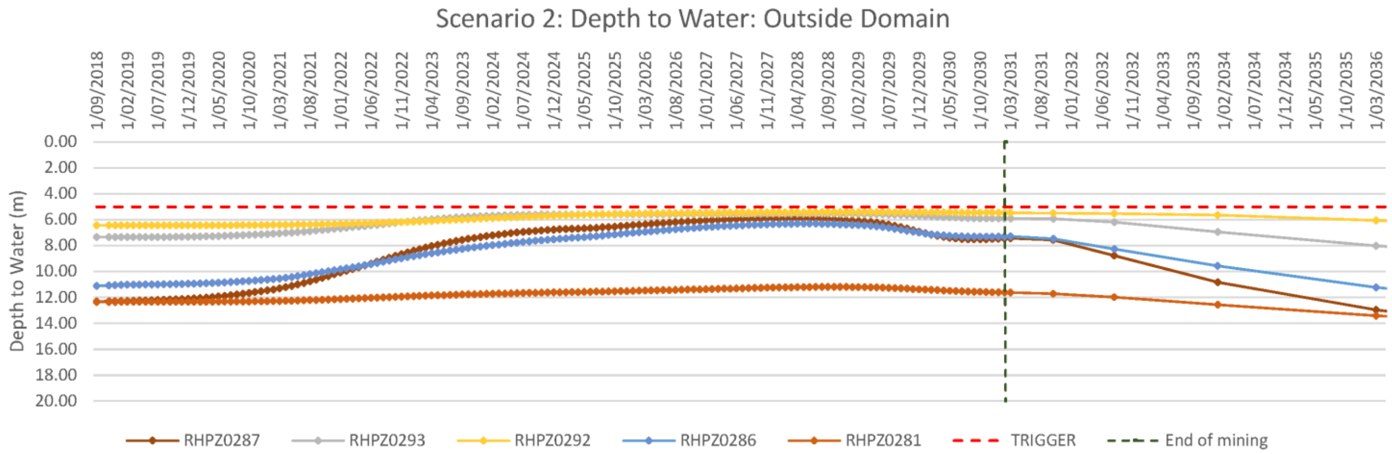
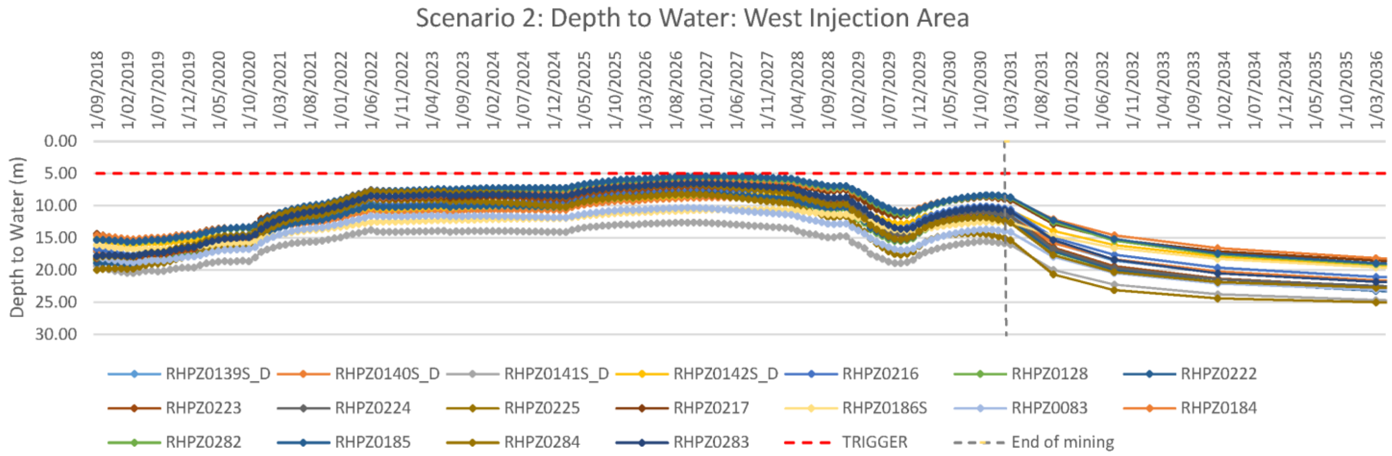
Predicted depth to water

Roy Hill - Remote MAR Study
Hydrographs





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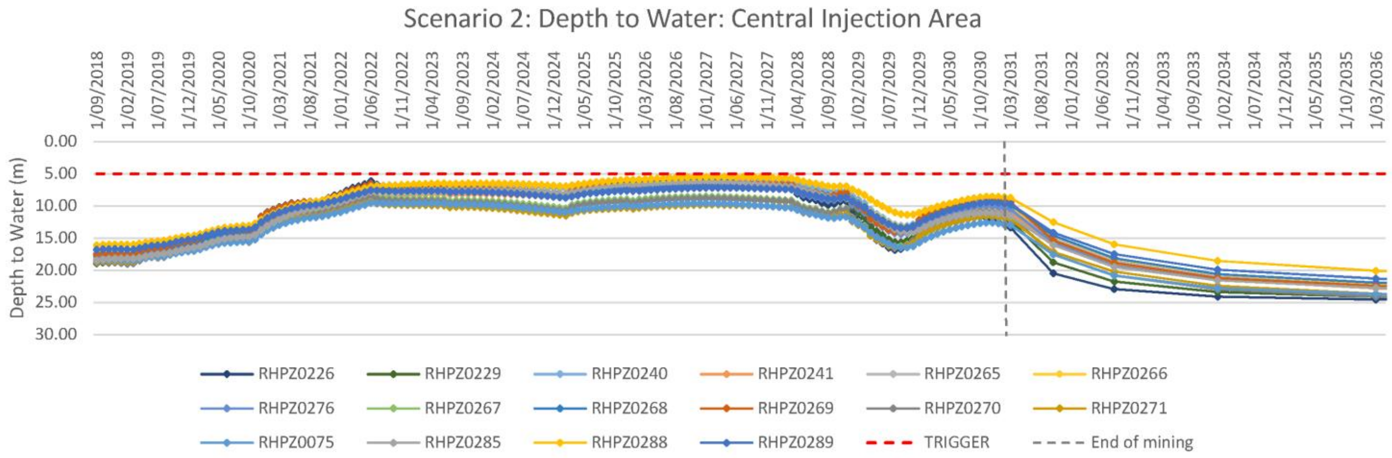
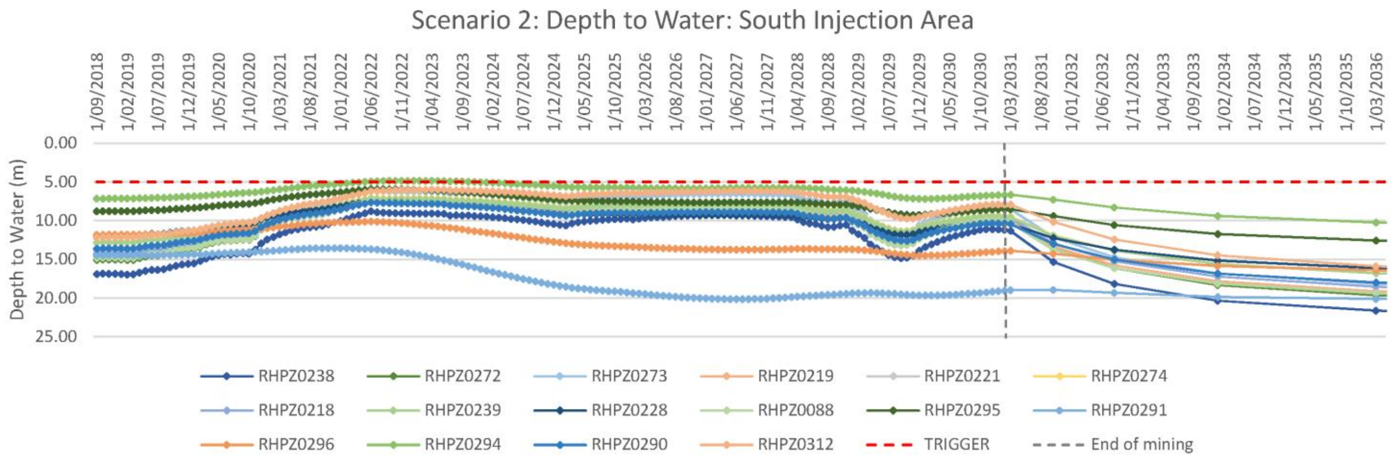
Predicted depth to water

