Groundwater Environmental Management Plan

West Angelas Revised Proposal

RTIO-HSE-0349522

Robe River Mining Co. Pty. Ltd.

152-158 St Georges Terrace, Perth

GPO Box A42, Perth WA 6837

Disclaimer and Limitation

This Groundwater Environmental Management Plan has been prepared by Rio Tinto's Iron Ore group (Rio Tinto), on behalf of Robe River Mining Co. Pty. Ltd. (the Proponent), specifically for the West Angelas Revised Proposal. Neither the document nor its contents may be referred to without the express approval of Rio Tinto, unless the document has been approved for implementation under Ministerial Statement 1113 and Decision Notice 2018/8299.

Document Status					
Rev	**Author**	**Reviewer/s**	**Date**	**Approved for Issue**	
				To Whom	**Date**
1	Rio Tinto	Water Resource Evaluation Approvals Operations	12 – 22 January 2021	DWER, DAWE	10 February 2021
2	Rio Tinto	Water Resource Evaluation Approvals Operations	4 October 2021	DWER, DAWE	4 October 2021
3	Rio Tinto	Water Resource Evaluation Approvals Operations	4 February 2022	DWER, DAWE	7 February 2022

EXECUTIVE SUMMARY

The West Angelas Revised Proposal Groundwater Environmental Management Plan (Groundwater EMP) is submitted by Rio Tinto on behalf of Robe River Mining Co. Pty. Ltd. (the Proponent), as the authorised manager and agent for the participants in the Robe River Iron Associates Joint Venture, in accordance with Ministerial Statement 1113 (MS 1113), and *Environment Protection Biodiversity Conservation Act 1999* (EPBC Act) Approval Decision Notice 2018/8299 (DN 2018/8299).

The purpose of this Groundwater EMP is to satisfy Condition 6 of MS 1113 and Conditions 3, 4, 5 and 6 of DN 2018/8299 in relation to groundwater drawdown associated with dewatering activities at Deposit C and Deposit D and use of a Managed Aquifer Recharge (MAR) scheme to mitigate potential impacts to Karijini National Park (Karijini NP).

This Groundwater EMP provides details of the adaptive management approach and supporting monitoring, which will ensure compliance with relevant State and Commonwealth Conditions. Table 1 below presents the environmental criteria and targets to measure achievement of the environmental outcomes and objectives to be met through implementation of this Groundwater EMP.

Table 1: Environmental criteria to measure achievement of environmental outcomes and objectives

Proposal title		West Angelas Revised Proposal
Proponent		Robe River Mining Co. Pty. Ltd.
Ministerial Statement		1113
EPBC Decision Notice (DN)		2018/8299
Purpose of this EMP		This Groundwater EMP fulfills the requirements of Condition 6 of MS 1113 and the requirements of Conditions 3, 4, 5 and 6 of DN 2018/8299, in relation to values associated with groundwater at the boundary of Karijini NP.
***Environmental Protection Act 1986*: Key environmental factor, outcome and objective**		**Inland Waters – Karijini NP** **EPA Objective:** *To maintain the hydrogeological regimes of groundwater and surface water so that environmental values are protected.*
Environmental Protection and Biodiversity Conservation Act 1999:		**Protection of EPBC Act listed species** **Condition 3:** *Minimise impacts to EPBC Act listed threatened species or their habitat.*
Drawdown (MS 1113 and DN 2018/8299)		
Objective-based Provisions	**Target 1:**	Water levels in boundary bores to the south and north of the MAR scheme in areas outside of the regional aquifer are above or equal to rolling 3 year, seasonally adjusted water levels (mbgl).
	Target 2:	Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 3 year, seasonally adjusted water levels (mbgl).

	Target 3:	Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 5 year, seasonally adjusted water levels (mbgl).
	Target 4:	Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 10 year, seasonally adjusted water levels (mbgl).
	Conditioned Environmental outcome	**Ministerial Statement 1113 Condition 6-1(1):** • Ensure that there is no drawdown of groundwater associated with the proposal at the boundary of, or within, Karijini NP. **Decision Notice 2018/8299 Condition 3(a):** • '…no drawdown of groundwater associated with the action at the boundary of, or within, Karijini NP.
	Early Response Indicator 1	Injection bores non operational outside of proposed plan for operation of the MAR scheme (more than 1 of a paired set of bores inoperable for more than 1 week).
	Early Response Indicator 2	Two consecutive monitoring periods of drawdown 25 cm greater than Grey Box level for modelled mitigation scenario in Zone 2 monitoring bores.
	Trigger Criteria Level 1	Two consecutive monitoring periods of drawdown 50 cm greater than Grey Box level for modelled mitigation scenario in Zone 2 monitoring bores.
Outcome-based Provisions	**Trigger Criteria Level 2**	Two consecutive monitoring periods of drawdown of 10 cm or greater than the Grey Box level for modelled mitigation scenario in Zone 3 monitoring bores or a single monitoring period of drawdown greater than 10 cm in Zone 3 monitoring bores if Trigger Criteria Level 1 exceeded in the current or preceding monitoring period or a single monitoring period of drawdown greater than 10 cm or greater than the Grey Box level recorded in two or more adjacent monitoring bores.
	Threshold Criteria	Two consecutive monitoring periods of drawdown associated with the proposal of 20 cm or greater than Grey Box level for modelled mitigation scenario in Zone 3 monitoring bores or a single monitoring period of drawdown exceeding 20 cm in Zone 3 monitoring bores if Trigger Criteria Level 2 exceeded in current or preceding monitoring period. or a single monitoring period of significant drawdown (over 40 cm drawdown) and the equipment is not damaged.
	Water Quality (DN 2018/8299 only)	
	Conditioned Environmental outcome	**Decision Notice 2018/8299 Condition 3(b):** • No change in groundwater water quality associated with the action at the boundary of, or within, Karijini NP.

	Early Response Indicator 1	pH trend in Zone 2 monitoring bores over two consecutive monitoring periods is not consistent with trend in control bore. or Proportional change in EC in Zone 2 monitoring bores is greater than 20% of proportional change in control bore EC over two consecutive monitoring periods.
	Trigger Criteria Level 1	pH in Zone 2 monitoring bores is not between 6.5 and 8 for two consecutive monitoring periods and trend is not consistent with trend in control bore. or Proportional change in EC in Zone 2 bores is greater than 50% of proportional change in control bore EC over two consecutive monitoring periods.
	Trigger Criteria Level 2	pH in Zone 2 monitoring bores is not between 6 and 8.5 for two consecutive monitoring periods and trend is not consistent with trend in control bore pH. or Proportional change in EC in Zone 3 monitoring bores is greater than 50% of proportional change in control bore EC over two consecutive monitoring periods.
	Threshold Criteria	pH in Zone 3 monitoring bores is not between 6 and 8.5 for two consecutive monitoring periods and trend is not consistent with trend in control bore pH and is associated with the action. or Proportional change in EC in Zone 3 monitoring bores is greater than 80% of proportional change in control bore EC over two consecutive monitoring periods and is associated with the action.

Corporate endorsement

I hereby certify that to the best of my knowledge, the provisions within this West Angelas Revised Proposal Groundwater Environmental Management Plan are true and correct.

Name: Mark Townson

Signed: 

Designation: GM, West Angelas

Date: 17/02/2021

Table of Contents

1.	**CONTEXT, SCOPE AND RATIONALE**	**1**
1.1	Project Description	2
1.2	Key Environmental Factors	5
1.3	Condition Requirements	14
1.4	Approach	17
1.5	Management Rationale	18
2.	**EMP PROVISIONS**	**25**
2.1	Reporting	34
3.	**ADAPTIVE MANAGEMENT AND REVIEW OF THIS EMP**	**39**
4.	**STAKEHOLDER CONSULTATION**	**41**
5.	**REFERENCES**	**44**
6.	**APPENDICES**	**45**

Tables

Table 1-1: Key environmental factors, associated environmental values, and potential impacts from the Project as addressed in this Groundwater EMP (as per the SPR model) 5

Table 1-2: Summary of Zonal Groundwater Physicochemical Characteristics 12

Table 1-3: MS 1113 Condition 6 for the Project relevant to this Groundwater EMP 15

Table 1-4: EPBC Act Approval DN 2018/8299 Conditions for the Project relevant to this Groundwater EMP 16

Table 1-5: Summary of Rationale for choice of provisions 23

Table 2-1: Objective-based Groundwater EMP Provisions – Inland Waters - Karijini NP Groundwater Level 27

Table 2-2: Outcome-based Groundwater EMP Provisions – Inland Waters - Karijini NP Groundwater Level 28

Table 2-3: Outcome-based Groundwater EMP Provisions – Inland Waters - Karijini NP Groundwater Water Quality – DN 2018/8299 Only 30

Table 2-4: Phased Groundwater Quality data collection & threshold review 31

Table 2-5: West Angelas Revised Proposal Groundwater EMP Reporting Table for MS 1113 35

Table 2-6: West Angelas Revised Proposal Groundwater EMP Reporting Table for DN 2018/8299 37

Table 3-1: Changes to the West Angelas Revised Proposal Groundwater EMP 40

Table 4-1: Stakeholder Consultation 42

Figures

Figure 1-1: Regional Location of the Project 4

Figure 1-2: Development Envelope and conceptual footprint of the Project 4

Figure 1-3: Deposit D and Eastern end of Karijini NP Hydrogeology Fence Diagram Note: bores are transposed onto section line 7

Figure 1-4: Groundwater System Conceptual Diagram 8

Figure 1-5: Historic Rainfall Record and Water Levels at West Angelas (rainfall source: SILO patched point) 9

Figure 1-6: Temporal variability of pH and EC data for bores in the area nearby to or within Karijini NP 11

Figure 1-7: Piper diagram of individual major ion concentrations for water quality zones 13

Figure 1-8: Particle tracking profiles for maximum (top) and minimum (bottom) drawdown models. Models run for 100 years with each dot representing a single year of water movement. 14

Figure 2-1: Interaction between observation, interaction and objective-based/outcome-based triggers 26

Figure 2-2: Indicative monitoring zones and monitoring bores (within Karijini NP, only WANG14 is currently operational and monitored) 32

Figure 2-3: Conceptual section between Mitigation and the Karijini NP. Zones relate to observation/ trigger zones 33

Appendices

Appendix 1: Conceptual Framework for the Development of Rio Tinto Environmental Management Plans

Appendix 2: Summary of Assessment of Management Level

Appendix 3: West Angelas Groundwater Modelling Report (IGS 2021)

Appendix 4: Description of Zonal monitoring, data collection and analysis

Appendix 5: Criteria, Monitoring Zones and Bore Summary

Abbreviations

ACAR	Annual Compliance Assessment Report
BWT	Below water table
DAWE	Department of Agriculture, Water and the Environment (Cwth)
DBCA	Department of Biodiversity, Conservation and Attractions
DN	EPBC Act Decision Notice
DWER	Department of Water and Environmental Regulation
EC	Electrical Conductivity
EMP	Environmental Management Plan
EP Act	*Environmental Protection Act 1986*
EPA	Western Australian Environmental Protection Authority
EPBC Act	*Environment Protection and Biodiversity Conservation Act 1999*
Framework for EMPs	Rio Tinto Framework for development of EMPs as described in Appendix 1.
Long term	Greater than 2 years (where possible)
Management level	Level of management appropriate for an environmental value, as determined by assessment described in the Framework for the Development of Rio Tinto Environmental Management Plans
MAR	Managed Aquifer Recharge
MNES	Matters of National Environmental Significance
NP	National Park
Proponent	Robe River Mining Co. Pty. Ltd.
Project	West Angelas Revised Proposal
SPR	A '*causal pathway conceptual model*' (Pressure, Stressor, Receptor) approach for potential impacts due to project (refer to Appendix 1).

1. CONTEXT, SCOPE AND RATIONALE

This Groundwater Environmental Management Plan (Groundwater EMP) has been prepared by Rio Tinto on behalf of Robe River Mining Co. Pty. Ltd. (the Proponent), as the authorised manager and agent for the participants in the Robe River Iron Associates Joint Venture, for the West Angelas Revised Proposal (the Project), in accordance with Ministerial Statement 1113 (MS 1113), and *Environment Protection Biodiversity Conservation 1999* (EPBC Act) Approval Decision Notice 2018/8299 (DN 2018/8299).

This Groundwater EMP was developed according to the Conceptual Framework for the Development of Rio Tinto Environmental Management Plans (internal guidance described in Appendix 1). This framework provides a standardised approach to environmental management at Rio Tinto's Pilbara Iron Ore Operations, in accordance with Western Australian (WA) and Commonwealth Policy and Guidance, including:

- *Environmental Impact Assessment (Part IV Divisions 1 and 2) Administrative Procedures 2016* (EPA 2016);
- Environment Protection Authority's (EPA) *Instructions on how to prepare Environmental Protection Act 1986 Part IV Environmental Management Plans* (EPA 2018a); and
- *Environmental Impact Assessment (Divisions 1 and 2) Procedures Manual* (EPA 2018b).
- *Environmental Management Plan Guidelines* (Australian Government 2014).
- *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (ANZECC & ARMCANZ 2000).

The scope of this Groundwater EMP is limited to satisfying the requirements of Condition 6 of MS 1113, which specifies no impact on groundwater water levels at the boundary of, or within Karijini National Park (Karijini NP) as a result of the proposal, and Condition 3 of DN 2018/8299 which specifies no impact on groundwater level and groundwater quality at the boundary of, or within Karijini NP as a result of the proposal. The scope of these conditions does not require the assessment of or outcomes for any receptors other than groundwater level and groundwater quality at the boundary of Karijini NP.

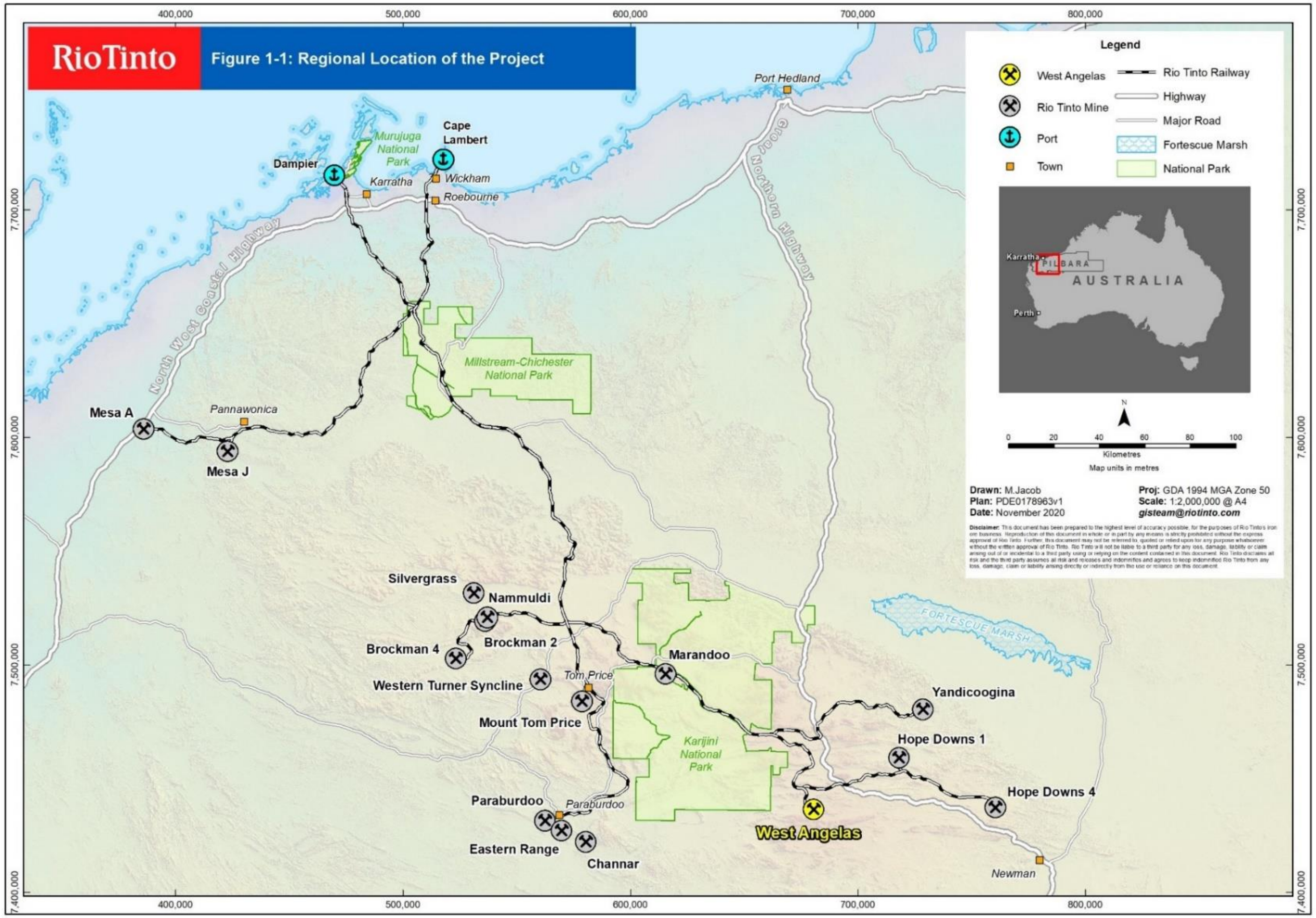
This Groundwater EMP is subject to approval by the Commonwealth Department of Agriculture, Water and Environment (DAWE) and the WA Environmental Protection Authority (EPA), and once approved, will subsequently be implemented. This version of the Groundwater EMP applies to Phase1 of the Managed Aquifer Recharge (MAR) operation to support dewatering for Deposit D only. Further revisions of this Groundwater EMP will be submitted to DAWE and EPA for progressive phases as the Project progresses. In accordance with Condition 4 of DN 2018/8299, dewatering will not commence until such time as the Federal Minister for the Environment has approved a relevant version of the Condition Environmental Plan for the required Phase in writing.

1.1 Project Description

The Project is located approximately 130 km west of Newman in the Pilbara region of Western Australia (Figure 1-1). Mineral Lease 248SA (ML248SA) which was granted in 1976 under the *Iron Ore (Robe River) Agreement Act 1964* (WA). The Project includes the following (Figure 1-2).

- Mining of above and below water table (AWT and BWT) open cut iron ore Deposits A, A west, B, C, D, E, F and G by conventional drill, blast, and load and haul techniques.
- Ore processing in central processing facilities.
- Surface waste dumps, which are used in backfilling of the mine pits as far as practicable.
- Infrastructure including but not limited to the following:
  - (a) Dewatering and surplus water management infrastructure, including the Turee Creek B borefield which provides potable water to the mine and camp facilities (and, when required, water for operational purposes) and the mine dewatering borefield which dewaters the ore bodies to allow below water table mining. Dewatering water is used onsite in the first instance to supply water for operational purposes. Surplus dewatering water, exceeding the operational requirement, is discharged to a local ephemeral tributary of Turee Creek East (TCE) at licenced discharge points.
  - (b) Surface water management infrastructure, including diversions to direct surface waterflows around deposits and infrastructure.
  - (c) Linear infrastructure Development Envelope, including the 413 km rail network which transports processed ore to port facilities located at Cape Lambert; the Turee Creek B borefield, pipeline and powerline and the 35 km mine access road which links the mine with the Great Northern Highway.
  - (d) Support facilities, including, but not limited to, dewatering and surplus water management infrastructure, surface water management infrastructure, roads, conveyor, power and communications distribution networks, hydrocarbon storage, offices, laydown areas and an accommodation village.

The Project was approved with Conditions by the State and Commonwealth in September 2019. Subsequent to these approvals, an application has been submitted to amend the Development Envelope prescribed in MS 1113 via Section 45C of the *Environmental Protection Act 1986* (EP Act). The amendment will allow for infrastructure associated with the MAR scheme, authorised via MS 1113, to be located fully within the Development Envelope (Figure 1-2).



Rio Tinto
Figure 1-1: Regional Location of the Project
Legend
West Angelas
Rio Tinto Mine
Port
Town
Rio Tinto Railway
Highway
Major Road
Fortescue Marsh
National Park
Karratha
PILBARA
AUSTRALIA
Perth
N
0
20
40
60
80
100
Kilometres
Map units in metres
Drawn: M.Jacob
Plan: PDE0178963v1
Date: November 2020
Proj: GDA 1994 MGA Zone 50
Scale: 1:2,000,000 @ A4
gisteam@riotinto.com
Port Hedland
Cape Lambert
Dampier
Murujuga National Park
Karratha
Wickham
Roebourne
Great Northern Highway
North West Coastal Highway
Millstream-Chichester National Park
Mesa A
Pannawonica
Mesa J
Silvergrass
Nammuldi
Brockman 4
Brockman 2
Marandoo
Western Turner Syncline
Tom Price
Mount Tom Price
Karijini National Park
Fortescue Marsh
Yandicoogina
Hope Downs 1
Hope Downs 4
West Angelas
Paraburdoo
Eastern Range
Channar
Newman
400,000
500,000
600,000
700,000
800,000
7,400,000
7,500,000
7,600,000
7,700,000

Figure 1-1: Regional Location of the Project

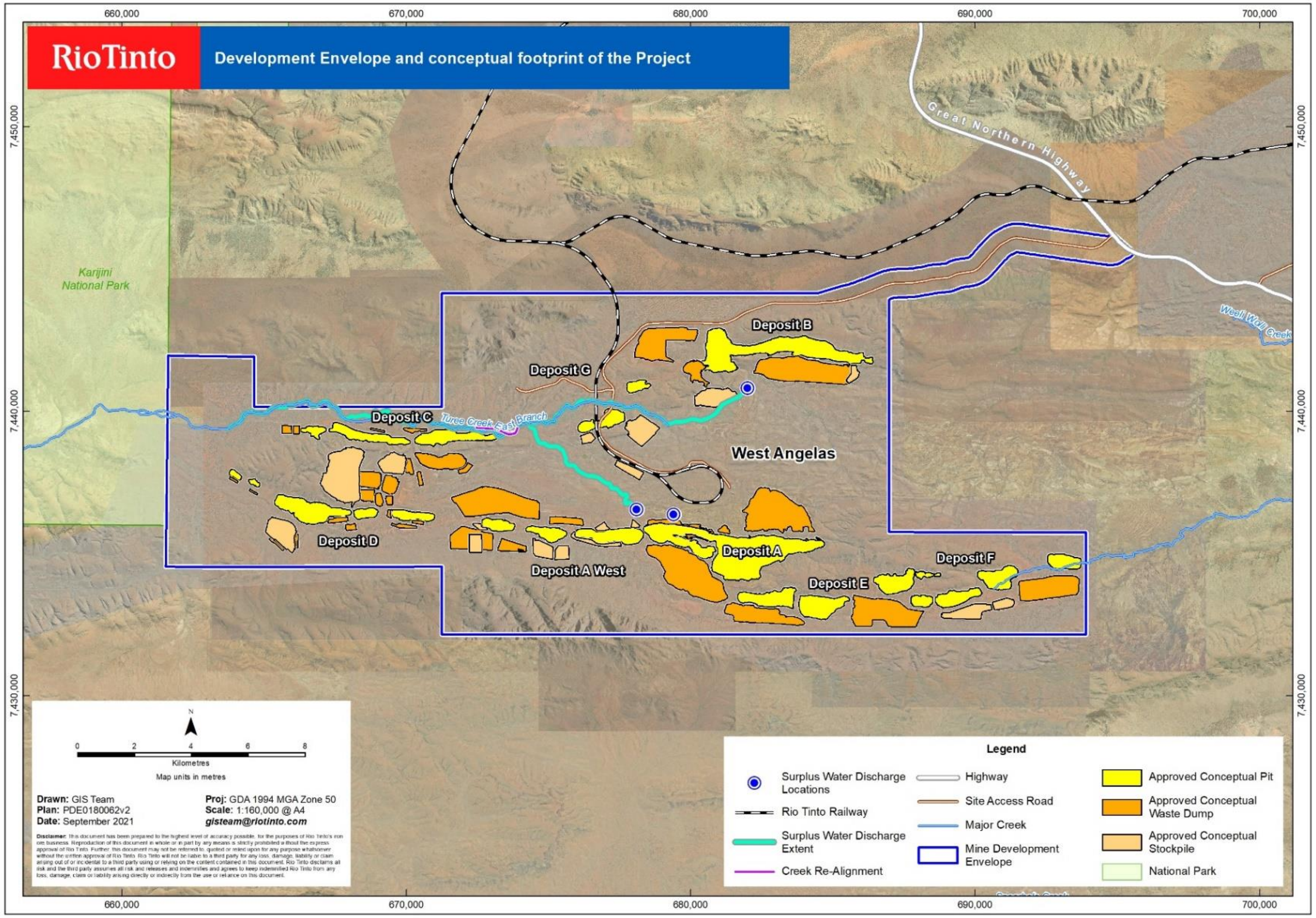


Figure 1-2: Development Envelope and conceptual footprint of the Project

1.2 Key Environmental Factors

The key EPA environmental factor relevant to this Groundwater EMP is *Inland Waters*, and the associated environmental value is:

- Karijini NP.

Potential impacts from the Project on this value are summarised in Table 1-1 and further detail on the regional groundwater system is provided in Section 1.2.1.

Table 1-1: Key environmental factors, associated environmental values, and potential impacts from the Project as addressed in this Groundwater EMP (as per the SPR model[1])

Environmental value (receptor)	Predicted impacts		Potential impacts Not predicted to occur	
	Direct (stressor, pressure)	Indirect (stressor, pressure)	Direct (stressor, pressure)	Indirect (stressor, pressure)
Environmental Factor: Inland Waters **Environmental value:** Groundwater located at boundary of, and within Karijini NP.	None predicted	**Dewatering of Deposit C and Deposit D:** • lowering of groundwater levels at the boundary of, or within, Karijini NP.	None predicted	**Dewatering of Deposit C and Deposit D:** • Change to groundwater quality at the boundary of, or within, Karijini NP

1.2.1 West Angelas Groundwater System

The conceptual groundwater system is characterised as a large basin-type aquifer with water in storage within the weathered Wittenoom formation, mineralised Marra Mamba formation and overlying alluvial dolocrete / detrital units. The groundwater system at Deposit C and Deposit D (the source for both dewatering and mitigation activities as a part of the Project) underlies part of the drainage system of TCE, a tributary of the Ashburton River. Groundwater is present within an interconnected alluvial and bedded stratigraphy that underlies both mining tenure and a relatively small area of the Karijini NP (Figure 1-3 and Figure 1-4).

The system is bounded to the west, north and south by prominent ridges of outcropping Brockman Iron Formation with an internal anticline (Wonmunna anticline) of unmineralized Marra Mamba Formation forming part of the eastern boundary. Two prominent dolerite dyke barriers are present in the system which bisect the groundwater system with observed groundwater compartments on either side. Several areas of Brockman Iron Formation are present as remnants atop the Wittenoom Formation and have been identified as hosting perched and disconnected to semi-connected aquifer systems. The Wittenoom Formation beneath these remnants is expected to be relatively impermeable.

The water table is relatively consistent (flat) at between 623mRL and 627mRL with a slight gradient from east to west. The gradient is inferred to be due to the presence of a discharge/evaporative zone (within Karijini NP) where groundwater is relatively shallow (5-15 m below ground level (mbgl)) and an area where creek alluvium provides a subsurface discharge pathway. Depth to water varies according to topography with depths in the vicinity of the deposits greater than 50mbgl and depths inside Karijini NP as shallow as 7 m in observed locations.

[1] A '*causal pathway conceptual model*' (Stressor, Pressure, Receptor [SPR]) approach for potential impacts due to a Project (Appendix 1).

Hydrogeological information is restricted both spatially within the groundwater system and temporally in certain areas of the system. Pumping tests to date have been focussed in the vicinity of the orebody deposits with minor testing completed in areas both within and near the eastern boundary of Karijini NP. Manual water level monitoring of the aquifer has occurred since 2004 with continuous levels recorded since 2016 via data loggers. A discrete field investigation in 1978 yielded several static groundwater level observations in Karijini NP. Water quality information is similarly limited, however static records for hydrochemistry have been collected in Karijini NP for the period prior to 2019.

Water level fluctuations are most pronounced in areas of potential recharge and pumping, with minimal seasonal variability in groundwater levels (~10 cm) recorded in years lacking large episodic rainfall events. Monitored observations and historical investigations have shown a reversal of hydraulic gradient away from Karijini NP for periods following significant rainfall/ recharge events.

A review of available information suggests that groundwater levels in the late 1970's have historically been lower than the present day which indicates that present day groundwater levels are possibly higher as a direct result of higher than average rainfall in the past ~20 years (Figure 1-5). Recharge response in the aquifer is expected to be most significant in the part of the aquifer system within Karijini NP where groundwater is closer to surface.

A cross section of the hydrogeology at Deposit D and the eastern end of Karijini NP is shown in

Figure **1-3** and a conceptual overview of the groundwater system and main geological units is shown in Figure 1-4.

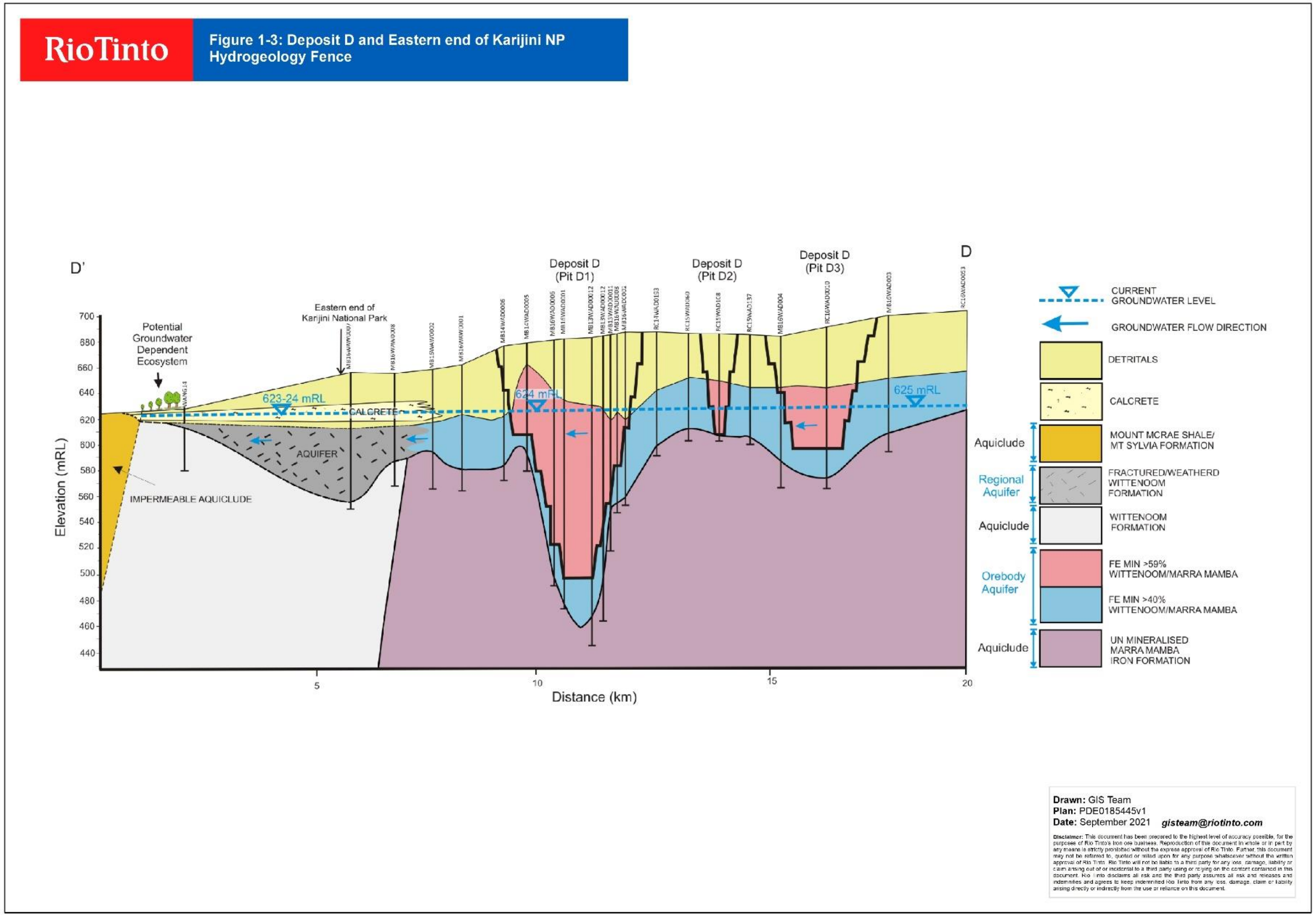


Figure 1-3: **Deposit D and Eastern end of Karijini NP Hydrogeology Fence Diagram** Note: bores are transposed onto section line

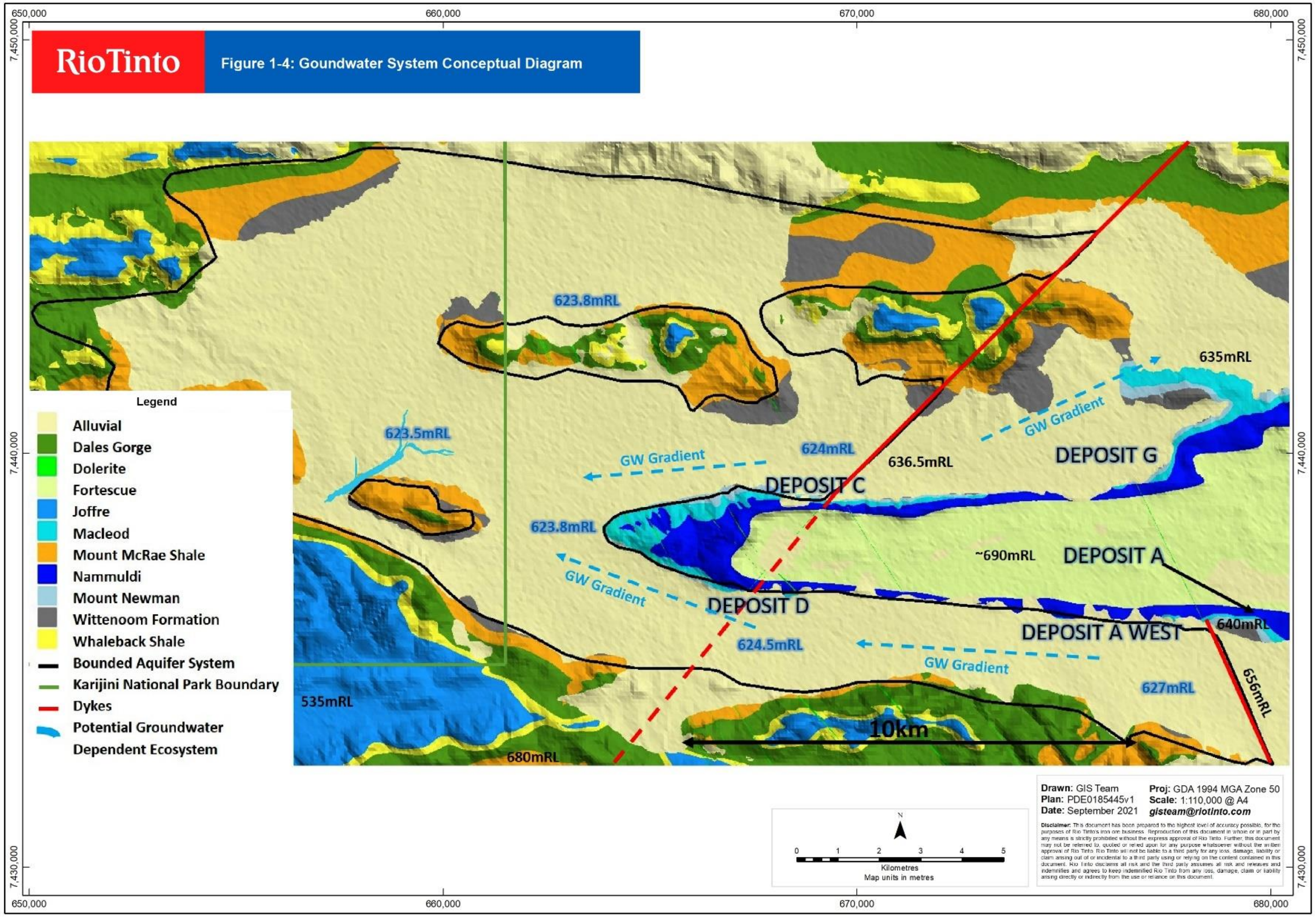


Figure 1-4: **Groundwater System Conceptual Diagram**

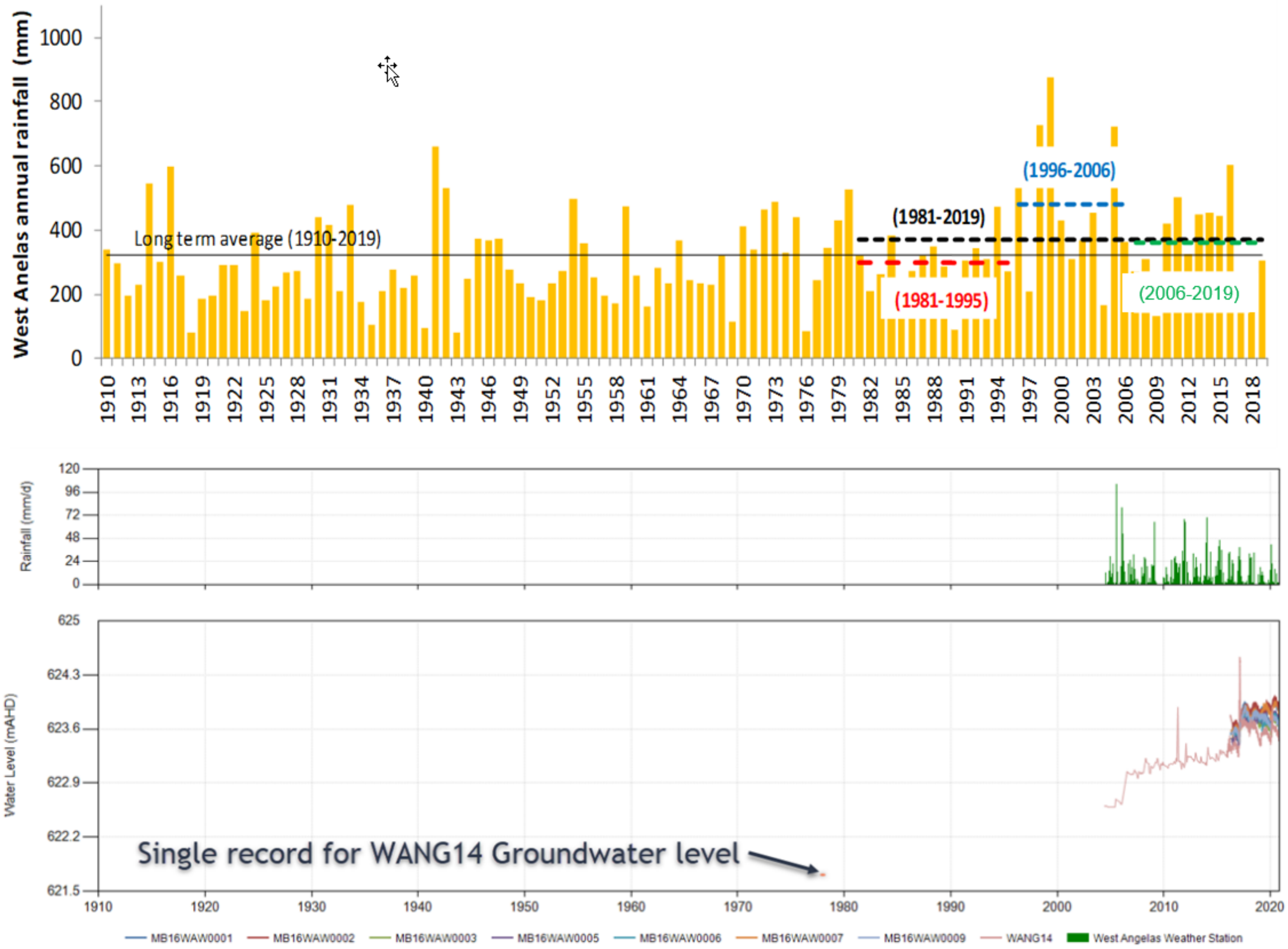


Figure 1-5: Historic Rainfall Record and Water Levels at West Angelas (rainfall source: SILO patched point)

Temporal groundwater level and water quality observations since mid-2000 within Karijini NP indicate an aquifer that is influenced by changes in climate, which is dissimilar to data collected over the 20 years of operation at West Angelas (Deposits A, B, E and F) which demonstrate very little by way of variability in both groundwater level fluctuation and fairly consistent chemical characteristics (Section 1.2.2.) over time. This is believed to be a direct result of substantially shallower water tables and the potential for rapid infiltration of the aquifer through a dolocrete unit (

Figure **1-3**). Actively mined and pumped areas have the potential for hydraulic barriers and laterally perching detrital layers that may smooth out or even prevent groundwater response to present day rainfall.

The current Pilbara climate is characterised by episodic, cyclonic rainfall with wet/ dry seasons and significantly higher evaporation than annual rainfall. This means that these cyclonic and highly variable seasonal events are a potential source of groundwater recharge. This depends on the capacity of the groundwater system to receive the water; currently much of the natural groundwater system is full as a result of post-glacial maxima recharge. After rainfall recharge events, groundwater levels recede following a typical relaxation response with more substantial and rapid rises within Karijini NP, in proximity of TCE where recharge may be concentrated for a longer period during streamflow, and more subdued responses are observed in areas of greater depth to groundwater and further away from Karijini NP.

Numerical modelling suggests that unmitigated dewatering of the western end of Deposit C and Deposit D could result in groundwater drawdown extending west to the Karijini NP boundary as early as 2024. Modelling of drawdown with inclusion of mitigation (e.g. MAR) suggests that drawdown can be negated.

1.2.2 Groundwater Quality

The groundwater system comprises areas of deep, relatively immobile (partly compartmentalised by dykes or other geological structures) groundwater within orebodies, areas of relatively deep groundwater which does not respond significantly to modern day recharge (nearby to the deposits in the Wittenoom Formation) and an area of shallow groundwater where water may be released through a narrow alluvial channel beneath the modern day TCE palaeo-drainage (within Karijini NP). The water quality in each area may fluctuate as a response to recharge and, in time, to subsequent MAR mitigation activities.

Groundwater within, and at the boundary of, Karijini NP varies in both pH and electrical conductivity (EC) as a direct result of rainfall recharge. Prior to 2020, laboratory samples of groundwater within Karijini NP comprised data from initial exploration boreholes (Layton Consultants, 1978) and several borehole samples collected from the Deposit C and Deposit D pre-feasibility and feasibility studies (RTIO 2016, RTIO 2017 and RTIO 2019).

Manual observation (bailed groundwater samples) from WANG14 (

Figure 1-3) were collected from 2004 with a change in monitoring requirements in 2008 resulting in sampling for this dataset not being continued. Continuous monitoring of EC in WANG14 via a datalogger commenced in 2017 (Figure 1-6). pH in WANG14 has fluctuated within the range of 6.5 and 9.2 (although results from 2006 including a quite significant change in pH may indicate a calibration issue), with a recorded average pH of 8. EC is low in all bores, with an average EC of 715.5 uS/cm.

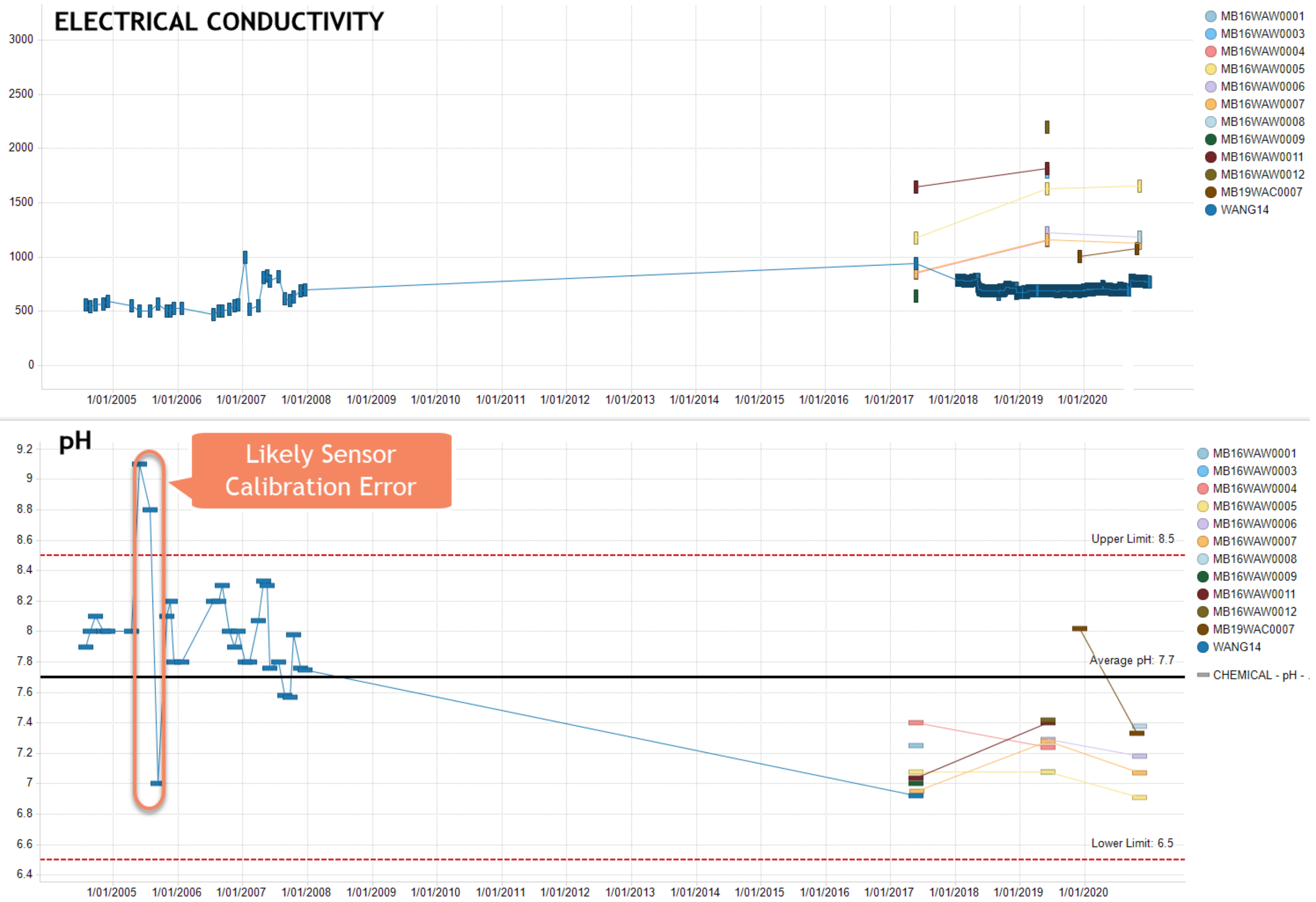


Figure 1-6: Temporal variability of pH and EC data for bores in the area nearby to or within Karijini NP

Groundwater at West Angelas has been broadly classified into zones to allow for evaluation of trends and for investigation of any potential source / receiving environment interaction in the event of mitigation. In each zone, an assessment of spatial coverage (i.e. all areas intended for pumping or injection are sampled at least once) and seasonal variability (all bores sampled before and after a wet season) was included (Table 1-2). The low number of samples (<15) presents a clear limitation in available information for all areas except Deposit E and hence further sampling and analysis prior to any detailed assessment of potential water quality change is proposed.

Table 1-2: **Summary of Zonal Groundwater Physicochemical Characteristics**

Parameter	Deposit D	Deposit C	Deposit E	Phase 1 MAR Area	KNP Area
No of Samples	13	4	72	20	15 (only 1 since 1978)
Seasonal Sampling	No	No	Yes	Yes	No
Spatial Coverage	Yes	No	Yes	Yes	No
pH	6.7-8.5	7.4-8.3	6.7-8.6	6.8-9.5	7-9.1
Electrical Conductivity (µS/cm)	400-1301	562-1271	440-1252	641-2200	470-1000
Sodium (mg/L)	64-79	72-105	27-92	36-156	49-130
Potassium (mg/L)	2-12	3-4	4-17	7-18	4-15
Calcium (mg/L)	43-84	68-84	30-72	5-111	60-110
Magnesium (mg/L)	55-66	63-80	25-42	27-88	68-106
Chloride (mg/L)	72-147	104-145	37-230	67-460	95-236
Sulphate (mg/L)	75-239	192-273	28-110	2-167	85-170
Total Nitrogen (mg/L)	3-6.2	0.3-3.0	0.4-10	2.3-2.6	1-10 (?)
Bicarbonate (from Alk) (mg/L)	199-314	235-266	101-229	86-378	205-544

Note: All production bores were used for Deposits D, C and E character and all available information was used for both the MAR and Karijini NP areas

Individual analyte concentrations are summarised and plotted in a piper diagram (Figure 1-7). The distribution of analytes demonstrates very little difference between waters in each zone which can be broadly taken to mean that mixing of waters from each zone would not result in significant changes in receiving zone analyte concentration.

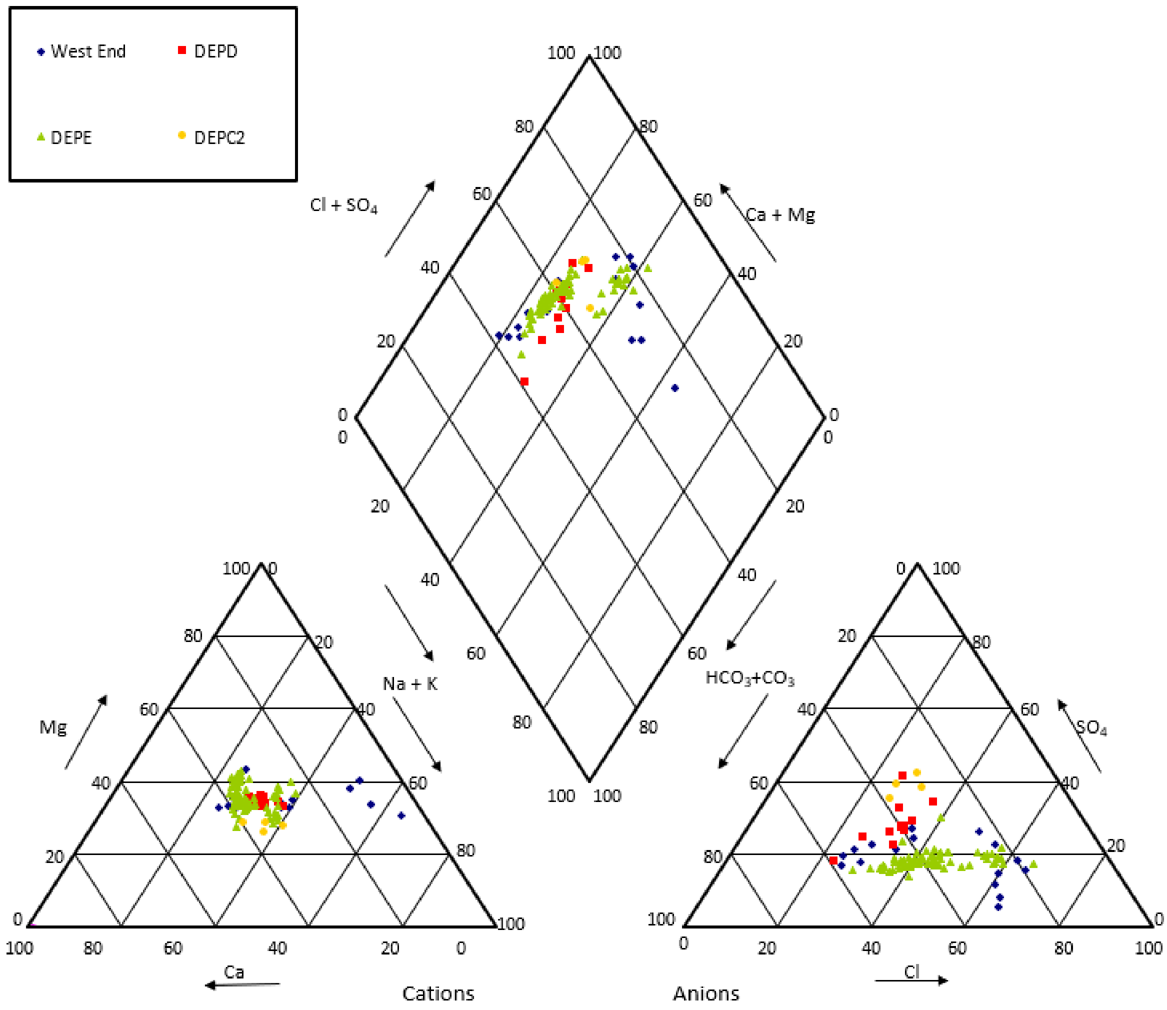


Figure 1-7: **Piper diagram of individual major ion concentrations for water quality zones**

In order to ensure that any change relating to reactions produced from the mixing of injectant and receiving waters does not propagate into the Karijini NP, particle tracking modelling has been undertaken (Appendix 3) to evaluate the worst case distribution of injectant given an 100 year duration of injection and book-end (or minimum/ maximum drawdown) parameter sets (Figure 1-8). This is viewed as highly conservative in that it both provides confidence in both the timeframes expected and also assumes that injectant water/ inferred contaminants are not diluted as they flow through the aquifer.

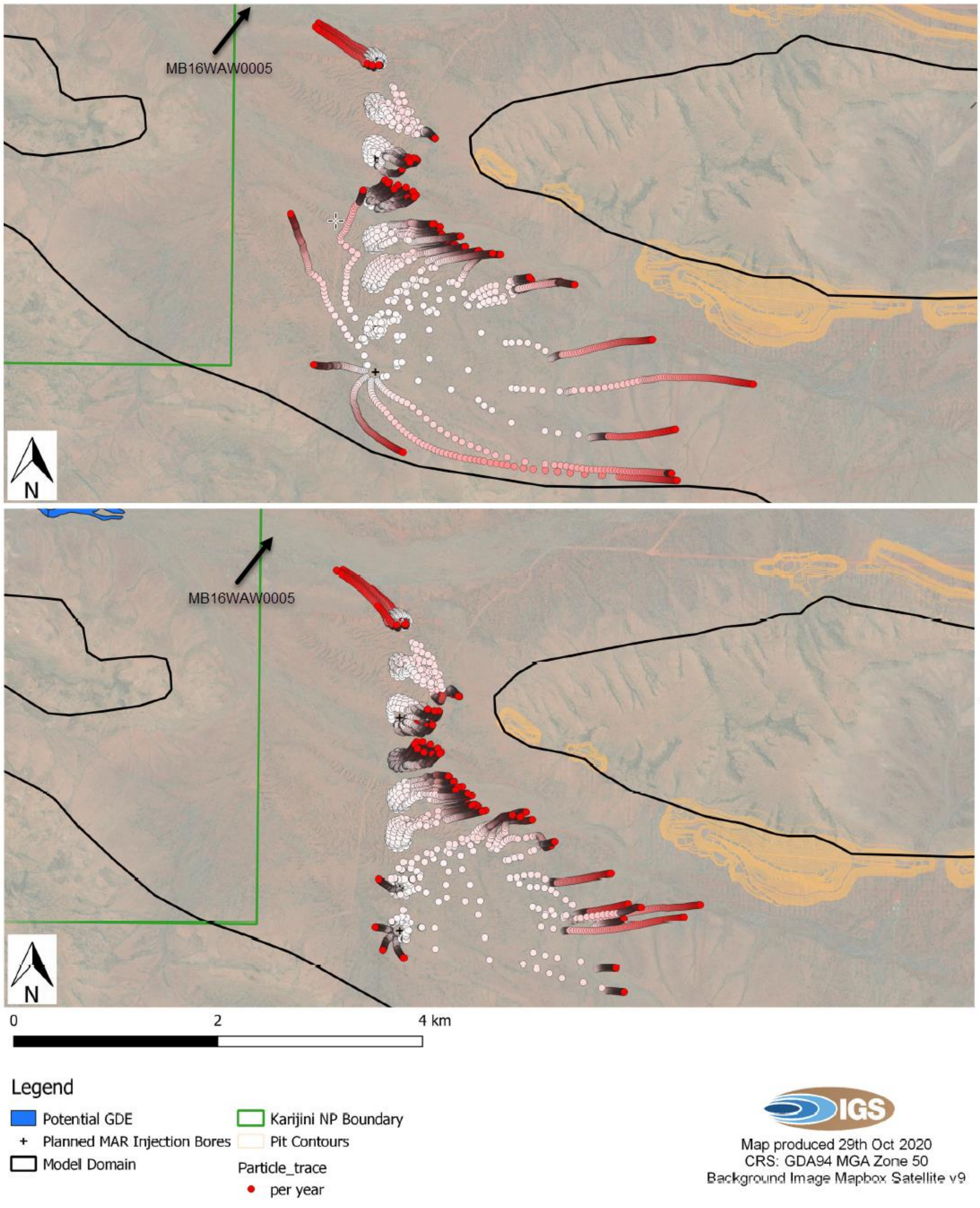


Figure 1-8: Particle tracking profiles for maximum (top) and minimum (bottom) drawdown models. Models run for 100 years with each dot representing a single year of water movement.

1.3 Condition Requirements

The Project was assessed under Part IV of the EP Act, and under the EPBC Act. Conditions, as per MS 1113, and DN 2018/8299, relevant to this Groundwater EMP are identified in Table 1-3 and Table 1-4 respectively.

Requirements of the relevant MS 1113 Conditions relate to management of groundwater levels, while relevant DN 2018/8299 Conditions relate to management of groundwater levels and groundwater quality.