Roy Hill - Remote MAR Study
Hydrographs





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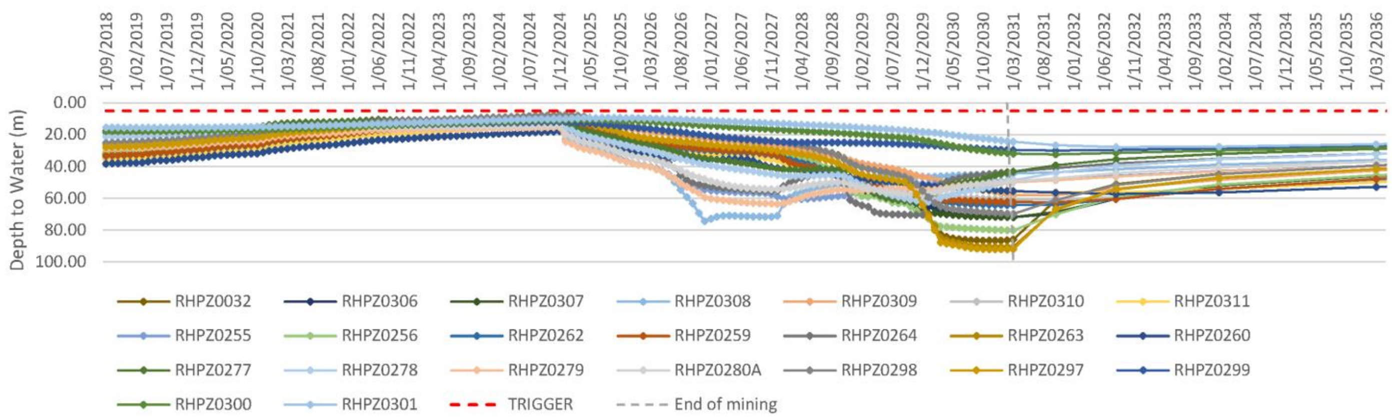
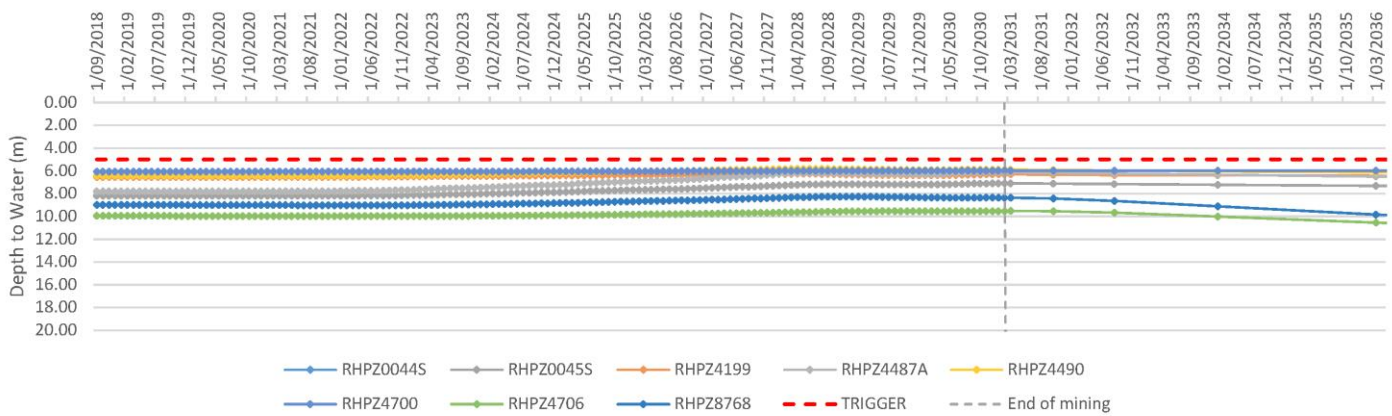
Predicted depth to water

Roy Hill - Remote MAR Study
Hydrographs

Scenario 2: Depth to Water: Stage 1 Borefield



Scenario 2: Depth to Water: Northern RMAR



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Predicted depth to water

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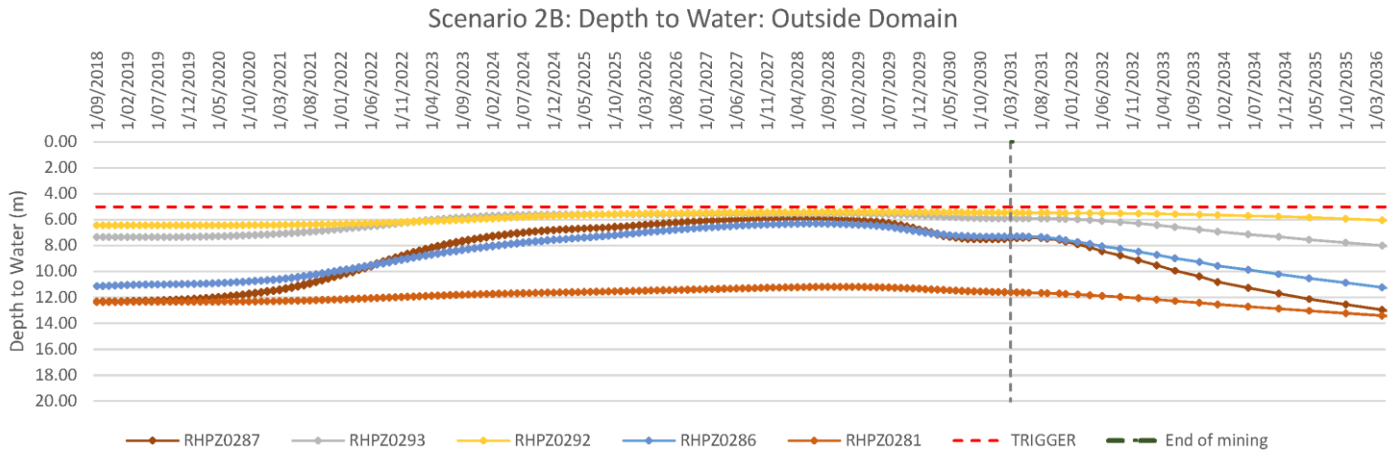