Table 1-3: MS 1113 Condition 6 for the Project relevant to this Groundwater EMP

Condition		Section in EMP
6	**Groundwater Management**	
6-1	Prior to dewatering of Deposits C or D, the Proponent shall prepare and submit a Condition Environmental Management Plan to meet the following outcome: (1) Ensure that there is no drawdown of groundwater associated with the proposal at the boundary of, or within, Karijini NP.	Section 2
6-2	The Condition Environmental Management Plan shall: (1) specify trigger criteria that must provide an early warning that the threshold criteria identified in Condition 6-2 may not be met; (2) specify threshold criteria to demonstrate compliance with the environmental outcomes specified in Condition 6-1. Exceedance of the threshold criteria represents non-compliance with these conditions; (3) specify monitoring to determine if trigger criteria and threshold criteria are exceeded; (4) specify trigger level actions to be implemented in the event that trigger criteria have been exceeded; (5) specify threshold contingency actions to be implemented in the event that threshold criteria are exceeded; and (6) provide the format and timing for the reporting of monitoring results against trigger criteria and threshold criteria to demonstrate that Condition 6-1 has been met over the reporting period in the Compliance Assessment Report required by Condition 3-1.	Section 2, Table 2-1 and Table 2-2
6-3	After receiving notice in writing from the CEO in consultation with the Department of Biodiversity, Conservation and Attractions that the Condition Environmental Management Plan satisfies the requirements of Condition 6-2, the Proponent shall: (1) implement the provisions of the Condition Environmental Management Plan; and (2) continue to implement the Condition Environmental Management Plan until the CEO has confirmed by notice in writing that the Proponent has demonstrated the outcomes and objectives specified in Condition 6-1 have been met.	Section 2
6-4	In the event that monitoring, tests, surveys or investigations indicates exceedance of threshold criteria specified in the Condition Environmental Management Plan, the Proponent shall: (1) report the exceedance in writing to the CEO within seven (7) days of the exceedance being identified; (2) implement the threshold level contingency actions specified in the Condition Environmental Management Plan within twenty-four (24) hours and continue implementation of those actions until the CEO has confirmed by notice in writing that it has been demonstrated that the threshold criteria are being met and the implementation of the threshold contingency actions is no longer required; (3) investigate to determine the cause of the threshold criteria being exceeded; (4) investigate to provide information for the CEO to determine potential environmental harm or alteration of the environment that occurred due to threshold criteria being exceeded; and (5) provide a report to the CEO within twenty-one (21) days of the exceedance being reported as required by condition 6-4(1). The report shall include; (a) details of threshold contingency actions implemented;	Section 2, Table 2-1 and Table 2-2

Condition		Section in EMP
	(b) the effectiveness of the threshold contingency actions implemented, against the threshold criteria; (c) the findings of investigations required by Condition 6-4(3) and 6-4(4); (d) measures to prevent the threshold criteria being exceeded in the future; (e) measures to prevent, control or abate the environmental harm which may have occurred; and (f) justification of the threshold remaining, or being adjusted based on better understanding, demonstrating that outcomes would continue to be met.	
6-5	The Proponent: (1) may review and revise the Condition Environmental Management Plan, or (2) shall review and revise the Condition Environmental Management Plan as and when directed by the CEO.	Section 3
6-6	The Proponent shall implement the latest revision of the Condition Environmental Management Plan, which the CEO has confirmed by notices in writing, satisfies the requirements of Condition 6-2.	N/A
6-7	The Proponent shall implement the Groundwater Management Plan component of the West Angelas Operations Environmental Management Program (RTIO-HSE-0210871) dated November 2013 until the CEO has confirmed by notice in writing the Condition Environmental Management Plan required by Condition 6-1 satisfies the requirements of Condition 6-2.	Section 3

Table 1-4: EPBC Act Approval DN 2018/8299 Conditions for the Project relevant to this Groundwater EMP

Condition		Section in EMP
3	To minimise impacts to EPBC Act listed threatened species or their habitat the approval holder must ensure that there is: a) no drawdown of groundwater associated with the action at the boundary of, or within, Karijini National Park and b) no change in groundwater quality associated with the action at the boundary of, or within, Karijini National Park.	Section 2
4	A Condition Environmental Management Plan to achieve the outcomes specified in Condition 3 must be submitted for approval by the Minister. The approved Condition Environmental Management Plan must be implemented. The approval holder must not commence dewatering activities unless the Minister has approved the Condition Environmental Management Plan in writing.	Section 1
5	The Condition Environmental Management Plan must: (a) provide an explanation of the method to be used to ensure the outcome required by Condition 3(a) is met; (b) specify threshold criteria to demonstrate compliance with the environmental outcomes specified in Condition 3. Exceedance of the threshold criteria represents non-compliance with these conditions; (c) specify trigger criteria that must provide an early warning that the threshold criteria identified in the Condition Environmental Management Plan may not be met; (d) specify monitoring capable of determining if trigger criteria and threshold criteria are exceeded. The approval holder must have a high degree of certainty that they will ensure the outcomes at Condition 3 are met;	Section 1.1, Section 2, Table 2-1 and Table 2-2 and Table 2-3.

	Condition	Section in EMP
	(e) specify actions to be implemented in the event that trigger criteria have been exceeded; (f) specify threshold contingency actions to be implemented in the event that threshold criteria are exceeded, including ceasing water extraction if necessary; (g) provide the format and timing for the reporting of monitoring results against trigger criteria and threshold criteria to demonstrate that Condition 3 has been met.	
6	In the event that monitoring, tests, surveys or investigations indicate exceedance of triggers or threshold criteria specified in the Condition Environmental Management Plan, the approval holder must: (a) report the exceedance in writing to the Department within five (5) business days of becoming aware of the exceedance; (b) commence implementing the trigger or threshold contingency actions specified in the Condition Environmental Management Plan specified at Condition 4 within 24 hours of becoming aware of the exceedance and, in respect of exceedance of threshold criteria, continue implementation of those actions until the Department has confirmed by notice in writing that the approval holder has demonstrated that the threshold contingency actions are no longer required; (c) investigate to determine the cause of the trigger or threshold criteria being exceeded; (d) investigate to provide information for the Department to determine potential environmental harm or alteration of the environment that occurred due to threshold criteria being exceeded; and (e) provide a report to the Department within twenty-one business days of the exceedance being reported as required by Condition 6(a). The report must include: (i) details of trigger or threshold contingency actions implemented; (ii) the effectiveness of the trigger or threshold contingency actions implemented, against the threshold criteria; (iii) the findings of the investigations required by Condition 6(c) and 6(d); (iv) measures to prevent the threshold criteria being exceeded in the future; (v) measures to prevent, mitigate and remedy the environmental harm which may have occurred; and (vi) justification of the threshold remaining, or being adjusted based on better understanding, demonstrating that outcomes will continue to be met.	Section 2, Table 2-1 and Table 2-2 and Table 2-3
7	Groundwater management and monitoring must continue until it can be demonstrated that the outcomes specified at Condition 3 can be met without active management.	Section 3

1.4 Approach

This Groundwater EMP was drafted in accordance with the Conceptual Framework for the Development of Rio Tinto Environmental Management Plans (internal guidance described in Appendix 1). This conceptual approach to management considers the conservation significance of the environmental value based on conservation status at local, state and regional levels. Management level (low, moderate or high) is assigned in order to achieve the environmental objective and/or outcome according to the conservation significance of the environmental value and the significance of impact/s predicted over spatial and temporal scales (Appendix 2). Assessment of the pathways over which impacts may occur provides the rationale for choice of provisions and choice of appropriate indicators to measure against the environmental outcome and/or objective.

1.5 Management Rationale

This Groundwater EMP adopts a combination of objective and outcome-based provisions, in order to achieve the environmental outcomes.

Environmental criteria are defined to assess performance against the environmental outcome. These are:

Trigger Criteria	Measures set at a conservative level to forewarn the approach of threshold criteria and ensure trigger level actions are implemented well in advance of the environmental outcome being compromised.
Threshold Criteria	This indicates there is risk that the environmental outcome will not be met.

Both objective and outcome-based provisions have been developed for this Groundwater EMP for the MAR scheme. Outcome-based provisions have been developed for management of the MAR scheme as a High[2] level of management is required, and/or a degree of uncertainty and complexity exists. Outcome-based provisions in this Groundwater EMP are quantitative triggers and threshold criteria for groundwater drawdown and quality characteristics based on modelling chosen to achieve the stated environmental outcome.

Objective-based provisions are applied where a level of uncertainty exists that prevents setting objective and measurable criteria. In this case, triggers are established to measure, review and refine the accuracy of Grey Box modelling which is used as the basis for the outcome-based provisions. This will ensure that outcome-based provisions are assessed using the most accurate and relevant modelling available and to accurately reflect groundwater status to ensure the stated environmental outcomes are achieved.

Details of the MAR scheme to be implemented to mitigate drawdown impacts is provided in Section 1.5.1, and rationale for the choice of provisions is provided in Table 1-5.

1.5.1 Managed Aquifer Recharge (MAR) Scheme

The Proponent will mitigate groundwater drawdown associated with dewatering activities (specifically at Deposit C and Deposit D) by use of a MAR scheme.

MAR is the intentional recharge of water to suitable aquifers for subsequent recovery and maintenance of groundwater level. Aquifer reinjection is an actively implemented technique within the Pilbara region for disposal of surplus water and will be used at the Project to mitigate potential impacts on groundwater within Karijini NP from drawdown associated with dewatering at Deposit C and Deposit D.

The planned MAR scheme will comprise four phases (Rio Tinto 2020). Initial phases will utilise aquifer reinjection, however future phases may include use of alternate MAR techniques, i.e. infiltration galleries. The planned phased approach is grouped as follows:

- Phase 1: mitigate drawdowns from active dewatering in Deposit D (from 2021);
- Phase 2: mitigate drawdowns from active dewatering in Deposit C2 (from ~2028);
- Phase 3: reinstate water levels in Deposit D to pre-mining water levels (from ~2028); and
- Phase 4: reinstate water levels in Deposit C2 to pre-mining water levels (from ~2036).

[2] In accordance with the Rio Tinto conceptual framework for development of EMPs (Appendix 1).

The Phase 1 Scheme includes:

- a supply and return pipeline;
- chlorination treatment system;
- injection supply and backflush removal lines;
- injection bore headworks and backflush pump/ generators in fenced enclosures;
- sedimentation pond; and
- transfer pumping station.

The initial 2019 Phase 1 MAR drilling programme and injection trial (Dec 2019 to Feb 2020) has proven that MAR using reinjection bores is practicable in the Phase 1 area. Custom built injection bores and discretely screened monitoring networks were installed to enable capture of detailed information during pumping and injection trials. Injection rates were in excess of 20L/s with a potential for rates of over 40L/s assuming no supply limitations. Impress heads (i.e. increases in water level due to injection) were observed at up to 700 m away from injection bores and backflush cycles were identified as being capable of the minimal clogging risk.

Injection volumes were identified to flow predominantly into below water table and near water table voids within subsurface dolocrete with response to injection in both the Wittenoom formation and Dolocrete units. A 2020 drilling and testing investigation in the Phase 1 area has further supported initial estimates of injection rates and capacity with significant volumes injected (>20L/s) and relatively small impress head in all tests completed to date.

The Phase 1 MAR scheme will include re-injection of dewatered groundwater from Deposit D into the Phase 1 injection area of the MAR scheme, approximately 1.4 km away from the Karijini NP boundary. The MAR scheme has been designed so that groundwater abstracted via dewatering activities could be piped directly to the injection bore/s via an overland pipeline to eliminate the requirement for holding tanks and potential air ingress which minimises potential water quality impacts. The chlorination treatment system is likely to be via a trickle-feeder mechanism and is required only to ensure biological activity in injection bores is kept to a minimum to prevent biological clogging. Injection rates are expected to vary depending upon aquifer drawdown propagation, aquifer responsiveness, clogging and infrastructure capacity. In addition, each injection bore will be equipped with a backflush pump to enable the active management of clogging and ensure capacity of injection assets. Backflush water will be piped to a central sedimentation pond where it will be collected and transferred to active mining areas for re-use.

An indicative Phase 1 scheme layout is provided in Figure 1-9, however note the layout is indicative only and is subject to change during construction.

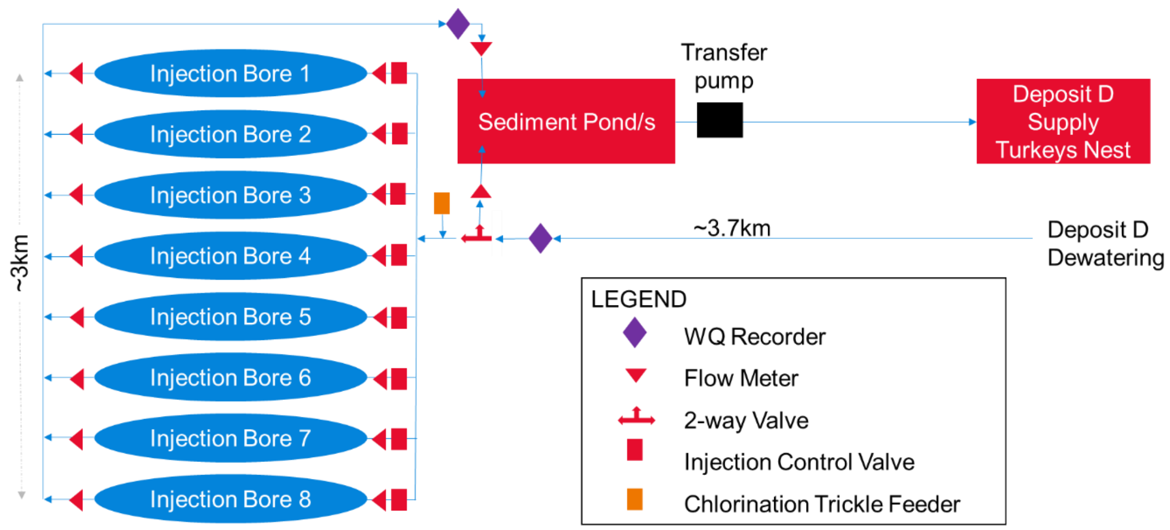


Figure 1-9: Indicative Phase 1 MAR Scheme Layout

Design of the MAR scheme has considered external influences, including: flood risk, animal/livestock interaction and access constraints with telemetered control and observation systems installed to enable automated operation and remote access to avoid any uncontrolled discharge or injection of water (RTIO, 2020).

Injected volumes will be sourced from abstraction in nearby deposits within the same aquifer system which will ensure compatibility of source and receiving environment water quality (Section 1.5.2.2) while maintaining a simple operating system.

The MAR scheme will be operated dependent upon measured and modelled aquifer responses within a purpose-built observation network in place to track progression of drawdown from dewatering activities with use of discrete observations being validated to continuous trends. Injection rates will then be adaptively managed to target no exceedance of triggers.

Adaptive management of drawdown will include but not be limited to changes to injection rates, distribution of injection, targeted monitoring and further drilling activities as required and permitted. Adaptive management of quality may include, but not be limited to filtration, de-sanders, chemical treatment and settling ponds. Treatment options will be designed to respond to the water quality objective.

Comprehensive observation and injection networks related to Phase 2 mitigation will be drilled in advance of further dewatering in Deposit C and be incorporated into management zone observation lists and this Groundwater EMP updated as required (Section 3).

1.5.2 Rationale for the choice of provisions

1.5.2.1 Groundwater Level

A numerical groundwater model was developed in MODFLOW-USG by Innovative Groundwater Solutions Pty Ltd (IGS 2021) to predict potential drawdown impacts to Karijini NP from dewatering of Deposit C and Deposit D and to inform the optimisation of the MAR scheme to mitigate these impacts.

The groundwater model encompasses the West Angelas regional groundwater system described in Section 1.2.1. The model was calibrated against hydraulic head values at monitoring locations and the MAR injection trial data, as summarised in Section 1.5.1. Based on this information, a conditioned ensemble of models with distributions of hydraulic conductivities and storage parameters were generated to capture the uncertainty in model predictions. Numerical modelling of the system was undertaken using a risk averse and conservative conceptual model (which effectively allowed for a worst-case drawdown, given conceptual uncertainty) and a range of hydraulic parameter sets which were based upon realistic and measured Pilbara wide parameters.

The ensemble of models was then used to simulate unmitigated and mitigated impacts from dewatering activities. Unmitigated impact simulations using the complete ensemble show drawdown propagating faster in the south than the north, reaching a maximum drawdown of between 1.9 m and 5.2 m at Karijini NP boundary by end of mining. Predictions were modelled for the full range of parameter sets. Mitigated impact results from the ensemble demonstrate the capacity for the MAR infrastructure to mitigate the likely propagation of drawdown to Karijini NP boundary associated with pit dewatering. Mitigation simulations comprised optimisation of injection volumes to ensure compliance with approval condition requirements of no drawdown impact at the Karijini NP boundary. Although a wide range of parameters were modelled to deliver different unmitigated drawdown distributions, the whole ensemble of models was effectively mitigated with Phase 1 reinjection with injection volumes not exceeding dewatering volumes at Deposit D. A summary of the model development, inputs and results is provided in Appendix 3.

Groundwater decline in the vicinity of Karijini NP is conceptually influenced by both climate and groundwater abstraction at Deposit C and Deposit D, which means that if drawdown from climate impacts are accepted while drawdown from dewatering must be mitigated, provisions must be triggered by the latter of these drawdowns. An approach was taken to accurately determine, isolate and remove climate related decline from observed water levels by means of simple, purpose built Grey Box models for each observation bore. This approach allows Rio Tinto to analyse ongoing climate related changes to the groundwater level and consider it within its management response.

Predictions of future climate in the Pilbara are numerous and variable with no clear reliable trend ([3]: *CSIRO 2015*). Modelling completed to support water management rationale at West Angelas has allowed for this variability through grey box models calibrating water level response to measured rainfall with ongoing recalibration to climate. Climate change is likely to be a factor in future water management at West Angelas, particularly in areas where dewatering has lowered the groundwater table, increasing the storage potential of the groundwater system. RTIO acknowledge that there may be residual uncertainty in modelling predictions and have accommodated conservatism and utilised parameter uncertainty to ensure that mitigation is effective. Rio Tinto will integrate key climate trends into its modelling to ensure various climatic predictive trends are accommodated. Time Series (TS) analysis can be used to assess the effects of stresses (e.g. groundwater pumping, climate variability, etc.) on groundwater system. Grey Box models using TS analysis are much simpler than numerical groundwater

---

[3] CSIRO (2015) Pilbara Water Resource Assessment: past, present and future hydroclimate. An overview report to the Government of Western Australia and industry partners from the CSIRO Pilbara Water Resource Assessment. CSIRO Land and Water, Australia

model and often provide a good fit. For this study, Grey Box models were developed and calibrated at relevant monitoring bores to simulate groundwater response from rainfall and evapotranspiration. These calibrated models can be used throughout the life of mine to predict groundwater level responses as a result of trends in rainfall and evapotranspiration and therefore quantify the contribution of natural system responses to observed hydrographs. Significant departure from the predicted system behaviour in drawdown would require a review of the Grey Box model, and potentially an adjustment to the MAR scheme. The Grey Box model approach is described in more detail in Appendix 3.

Multiple levels of triggers with an escalating severity of response based upon consecutive and validated exceedances is intended to ensure an appropriate level of adaptive management. As triggers are at the sub metre scale, measurement error is expected to be dealt with by means of manual validation and comparison with continuous trends.

1.5.2.2 Groundwater Quality

Groundwater quality information, and interpreted knowledge of natural variability, is only available over discrete periods of time in a highly restricted number of bores which impedes the ability to allow the groundwater system to vary naturally in a highly erratic and variable climate. As a result, water quality provisions incorporate use of a comparison with a control bore (MB16WAW0005) (as per Appendix 3) that is inside of the aquifer relevant to the provision and outside of the worst-case area of influence (Figure 1-8) from the MAR scheme.

Groundwater quality triggers are physical water characteristic based (i.e. EC and pH). These have been demonstrated as likely to fluctuate dependent upon injectant water quality (RTIO, 2020) and are expected to remain relevant to the condition until a specific analyte becomes apparent in subsequent trend analysis (during subsequent compliance reporting or trigger particulate dispersion modelling).

Condition 3(b) (as per DN 2018/8299) states a requirement for no change in groundwater quality as a result of the action at the boundary of, or within, Karijini NP. As a direct result, any bores inside the Karijini NP are, by default, unable to be used as trigger bores. Impacts to water quality values inside Karijini NP are assumed to be impacted by the proposal as a direct transmission through the aquifer at the boundary of the mapped aquifer, therefore observation of water quality change inside the Karijini NP is to be a part of regional baseline and modelling inputs.

Impacts to water quality values inside Karijini NP can only be as a direct transmission through the aquifer at the boundary therefore, observation of water quality change inside Karijini NP is not to be relied upon as a trigger.

Table 1-5: Summary of Rationale for choice of provisions

Current knowledge and description of impacts	Key assumptions and uncertainties	Rationale for choice of provision
Karijini NP		
Level of Management[4] HIGH		
Key surveys and studies: Rio Tinto 2016, 2017, 2018, 2019 and 2020, IGS 2021		
Dewatering of Deposit C: • The geological model indicates that a large proportion of the Deposit C resource occurs below the water table. The Proponent conservatively estimates that up to approximately 20 GL of groundwater will need to be pumped from Deposit C, commencing in 2023. The expected maximum depth of mining is the 568 m RL, with an associated maximum depth of dewatering of up to approximately 68 m in the eastern end of the deposit. **Dewatering of Deposit D:** • The geological model indicates that a significant proportion of the Deposit D resource occurs below the water table. The Proponent conservatively estimates that up to approximately 26 GL of groundwater will need to be pumped from Deposit D, commencing in 2021. The expected maximum depth of dewatering is up to approximately 130 m in the western end of the deposit. **Groundwater System:** • Below water table portions of Deposit C and Deposit D lie within a connected groundwater system, with the aquifer extending inside Karijini NP. • Unmitigated dewatering of the western end of Deposit C and Deposit D could result in groundwater drawdown extending west to Karijini NP around 2024. **MAR:** • The Proponent will mitigate groundwater drawdown associated with dewatering activities (specifically at Deposit C and Deposit D) by use of a MAR scheme. • The MAR scheme will comprise 4 phases. Trials confirm Phase 1 is practicable and it will include re-injection of dewatered groundwater from Deposit D into an area approximately 1.4 km away from the Karijini NP boundary. • Water level response to injection was observed at distances greater than adjacent injection bores. • Water quality response to injection was very minor with very little change in pH or EC and no observable change to dissolved chemistry. **Predictive Modelling:** • Numerical modelling suggests that southern injection bores are likely to be in use early, at higher rates and for extended periods. • Mitigation simulations suggest that conditions can be met under a full range of hydraulic parameter sets. • Uncertainties in hydraulic conductivity contrast between dolocrete and detrital units was identified as resulting in some significantly different unmitigated drawdown distributions.	**Assumptions:** • The aquifer between Deposit C and Deposit D and Karijini NP is not intersected by any hydraulic barriers (i.e. Dolerite dykes/ faults). • Hydraulic parameters within the aquifer are within ranges applied to groundwater modelling. • The aquifer does not extend beyond barriers associated with surrounding low permeability Brockman Formation or Marra Mamba Formation units (i.e. Mt Macrae Shale). • Modelling inputs and therefore outputs represent potential actual scenarios and are based on the best knowledge of the aquifer and constraints at the time. • Trigger level criteria do not represent an impact on either water level and/or quality at the boundary of, or within Karijini NP. No impact on water level or quality at sentinel bores (Karijini NP boundary) indicates no impact on water level or quality within Karijini NP. **Uncertainties:** • A variable climate may either naturally recharge or deplete the groundwater system in the same timeframe as pumping induces drawdown. • The spatial distribution and character of the aquifer inside Karijini NP is not validated by any drilling information. • Water quality temporal variability during periods of dry climate.	The intent of the environmental outcomes is to ensure that the potential impacts from dewatering of Deposit C and Deposit D do not reach the Karijini NP boundary. A high level of management has been assigned to mitigate and manage the drawdown associated with dewatering activities at Deposit C and Deposit D and complementary provisions (including both outcome and objective-based) have been applied to manage the MAR scheme and monitor changes in groundwater level and quality to ensure no change at the boundary of, or within, Karijini NP. MS 1113 specifies the requirement for triggers and thresholds (outcomes-based) provisions in the Groundwater EMP. Outcomes-based provisions in this Groundwater EMP include a comparison of groundwater levels in monitoring bores against seasonally adjusted predicted water levels as modelled by Grey Box modelling (IGS 2021). To provide certainty that Grey Box modelling accurately predicts natural groundwater levels for the life of the project, and ensure outcome-based provisions are accurately assessed, targets for Grey Box modelling have been included as objective-based provisions. If targets are exceeded, Grey Box modelling will be assessed and updated if required to ensure accuracy. A summary of the rationale for objective-based and outcome-based provisions is below. **Objective-based Provisions:** Objective-based provisions have been applied to groundwater modelling within the project area and eastern Karijini NP to ensure currency and accuracy of groundwater modelling and to guarantee it is a representative and robust base to inform outcome-based provisions. Objective-based management targets and indicative monitoring zones have been established in Table 2-1 and Figure 2-2. Objective-based targets identify groundwater levels in Zone 2 and 3 monitoring bores which are to be used for assessment of outcome-based provisions. Target 1 was chosen as an indicator to confirm that the regional aquifer is modelled correctly. These bores should reflect natural seasonal variations in water level and not fluctuate as a result of mine groundwater activities. Remaining targets were chosen using different duration rolling seasonally adjusted averages in Zone 3 monitoring bores to ensure that the model is accurately capturing natural variations in groundwater due seasonal and climatic influences. Zone 3 monitoring bores were chosen as they are the most distant from the MAR scheme and most likely to represent natural variation at Karijini NP. As additional data are collected the model should become more accurate at simulating trends, which is reflected in targets. **Outcome-based Provisions** Outcome-based provisions have been applied to drawdown and water quality based on monitoring against modelling outputs to: • Ensure that there is no drawdown of groundwater associated with the Project at the boundary of, or within, Karijini NP (MS 1113 and DN 2018/8299). • Ensure no change in groundwater quality at the boundary of, or within, Karijini NP (DN 2018/8299). The MAR scheme will be implemented over four phases. Monitoring data collected during each phase, including inputs and responses, will be reviewed regularly and used to update models and adapt the use of the scheme to mitigate observed impacts from drawdown associated with dewatering activities. **Groundwater Level Early Response Indicators, Trigger and Threshold Criteria:** Early Response Indicator 1 for groundwater level is based on the premise that if the MAR scheme is not operating as expected then there is a risk that groundwater levels may be impacted at the boundary of or within Karijini NP. Any deviation from the operational plan for the MAR will be investigated and rectified or adjustments made as required. Early Response Indicator 2 and Trigger and Threshold Criteria were determined through assessment of natural (simulated unimpacted seasonally adjusted) water levels (as predicted by Grey Box modelling, Appendix 3), proximity of monitoring bores to Karijini NP and modelled timeframe of potential impact, and limits of measurement accuracy. Groundwater level Early Response Indicator 2 and Trigger and Threshold Criteria are based on comparison of groundwater levels in monitoring bores against simulated unimpacted, seasonally adjusted water levels (as predicted by Grey Box modelling) levels in different monitoring Zones (Section

[4] Summary of assessment for determination of required level of management provided in Appendix 2, as per the conceptual framework for development of Rio Tinto's EMPS (Appendix 1).

		2, Figure 2-2). Early Response Indicator and Trigger Level 1 Criteria are assessed in Zone 2 monitoring bores, located approximately 600 m from MAR injection bores and 1.4 km from Karijini NP (Section 2, Figure 2-2). Trigger Level 2 and Threshold Criteria are assessed in Zone 3 monitoring bores located approximately 600 m from Karijini NP and 1.4 km from MAR injection bores. Zone 1 monitoring bores are operational monitoring bores, located adjacent to MAR injection bores and are not used to assess Early Response Indicators or Trigger and Threshold Criteria (Figure 2-3). Early Response Indicator 2 and Trigger and Threshold Criteria require groundwater levels to be within the specified drawdown limit over two consecutive monitoring periods to account for anomalies in results due to errors in field measurement or calculation, extreme natural events e.g. cyclone, or unforeseen access issues or damage to monitoring bores. This is not considered to be a risk as maximum modelled unmitigated drawdown in Zone 2 monitoring bores is not expected to occur until approximately 3 years after commencement of dewatering and at the Karijini NP boundary (Zone 3), between 5 and 10 years after commencement of dewatering. It is expected that if an exceedance of Early Response Indicators and/or Trigger Level 1 criteria in Zone 2 monitoring bores occurs, there will be sufficient time to implement identified response actions to mitigate potential impacts prior to Trigger Level 2 or Threshold criteria being exceeded. During this time modelling will continue to be updated to ensure accuracy and relevance of model as a basis for Early Response Indicator 2, and Trigger and Threshold Criteria. **Groundwater Quality Trigger and Threshold Criteria:** Groundwater quality in the area is good with circum-neutral pH and low EC, and groundwater quality Early Response Indicator and Trigger and Threshold Criteria are based on known previous ranges of pH and EC. There is a lack of historic water quality data for the Karijini NP and also within the MAR scheme area of impact. Historic pH data indicates the range of these analytes are between 6.5 and 8.5, however a pH of greater than 8 is not common historically. Historic EC data indicates that EC is fairly constant over time, taking into account seasonal variation. Any significant variation in EC from control bores may indicate an impact on groundwater quality from the MAR scheme. Modelled particle tracking profiles for maximum and minimum drawdowns (Figure 2-2) indicate that potential water quality impacts will not occur within Zone 3 monitoring bores within 100 years, with impacts only predicted in Zone 2 monitoring bores for maximum drawdown model and only in isolated locations. The requirement for two consecutive monitoring periods (6 months) to determine compliance with Early Response Indicator, and Trigger or Threshold Criteria is not considered to present a risk of potential impact at the boundary of or within Karijini NP as modelled timeframes indicate that potential impacts will occur over a period of years rather than months. It is expected that an exceedance of Early Response Indicator and/or Trigger Level 1 criteria in Zone 2 monitoring bores will allow sufficient time to implement identified response actions to mitigate potential impacts prior to Trigger Level 2 or Threshold criteria being exceeded.

2. EMP PROVISIONS

This section identifies the provisions that the Proponent will implement upon approval of this Groundwater EMP by DWER in consultation with DBCA, and DAWE to meet the requirements of Condition 6-3 of MS 1113 and Condition 3(a) and 3(b) of DN 8299/2018 and to ensure that the defined environmental outcomes are met during implementation of the Project. Objective-based and outcome-based provisions will be implemented concurrently for the duration of the Groundwater EMP. Objective-based provisions apply to groundwater levels only and are used to ensure the model used to determine compliance with outcome-based triggers and thresholds for drawdown is accurate. Review of the model (objective-based) and drawdown and water quality (outcome-based) provisions will occur concurrently with the model adjusted and refined as required based on management targets, to inform outcome-based provisions. Outcome-based provisions apply to drawdown and water quality and are assessed against deviation from the modelled drawdown scenarios and water quality in control bores.

Objective-based water level provisions are detailed in Table 2-1. Outcome-based drawdown provisions are detailed in Table 2-2, and outcome-based water quality provisions are detailed in Table 2-3. Monitoring and reporting for each provision is also detailed in these tables. A summary of relevant criteria applied to each monitoring zone and current and future Phase 1 bores is provided in Appendix 5. Appendix 5 will be updated as project phases progress. Interactions between objective-based and outcome-based provisions and response flow to different level provisions are shown in Figure 2-1.

Manual observations will be compared to objective-based (water level) triggers and will initially trigger a validation of drawdown. This drawdown will then be cross-checked against Grey Box quantified drawdown and may then trigger response actions. Drawdown will be evaluated using Grey Box modelling which is intended to apportion groundwater level decline to either climate or pumping induced impacts.