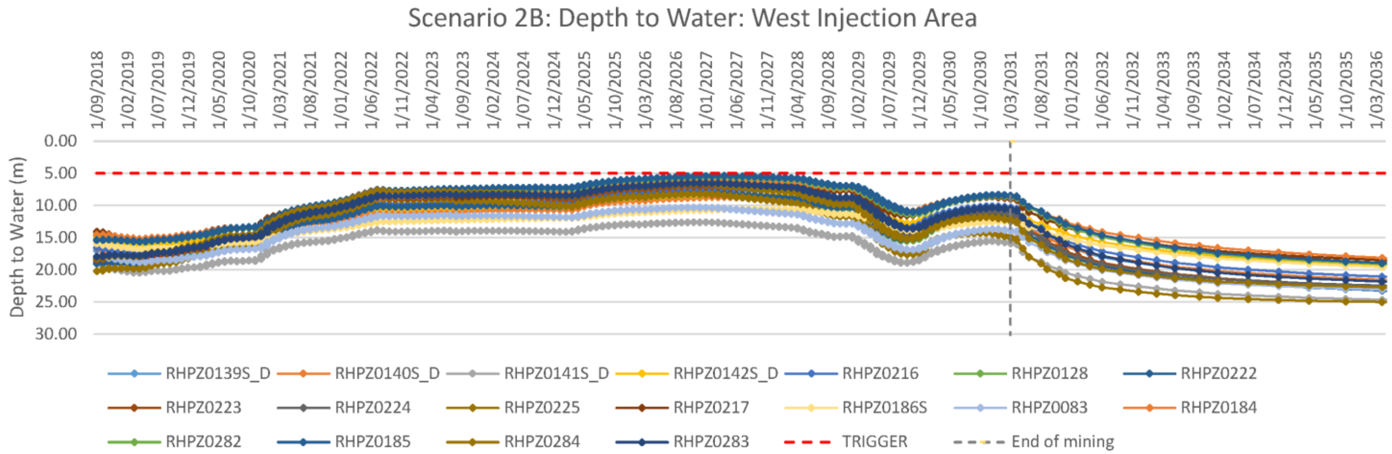

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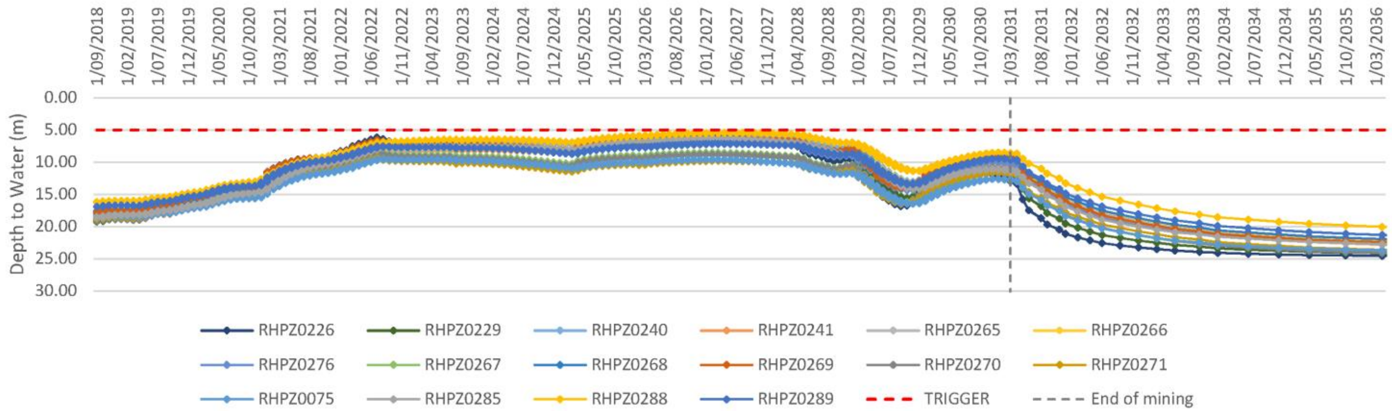
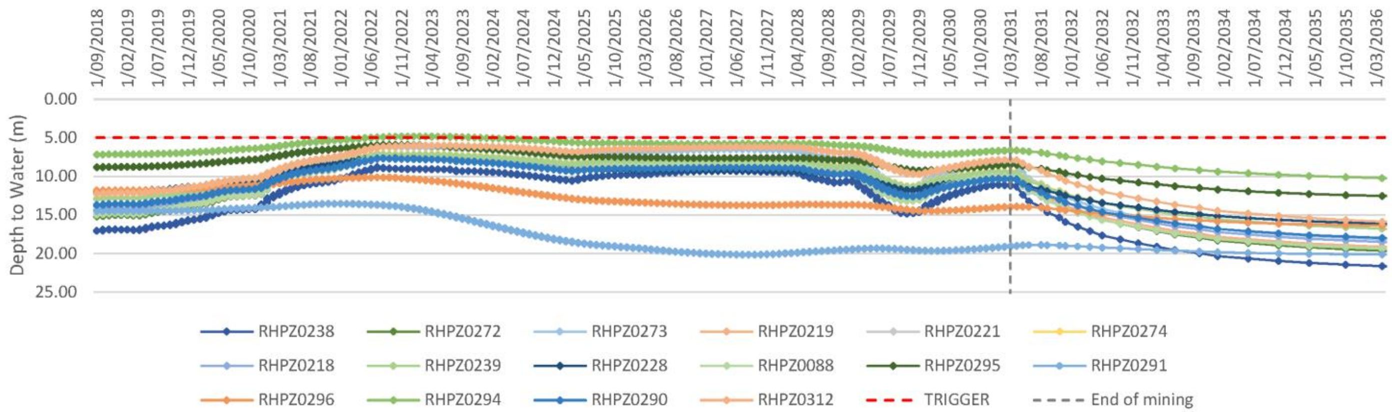
Predicted depth to water

Roy Hill - Remote MAR Study
Hydrographs

Scenario 2B: Depth to Water: Central Injection Area



Scenario 2B: Depth to Water: South Injection Area



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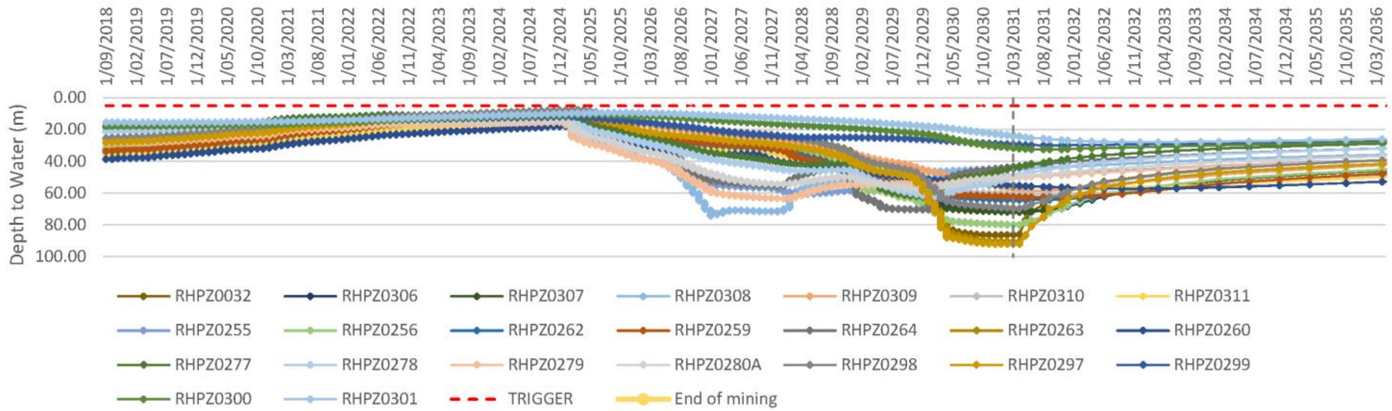
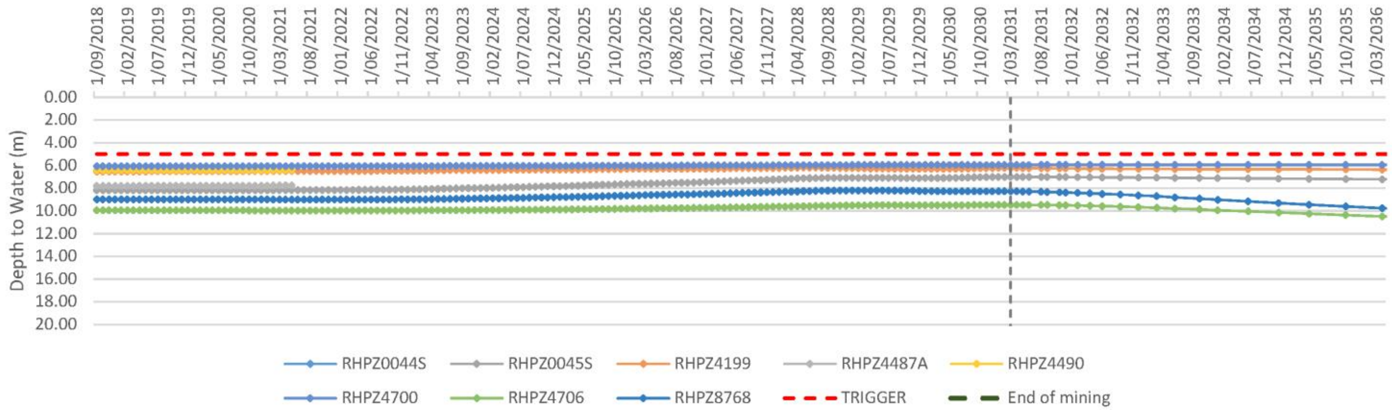
Scenario 2B: Depth to Water: Stage 1 Borefield



Scenario 2B: Depth to Water: Northern RMAR



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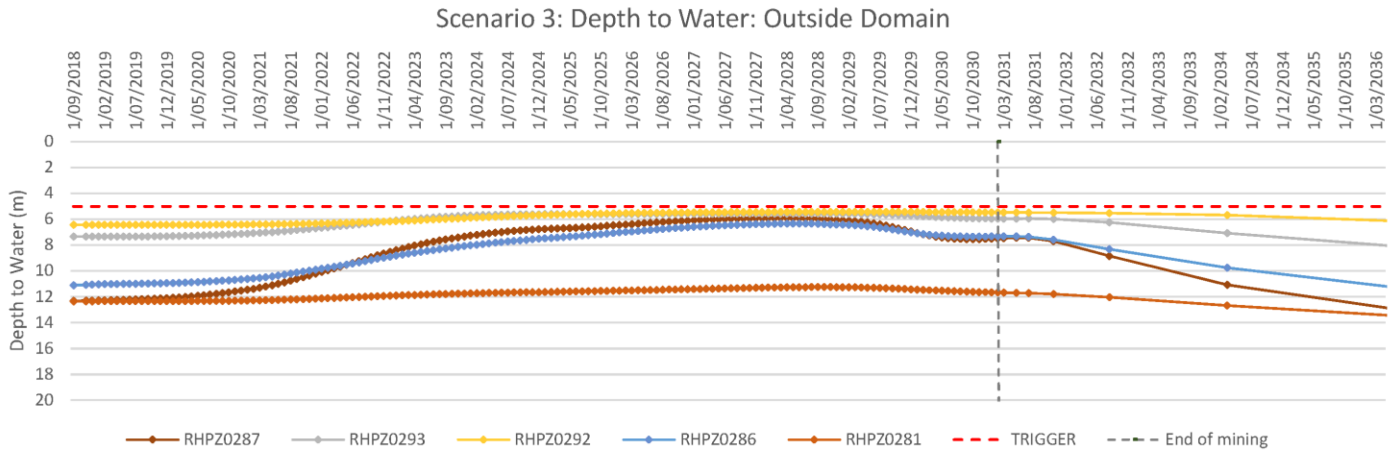
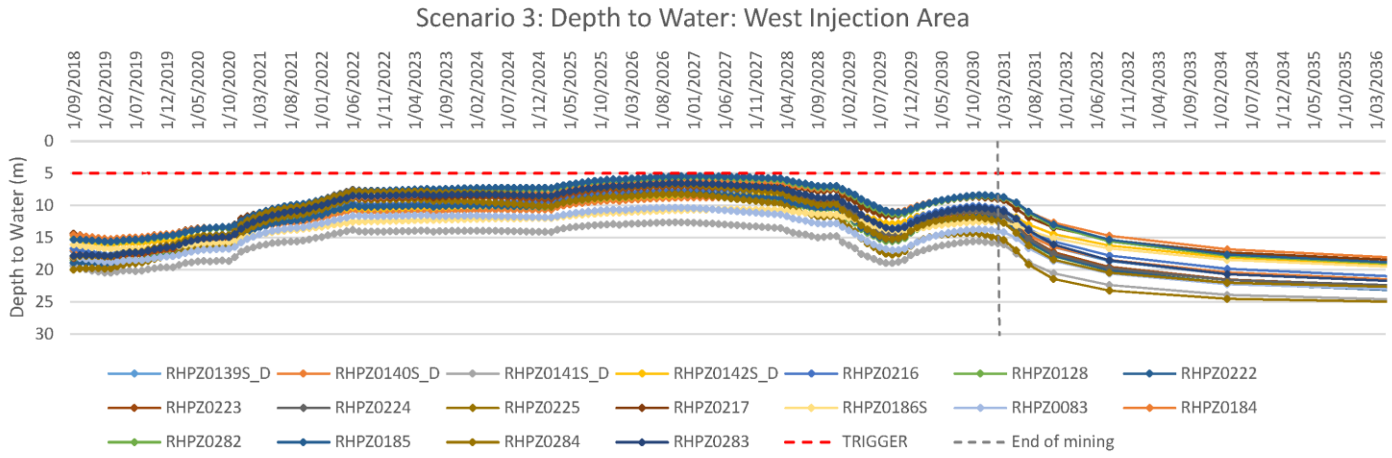
Predicted depth to water

Roy Hill - Remote MAR Study
Hydrographs





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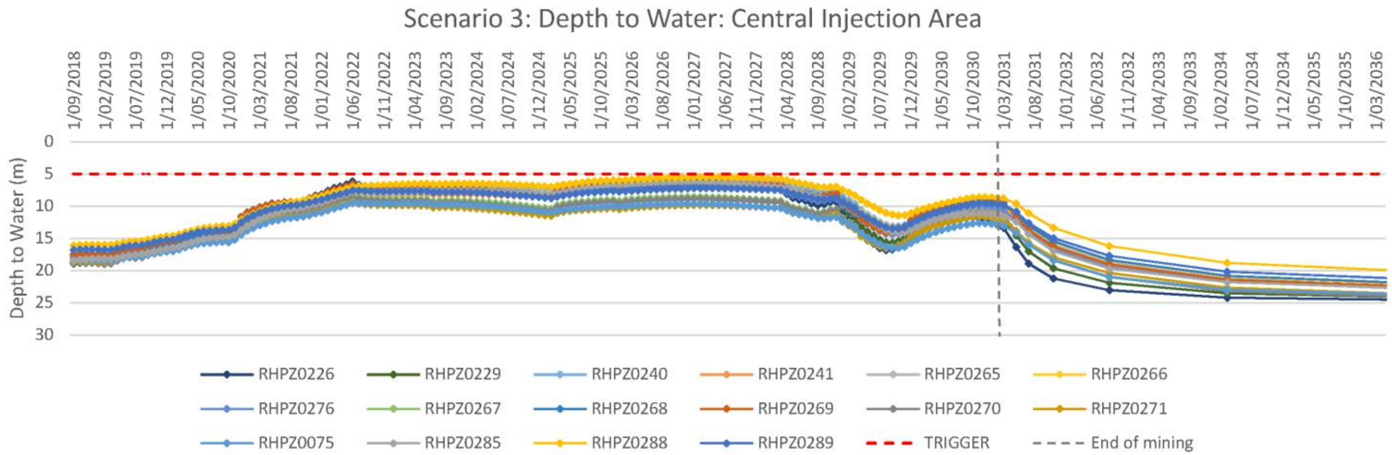