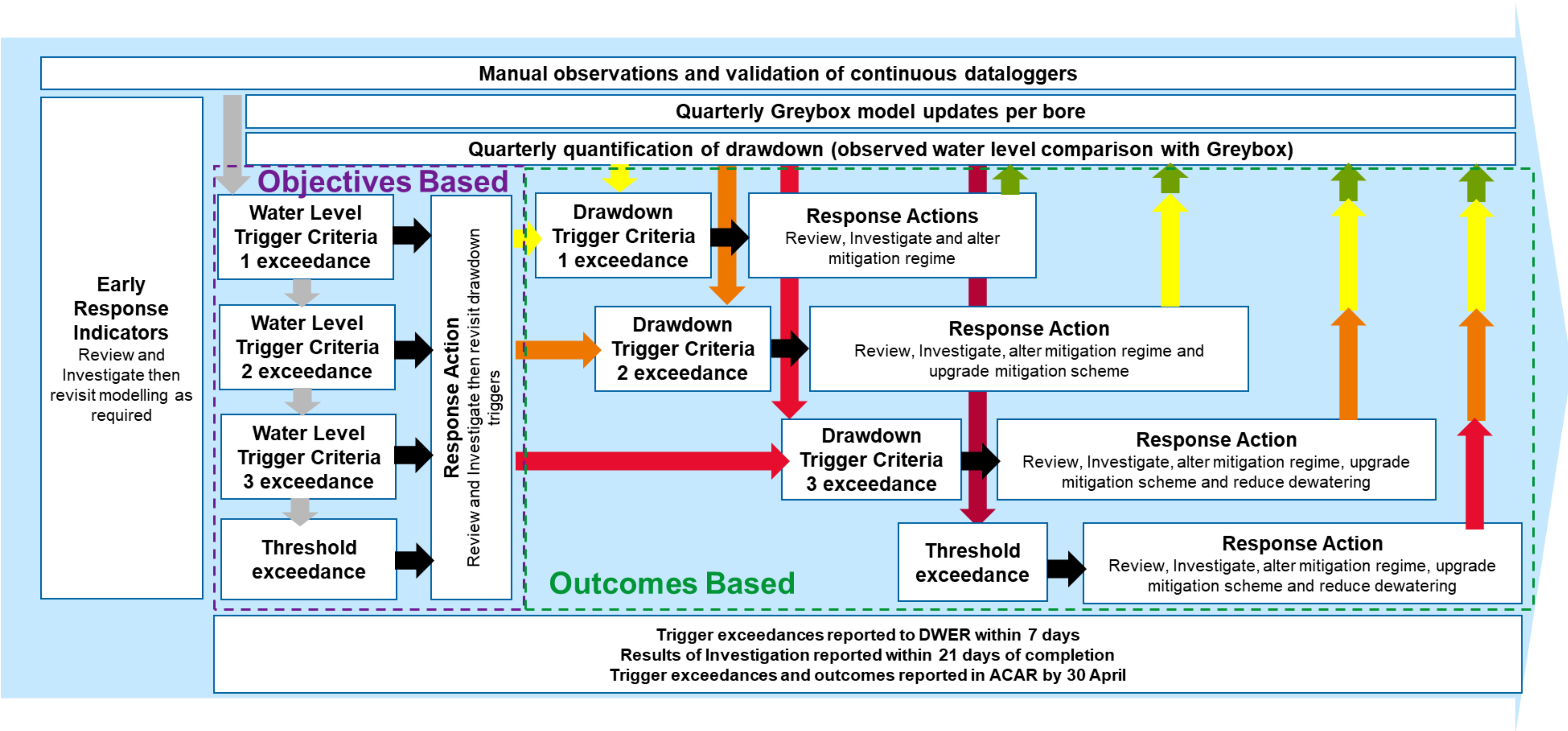


Figure 2-1: **Interaction between observation, interaction and objective-based/outcome-based triggers**

Table 2-1: Objective-based Groundwater EMP Provisions – Inland Waters - Karijini NP Groundwater Level

EPA Factor: Inland waters

EPA objective: *To maintain the hydrogeological regimes of groundwater and surface water so that environmental values are protected.*

Objective: Maintain an accurate and up to date groundwater model of the West Angelas Deposit C and Deposit D and East Karijini NP to inform outcomes-based provisions to ensure that there is no drawdown of groundwater associated with the Project at the boundary of, or within, Karijini NP.

Key environmental values: Karijini NP.

Key impacts and risks: Accuracy of Grey Box model (to enable assessment of Change to groundwater levels at the boundary of, or within, Karijini NP, as a result of Project dewatering at Deposit C and/or Deposit D.)

Objective-based provisions (to ensure relevance and accuracy of modelling used to access outcomes-based provisions)

High Management Zone (Appendix 2)

Applicability: Targets selected to support Grey Box accuracy to verify:

- **MS 1113 Condition 6-1(1):** Ensure that there is no drawdown of groundwater associated with the proposal at the boundary of, or within, Karijini NP.
- **DN 2018/8299 Condition 3 (a)**: No drawdown of groundwater associated with the action at the boundary of, or within, Karijini NP.

Management Target	Management Actions	Monitoring	Location	Timing/Frequency	Reporting
Target 1: **1.** Water levels in boundary bores to the south and north of the MAR scheme in areas outside of the regional aquifer are above or equal to rolling 3 year, seasonally adjusted water levels (mbgl).	1. Review and check modelling inputs and other complimentary monitoring data to ensure model is accurate and current. 2. Review MAR operational monitoring data and compare against modelled operation. 3. Review monitoring data to assess whether model is accurate and representative of the current environment and activities. If not, investigate and reinterpret models if required or implement corrective/mitigation actions which could include: a. Amend/increase monitoring frequency and/or location. b. Conduct additional monitoring to validate model. c. Review outcome-based provisions and implement response actions as appropriate.	Comparison of manual water levels in boundary bores with Grey Box model.	Boundary Bores, Figure 2-2, Appendix 4[5].	Monthly water level of bores reviewed against quarterly.	**MS 1113:** • Management actions and targets will be reported annually by 30 April in the ACAR. **DN 2018/8299:** • Monitoring, management actions and outcomes against targets will be reported annually by 30 April in the ACAR.
Target 2: **2.** Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 3 year, seasonally adjusted water levels (mbgl).		Comparison of recorded (data logger) water levels in Zone 3 monitoring bores (mbgl) and modelled 3 year (seasonally adjusted) water levels.	Data logger output from Zone 3 monitoring bores, Figure 2-2 Appendix 4[5].	Continuous logging data to be reviewed and assessed quarterly.	
Target 3: **3.** Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 5 year, seasonally adjusted water levels (mbgl).		Comparison of recorded (data logger) water levels in Zone 3 monitoring bores (mbgl) and modelled 5 year (seasonally adjusted) water levels.	Data logger output from Zone 3 monitoring bores, Figure 2-2 Appendix 4[5].	Continuous logging data to be reviewed and assessed quarterly.	
Target 4: **4.** Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 10 year, seasonally adjusted water levels (mbgl).		Comparison of recorded (data logger) water levels in Zone 3 monitoring bores (mbgl) and modelled 10 year (seasonally adjusted) water levels.	Manual water levels in Zone 3 monitoring bores, Figure 2-2 Appendix 4[5].	Continuous logging data to be reviewed and assessed quarterly.	

[5] Some bores are not drilled as at Q1 2021. RTIO commits to commission monitoring bores as per Appendix 4.

Table 2-2: Outcome-based Groundwater EMP Provisions – Inland Waters - Karijini NP Groundwater Level

EPA Factor: Inland waters

EPA objective: *To maintain the hydrogeological regimes of groundwater and surface water so that environmental values are protected.*

Outcome: Ensure that there is no drawdown of groundwater associated with the Project at the boundary of, or within, Karijini NP.

Key environmental values: Karijini NP.

Key impacts and risks: Change to groundwater levels at the boundary of, or within, Karijini NP, as a result of Project dewatering at Deposit C and/or Deposit D.

Outcome-based Provisions

High Management Zone (Appendix 2)

Applicability:

MS 1113 Condition 6-1(1): Ensure that there is no drawdown of groundwater associated with the proposal at the boundary of, or within, Karijini NP.

DN 2018/8299 Condition 3 (a): No drawdown of groundwater associated with the action at the boundary of, or within, Karijini NP.

Criteria	Response Actions	Monitoring	Timing/Frequency	Reporting
Early Response Indicator 1: **1.** Injection bores non operational outside of proposed plan for operation of the MAR scheme (more than 1 of a paired set of bores inoperable for more than 1 week).	**Investigate and if appropriate implement corrective actions:** • Bore maintenance/refurbishment if required • Improve operability of scheme -better planning, maintenance, scheduling etc.	Zone 1 injection bores as per Figure 2-2, Appendix 4[5].	• Quarterly	**MS 1113** • Outcomes of this Groundwater EMP will be reported annually by 30 April in the ACAR. • Early response criterion exceeded during the reporting period will be summarised in the ACAR, including potential reasons for exceedance and a description of the effectiveness of trigger level actions. **DN 2018/8299:** • In the event that an exceedance of trigger criteria, the exceedance will be reported in writing to the DAWE within five (5) business days of becoming aware of the exceedance. • The Proponent will provide a report to DAWE within twenty-one (21) business days of the exceedance being reported specifying details as required by Condition 6(e) of DN 2018/8299. • Outcomes, monitoring and response actions will be reported annually by 30 April in the ACAR.
Early Response Indicator 2: **2.** Two consecutive monitoring periods of drawdown 25 cm greater than Grey Box level for modelled mitigation scenario in Zone 2 monitoring bores.	**Investigate, this could include but is not limited to:** • Review MAR operational monitoring data. • Review monitoring data. • Investigate and reinterpret models if required. • Water balance assessment. If investigations determine early response represents impact on groundwater due to the Project, the Proponent will implement response actions which may include: • Amend/increase monitoring frequency and/or location. • Conduct additional monitoring. • Increase or alter reinjection rate and/or location (as appropriate). • Monitor until results indicate water level is in accordance with modelling prediction.	Zone 2 monitoring bores as per Figure 2-2, Appendix [5].	• Quarterly water level recording (manual).	**MS 1113** • Outcomes of this Groundwater EMP will be reported annually by 30 April in the ACAR. • Early response criterion exceeded during the reporting period will be summarised in the ACAR, including potential reasons for exceedance and a description of the effectiveness of trigger level actions. **DN 2018/8299:** • In the event that an exceedance of trigger criteria, the exceedance will be reported in writing to the DAWE within five (5) business days of becoming aware of the exceedance. • The Proponent will provide a report to DAWE within twenty-one (21) business days of the exceedance being reported specifying details as required by Condition 6(e) of DN 2018/8299. • Outcomes, monitoring and response actions will be reported annually by 30 April in the ACAR.
Trigger Criteria Level 1: **3.** Two consecutive monitoring periods of drawdown 50 cm greater than Grey Box level for modelled mitigation scenario in Zone 2 monitoring bores.	**Implement within twenty-four (24) hours:** • Investigations as per Early Response Indicator 2. If investigations determine trigger exceedance represents impact on groundwater due to the Project, the Proponent will implement response actions which may include but are not limited to: • As per Early Response Indicator 2. • Commence infrastructure upgrades to accommodate any further increases to injection rate and investigate alternative supply.	Zone 2 monitoring bores as per Figure 2-2, Appendix 4[5].	• Quarterly water level recording (manual).	**MS 1113** • Outcomes of this Groundwater EMP will be reported annually by 30 April in the ACAR. • Trigger criterion exceeded during the reporting period will be summarised in the ACAR, including potential reasons for exceedance and a description of the effectiveness of trigger level actions. **DN 2018/8299:** • In the event that an exceedance of trigger criteria, the exceedance will be reported in writing to the DAWE within five (5) business days of becoming aware of the exceedance. • The Proponent will provide a report to DAWE within twenty-one (21) business days of the exceedance being reported specifying details as required by Condition 6(e) of DN 2018/8299. • Outcomes, monitoring and response actions will be reported annually by 30 April in the ACAR.

EPA Factor: Inland waters

EPA objective: *To maintain the hydrogeological regimes of groundwater and surface water so that environmental values are protected.*

Outcome: Ensure that there is no drawdown of groundwater associated with the Project at the boundary of, or within, Karijini NP.

Key environmental values: Karijini NP.

Key impacts and risks: Change to groundwater levels at the boundary of, or within, Karijini NP, as a result of Project dewatering at Deposit C and/or Deposit D.

Outcome-based Provisions

High Management Zone (Appendix 2)

Applicability:

MS 1113 Condition 6-1(1): Ensure that there is no drawdown of groundwater associated with the proposal at the boundary of, or within, Karijini NP.

DN 2018/8299 Condition 3 (a): No drawdown of groundwater associated with the action at the boundary of, or within, Karijini NP.

Criteria	Response Actions	Monitoring	Timing/Frequency	Reporting
Trigger Criteria Level 2: **4.** Two consecutive monitoring periods of drawdown of 10 cm or greater than the Grey Box level for modelled mitigation scenario in Zone 3 monitoring bores or **5.** a single monitoring period of drawdown greater than 10cm in Zone 3 bores if Trigger Criteria Level 1 exceeded in the current or preceding monitoring period or **6.** a single monitoring period of drawdown greater than 10 cm or greater than the Grey Box level recorded in two or more adjacent monitoring bores.	**Implement within twenty-four (24) hours:** • Investigations as per Trigger Criteria level 1: If investigations determine trigger exceedance represents impact on groundwater due to the Project, the Proponent will implement response actions which may include but is not limited to: • As per Trigger Criteria Level 1. • Cease dewatering from drawdown source areas while maintaining safe operations and supply of water to the MAR scheme.	Zone 3 monitoring bores as per Figure 2-2, Appendix 4[5].	• Quarterly water level recording (manual).	**MS 1113** • Outcomes of this Groundwater EMP will be reported annually by 30 April in the ACAR. • Trigger criterion exceeded during the reporting period will be summarised in the ACAR, including potential reasons for exceedance and a description of the effectiveness of trigger level actions. **DN 2018/8299:** • In the event that an exceedance of trigger criteria, the exceedance will be reported in writing to the DAWE within five (5) business days of becoming aware of the exceedance. • The Proponent will provide a report to DAWE within twenty-one (21) business days of the threshold exceedance being reported specifying details as required by Condition 6(e) of DN 2018/8299. • Outcomes, monitoring and response actions will be reported annually by 30 April in the ACAR.
Threshold Criteria: **7.** Two consecutive monitoring periods of drawdown associated with the proposal of 20 cm or greater than Grey Box level for modelled mitigation scenario in Zone 3 monitoring bores or **8.** a single monitoring period of drawdown exceeding 20cm in Zone 3 bores if Trigger Criteria Level 2 exceeded in current or preceding monitoring period. or **9.** a single monitoring period of significant drawdown (over 40 cm drawdown) and the equipment is not damaged.	**Implement within twenty-four (24) hours:** • Review data, investigate driver of threshold breach using Grey Box model to determine the degree to which the project has contributed. • Develop and implement recovery plan which may include ceasing dewatering, increasing or altering reinjection rate and/or locations (as appropriate) and potential additional reinjection bores. • Monitor until results indicate water level is in accordance with modelling prediction. • Continue to implement threshold contingency actions until the CEO has confirmed by notice in writing that it has been demonstrated that the impact is below the threshold criteria. • Monitor to validate success of threshold contingency actions.	Zone 3 monitoring bores as per Figure 2-2, Appendix 4[5].	• Quarterly water level recording (manual).	**MS 1113:** • Report as non compliance with Condition 6-1(1) of MS 1113 within seven (7) days. • Outcomes will be reported annually by 30 April in the ACAR. • If any trigger criterion was exceeded during the reporting period, the ACAR will discuss potential reasons for exceedance of the trigger criterion and include a description of the effectiveness of trigger level actions. **DN 2018/8299:** • In the event that an exceedance of threshold criteria, the exceedance will be reported in writing to the DAWE within five (5) business days of becoming aware of the exceedance. • The Proponent will provide a report to DAWE within twenty-one (21) business days of the exceedance being reported specifying details as required by Condition 6(e) of DN 2018/8299. • Outcomes, monitoring and response actions will be reported annually by 30 April in the ACAR.

Table 2-3: Outcome-based Groundwater EMP Provisions – Inland Waters - Karijini NP Groundwater Water Quality – DN 2018/8299 Only

EPA Factor: N/A				
EPA objective: N/A				
Outcome: Ensure no change in groundwater quality at the boundary of, or within, Karijini NP.				
Key environmental values: Karijini NP.				
Key impacts and risks: Change to groundwater quality at the boundary of, or within, Karijini NP, as a result of Project dewatering at Deposit C and/or Deposit D.				
Outcome-based Provisions				
High Management Zone (Appendix 2**)**				
Applicability: **DN 2018/8299 Condition 3(b):** No change in groundwater quality associated with the action at the boundary of, or within, Karijini NP.				
Criteria	**Response Actions**	**Monitoring**	**Timing/Frequency**	**Reporting**
Early Response Indicator: **10.** Long term pH trend in Zone 2 monitoring bores over two consecutive monitoring periods is not consistent with trend in control bore. or **11.** Proportional change in EC in Zone 2 monitoring bores is greater than 20% of proportional change in control bore EC over two consecutive monitoring periods.	**Investigate potential cause of exceedance which may include:** • Resample monitoring bores and reinjection feed water • Investigate potential cause of change. • Review/ complete particulate dispersion modelling to ensure model is calibrated and accurate. Re-model particulate dispersal if required to inform water quality modelling. If investigations indicate that trigger exceedance is due to the Project, implement trigger level response actions, for example: • Investigate treatment or alternative source of feed water. • Investigate reduction in reinjection until water quality improves (only if no impact to groundwater levels).	Field analysis for pH and EC of water samples from Zone 2 bores as per Figure 2-2, Appendix 4[5].	Quarterly	**DN 2018/8299:** • In the event that an exceedance of trigger criteria, the exceedance will be reported in writing to the DAWE within five (5) business days of becoming aware of the exceedance. • The Proponent will provide a report to DAWE within twenty-one (21) business days of the exceedance being reported specifying details as required by Condition 6(e) of DN 2018/8299. • Outcomes, monitoring and response actions will be reported annually by 30 April in the ACAR.
Trigger Criteria Level 1: **12.** Long term pH in Zone 2 monitoring bores is not between 6.5 and 8 for two consecutive monitoring periods and trend is not consistent with trend in control bore. **or** **13.** Proportional change in EC in Zone 2 monitoring bores is greater than 50% of proportional change in control bore EC over two consecutive monitoring periods.	**Implement within twenty-four (24) hours:** • Investigate potential cause of exceedance as per Early Response Indicator with the addition of a review of monitoring. If investigations indicate that trigger exceedance is due to the Project, implement trigger level response actions, for example: • As per Early Response Indicator. • If necessary, expand the monitoring network.	Field analysis for pH and EC of water samples from Zone 2 Bores as per Figure 2-2, Appendix 4[5].	Quarterly	**DN 2018/8299:** • In the event that an exceedance of trigger criteria, the exceedance will be reported in writing to the DAWE within five (5) business days of becoming aware of the exceedance. • The Proponent will provide a report to DAWE within twenty-one (21) business days of the exceedance being reported specifying details as required by Condition 6(e) of DN 2018/8299. • Outcomes, monitoring and response actions will be reported annually by 30 April in the ACAR.
Trigger Criteria Level 2: **14.** Long term pH in Zone 3 monitoring bores is not between 6 and 8.5 for two consecutive monitoring periods and trend is not consistent with trend in control bore pH. **or** **15.** Proportional change in EC in Zone 3 monitoring bores is greater than 50% of proportional change in control bore EC over two consecutive monitoring periods.	**Implement within twenty-four (24) hours:** • Investigate potential cause of exceedance as per Trigger Criteria Level 1: If investigations indicate that trigger exceedance is due to the Project, implement response actions, which could include but are not limited to: • As per Trigger Criteria Level 1 response. • Investigate and implement if required alternatives and/or treatment options for injection feedwater. • Investigate reduction in reinjection until water quality improves (only if no impact to groundwater levels). • Commence infrastructure upgrades required for treatment or alternative supply options if appropriate.	Field analysis for pH and EC of water samples from Zone 3 monitoring bores as per Figure 2-2, Appendix 4[5].	Quarterly	
Threshold Criteria: **16.** Long term pH in Zone 3 monitoring bores is not between 6 and 8.5 for two consecutive monitoring periods and trend is not consistent with trend in control bore pH as a result of the action. **or** **17.** Proportional change in EC in Zone 3 monitoring bores is greater than 80% of proportional change in control bore EC over two consecutive monitoring periods as a result of the action.	**Implement within twenty-four (24) hours:** • Investigate potential cause of exceedance as per Trigger Criteria Level 2: If investigations indicate that trigger exceedance is due to the Project, implement response actions, which could include but are not limited to: • As per Trigger Criteria Level 2 response. • Investigate in situ treatment options if detrimental impacts to Karijini NP and/or other environmental values are expected. • Continue to implement threshold contingency actions until the CEO has confirmed by notice in writing that it has been demonstrated that the impact is below the threshold and trigger criteria. • Monitor to validate success of threshold contingency actions.	Field analysis for pH and EC of water samples from Zone 3 monitoring bores as per Figure 2-2, Appendix 4[5].	Quarterly	**DN 2018/8299:** • In the event that an exceedance of threshold criteria, the exceedance will be reported in writing to the DAWE within five (5) business days of becoming aware of the exceedance. • The Proponent will provide a report to DAWE within twenty-one (21) business days of the exceedance being reported specifying details as required by Condition 6(e) of DN 2018/8299.

				• Outcomes, monitoring and response actions will be reported annually by 30 April in the ACAR.

Baseline water quality data will be collected throughout the planning, construction and early implementation phases of the MAR scheme to ensure the threshold criteria are reflective of groundwater quality and will capture any potential changes early enough to ensure potential impacts to Karijini NP are not realised. It is intended to review the threshold criteria for water quality when an appropriate baseline dataset has been established.

Particle modelling to date has shown that potential migration of particles in groundwater towards Karijini NP is very slow with particles not reaching Karijni NP for a modelled period of 100 years after reinjection commences. The risk of potential impacts to Karijini NP groundwater is very low in the initial stages of the Project. Anticipated timeline for baseline data collection and intended review of threshold criteria is detailed below.

Table 2-4: Phased Groundwater Quality data collection & threshold review

Phase	Implementation Stage	Timing	Threshold review	Potential Risk of Impact at Karijini NP Boundary
1	Planning	~ 2 years (8 quarterly monitoring periods)	Threshold adequate – risk to groundwater nil to very low.	Nil (dewatering not commenced)
	Construction	~ 18 months (6 quarterly monitoring periods)		Nil (dewatering not commenced)
	Implementation (Dewatering Commence)	Ongoing (quarterly monitoring)		Very low - changes to groundwater would be identified in Zone 2 monitoring bores (Early Response Indicator and Trigger Criteria Level 1). Modelled particle tracking profiles for maximum and minimum drawdowns (Figure 2-2) indicate that potential water quality impacts will not occur within Zone 3 monitoring bores within 100 years, with impacts only predicted in Zone 2 monitoring bores for maximum drawdown model and only in isolated locations
	Implementation (Reinjection commences if required – years 1 - 5)	Ongoing (quarterly monitoring)	Threshold to be reviewed 3 – 5 years after commencement of reinjection.	Very low - changes to groundwater would be identified in Zone 2 monitoring bores (Early Response Indicator and Trigger Criteria Level 1). Modelled particle tracking profiles for maximum and minimum drawdowns (Figure 2-2) indicate that potential water quality impacts will not occur within Zone 3 monitoring bores within 100 years, with impacts only predicted in Zone 2 monitoring bores for maximum drawdown model and only in isolated locations.
	Implementation (Reinjection - year 5 onwards)	Ongoing (quarterly monitoring)	Review annually and update threshold if required.	Low - modelling indicates particles move towards mining area to the east, away from Karijini NP in the west. Modelling predicts potential changes to groundwater quality near Karijini NP are unlikely to be realised within 100 years.x. Reinjected water is from the same aquifer and is unlikely to differ in quality to that near Karijini NP.
2	As above (schedule for each phase to be as per Phase 1).	To be determined - additional groundwater baseline monitoring to be carried out to support this Phase and inform water quality threshold.	Review annually and update threshold if required	Very low – modelling indicates particles move towards mining area, away from Karijini NP.

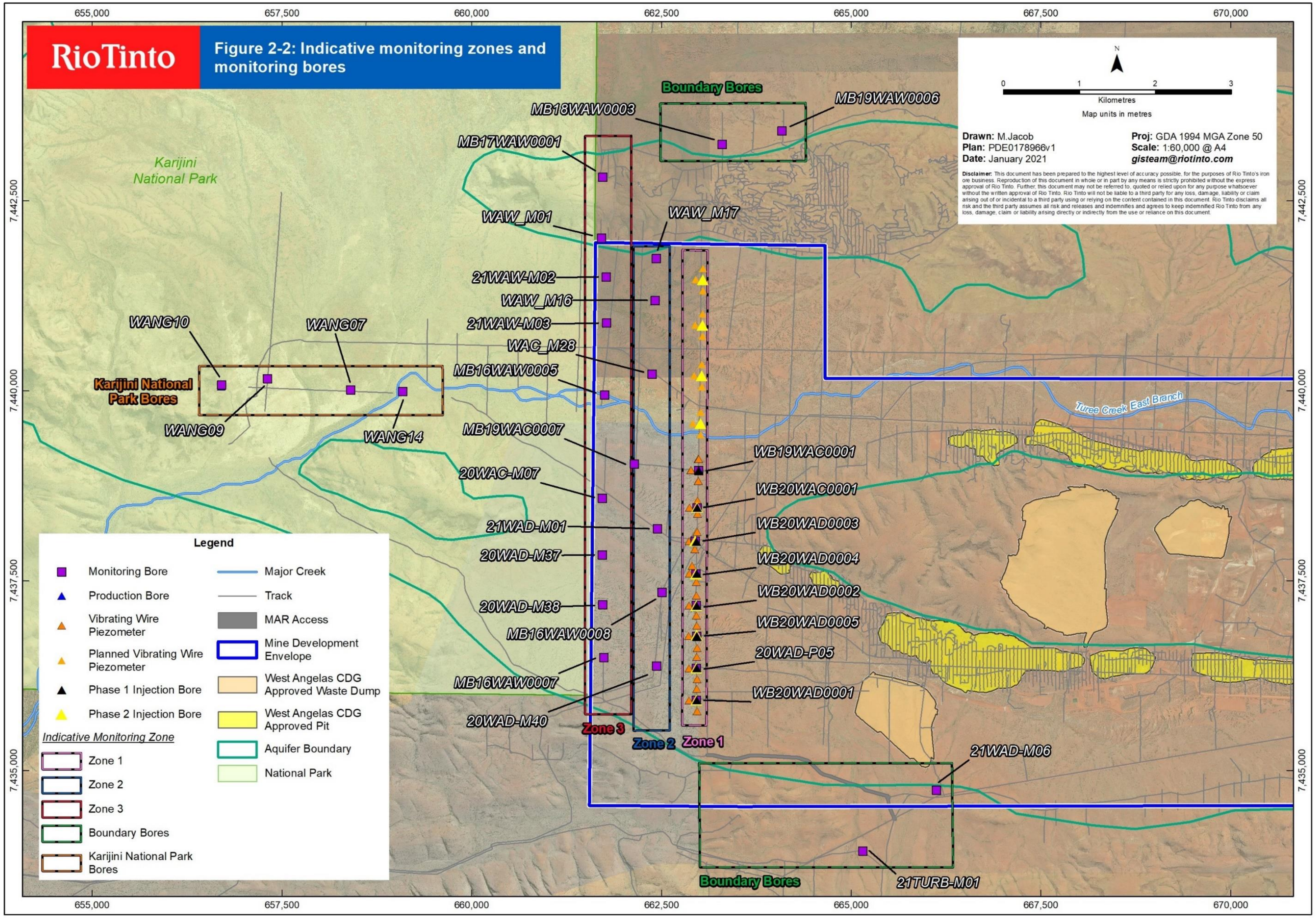


Figure 2-2: **Indicative monitoring zones and monitoring bores (within Karijini NP, only WANG14 is currently operational and monitored)**

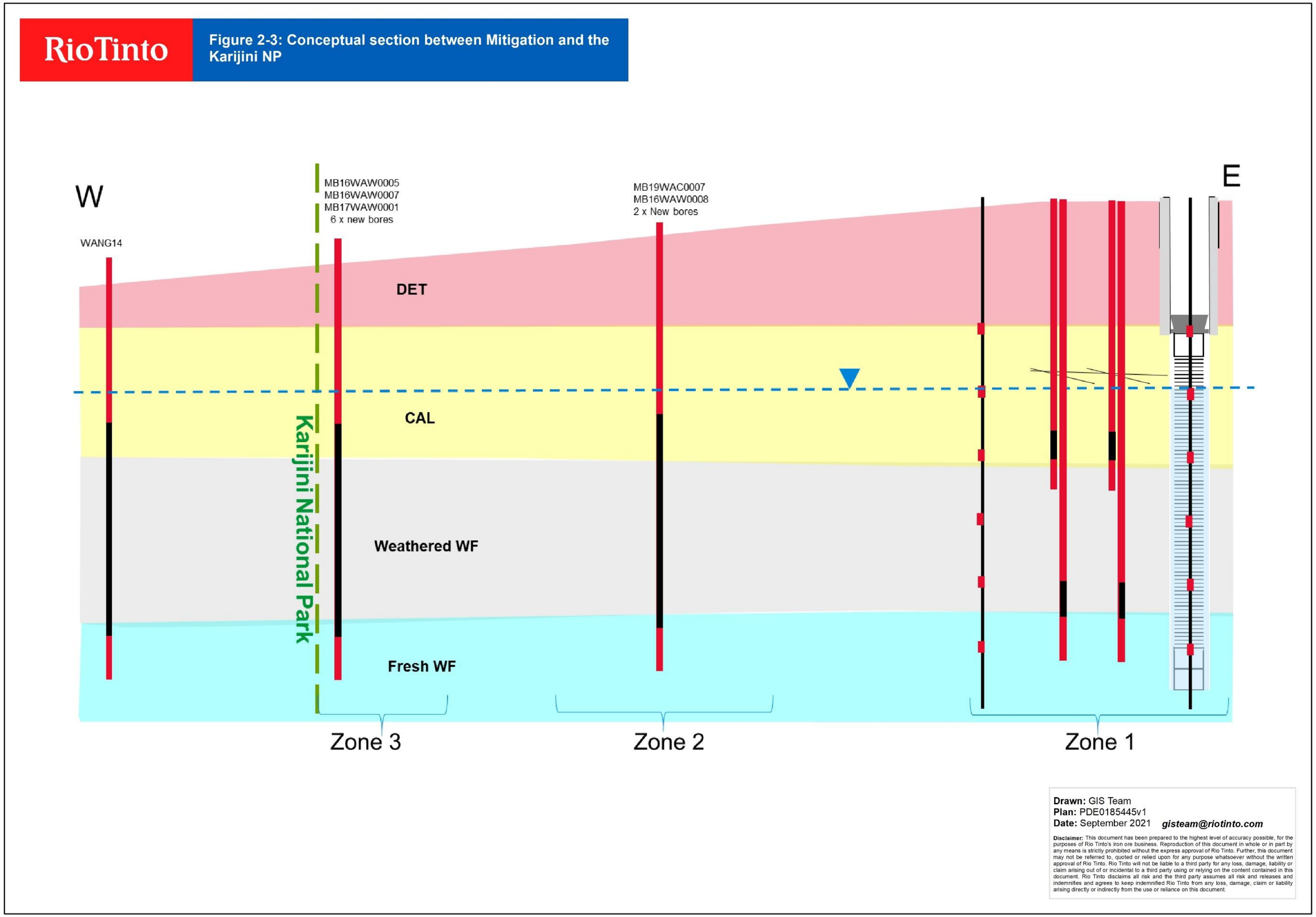


Figure 2-3: **Conceptual section between Mitigation and the Karijini NP. Zones relate to observation/ trigger zones**

2.1 Reporting

MS 1113

Any exceedance of threshold criteria specified in this Groundwater EMP will be reported to the CEO in writing within seven (7) days of the exceedance being identified (Condition 6-4(1)).