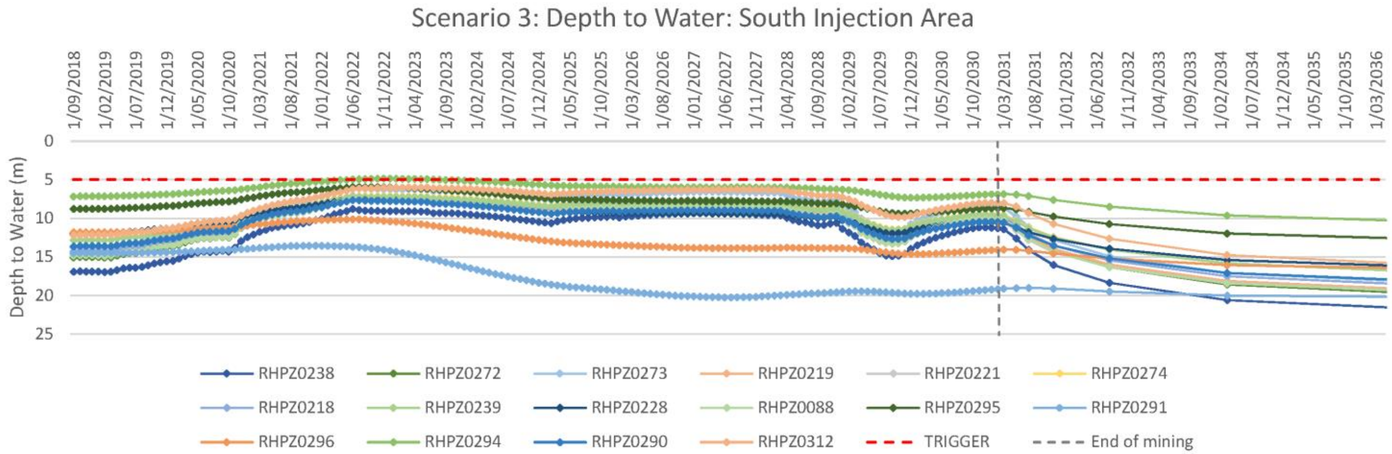

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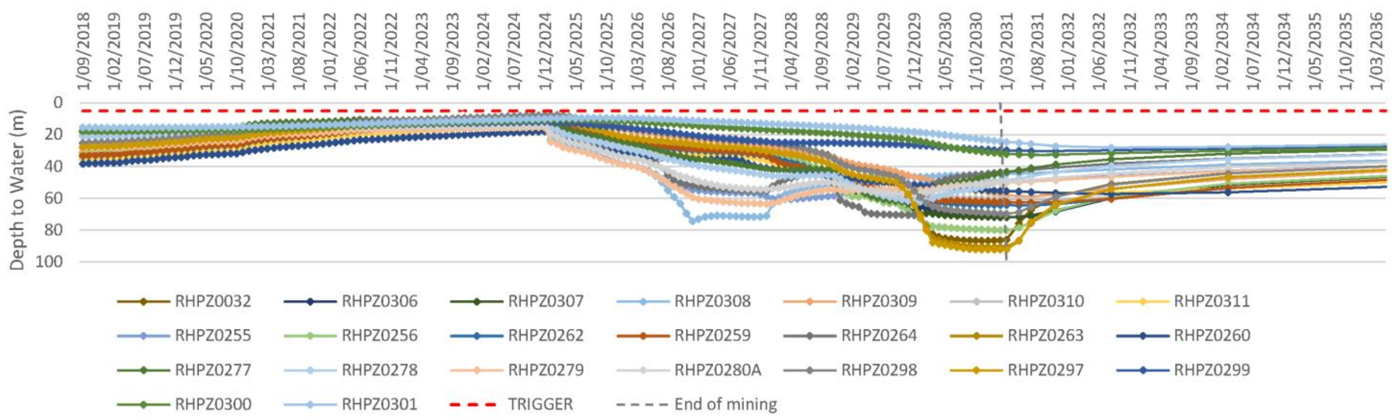
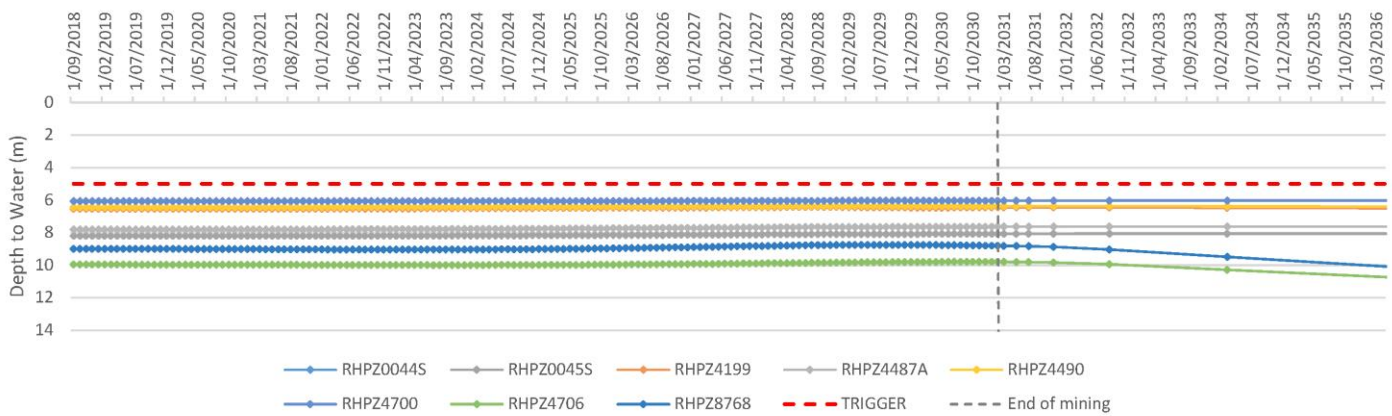
Scenario 3: Depth to Water: Stage 1 Borefield



Scenario 3: Depth to Water: Northern RMAR



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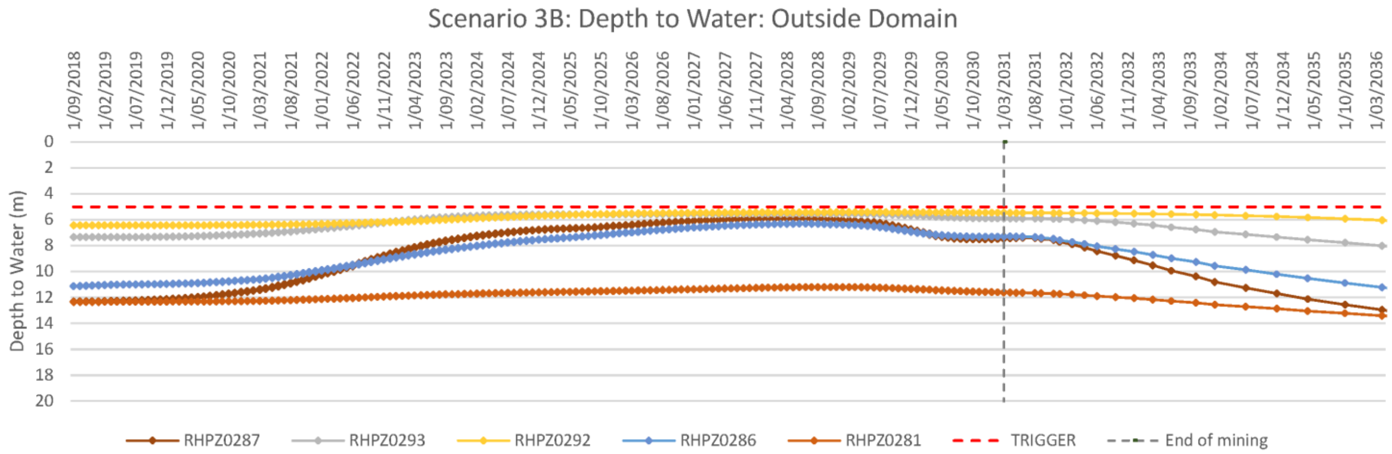

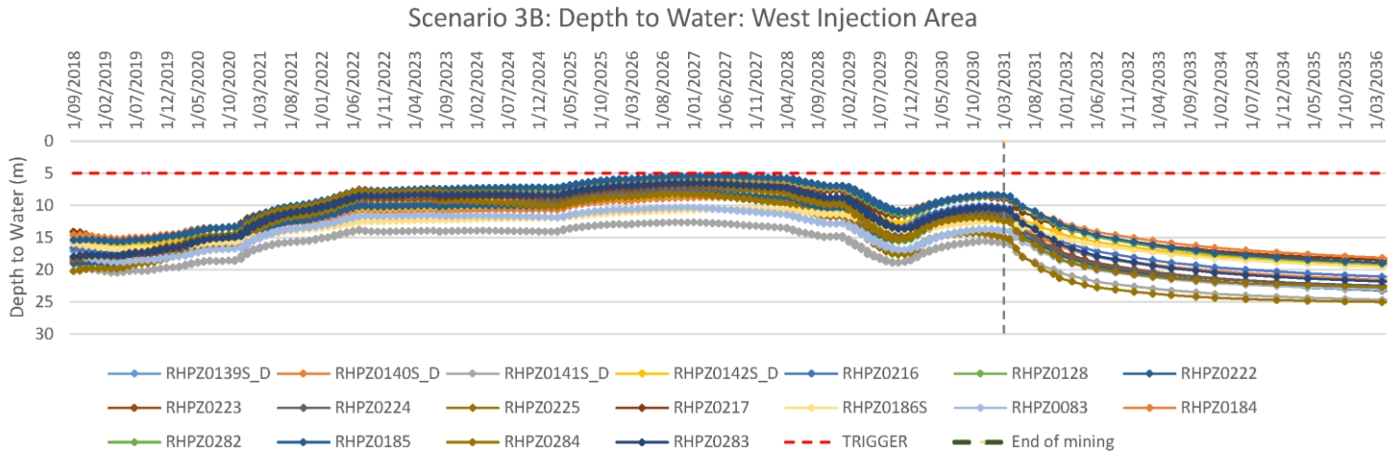

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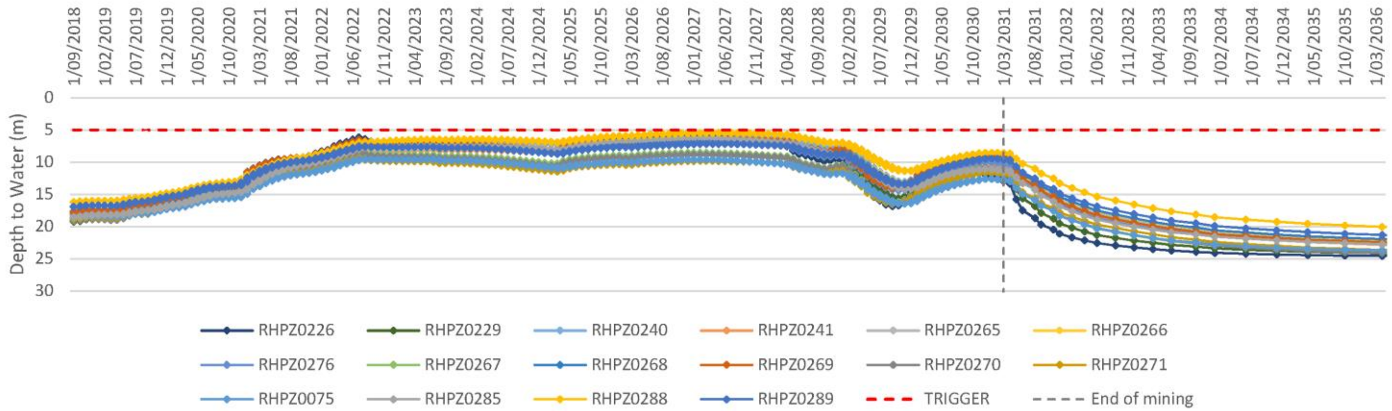
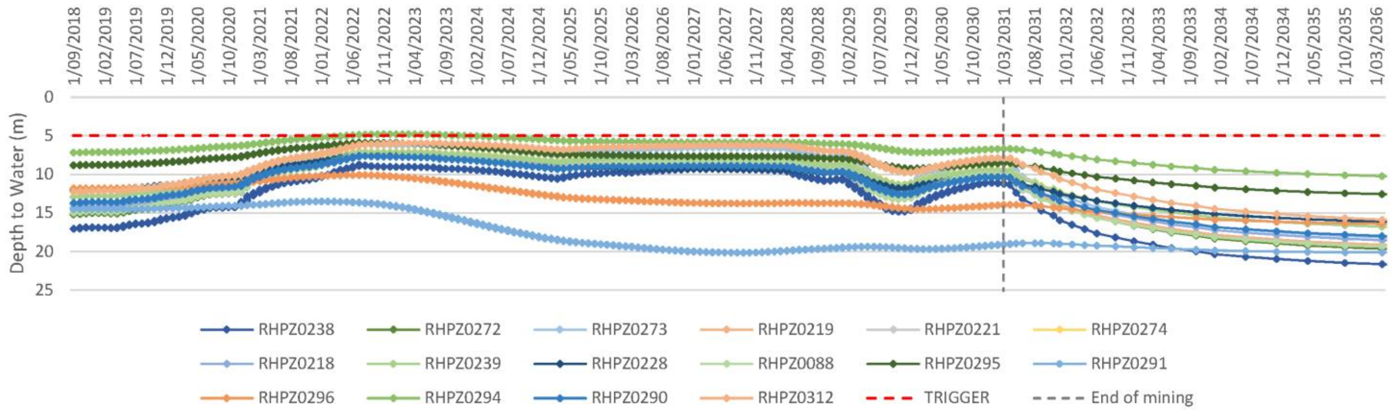
Scenario 3B: Depth to Water: Central Injection Area