For each calendar year, during the operational phase, monitoring results will be reported against associated trigger and threshold criteria and objectives in the Annual Compliance Assessment Report (ACAR) for the Project. The ACAR will include a summary of quarterly monitoring results for the period as specified in Table 2-1, Table 2-2 and Table 2-3 against trigger and threshold criteria to demonstrate Condition 6-1 has been met during the reporting period. A summary of compliance against triggers and thresholds for the reporting period will be reported in the ACAR as shown in Table 2-5.

Monitoring results will be presented with trigger and threshold criteria indicated. Graphs (where appropriate) will include results of previous monitoring periods and include an assessment of current and historic monitoring results to allow adaptive management. A description of the effectiveness of any management contingency actions that have been implemented to manage the impact will be included in the ACAR (Condition 6-2(6)).

DN 2018/8299

Compliance against the conditions of DN 2018/8299 will be reported annually in the Annual Compliance Report as required by Condition 19 of DN 2018/8299. Monitoring data recorded through implementation of provisions stated in Table 2-1, Table 2-2 and Table 2-3 will be provided in graph format along with a written assessment of:

- Function and adequacy of Grey Box modelling and any updates to the model throughout the monitoring period.
- Groundwater levels and quality in relation to Grey Box modelling and triggers and thresholds.
- Groundwater level and quality trends over the reporting period and historically.
- Assessment of any potential future trends or issues and amendments to modelling, triggers and thresholds, or monitoring.
- Summary of groundwater impacts and compliance.

For conditions related to this Groundwater EMP, the information to be reported as part of annual compliance reporting is shown in Table 2-6. In the event that trigger and threshold criteria are exceeded, the Proponent will notify DAWE within five (5) business days of becoming aware of the exceedance and any further reporting will be provided as per response actions for triggers and thresholds as specified in Table 2-1, Table 2-2 and Table 2-3.

In the event of an incident, non-compliance against the conditions of DN 2018/8299, or non-compliance with the commitments made in plans, the DAWE will be notified in writing as soon as practicable, and no later than two (2) business days of the non-compliance being known. The Commonwealth Department will also be provided with details of the non-compliance as required by Condition 20 of DN 2018/8299 as soon as practicable, and no later than ten (10) business days of the non-compliance being known.

Table 2-5: West Angelas Revised Proposal Groundwater EMP Reporting Table for MS 1113

EPA Key environmental factors: Inland waters – Karijini NP Groundwater Level	
Condition 6-1(1) – Ensure that there is no drawdown of groundwater associated with the proposal at the boundary of, or within, Karijini National Park	**Reporting periods 1 January-31 December**
Objective-based Provisions	
Management Targets	**MS 1113 Status report:** Target achieved Target not achieved
1. **Target 1**: Water levels in bores to the south and north of the MAR scheme in areas outside of the regional aquifer are above or equal to rolling 3 year, seasonally adjusted water levels (mbgl). 2. **Target 2:** Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 3 year, seasonally adjusted water levels (mbgl). 3. **Target 3:** Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 5 year, seasonally adjusted water levels (mbgl). 4. **Target 4:** Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 10 year, seasonally adjusted water levels (mbgl).	
Outcome-based Provisions (Triggers and Thresholds)	
Early Response Indicators	**MS 1113 Status report:** Early Response Indicator not reached Early Response Indicator reached
1. **Early Response Indicator 1:** Injection bores non-operational outside of proposed plan for operation of the MAR scheme (more than 1 of a paired set of bores inoperable for more than 1 week). 2. **Early Response Indicator 2:** Two consecutive monitoring periods of drawdown 25 cm greater than Grey Box level for modelled mitigation scenario in Zone 2 monitoring bores.	
Trigger Criteria	**MS 1113 Status report:** Trigger criteria not exceeded Trigger criteria exceeded
3. **Trigger Level 1:** Two consecutive monitoring periods of drawdown 50 cm greater than Grey Box level for modelled mitigation scenario in Zone 2 monitoring bores. 4. **Trigger Level 2:** Two consecutive monitoring periods of drawdown associated with the proposal of 10 cm or greater than the Grey Box level for modelled mitigation scenario in Zone 3 monitoring bores.	
Threshold criteria:	**MS 1113 Status report:** Threshold criteria not exceeded Threshold criteria exceeded

EPA Key environmental factors: Inland waters – Karijini NP Groundwater Level	
Condition 6-1(1) – Ensure that there is no drawdown of groundwater associated with the proposal at the boundary of, or within, Karijini National Park	**Reporting periods 1 January-31 December**
5. **Threshold Criteria**: Two consecutive monitoring periods of drawdown associated with the proposal of 20 cm or greater than Grey Box level for modelled mitigation scenario in Zone 3 monitoring bores.	

Table 2-6: West Angelas Revised Proposal Groundwater EMP Reporting Table for DN 2018/8299

Key environmental values: Karijini NP Groundwater Level	
Condition 3(a) - Ensure that there is no drawdown of groundwater associated with the action at the boundary of, or within, Karijini National Park	**Reporting periods 1 January-31 December**
Objective-based Provisions	
Management Targets	**DN 2018/8299 Status report:** Target achieved Target not achieved
1. **Target 1**: Water levels in bores to the south and north of the MAR scheme in areas outside of the regional aquifer are above or equal to rolling 3 year, seasonally adjusted water levels (mbgl). 2. **Target 2:** Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 3 year, seasonally adjusted water levels (mbgl). 3. **Target 3:** Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 5 year, seasonally adjusted water levels (mbgl). 4. **Target 4:** Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 10 year, seasonally adjusted water levels (mbgl).	
Outcome-based Provisions (Triggers and Thresholds)	
Early Response Indicators	**DN 2018/8299 Status report:** Early Response Indicator not reached Early Response Indicator reached
1. **Early Response Indicator 1:** Injection bores non-operational outside of proposed plan for operation of the MAR scheme (more than 1 of a paired set of bores inoperable for more than 1 week). 2. **Early Response Indicator 2:** Two consecutive monitoring periods of drawdown 25 cm greater than Grey Box level for modelled mitigation scenario in Zone 2 monitoring bores.	
Trigger Criteria	**DN 2018/8299 Status report:** Trigger criteria not exceeded Trigger criteria exceeded
3. **Trigger Level 1:** Two consecutive monitoring periods of drawdown 50 cm greater than Grey Box level for modelled mitigation scenario in Zone 2 monitoring bores. 4. **Trigger Level 2:** Two consecutive monitoring periods of drawdown associated with the proposal of 10 cm or greater than the Grey Box level for modelled mitigation scenario in Zone 3 monitoring bores.	
Threshold criteria:	**DN 2018/8299 Status report:** Threshold criteria not exceeded Threshold criteria exceeded

5. **Threshold Criteria**: Two consecutive monitoring periods of drawdown associated with the proposal of 20 cm or greater than Grey Box level for modelled mitigation scenario in Zone 3 monitoring bores.	
Key environmental Value: Karijini NP Groundwater Quality	
<u>Condition</u> 3(b) - no change in groundwater water quality associated with the action at the boundary of, or within, Karijini National Park.	**Reporting periods 1 January-31 December**
<u>Early Response Indicators</u>	**DN 2018/8299 Status report:** Early Response Indicator not reached Early Response Indicator reached
Early Response Indicator: 1. Long term pH trend in Zone 2 monitoring bores over two consecutive monitoring periods is not consistent with trend in control bore. or 2. Proportional change in EC in Zone 2 monitoring bores is greater than 20% of proportional change in control bore EC over two consecutive monitoring periods.	
<u>Trigger Criteria</u>	**DN 2018/8299 Status report:** Trigger criteria not exceeded Trigger criteria exceeded
Trigger Criteria Level 1: 3. Long term pH in Zone 2 monitoring bores is not between 6.5 and 8 for two consecutive monitoring periods and trend is not consistent with trend in control bore and is associated with the action. or 4. Proportional change in EC in Zone 2 monitoring bores is greater than 50% of proportional change in control bore EC over two consecutive monitoring periods and is associated with the action.	
<u>Threshold Criteria</u>	**DN 2018/8299 Status report:** Threshold criteria not exceeded Threshold criteria exceeded
Threshold Criteria: 7. Long term pH in Zone 3 monitoring bores is not between 6 and 8.5 for two consecutive monitoring periods and trend is not consistent with trend in control bore pH and is associated with the action. or 8. Proportional change in EC in Zone 3 monitoring bores is greater than 80% of proportional change in control bore EC over two consecutive monitoring periods and is associated with the action.	

3. ADAPTIVE MANAGEMENT AND REVIEW OF THIS EMP

The conceptual framework for the development of Rio Tinto Environmental Management Plans provides details of the review and adaptive management process (Appendix 1). The approach will include evaluation of:

- Monitoring data and comparison to baseline and reference site data on a regular basis to verify responses to potential impacts.
- The effectiveness and relevance of trigger and threshold criteria and contingency actions against environmental objectives, on an annual basis, to determine if any changes to the criteria, monitoring or response actions are required.
- The effectiveness and relevance of management actions and targets against environmental objectives, on an annual basis, to determine if any changes to actions, targets or monitoring are required.

Based on the results of the review process the Proponent will update and adjust the management measures and strategies in consultation with DWER (Table 3-1). No changes to early response indicators, triggers, thresholds or management actions will be implemented without prior consultation with and approval by DWER and DAWE.

This Groundwater EMP will be updated with the necessary monitoring, outcome modelling and reporting for all phases of the proposed MAR scheme. Updates to this Groundwater EMP will be approved as required as specified in Condition 6-2 of MS 1113 and Condition 4 of DN 2018/8299. The updated Groundwater EMP will be implemented in accordance with Condition 6-3(1) of MS 1113.

Groundwater management and monitoring will continue until it can be demonstrated that the outcomes specified at Condition 3 of DN 2018/8299 can be met without active management as required by Condition 7 of DN 2018/8299. The Proponent will consult with DWER and DAWE prior to amending or ceasing groundwater management and/or monitoring to develop a plan to demonstrate that outcomes specified in Condition 3 of DN 2018/8299 and Condition 6-1(1) of MS 1113 can be achieved without active management.

Table 3-1: Changes to the West Angelas Revised Proposal Groundwater EMP

Complexity of Changes	**Minor Revisions** ☐		**Moderate Revisions** ☐	**Major Revisions** ☐
Number of Key Environmental Factors		**One** ☐	**2 – 3** ☐	**> 3** ☐
Date Revision submitted to EPA and DAWE: DD/MM/YYYY				
Proponent's operational requirement timeframe for approval of revision **Reason for Timeframe:**			**< One Month** ☐ **< Six Months** ☐	**> Six Months** ☐ **None** ☐
Item No.	**EMP Section No.**	**EMP Page No.**	**Summary of Change**	**Reason for Change**

4. STAKEHOLDER CONSULTATION

Consistent with the DAWE and DWER expectations for this Groundwater EMP to align with the principles of EIA, the Proponent has consulted with stakeholders, including but not limited to the Department of Biodiversity, Conservation and Attraction - Park and Wildlife Service, the DWER EPA Services, and DAWE during the development of this Groundwater EMP.

The Proponent has consulted with the Yinhawangka Traditional Owners, on whose country the MAR scheme will operate. The Proponent is committed to continued engagement with the Yinhawangka Traditional Owners regarding the development and implementation of this Groundwater EMP.

A summary of stakeholder consultation with respect to this Groundwater EMP is provided in Table 4-1.

Table 4-1: Stakeholder Consultation

Stakeholder	Date	Purpose of Contact	Comments Raised	Resolution Comments
DWER-EPA, DWER-Water, DBCA, DAWE	27th May 2020	Briefing to provide overview of the conditions, MAR, EMP development and timing.	Queries with regards to MAR project, key points: • Water quality appears to be very good, how will this affect triggers and thresholds? • Modelling approach; single layer was used and did not consider indirect recharge. • Rainfall levels have changed since 1970's how has this been considered? • Number of aquifers being interacted with?	Response: • Water quality is good, some analytes only have trace concentrations so % change may not apply. Water quality inside KNP is likely to be more of an end member that is the product of evapotranspiration, while water in the deposits (source) and water near the MAR scheme (receiving) is likely to be the product of flow and infiltration processes which means it's quite similar. • A multi-layer model has been developed to support the development of the MAR scheme. • Recent rainfall levels have been used in modelling and will continue to be amended to include more recent knowledge. • Effectively only one aquifer present.
DWER-EPA, DWER-Water, DBCA, DAWE	19th August 2020	Briefing to provide hydrogeology background relevant to the EMP.	Queries with regards to hydrogeological setting, key points: • Hydrogeological setting including presence of different formations within the project area. • Presence of dykes before and after mining. • Hydraulic connections and further monitoring.	Response: • Further information supplied in response to queries regarding hydrogeological setting. • An overview of additional/future monitoring was provided.
DWER-EPA, DAWE	3rd November 2020	Briefing to present modelling inputs	Queries with regards to model and triggers, key points: • Will mean be presented in model outputs? • Will triggers be provided for each associated aquifer or specific to bores? • Will control bores be included in monitoring network?	Response: • All model simulations will be presented. • All units are connected, triggers and thresholds will be related to the aquifer system and bore specific. • Control bores will be included in monitoring network.
DWER-EPA, DWER-Water, DBCA, DAWE	23rd November 2020	Briefing to present modelling outputs and propose trigger and threshold criteria.	Queries with regards to model and monitoring, key points: • Linear regression was used but not adequate? • Has Grey Box modelling been used in similar scenarios? Will it be updated regularly? • Include justification for triggers and thresholds in Groundwater EMP.	Response: • Linear regression used initially to simulate climate variability on groundwater levels but has been replaced by grey box model. • Not that the proponent is specifically aware of, data driven models such as the Grey Box modelling are widely used in hydrological applications. Modelling will be checked for accuracy every three months and updated required.
DAWE, DWER and DBCA	20th April 2021 (DAWE), 8th June 2021 (DWER, DBCA)	Comments on draft Groundwater EMP received.	Comments as specified in correspondence.	Groundwater EMP amended as determined appropriate. Response sent to DAWE and DWER 5 October 2021.

DAWE, DWER and DBCA	24th November 2021 (DAWE), 27th January 2022 (DWER, DBCA)	Comments on draft Groundwater EMP received.	Comments as specified in correspondence.	Groundwater EMP amended as determined appropriate. Response sent to DAWE and DWER 9 February 2022.

5. REFERENCES

ANZECC & ARMCANZ 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Governments and Australian state and territory governments, Canberra ACT, Australia.

Australian Government 2014, Environmental Management Plan Guidelines, Department of the Environment, Canberra

CSIRO 2015 Pilbara Water Resource Assessment: past, present and future hydroclimate. An overview report to the Government of Western Australia and industry partners from the CSIRO Pilbara Water Resource Assessment. CSIRO Land and Water, Australia

Environmental Protection Authority (EPA) 2016, Environmental Impact Assessment (Part IV Divisions 1 and 2) Administrative Procedures 2016, Western Australian Government Gazette No. 223.

Environmental Protection Authority (EPA) 2018a, Instructions on how to prepare Environmental Protection Act 1986 Part IV Environmental Management Plans, Environmental Protection Authority, Perth.

Environmental Protection Authority (EPA) 2018b, Environmental Impact Assessment (Part IV Divisions 1 and 2) Procedures Manual, Environmental Protection Authority, Perth.

IGS 2021. West Angelas groundwater modelling to support MAR design and operation.

Final Report. 16th December 2020. Unpublished report prepared for Rio Tinto Iron Ore, Perth

Layton Consultants, 1978. West Angelas Project – Stage 2 Groundwater Exploration. Unpublished report prepared for Cliffs International Inc, Perth.

Rio Tinto 2016. Deposit C and D 2016 Field Programme Report (Internal Report).

Rio Tinto 2017. Deposit C and D 2017 Field Programme Report (Internal Report).

Rio Tinto 2019 West Angelas 2019 Hydrogeological Field Programme Factual Report: Sustaining Capital, Implementation Phase and Managed Aquifer Recharge Field Trial (Internal)

Rio Tinto 2020. Deposit CD 2020 Managed Aquifer Recharge Basis of Design. 30 April 2020. RTIO-PDE-0175509.

6. APPENDICES

Appendix 1: Conceptual Framework for the Development of Rio Tinto Environmental Management Plans

For the development of Environmental Management Plans (EMPs), a conceptual framework model has been applied. The framework ensures linkages between current understanding, potential impacts, outcomes, adaptive management, and consistent monitoring and management practices. The framework is a stepwise process that considers the environmental values as identified in the Proposal's Environmental Impact Assessment Documents, in order to implement appropriate management measures and actions to ensure the environmental objective can be achieved.

The first step of the framework examines in detail the current knowledge of the environmental value(s) associated with the Proposal. This is compiled from information provided in the EIA documents, any additional environmental surveys and examined with input from internal experts. Environmental values associated with the Proposal are evaluated based on their conservation status at local, state and regional levels.

The second step of the framework is to define relevant indicators, level of management and type of provisions (outcome vs management-based) and associated criteria and/or targets.

A source-pathway receptor (SPR) conceptual modelling approach is used to inform the selection of indicators, as recommended by national and international guidance (DIIS 2016). The SPR conceptual model sets out the collective knowledge, experience and perspective on the environmental value (system of interest) and illustrates assumptions about how the value (system) functions and what is believed to be the important or dominant processes and their linkages. This includes factors that are perceived to be driving changes in the value (system) and the consequences of changes in these factors. The conceptual model also includes factors such as spatial boundaries as well as temporal and seasonal variations.

The number and type of indicators selected to monitor and measure changes in individual environmental values will depend on several factors including; the conservation status of the environmental value; the level of management required; the environmental outcome or objectives; location; and the types of pressures and stressors identified.

The required level of management (Low, Moderate or High) is determined using an matrix assessment with four factors relating to predicted impacts from the Proposal including: likelihood; consequence; spatial extent; and temporal duration (Table A 1). The higher the level of management, the more lines of evidence may be deemed necessary to meet the environmental outcome or objective (that is more indicators and / or more frequent monitoring schedules).

Draft (interim) trigger and threshold criteria and/or draft management targets will be determined for each environmental value. Early response criteria (if appropriate) may be defined for indicators for the environmental value (e.g. groundwater depth) or the environmental value itself (e.g. vegetation status). Trigger and threshold criteria will directly relate to the environmental value and objective itself.

The number of trigger criteria, and the sensitivity of both trigger and threshold criteria, will be determined by the associated management level for the environmental value.

The third step of the framework is to undertake an evaluation of the baseline and/ or current data to assess against criteria and determine whether the environmental outcome or objectives are likely to be met with existing proposed indicators. This step should also occur as part of reporting requirements when criteria are exceeded. Where criteria are not being met the adaptive management process should be implemented.

The fourth step of the framework is to implement the EMP. To ensure successful implementation, relevant internal and external (regulatory) stakeholders are consulted to ensure the EMP meets management expectations, and can be implemented for the associated Proposal.

The fifth, final step of the framework considers a revision of or alternatives of management objectives, indicators and/ or criteria. This step is considered where monitoring and assessment indicates objectives are not being met. Where data suggests that objectives cannot be met using current associated indicators and criteria, repeat the second to fifth step of the framework, with consideration of the additional information gained through monitoring.

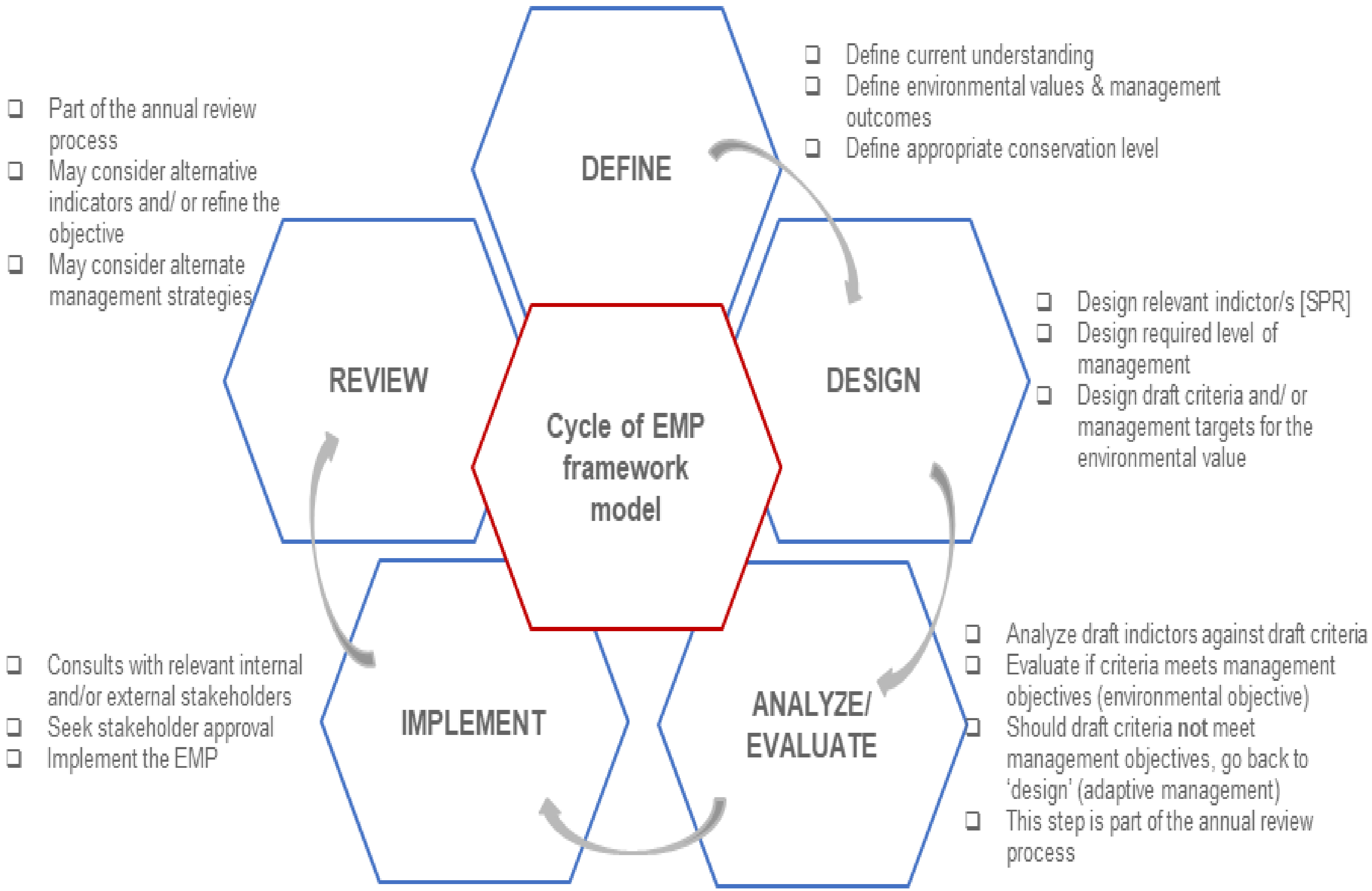


Figure A 1: Cycle of the conceptual Environmental Management Plan framework model

Table A 1: Management level assessment matrix

Factor	Level of required management (increasing to right)				
Likelihood	Rare	Unlikely	Possible	Likely	Almost Certain
Consequence	Environmental values (species, communities /ecosystems) with no formal recognition for conservation purposes	Environmental values (species, communities /ecosystems) with no formal recognition for conservation purposes but may hold local environmental significance	Environmental values (species, communities /ecosystems) recognised as being of conservation interest	Environmental values (species, communities /ecosystems) directly protected under State and Commonwealth legislation	Environmental values (species, communities /ecosystems) directly protected under State and Commonwealth legislation (with potential severe consequence).
Extent	Immediate	Surrounds	Local	Catchment	Sub-regional
Duration	Days	Months	Years	Decades	Centuries

- The factors act independently of one another, and an increased risk of one factor will not necessarily result in other factors with higher risk.
- Level/s of management gives an indication of potential importance, however important to note that regulatory focus, cumulative impact and heritage values may impact the way the environmental values are treated/ managed.

Reference

DIIS (2016). Leading Practice Sustainable Development Program for the Mining Industry - Preventing Acid and Metalliferous Drainage Handbook Department of Industry, Innovation and Science (DIIS), Canberra, Australia.

Appendix 2: Summary of assessment for required management zone

The environmental value, described in Section 1.4, was assigned a level of management based on the matrix level assessment (Appendix 1, Step 2). A summary of the assessment for the Project, which takes into account information provided in 1 and Table 1-5 is provided in the table below along with the resulting management zone for the environmental value relevant to this Groundwater EMP. The assessment considers all impacts collectively (direct, indirect) and assigns against the highest level of management zone.

Table A-2: Summary of assessment for assignment of management zone.

Environmental Value	Predicted and potential impact/s	Assessment				Management Zone
		Likelihood	Consequence	Extent	Duration	
Inland Waters						
Karijini National Park	**Indirect**: potential for changes to groundwater level and groundwater quality at the boundary of, and within, Karijini National Park as a result of dewatering associated with the Project.	**Unlikely** Unmitigated dewatering of the western end of Deposit C and Deposit D will result in groundwater drawdown extending west to Karijini National Park (Rio Tino, 2018). An initial 2019 Phase 1 MAR drilling programme and injection trial (Dec 2019 to Feb 2020) has proven that MAR using reinjection bores is practicable in the Phase 1 area, and is expected to mitigate impacts from dewatering.	**Major** Potential impact on values within a National Park.	**Catchment** The Project (including Deposit C and D) are located in the Turee Creek catchment. Deposits C and D lie within a connected groundwater system, with the aquifer extending inside Karijini National Park (Rio Tino, 2018).	**Centuries** Numerical groundwater modelling conservatively assumes that the drawdown of the groundwater beneath Karijini National Park will recover but not to initial conditions within 100 years (Rio Tinto, 2018).	HIGH

Appendix 3: West Angelas Groundwater Modelling Report (IGS 2021).

West Angelas Groundwater Modelling to Support MAR Design and Operation – Summary to Support Groundwater Environmental Management Plan

A report prepared for Rio Tinto Iron Ore

8 February 2022

West Angelas Groundwater Modelling to Support MAR Design and Operation – Summary to Support Groundwater Environmental Management Plan

A report prepared for Rio Tinto Iron Ore

by

Innovative Groundwater Solutions

8 February 2022

Document control

Version	Date Issued	Author	Reviewed by	Date Approved	Revision Required
1.3	14th Dec 2020	T. Laattoe N. Harrington	G. Harrington	14th Dec 2020	Minor
Final	16th Dec 2020	T. Laattoe N. Harrington	RTIO	5th Feb 2021	Minor.
					Revision to suit inclusion in EMP.

Distribution

Date	Version	Issued To
16th Dec 2020	Final	R. Milton, I. Dionne (RTIO)
10th Feb 2021	Revised Final Report	R. Milton, I. Dionne (RTIO)
10th Feb 2021	Summary to Support EMP	R. Milton, I. Dionne (RTIO)

ACKNOWLEDGEMENTS

IGS is very grateful to Rob Milton, Albert Bai, Tom Tugwell-Wotton and Emma McGivern for data provision, conceptual insight and feedback on this work.

Cover photo: Rob Milton

SUGGESTED CITATION

IGS. (2021). West Angelas Groundwater modelling to Support MAR Design and Operation – Summary to Support Groundwater Environmental Management Plan. 10th February 2021.

DISCLAIMER

This report is solely for the use of Rio Tinto Iron Ore and may not contain sufficient information for purposes of other parties or for other uses. Any reliance on this report by third parties shall be at such parties' sole risk.

The information in this report is considered to be accurate with respect to information provided and conditions encountered at the site at the time of investigation. IGS has used the methodology and sources of information outlined within this report and have made no independent verification of this information beyond the agreed scope of works. IGS assumes no responsibility for any inaccuracies or omissions. No indications were found during our investigations that the information provided to IGS was false.

Innovative Groundwater Solutions Pty Ltd.
PO Box 2123, Victor Harbor SA 5211
Phone: 0458 636 988
ABN: 17 164 365 495 ACN: 164 365 495
Web: www.innovativegroundwater.com.au
Email: glenn@innovativegroundwater.com.au

CONTENTS

1. Introduction **1**

2. Project Approach **3**

3. Conceptual Hydrogeological Model **1**

3.1. Site Description 1

3.2. Regional Geology 3

3.3. Regional Hydrogeology 6

3.4. Local Hydrostratigraphy 6

3.5. Groundwater Levels and Flow 6

3.6. Aquifer Properties 20

3.7. Recharge and Evapotranspiration 24

3.8. Managed Aquifer Recharge 24

4. Regional Groundwater Flow Model Design and Calibration **25**

4.1.1. Modelling Platform, Domain and Grid 25

4.1.2. Model Boundaries 26

4.1.3. Recharge and Evapotranspiration 26

4.1.4. Aquifer Properties 27

4.2. Steady-State Calibration 27

4.2.1. Calibration Methodology 27

4.2.2. Results 29

4.3. Transient calibration using MAR trial data 34

4.3.1. Calibration Methodology 34

4.3.2. Results 34

4.4. Conditioning an Ensemble Using Steady-State and MAR Trial Data 40

5. Transient Simulation of Unmitigated Drawdown: Dewatering of Pit D1 **45**

6. Optimization of MAR Injection Rates **53**

6.1. Methodology 53

6.2. Results 54

6.3. Discussion 59

7. Preliminary Risk Assessment for Contaminant Transport to Karijini National Park **59**

7.1. Methodology 59

7.2. Results 60

7.3. Discussion 65

8. Hydrograph Analysis and Grey Box Modelling to Support Trigger Development and Assessment **66**

8.1. Observed Historical Ranges of Water Level Declines 66
8.2. Historical Ranges of Hydraulic Gradients 67
8.3. Grey Box Modelling to Assess Mine Contributions to Hydraulic Head Declines or Increased Hydraulic Gradients 67
8.3.1. Overview 67
8.3.2. Methodology 67
8.4. Results 70
8.5. Discussion 71

9. Summary and Conclusions 72

10. Limitations 74

References 75

1. Introduction

Dewatering of deposits C and D at Rio Tinto Iron Ore's (RTIOs) West Angelas mining operations (Figure 4) is planned to allow below water table mining of these deposits.

The cone of water table depression caused by dewatering in deposits C and D is predicted to reach the boundary of Karijini National Park (KNP) and RTIO propose to mitigate this impact using a Managed Aquifer Recharge (MAR) Scheme installed between the mine pits and the KNP boundary.

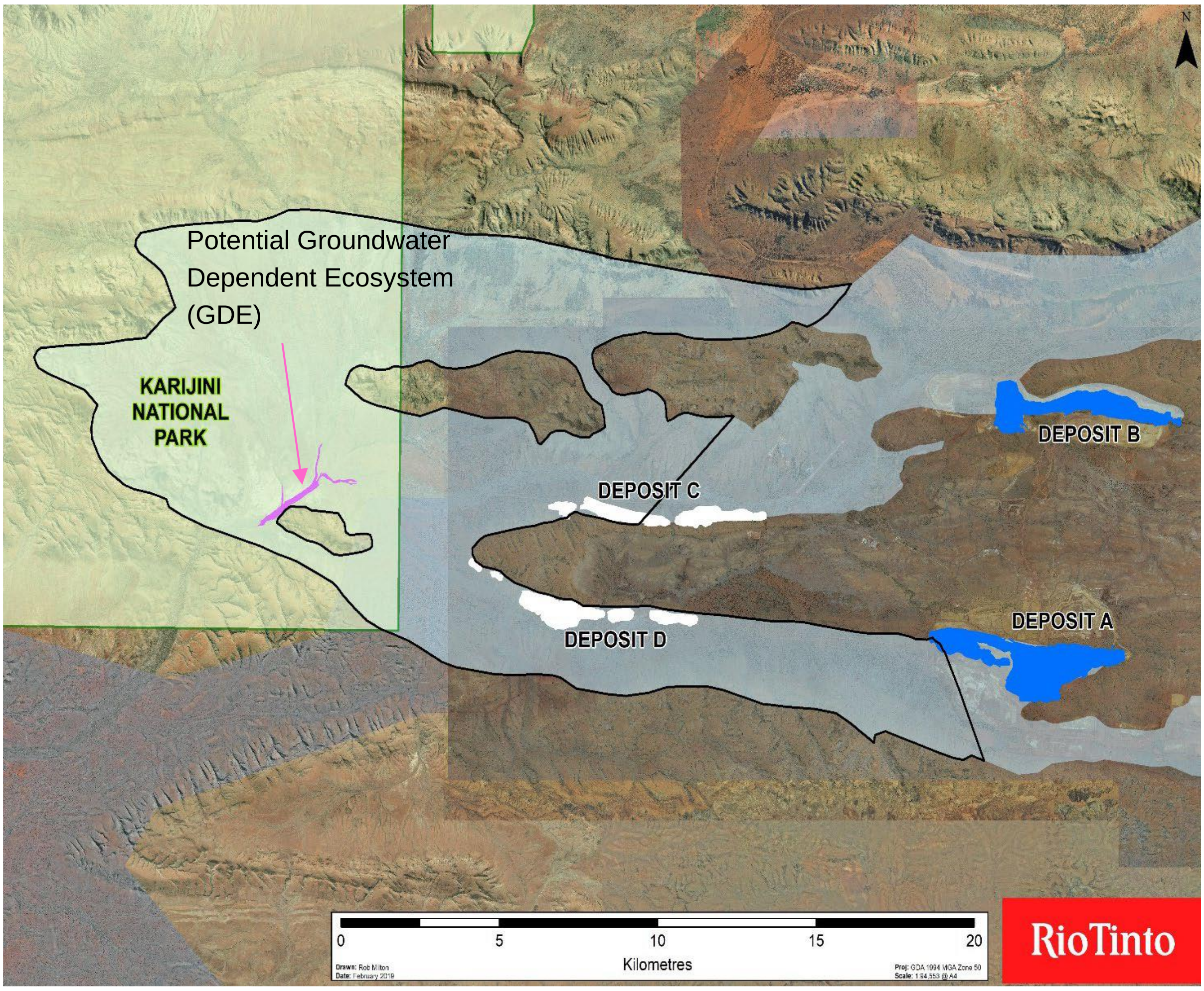


Figure 4. Locations of West Angelas deposits A, B, C and D relative to the boundary of Karijini National Park. The groundwater domain for deposits C and D is delineated by the thick black line. This is separated from deposits A and B by dykes, which form barriers to groundwater flow. Source: RTIO (2019).

Innovative Groundwater Solutions Pty Ltd (IGS) was contracted by RTIO to undertake groundwater flow modelling to simulate drawdown impacts from the dewatering of deposit D1, and to inform the optimization of the proposed MAR scheme to mitigate these impacts. The receptor for drawdown impacts is Karijini National Park. The objective of the proposed MAR scheme is to ensure that there is zero drawdown impact at the boundary of Karijini National Park.

Furthermore, approval and operation of the proposed MAR scheme requires the identification of any potential water quality risks to Karijini National Park as a result of injection of groundwater dewatered from the mine pits. An understanding of these risks is also required to provide a basis for establishing regulatory water quality triggers.

The heterogeneous nature of any groundwater system, and the general deficiencies in field data sets available to characterize them, mean that all groundwater models carry uncertainty. In addressing the above requirements, predictions of unmitigated and mitigated drawdown, optimization of the MAR scheme and predictions of water quality impacts must account for this uncertainty.

Finally, a methodology is required to account for the effects of natural climate variability on groundwater levels in both the operation of the MAR scheme and setting and assessing regulatory water level triggers. The MAR scheme is required to mitigate mine-related impacts only. As there is insufficient information available on recharge processes and rates for the West Angelas area to allow for the incorporation of climate variability in a regional groundwater model, a robust and defensible methodology is required to untangle mine-related impacts from natural climate effects.

Based on the above requirements, the objectives of the modelling project were therefore to:

1. Inform the design of the proposed MAR scheme to mitigate drawdown impacts from dewatering of deposit D1. That is, determine the optimum injection rates for the planned MAR bores.
2. Inform the development of operational and management groundwater level triggers.
3. Determine the risk of MAR injectant reaching the KNP boundary.
4. Account for uncertainty in the hydrogeological conceptual model in 1-3 above.
5. Identify the best locations for water quality triggers and areas outside the zone of influence that can be used to collect baseline water quality information.
6. Support the H3 Hydrogeological Assessment and Environmental Management Plan currently being prepared by RTIO.

A final project report, containing all background information and datasets required for internal review, and to support ongoing studies by RTIO was delivered on 16th December 2020. Minor revisions were made in response to RTIO's comments, with the final version of that report delivered on 10th February 2021 (IGS, 2020a). The current version of the report has undergone further minor modifications to make it suitable for inclusion as an appendix in the Groundwater Environmental Management Plan.

2. Project Approach

The overall approach for this project was divided into a series of tasks, based around two stages of modelling.

The first stage of modelling utilized an analytical element model of the MAR injection trial carried out in February/March 2020 (IGS, 2020b). Calibration of this model to the transient injection trial data was used to assess local- and sub-regional-scale hydraulic properties of each aquifer unit intersected by the injection bore. The outcomes of the injection trial simulation were then used to inform the ranges in aquifer parameters adopted in the calibration of an initial regional-scale groundwater flow model (IGS, 2020b).

The second stage, which is described in this report and summarized visually in Figure 5, includes refinement of the regional model calibration, whereby the model was calibrated to both regional historical (steady-state) head data and transient data collected during the injection trial. An ensemble of models capturing the range of uncertainty in aquifer parameters was then developed and conditioned to both the steady-state and transient MAR trial data. This ensemble was used to simulate unmitigated drawdown due to dewatering of pit D1 and as a basis for an optimized injection regime with high confidence of mitigating drawdown whilst accounting for uncertainty in the model.

Particle tracking has been used with the regional groundwater flow model and optimized injection regime to provide a preliminary risk assessment for water quality impacts at the KNP boundary; that is, the likelihood of MAR injectant reaching the boundary.

Finally, a new approach has been developed to account for climate variability in the selection and assessment of operational and management water level triggers. This approach is designed for use alongside the regional model outputs in designing water level triggers. It uses historical ranges of observed water level declines and historical hydraulic gradients to determine appropriate triggers. As a next step, a Grey Box Model for the relationship between rainfall and groundwater levels is used to determine the contribution of mining to any trigger exceedances.

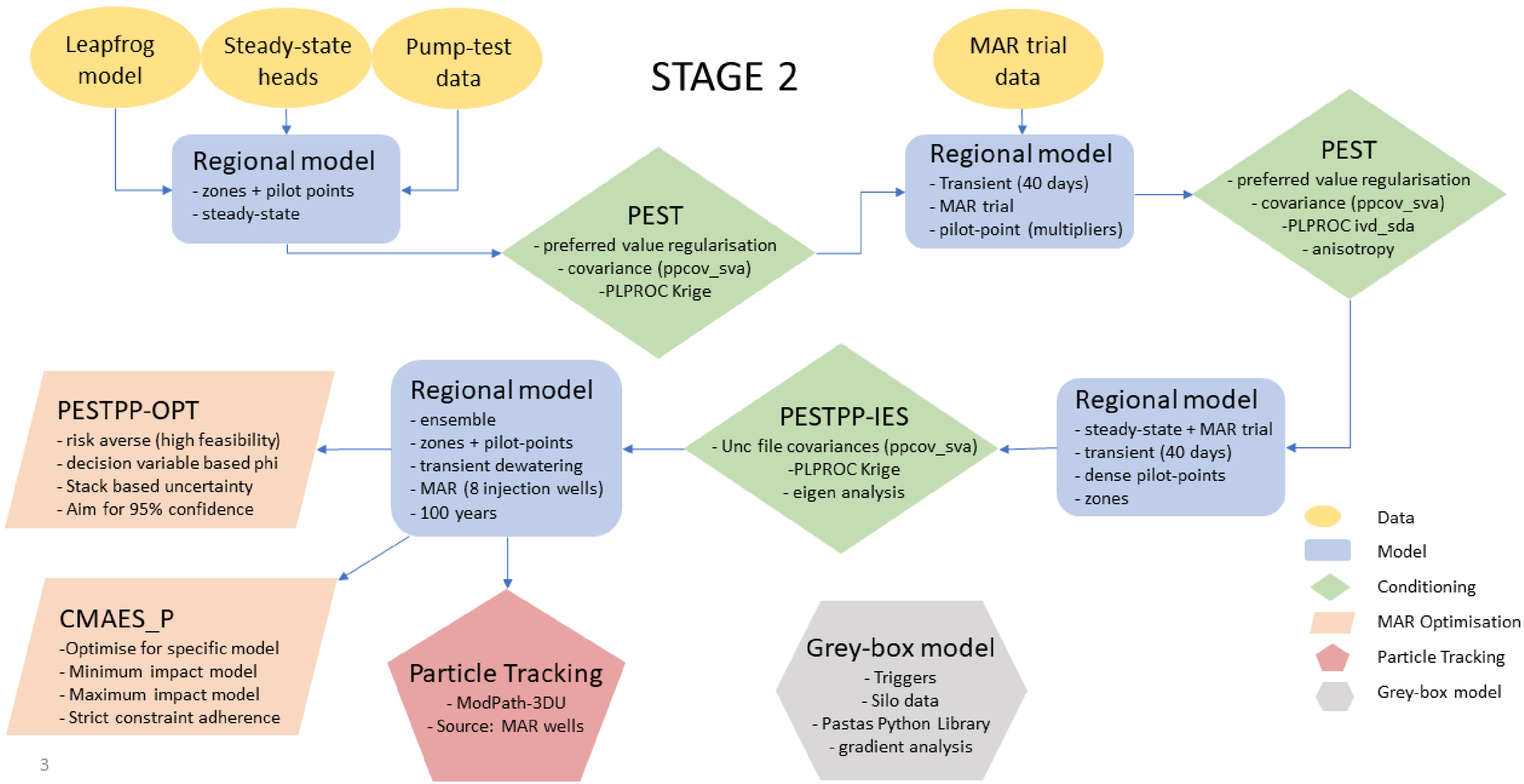


Figure 5. Flowchart showing the interactions between the modelling tasks undertaken in Stage 2 of this project and described in this report.

3. Conceptual Hydrogeological Model

3.1. Site Description

RTIO's West Angelas mining operations are located in the Pilbara region of Western Australia, and approximately 100 km west-northwest of the township of Newman. Geologically, the study area is situated in the Hamersley Basin of the central Pilbara Craton. The Hamersley Basin extends approximately 400 km inland and covers an area of more than 100,000 km^2 (Dogramaci et al., 2012). The region is characterised by a sub-tropical semi-arid to arid climate, with a mean annual rainfall of 296 mm/yr. at Paraburdoo (BoM station no. 7185) and a mean annual evaporation of 3,258 mm/yr. Rainfall is highly variable from year to year and there are prolonged periods of drought (Figure 6a). Rainfall is generally concentrated during the months of January to March, coinciding with high evaporation, although significant rainfall events can occur any time throughout the year (Figure 6b and c). Rainfall events associated with tropical cyclones and localised thunderstorm events over the summer months can be intense, producing very large runoff. The low annual rainfall coupled with high evaporation rates result in extreme water deficits and short retention times for surface water across the Pilbara region.

Surface water flows across the Hamersley Basin occur via braided, meandering flow paths across the plains and single channels in discrete valleys within the ranges. Surface flow only occurs after heavy rainfall events (Dogramaci et al., 2012). There is no permanent surface water in the study area, although ephemeral surface water drainage lines can be observed from aerial photography (Figure 7). Figure 7 also shows the location of a potential groundwater dependent ecosystem that has been identified within Karijini National Park, where a major watercourse crosses an area of shallow water tables (depth to groundwater < 5m).

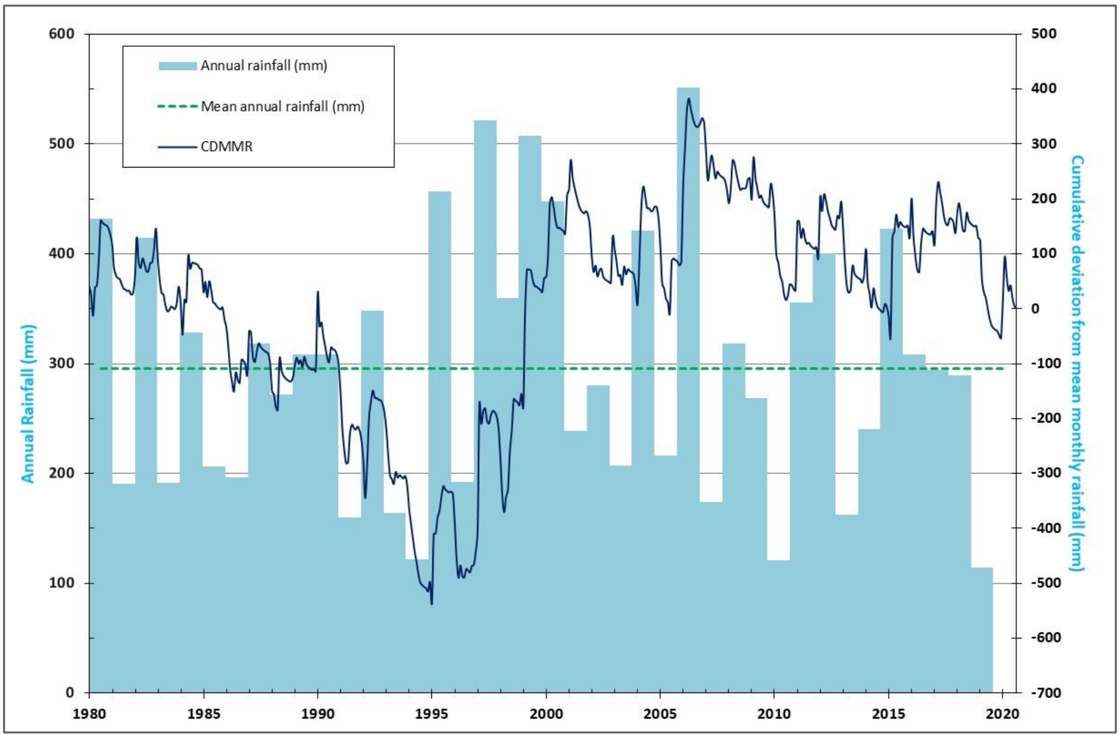


Figure 6 (a)

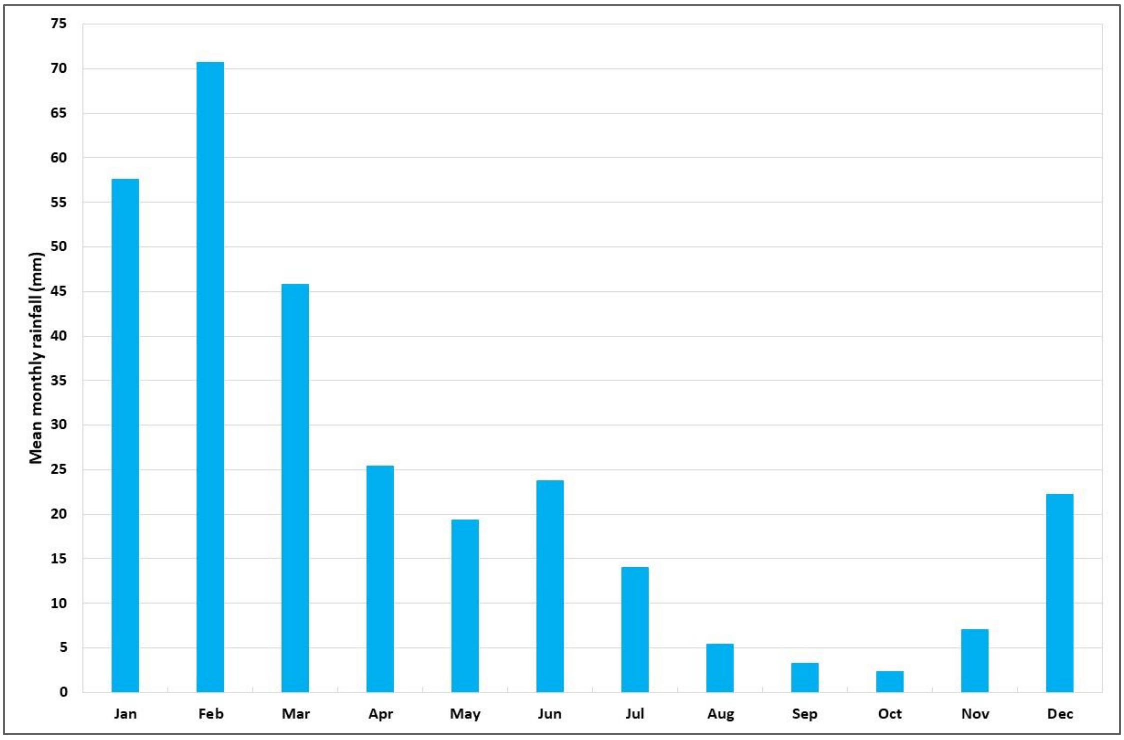


Figure 6 (b)

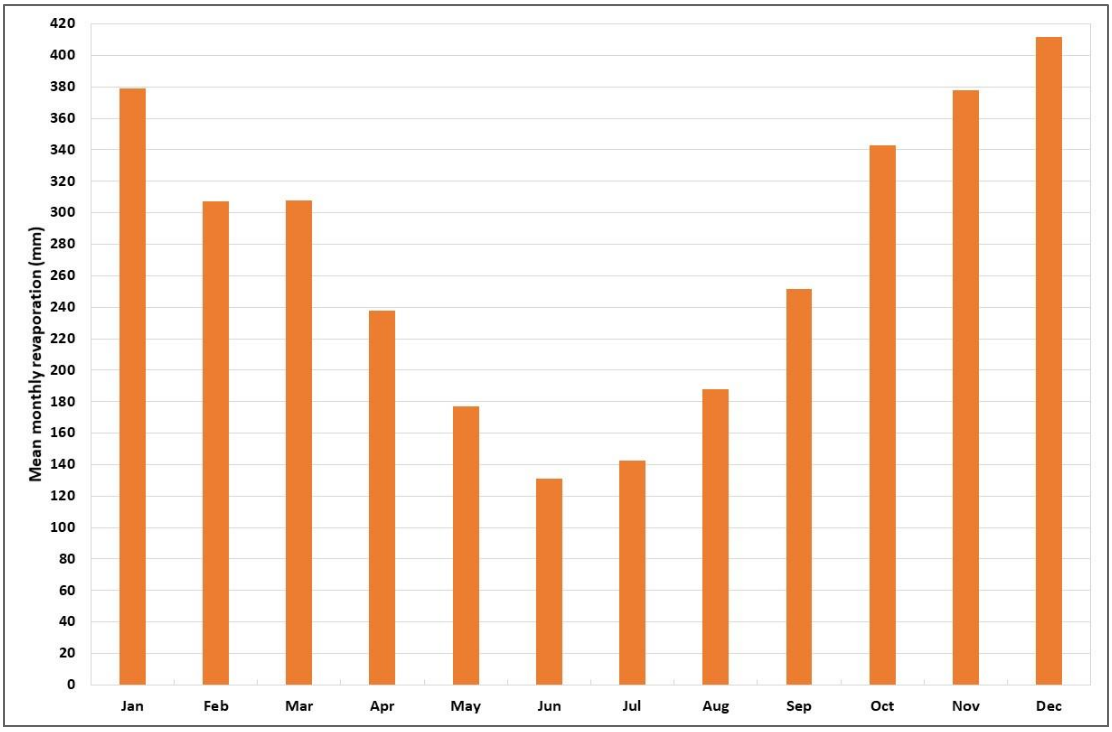


Figure 6 (c)

Figure 6. Rainfall and evaporation for the West Angelas site, obtained using Bureau of Meteorology SILO data. (a) Annual rainfall with Cumulative Deviation from Mean Monthly Rainfall (CDMMR) (b) Mean monthly rainfall (c) Mean monthly evaporation.

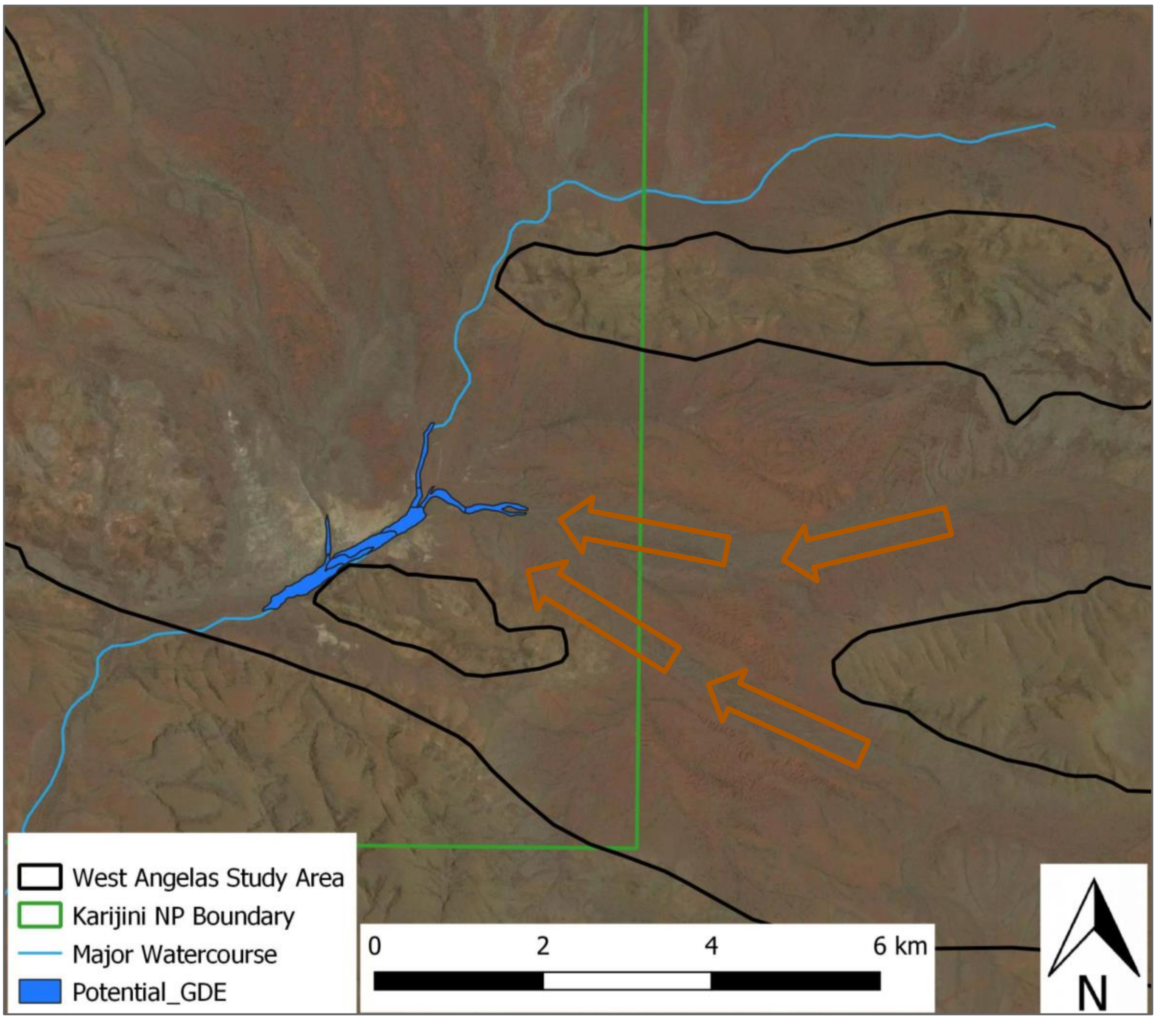


Figure 7. Aerial view of the western portion of the study area, from which surface water drainage lines can be identified, and the potential GDE with associated major watercourse. Arrows indicate locations of major surface water drainage lines identified from the aerial imagery. Minor drainage lines can also be identified from the aerial imagery. Imagery source: Mapbox Satellite v9.

Vegetation across the study area is consistent with typical vegetation for the Hamersley Basin, which comprises scattered eucalypts and *Acacia* over shrubs and hummock grassland on the rugged ridges, with mulga (*Acacia aneura*) woodlands, shrubs and *Triodia pungens* and *T. wiseanna* in the valleys. Eucalypt woodlands consisting of coolabah (*Eucalyptus victrix*), river redgums (*E. camaldulensis* subsp. *refulgens*) and *Acacia citrinoviridis* line major rivers and larger streams. *Melaleuca argentea* can be found only where permanent water exists close to the surface.

3.2. Regional Geology

The following description of the regional geology of the Hamersley Province of the Pilbara Craton is obtained from the Parsons Brinckerhoff (2013) report on the nearby Koodaideri project area. In the Hamersley Province, the Pilbara Craton is unconformably overlain by a thick sequence of late

Archean to Proterozoic (2,770–2,300 Ma) sedimentary and volcanic rocks of the Mount Bruce Supergroup (MacLeod et al. 1963, subsequently redefined by Trendall 1979).

The Mount Bruce Supergroup includes three stratigraphic units (Table 2):

- Fortescue Group (Richards & Blockley, 1984; Ardnt et al., 1991): the oldest stratigraphic unit, this is a sequence of predominantly plateau volcanic rocks up to 6 km thick that were deposited during a period of tectonic crustal extension (Arndt et al., 1991).
- Hamersley Group (MacLeod et al., 1963; Trendall & Blockley, 1990): conformably overlies the Fortescue Group and is a sequence of Banded Iron Formation approximately 2.5 km thick (James, 1954, 1983) that was deposited in a subsiding passive margin setting (Simonson et al., 1993). Four Banded Iron formations are recognised: the Marra Mamba, Brockman and Boolgeeda iron formations and the Weeli Wolli Formation. The Wittenoom Formation, a carbonate dominated sequence of sedimentary rocks, separates the Marra Mamba and Brockman iron formations.
- Turee Creek Basin Group (Krapez 1996): the youngest stratigraphic unit, this is a sequence of sediments, up to 5 km deep, deposited in a basin environment (Krapez 1996). The Turee Creek Basin conformably overlies the Hamersley Group rocks and is located close to the southern margin of the Pilbara Craton.

Table 2. Regional geological sequence of the Pilbara Craton. From Parsons Brinckerhoff (2013). After Thorne and Tyler (1997).