Scenario 3B: Depth to Water: South Injection Area



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Predicted depth to water

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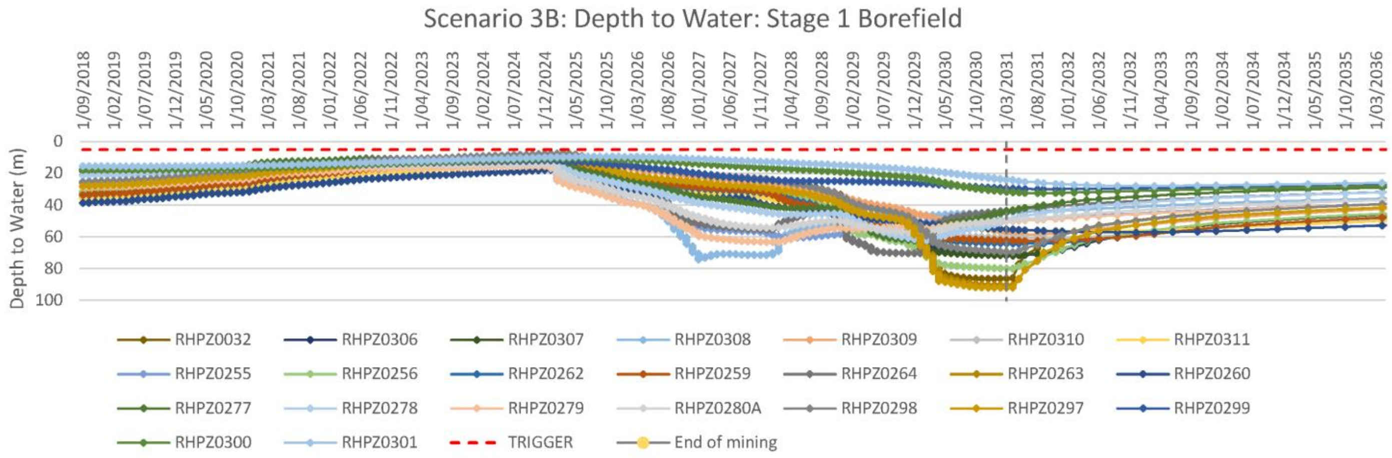
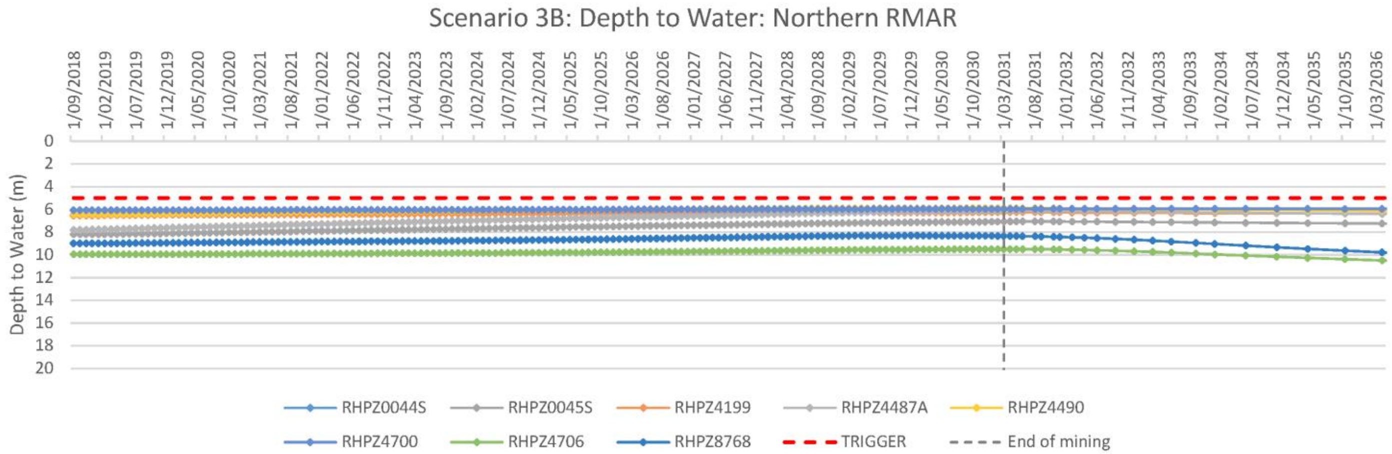
Hydrographs





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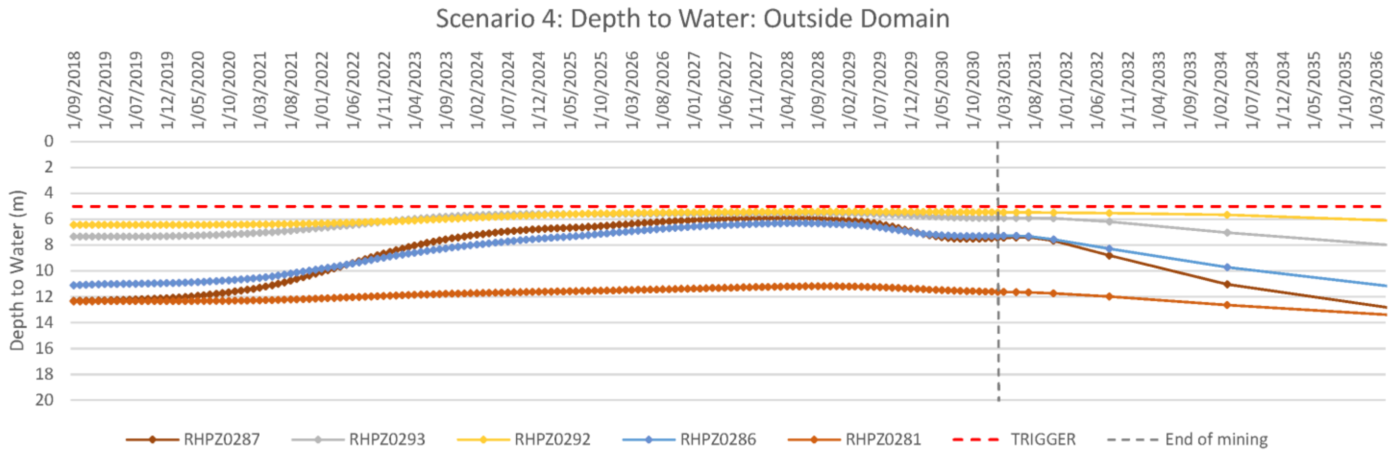