Age	Group	Formation	Member	Dominant lithology
Cainozoic		Alluvium		Unconsolidated silt, sand, and gravel, in drainage channels and on adjacent floodplains
		Colluvium		Unconsolidated quartz and rock fragments in soil
		Eolian deposits		Sand in sheets and longitudinal dunes
		Calcrete		Sheet carbonate; found along major drainage lines
		Alluvium and colluvium		Red brown sandy and clayey soil; on low slopes and sheetwash areas
		Lateritic deposits		Massive and pisolitic ferruginous duricrust
Proterozoic	Turee Creek Group			Pelites, sandstones and conglomerates. Quartzites, carbonates and shales.
	Hamersley Group	Brockman Iron Formation	Boolgeeda Iron Formation	BIF, shales and chert
			Woongarra Rhyolite	Lower and upper rhyolite separated by BIF, dolerite, shale
			Weeli Wolli Formation	Alternating BIF and shale with dolerite sills
			Yandicoogina Shale Member	Interbedded chert and shale
			Joffre Member	BIF with minor shale bands
			Whaleback Shale Member	Interbedded shale, chert and BIF
			Dales Gorge Member	Interbedded BIF and shale
Early Proterozoic - Achaean		Mount McRae Shale		Shale and dolomitic shale with minor thinly bedded chert
		Mount Sylvia Formation		Shale, dolomitic shale, and BIF
		Wittenoom Formation	Bee Gorge Member	Graphitic shale with minor sequences of carbonate, chert, volcaniclastic rock, and BIF
			Paraburdoo Member	Dolomite with minor amounts of chert and shale - karstic in areas
			West Angela Member	Dolomite, dolomitic shale, and chert
		Marra Mamba Iron Formation	Mount Newman Member	Chert, banded iron-formation, and shale
			MacLeod Member	BIF, cherts, carbonates and interbedded shales
			Nammuldi Member	Poddy cherty BIF, interbedded thin shales
Achaean	Fortescue Group	Jeerinah Formation	Jeerinah Formation	Shale, chert, and thin-bedded metasandstone
			Woodiana Member	Metamorphosed silicified sandstone, shale, and chert
		Maddina Formation	Maddina Basalt	Amygdaloidal metabasaltic flows and breccia
			Kuruna Member	Metamorphosed volcanic sandstone, shale, chert, and metadolomite
		Tumbiana Formation		Mafic to intermediate volcaniclastic rocks, stromatolitic carbonate rock, basalt and minor chert
		Kylena Formation		Thin to very thick, massive or amygdaloidal metabasaltic flows, minor metabasaltic breccia and metasandstone
	Shaw/Yule Granitic Complex	Granite and greenstone belt		Granodiorite, metamorphosed biotite, and monzogranite

3.3. Regional Hydrogeology

Three major aquifer systems have been identified in the Pilbara Region (Johnson and Wright, 2001):

1. Unconsolidated Sedimentary Aquifers, which are further sub-divided into:
    a. Valley Fill Aquifers, consisting of unconsolidated valley fill typically alluvium and colluvium.
    b. Calcrete Aquifers characterised by secondary porosity with karstic features. In the study area calcrete typically forms as a chemical precipitate in weathered horizons within igneous units of the Fortescue Group. The calcrete deposits coincide with existing drainage channels.
2. Pisolitic Limonite Aquifers, which can be high yielding but generally only constitute an aquifer where it occupies channels incised into basement rock developed in paleodrainage systems.
3. Fractured Rock Aquifers, which occur where secondary porosity has developed in basement rock due to fracturing, weathering or mineralisation. The regional aquifer for the Pilbara is the weathered dolomite associated with the Wittenoom Formation. However, depending on the degree of mineralisation, orebodies in the Marra Mamba Iron and Wittenoom Formations can also have good aquifer potential.

3.4. Local Hydrostratigraphy

The predominant aquifer units hosting groundwater resources at West Angelas comprise, from oldest to youngest (Figure 8):

- Marra Mamba Formation: MacLeod and Mount Newman Members
- Wittenoom Formation: West Angela Member
- Detritals: alluvium and colluvium
- Calcrete: this usually sits near the base of the Detrital aquifer.

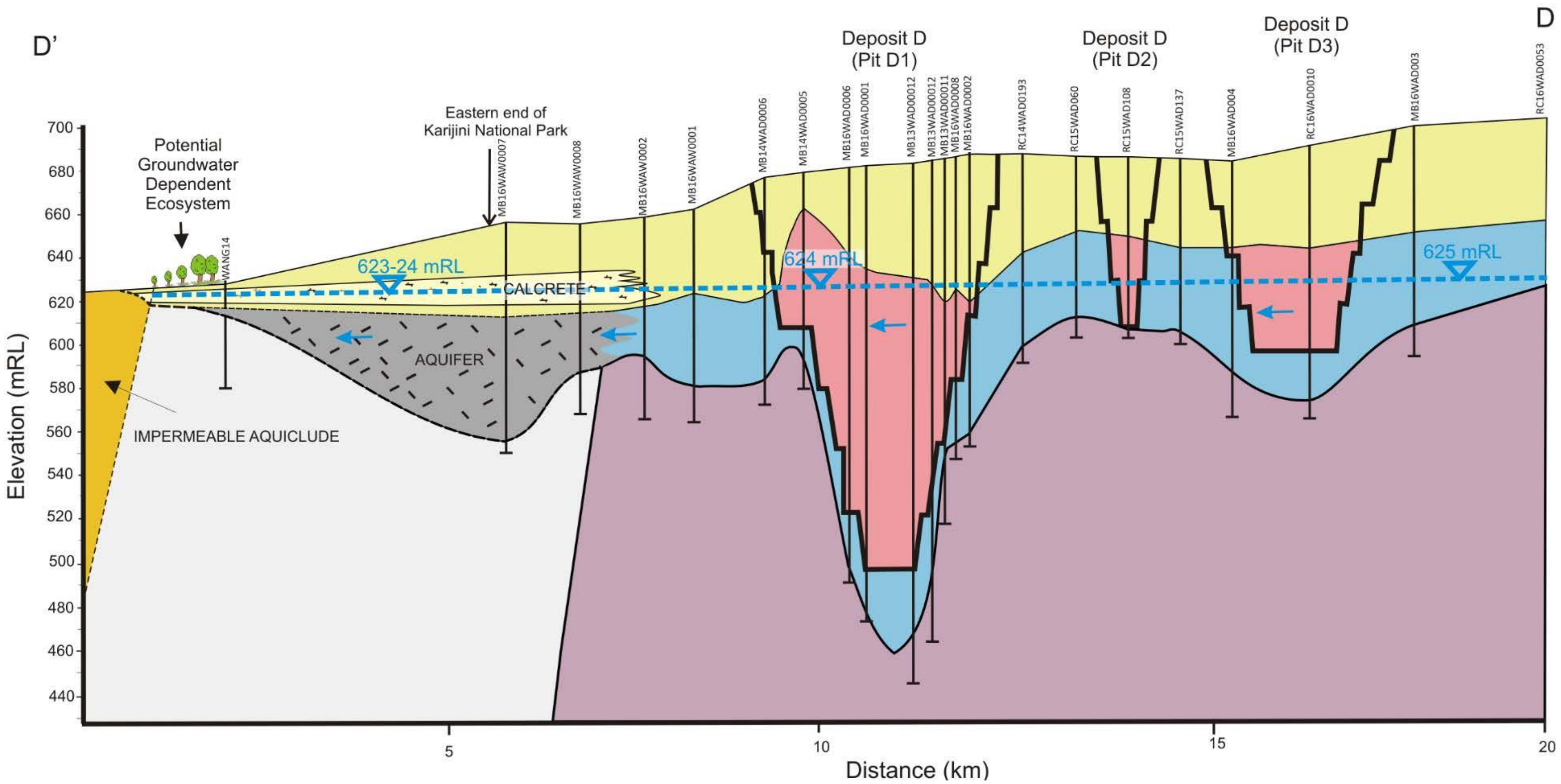
Figure 9 and Figure 10 show the extents of the Detrital and Calcrete aquifer units as obtained from RTIO's Leapfrog model of the study area. A large proportion of groundwater flow is thought to occur via the weathered upper portion of the Wittenoom Formation (R. Milton, pers. Comm, 12th Nov 2019). There is sparse data available to construct a regional-scale map of the thickness / lower boundary of the weathered Wittenoom Formation. Consequently, RTIO have developed such a map using the data available and the assumption that deeper weathering occurs beneath existing drainage lines (R. Milton, pers. comm. 20th April 2020) (Figure 11).

3.5. Groundwater Levels and Flow

The main aquifers that transmit groundwater in the study area comprise the mineralized zones of the Marra Mamba and Wittenoom Formations, the weathered upper portion of the Wittenoom Formation, and the Detritals/ Calcrete where these are saturated. Groundwater flows from east to west (Figure 12) and the groundwater system is conceptualized as being closed, with the southern and northern margins of the valleys formed by unmineralized Marra Mamba Formation and impermeable members of the Fortescue Group. In the east, northeast-southwest trending impermeable structures, thought to be dykes, form barriers to groundwater flow (Figure 9 to Figure 11) and Mount McRae Shale and Mount Sylvia Formation form an aquiclude to the west (Figure 8). The only inflow to the study area is therefore via rainfall recharge. Groundwater discharge is conceptualized to occur via evapotranspiration from shallow water tables at the potential GDE (Figure 8).

Some of the monitoring bores shown in Figure 13 were installed in 2013 and 2014, although the majority were installed between 2016 to 2019. Bore hydrographs have been provided and discussed by IGS (2020a). A summary is provided here. At bore WANG14, in Karijini National Park, there has been a gradual rise in groundwater levels over the period of record between 2012 and 2019. This is thought to be due to the occurrence of a period of below average rainfall between 1980 and 1995, followed by a period of above average rainfall since 1995 (Figure 6a). A rapid rise in groundwater levels of approximately 1.1 m occurred in early 2017, after which groundwater levels quickly receded. This rise is also observed in bores MB16WAW005 and MB16WAW007, located just east of the Park boundary. Here, the water table is in the Calcrete at a depth of approximately 19 m (MB16WAW0005) and 32 m (MB16WAW0007).

Between Deposits C and D and Karijini National Park (i.e. in the area of the proposed Stage 1 MAR scheme), the water table is in the Calcrete at a depth of 25 to 30 m (MB16WAW0006, MB16WAW0008), the Detritals (e.g. MB16WAW0002, MB16WAW0011) or top of the Mount Newman member (e.g. MB16WAW0001, MB16WAW0010). A rise in groundwater levels of approximately 20 to 30 cm occurred between 2016 and 2019, consistent with the long-term rise observed at WANG14 inside Karijini National Park. Seasonal responses to recharge of up to 25 cm are also observed in the area between Deposits C and D. A gentle rise in groundwater levels of between 20 and 30 cm also occurred in the Deposit C area, where depths to groundwater are around 55 m between 2015 and 2019.


D'
D
Potential Groundwater Dependent Ecosystem
Eastern end of Karijini National Park
Deposit D (Pit D1)
Deposit D (Pit D2)
Deposit D (Pit D3)
WANG14
MB16WAW0007
MB16WAW0008
MB16WAW0002
MB16WAW0001
MB14WAD0006
MB14WAD0005
MB16WAD0006
MB16WAD0001
MB13WAD00012
MB13WAD00012
MB13WAD00011
MB16WAD0008
MB16WAD0002
RC14WAD0193
RC15WAD060
RC15WAD108
RC15WAD137
MB16WAD004
RC16WAD0010
MB16WAD003
RC16WAD0053
623-24 mRL
624 mRL
625 mRL
CALCRETE
AQUIFER
IMPERMEABLE AQUICLUDE
Elevation (mRL)
Distance (km)
700
680
660
640
620
600
580
560
540
520
500
480
460
440
5
10
15
20

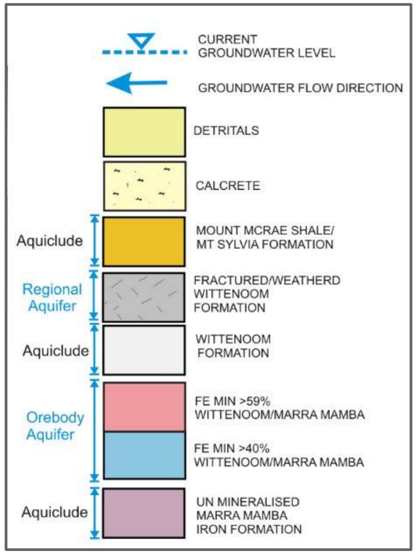


Figure 8. East-west hydrogeological cross section through Deposit D (RTIO).

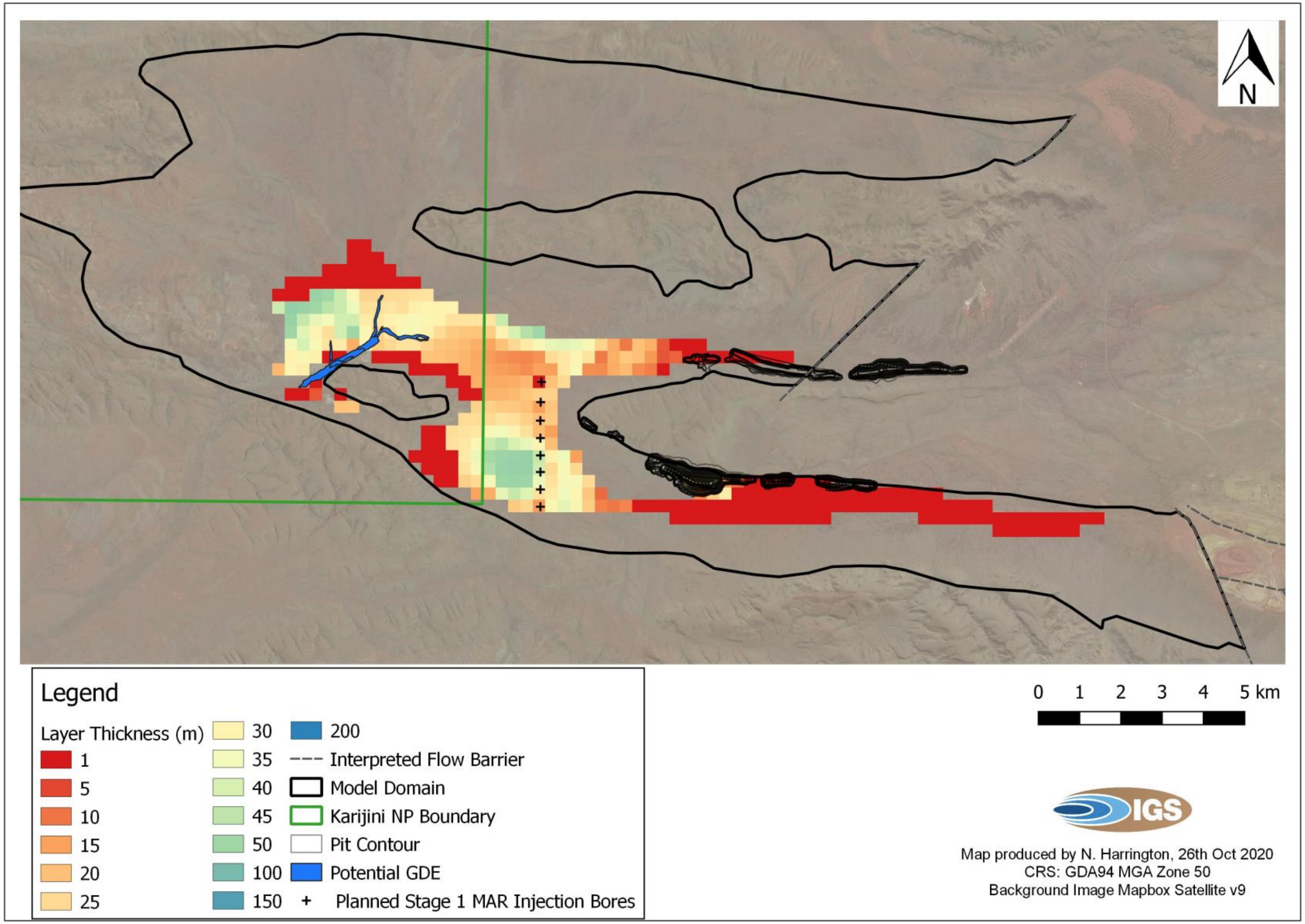

N
Legend
Layer Thickness (m)
1
5
10
15
20
25
30
35
40
45
50
100
150
200
Interpreted Flow Barrier
Model Domain
Karijini NP Boundary
Pit Contour
Potential GDE
Planned Stage 1 MAR Injection Bores
0 1 2 3 4 5 km
Map produced by N. Harrington, 26th Oct 2020
CRS: GDA94 MGA Zone 50
Background Image Mapbox Satellite v9

Figure 9. Extent and thickness of the Calcrete Aquifer unit at West Angelas as obtained from RTIO's Leapfrog model.

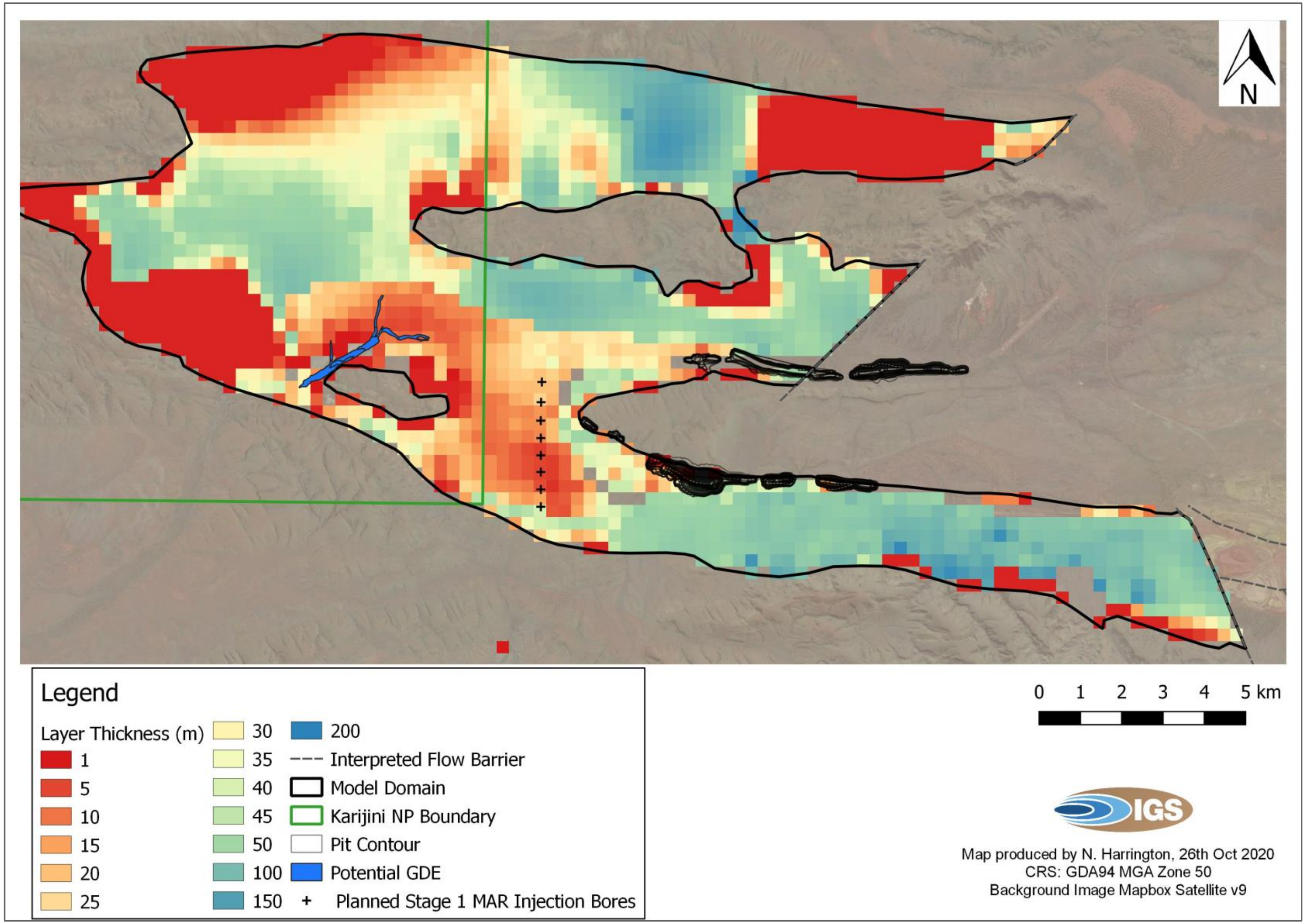

N
Legend
Layer Thickness (m)
1
5
10
15
20
25
30
35
40
45
50
100
150
200
Interpreted Flow Barrier
Model Domain
Karijini NP Boundary
Pit Contour
Potential GDE
Planned Stage 1 MAR Injection Bores
0 1 2 3 4 5 km
Map produced by N. Harrington, 26th Oct 2020
CRS: GDA94 MGA Zone 50
Background Image Mapbox Satellite v9

Figure 10. Extent and thickness of the Detrital Aquifer Unit at West Angelas as obtained from RTIO’s Leapfrog model.

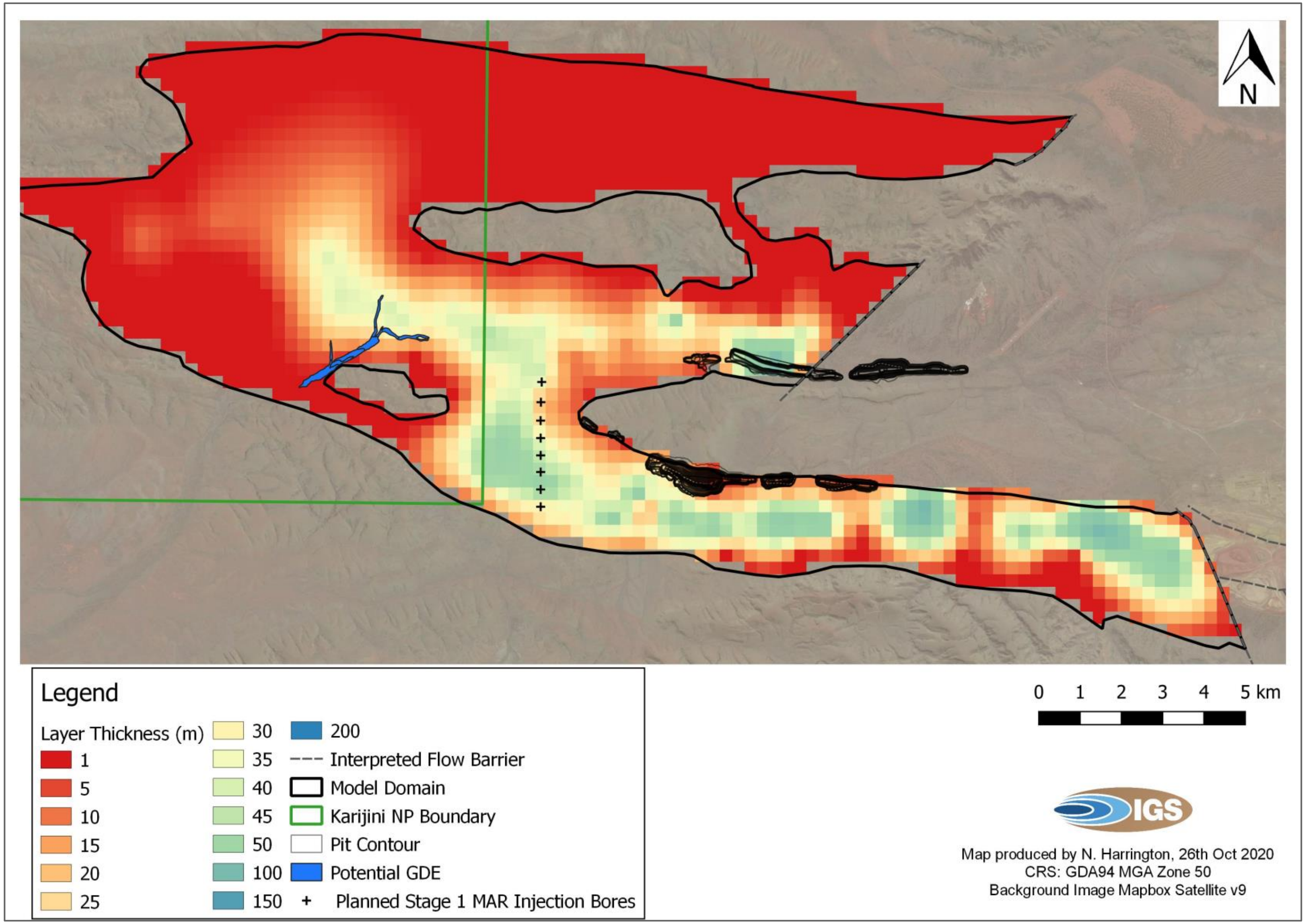

N
Legend
Layer Thickness (m)
1
5
10
15
20
25
30
35
40
45
50
100
150
200
Interpreted Flow Barrier
Model Domain
Karijini NP Boundary
Pit Contour
Potential GDE
Planned Stage 1 MAR Injection Bores
0 1 2 3 4 5 km
Map produced by N. Harrington, 26th Oct 2020
CRS: GDA94 MGA Zone 50
Background Image Mapbox Satellite v9

Figure 11. Thickness of weathered Wittenoom Formation used in the development of the regional groundwater flow model.

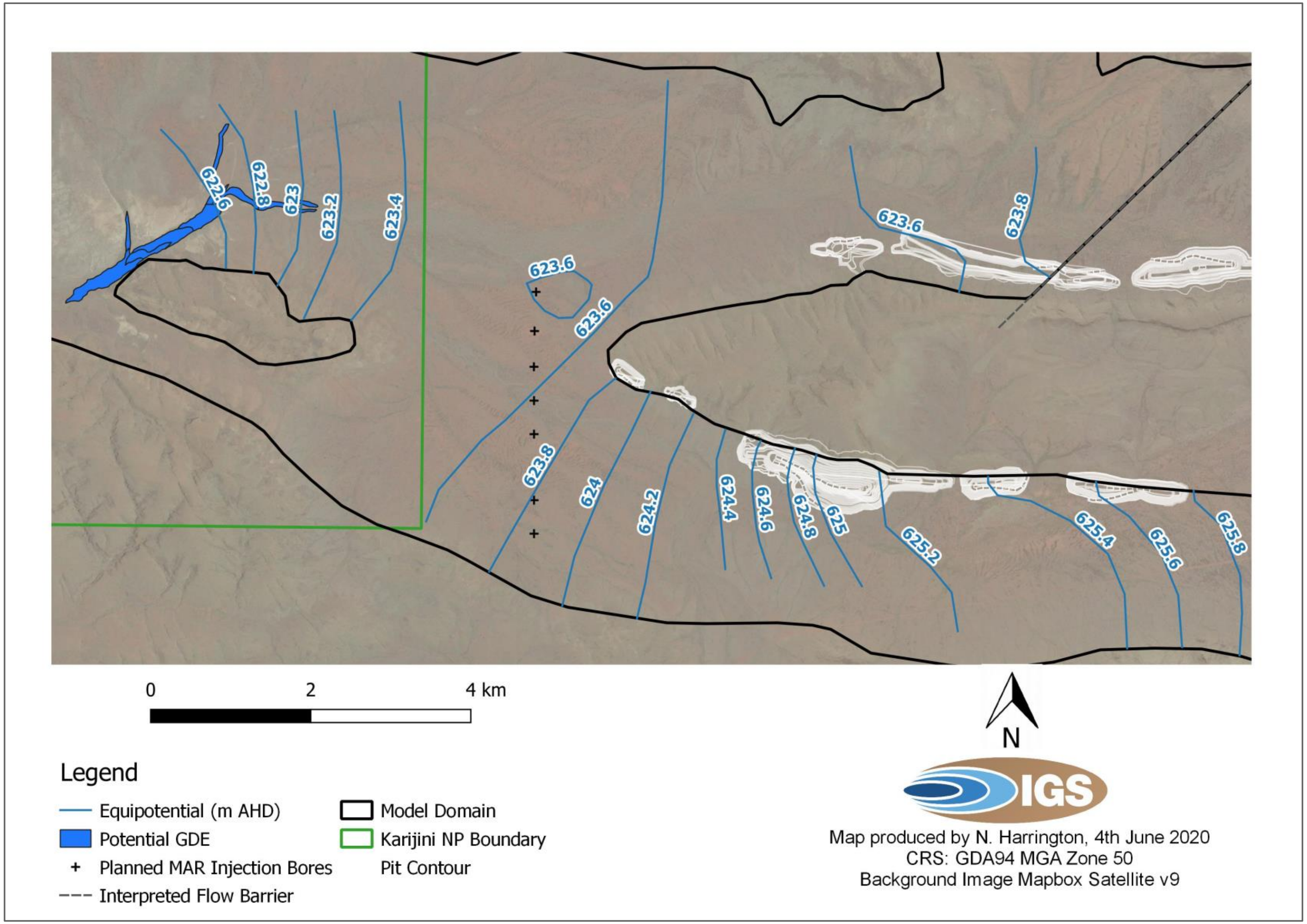

622.6
622.8
623
623.2
623.4
623.6
623.6
623.6
623.8
623.8
624
624.2
624.4
624.6
624.8
625
625.2
625.4
625.6
625.8
0
2
4 km
N
Legend
Equipotential (m AHD)
Potential GDE
Planned MAR Injection Bores
Interpreted Flow Barrier
Model Domain
Karijini NP Boundary
Pit Contour
Map produced by N. Harrington, 4th June 2020
CRS: GDA94 MGA Zone 50
Background Image Mapbox Satellite v9

Figure 12. Pre-mining steady state potentiometric surface developed using average pre-mining heads for each observation bore (locations shown in Figure 13).