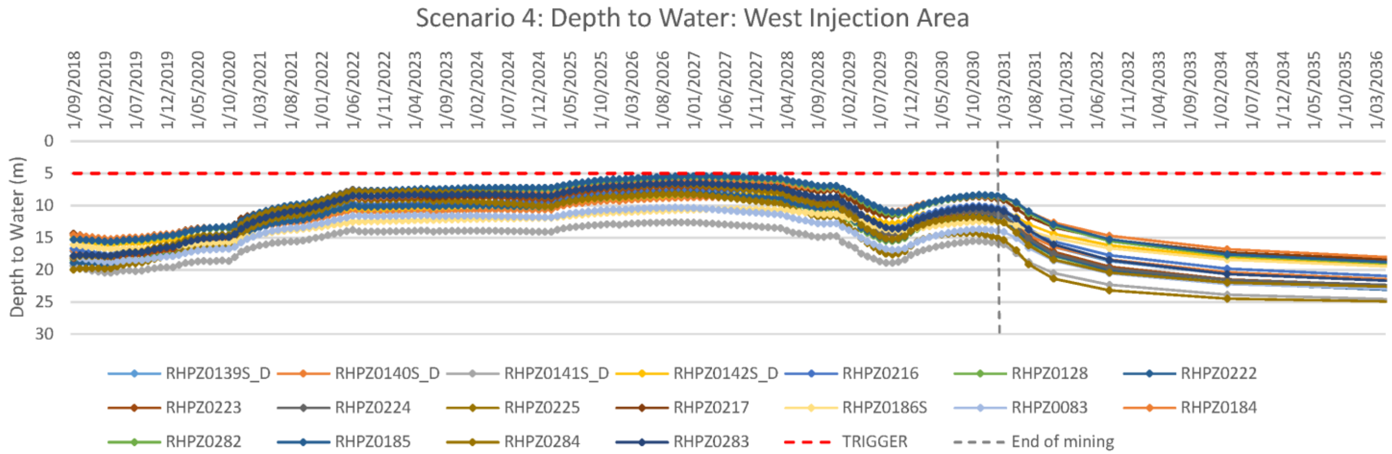

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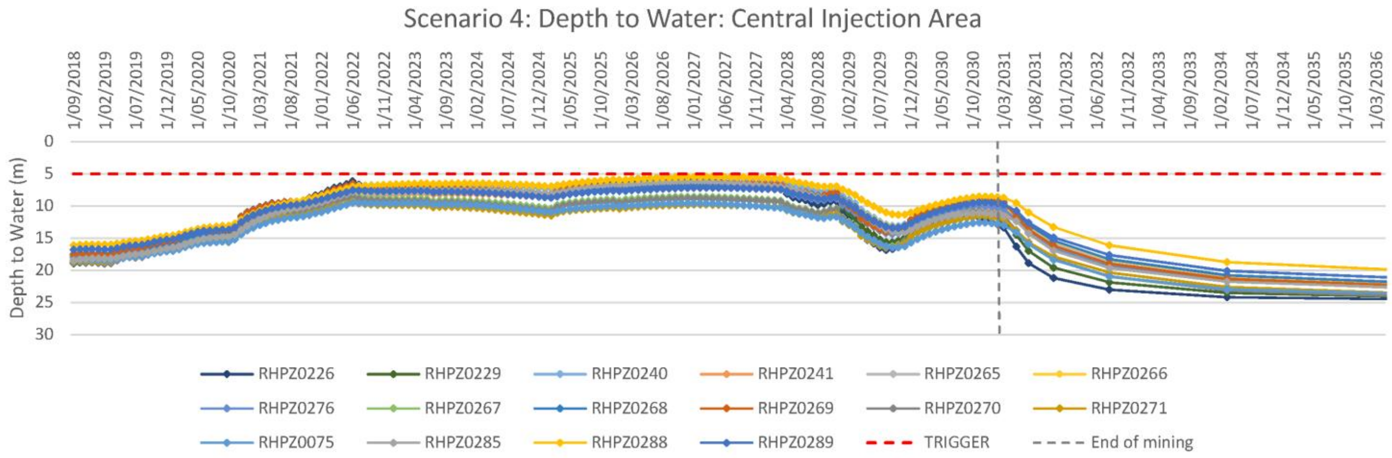

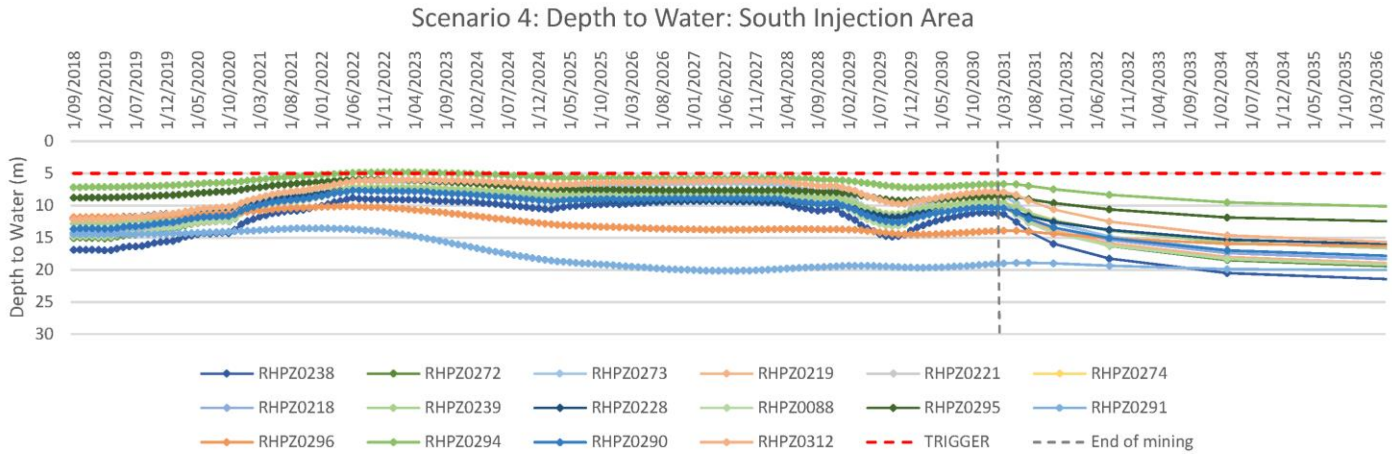

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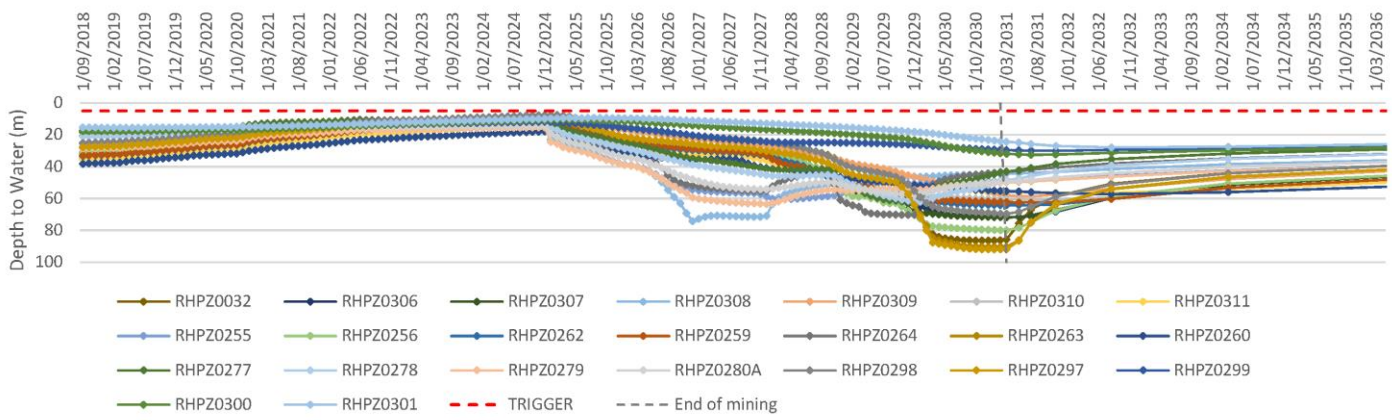
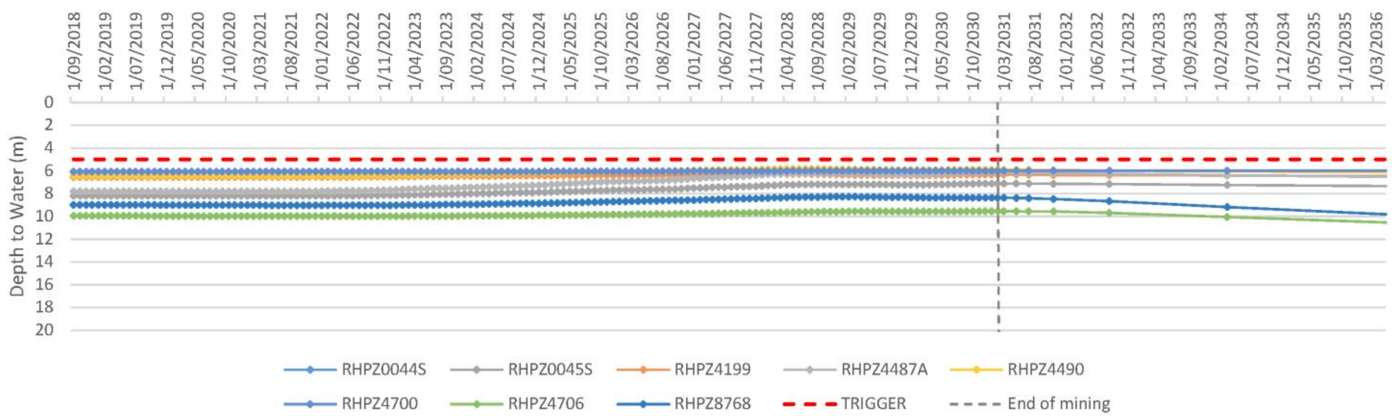
Scenario 4: Depth to Water: Stage 1 Borefield



Scenario 4: Depth to Water: Northern RMAR



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Document Status

Revision	Author	Reviewer		Approved for Issue		
		Name	Signature	Name	Signature	Date
A	MS	BWJ/GF				12/10/18
B	MS	BWJ/SB/BK				15/10/18
C	MS	BWJ/SB/BK				19/11/18
D	MS	BWJ/BK				30/11/18
0	M Simonic	BWJ/BK				4/12/18
1	M Simonic	BWJ/BK		P Hamer		15/01/19

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