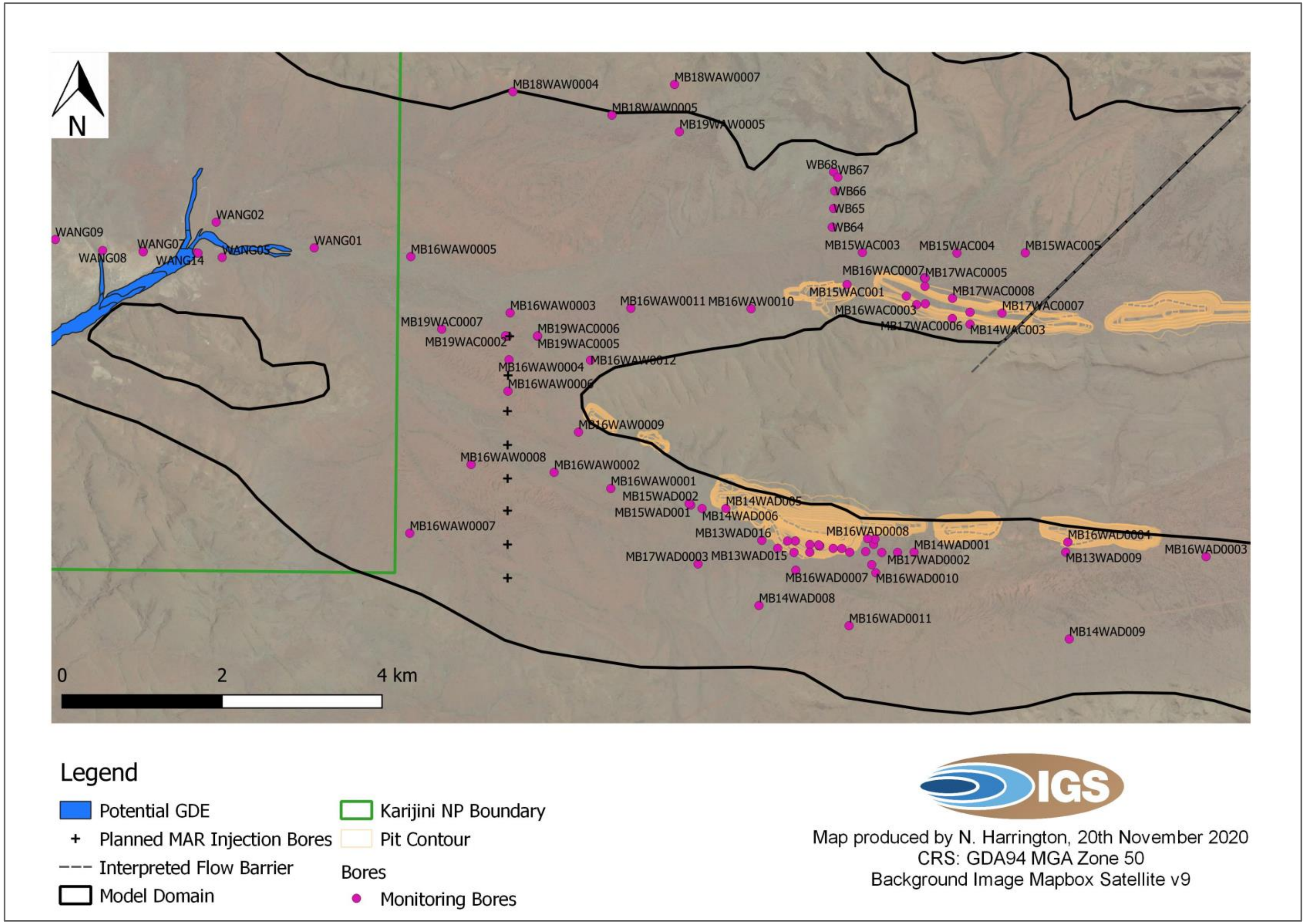

N
WANG09
WANG08
WANG07
WANG14
WANG02
WANG05
WANG01
MB16WAW0005
MB18WAW0004
MB18WAW0007
MB18WAW0005
MB19WAW0005
WB68
WB67
WB66
WB65
WB64
MB15WAC003
MB15WAC004
MB15WAC005
MB16WAC0007
MB17WAC0005
MB15WAC001
MB17WAC0008
MB16WAC0003
MB17WAC0007
MB17WAC0006
MB14WAC003
MB16WAW0003
MB16WAW0011
MB16WAW0010
MB19WAC0007
MB19WAC0002
MB19WAC0006
MB19WAC0005
MB16WAW0004
MB16WAW0012
MB16WAW0006
MB16WAW0009
MB16WAW0008
MB16WAW0002
MB16WAW0001
MB15WAD002
MB15WAD001
MB14WAD005
MB14WAD006
MB16WAW0007
MB13WAD016
MB16WAD0008
MB14WAD001
MB16WAD0004
MB16WAD0003
MB17WAD0003
MB13WAD015
MB17WAD0002
MB13WAD009
MB16WAD0007
MB16WAD0010
MB14WAD008
MB16WAD0011
MB14WAD009
0
2
4 km
Legend
Potential GDE
Planned MAR Injection Bores
Interpreted Flow Barrier
Model Domain
Karijini NP Boundary
Pit Contour
Bores
Monitoring Bores
Map produced by N. Harrington, 20th November 2020
CRS: GDA94 MGA Zone 50
Background Image Mapbox Satellite v9

Figure 13. West Angelas monitoring bore locations.

A review of measured hydraulic gradients between monitoring bores MB16WAW0001 and MB16WAW0007 (Figure 14) shows that, most of the time, the hydraulic gradient is towards Karijini National Park (to the west). Occasionally the hydraulic gradient reverses, presumably due to recharge associated with the watercourse connected to the potential GDE located in Karijini National Park (see further discussion in Section 3.7).

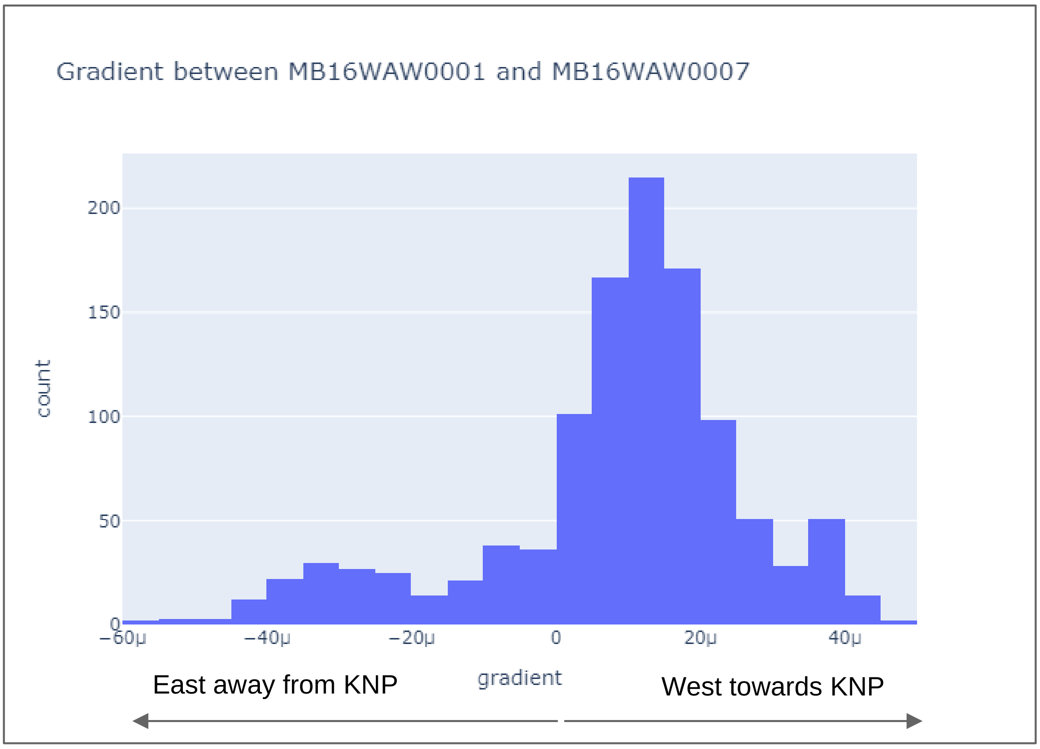


Figure 14. Histogram of observed hydraulic gradients between monitoring bores MB16WAW0001 and MB16WAW0007 for each time where there were head measurements available for both bores.

3.6. Aquifer Properties

There is a paucity of field data available for aquifer properties across the West Angelas site (Table 3). Most of this data is concentrated around Deposits C and D and half of it relates to boreholes screened across multiple aquifers. The ranges shown in Table 3 indicate significant heterogeneity across individual units. Table 4 provides a broad comparison between aquifer property values obtained in Stage 1 through calibration of an Analytic Element Model (AEM) of the MAR Injection Trial (IGS, 2020b), the outcomes of the steady state regional flow model calibration (Section 4.2) and the available field data, noting again that much of the field data relates to bores screened across multiple aquifers.

Table 3. Existing field data on aquifer properties.

Aquifer	K (m/d)	S (-)	n
Detritals	26	0.02	1
Calcrete/Wittenoom	0.5	0.15	1
Wittenoom	0.3 to 5.1	0.001 to 0.005	3
Wittenoom / Mt Newman	0.7 to 3.5	0.0006 to 0.02	4
Mt Newman	0.75 to 9.5	0.0008 to 0.003	2

Detritals / Wittenoom / Mt Newman	0.9	0.003	1

Table 4. Comparison of aquifer parameter values determined through transient calibration of the AEM model using different methods, steady-state calibration of the initial (Stage 1) zoned regional groundwater flow model (IGS, 2020b), available field data and the values adopted as a starting position for pilot points in the updated (Stage 2) regional model.

	Field Data*	AEM Model	Regional Model Initial (Stage 1) Calibration		
	(see Table 3)	(various calibration methods)	Zones - Variable Weights	Zones - Tikhonov	Adopted Pilot Point Start Value
Single Layer Domain					
K_H (m/d)	-	19.6 – 39.0	-	-	-
K_V (m/d)	-	18.0 - 20.0	-	-	-
Sy (-)	-	0.15	-	-	-
Detritals	n=1				
K_H m/d	26		4.1	3.0	4.1
K_V m/d	-		8.6	1.5	8.6
Sy (-)	0.02		-	-	0.02
Above WT Calcrete					
K_H (m/d)	-	21.3 - 44.1	-	-	-
K_V (m/d)	-	40.0 - 44.1	-	-	-
Sy (-)	-	0.10 – 0.24	-	-	-
Below WT Calcrete	n=1				
K_H (m/d)	0.5?	100 – 134.1	9.4	18.6	9.4
K_V (m/d)	-	7.8 - 100	0.53	5.9	0.53
Sy (-)	0.15?	0.05 - 0.13	-		0.13
Weathered Wittenoom	n=7				
K_H (m/d)	0.3 to 5.1?	5.0 – 11.2	2.7	1.1	2.7
K_V (m/d)	-	4.7 – 15.0	5.3	1.5	5.3
Sy (-)	0.0006 to 0.02?	0.14 - 0.17	-		0.14

	Field Data (see Table 3)	AEM Model	Regional Model Zones – Variable Weights	Regional Model Zones – Tikhonov	Adopted Pilot Point Start Value
Unweathered Wittenoom	n=7				
K_H (m/d)	0.3 to 5.1?	-	0.17	0.17	0.17
K_V (m/d)	-	-	0.82	4.7	0.82
Sy (-)	0.0006 to 0.02?				0.02
Newman & McLeod	n=2				
K_H (m/d)	0.75 to 9.5		0.12	0.14	2.7
K_V (m/d)	-		0.30	1.5	5.3
Sy (-)	0.0008 to 0.003				0.01
Fortescue					
K_H (m/d)	-	-	100.0	0.01	0.01
K_V (m/d)	-	-	2.9	0.05	0.05
Sy (-)	-	-	-	-	0.01

*Question marks indicate that data relates to a bore screened over multiple hydrostratigraphic units or may not be relevant to the weathered or unweathered portion of the aquifer (see Table 3).

3.7. Recharge and Evapotranspiration

Both rainfall recharge and evapotranspiration are thought to be minor across the majority of the study area due to large depths to groundwater (> 20 m). This is supported by hydrographs of bores in and to the east of the Deposit D area, which show relatively constant groundwater levels over time prior to the commencement of groundwater pumping to the east of Deposit D in March 2016. As a consequence of this, a previous model of the West Angelas site implemented a low diffuse recharge rate of 0.5 mm/yr. across the study area (RTIO, 2017).

Preferential rainfall recharge can occur locally via surface drainage features during and immediately following periods of intense rainfall. Attempts were made to calibrate a variety of recharge models at locations in West Angelas that demonstrated macropore flow events following intense rainfall, evidenced as step increases in the hydrographs. This included a Berendrecht model (Berendrecht, 2006), a Flexmodel (Collenteur, in review) and PEST's new LUMPREM model (Doherty, 2020b). All were unsuccessful due to the inconsistencies between the hydrograph responses and rainfall and potential evaporation records.

A review of aerial photography and maps of major surface water features indicates that surface runoff in the study area is towards the potential GDE inside Karijini National Park, where water tables are less than 5 m deep. This is therefore likely to result in significant seasonal recharge in the vicinity of the National Park boundary and potential GDE. Seasonal variations in groundwater level within and to the east of the Karijini National Park boundary are evidence of this process (see Section 3.5). Occasional reversal of the normally western regional hydraulic gradient provides further evidence of significant recharge occurring periodically in the vicinity of the Karijini National Park (Section 3.5).

3.8. Managed Aquifer Recharge

Dewatering of Pits C and D is expected to cause drawdown extending to the Karijini National Park boundary. RTIO plan to mitigate this impact via operation of a Managed Aquifer Recharge (MAR) scheme between the deposits and the National Park. Stage 1 of the MAR scheme, which is designed to mitigate impacts from dewatering of Deposit D only, is the focus of the modelling described in this report. The planned configuration of the Stage 1 MAR injection bores is shown in Figure 13. It is expected that each injection bore will be screened across the Detritals, Calcrete and weathered Wittenoom Formation and will have an associated network of monitoring bores and Vibrating Wire Piezometers (VWPs). An injection trial was carried out on the northern bore (WB19WAC0001) between 20th February 2020 and 23rd March 2020. An overview of the injection trial and its outcomes are provided in IGS (2020b).

4. Regional Groundwater Flow Model Design and Calibration

4.1.1. Modelling Platform, Domain and Grid

The regional groundwater flow model is constructed in MODFLOW-USG (Panday et al., 2013) and adopts a Voronoi polygon grid (Figure 15). The domain boundary was provided by RTIO and comprises the valley area bounded by the Fortescue Group and the Brockman Iron Formation of the Hammersley Group. Development of the grid and initial simulation testing was performed in Algomesh (HydroAlgorithmics, 2016). Refinements were made to the grid in locations where stresses were likely to be implemented including injection and extraction wells, dewatered mine pits and the groundwater dependent ecosystem. The grid between the MAR injection bores and the Karijini National Park (KNP) boundary was also refined to facilitate better spatial and temporal resolution of drawdown impacts. Additionally, provision was made for the inclusion of dykes in a refined zone diagonally across the model, although these are not implemented in the present version of the model. The model was transferred to Groundwater Vistas (ESI, 2017) where further testing and refinements were made specific to optimising convergence and solution speed.

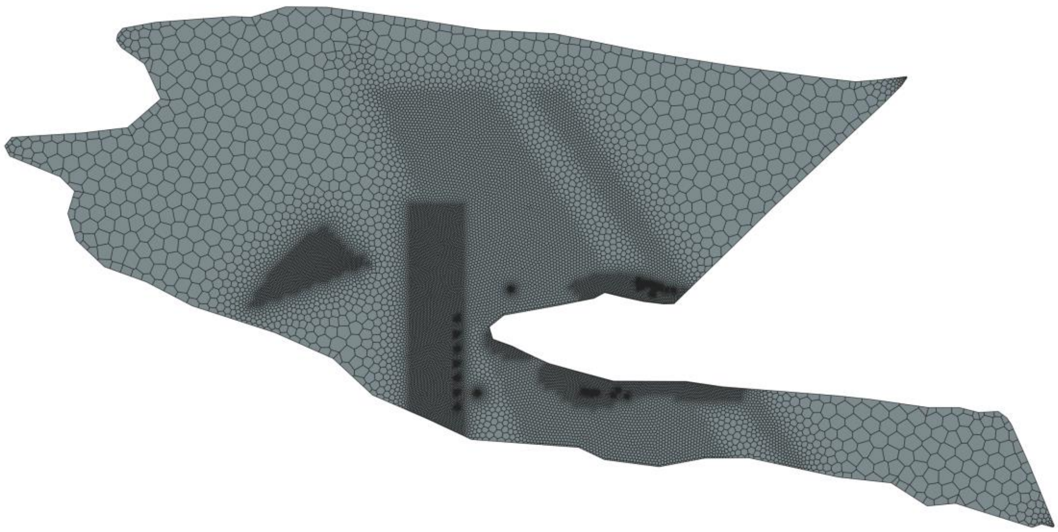


Figure 15 The grid developed for the West Angeles regional groundwater flow model

Initial model development included explicit representation of geological units from surfaces and thicknesses provided by RTIO's geological Leapfrog model of the area. According to the geological model, several units 'pinch out' within the model domain. However, incorporation of layer 'pinch outs' and lateral flow connections between pinched layers increased model run times and general instability. A continuous layered model was therefore developed, with zoned regions to represent the geological units.

The model comprises five layers, with many of the geological formations and their associated property zones spanning several layers. Accurate representation of the upper surface is not essential because there are no fluxes in the domain that are affected by surface elevation. The layer sequence follows the uppermost major aquifer units and those expected to be impacted by future mine pit dewatering. Numbered according to layer, these are:

1. Detritals
2. Calcrete
3. Weathered Wittenoom Formation
4. Unweathered Wittenoom Formation
5. Combination of the Mt Newman and MacLeod Formations

The base of the model is defined by the upper surface of the Fortescue Group. However, a unit comprising a combination of upper Fortescue and the Nammuldi member of the Marra Mamba Iron formation was included as a zone that intersects all model layers. This inclusion simplified the model grid development process by keeping the same number of active nodes in each layer, which aids in simplifying scripted post processing. Surface elevations and lateral extents for geological units were obtained from RTIO and translated for input to the model via Golden Software's Surfer application.

4.1.2. Model Boundaries

The external model boundaries are all designated as no-flow. There are internal regions that are also implemented as inactive cells and these are projected through all model layers (Figure 16). Drain-type boundary conditions are used to represent the potential GDE located in Karijini National Park, which is conceptualized as the only discharge point in the system (Section 3.5). The elevation of the potential GDE is set at four metres below the surface elevation and its conductance is a calibrated model parameter. There are no permanent surface water features in the region and therefore these did not require representation in the model.

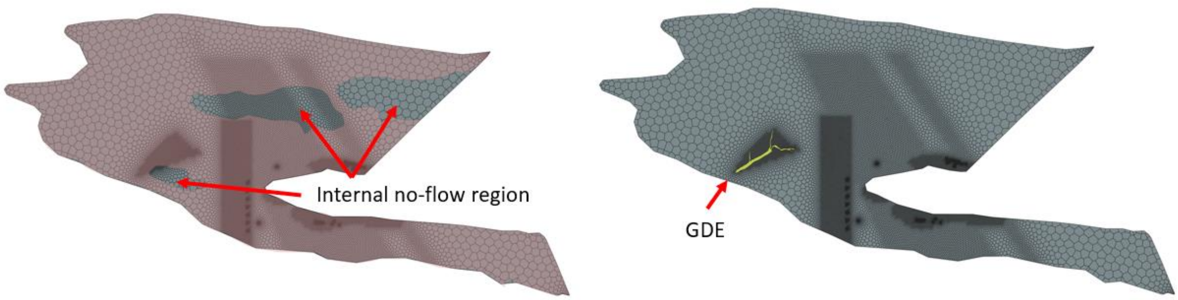


Figure 16 No-flow and potential GDE locations in the model domain

4.1.3. Recharge and Evapotranspiration

A spatially and temporally uniform recharge rate of 0.5 mm/yr. is applied to the model upper surface, representing the only source of water in the domain. This is considered to be a conservative value for recharge and the model does not account for episodic and spatially variable (preferential) recharge along surface drainage features. There is no data available on such recharge processes in the study area and therefore inclusion of spatially and temporally variable recharge would not add any additional confidence to model results (see Section 3.7 for details on assessment). Evapotranspiration is not implemented in the model due to large depths to groundwater across the majority of the model domain (Section 3.5). The major contributor to evapotranspiration is the potential GDE located in Karijini National Park, which is implemented as a drain (Section 4.1.2).

4.1.4. Aquifer Properties

The zones representing formations in each layer of the model are shown in Figure 17. These zones are assigned hydraulic properties based on values presented in Table 3 and Table 4. These include model- and field-derived values, as well as literature values where limited data is available. The results of the AEM analysis (IGS, 2020b) were used to inform the likely bounds on parameters during calibration and the subsequent MAR optimisation (Section 5). The aquifer properties assigned in the model are:

1. Horizontal hydraulic conductivity
2. Vertical hydraulic conductivity
3. Storage coefficient
4. Specific yield

There is no evidence of confining units or confined aquifer behaviour in the region. Consequently, specific yield estimates were used for the storage coefficient thereby ensuring unconfined storage behaviour irrespective of model cell confined/unconfined status. The weathered Wittenoom Formation did not feature in the geological model explicitly and was inferred from drill hole logs (R. Milton, pers. comm. 20th April 2020). The extent of this unit is mostly hypothesized in the northern parts model domain where it is relatively thin.

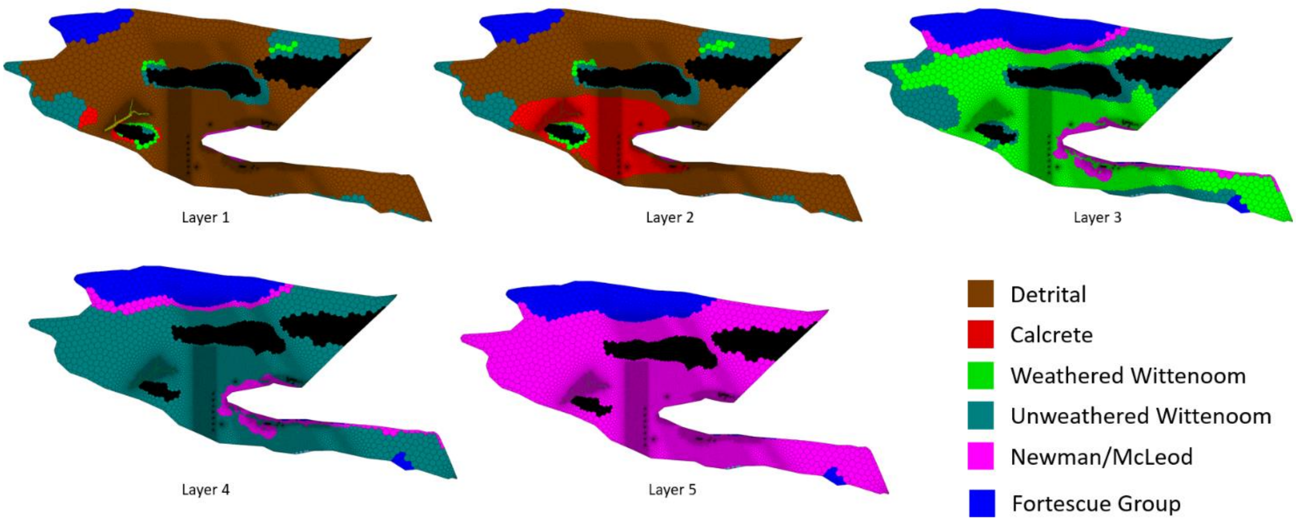


Figure 17. Zones representing formations in the regional groundwater flow model. Black zones represent inactive cells.

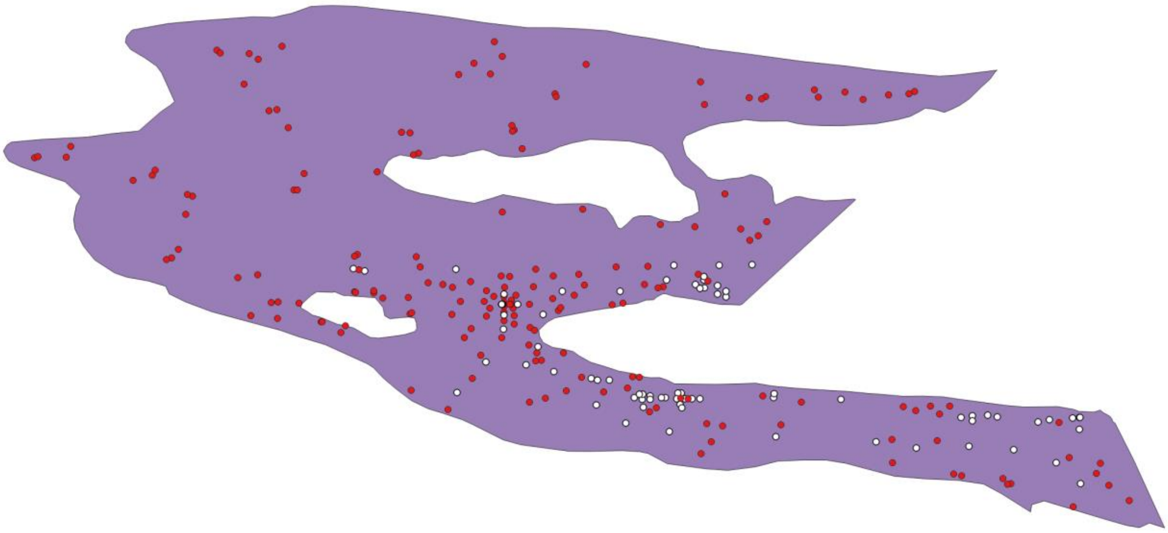
4.2. Steady-State Calibration

4.2.1. Calibration Methodology

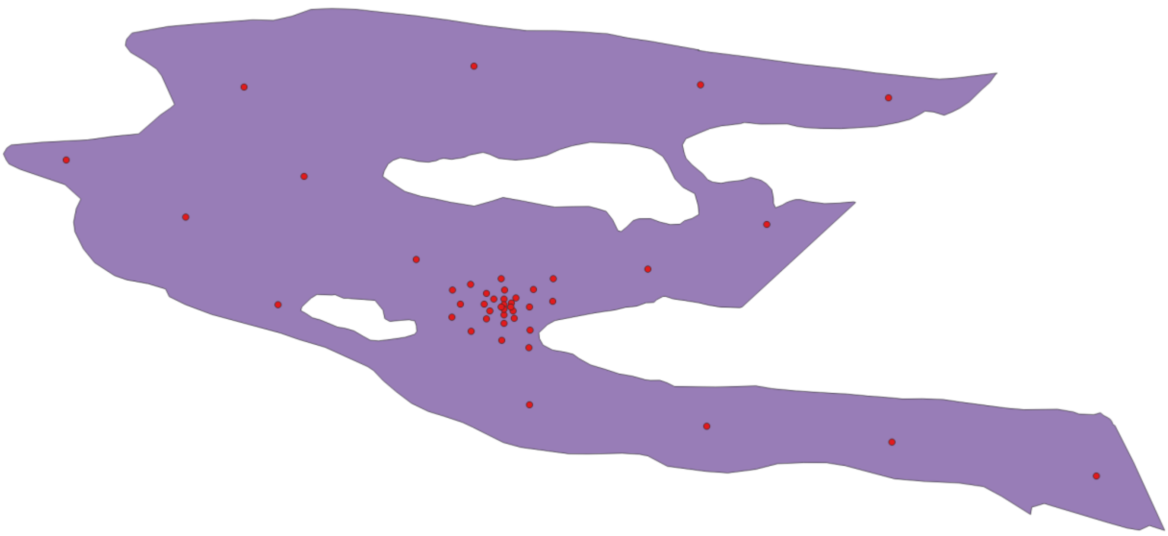
Stage 1 of the model development utilized a combination of analytical element modelling (AEM) and a MF-USG model with zones based on known extents of geological formations. Steady-state hydraulic head values for monitoring locations in the region were provided by RTIO and used as observations for conditioning hydraulic properties of the model. The horizontal and vertical hydraulic conductivities for each zone and the potential GDE conductance were estimated using PEST (Doherty, 2020a) in estimation mode with the steady-state model. The initial approach used unit observation weighting and parameter bounds spanning three orders of magnitude. Overall, a favourable match was produced. However, there remained several observations located in between the KNP, MAR site and future mine pits that demonstrated an unacceptable level of model to measurement misfit. Recognising that significant heterogeneity is likely across all units simulated, and that the use of single zones for all units is restrictive in allowing the calibration to arrive at representative aquifer parameters, the calibration strategy was focused on the key area of interest for the current model, between the pits, MAR scheme and KNP boundary. A weighting strategy was devised that sought to improve the match in this region. Observations pertinent to drawdown at the KNP boundary were grouped separately from the rest thereby facilitating a multicomponent objective function. Contributions of each group were then balanced before a four times multiplier was used on the group considered most influential to hydraulic behaviour between the KNP boundary and the MAR site.

Despite improvements to the calibration, eigenvalues reported in PEST output files indicated insensitivity in at least two directions of parameter space. The primary contributors were identified as the hydraulic conductivities for the combined Nammuldi/Fortescue Group zone. This prompted re-calibration using both Singular Value Decomposition and preferred value Tikhonov regularization for each zone based on field derived values (see Table 4).

In stage 2, further improvements to the steady-state model calibration were then obtained with a sparse irregular distribution of pilot points in each zone. Pilot points were located approximately midway between observations and then towards the outer edges of each zone (Figure 18). The initial values were set equivalent to the adopted zone values informed by the steady- state calibration of the regional model in Stage 1 (Table 4) and bounds within +/- one order of magnitude. Preferred value Tikhonov regularisation was used with weighting according to pilot point spatial distribution via 3D covariance matrices specific to the geological formations. The covariance matrices were developed using the *ppcov3d_sva* utility in PEST's groundwater utilities suite. Hydraulic conductivity fields were kriged using a combination of PLPROC's *calc_kriging_factors_auto_2D* and *krige_using_file* (Doherty, 2020d) functions with enforcement of maximum and minimum values. Zone boundaries were maintained throughout, that is, kriging across a zone boundary was prohibited during the estimation process. The best target measurement objective function was sought initially using a low value for PHIMLIM, which behaves as a user prescribed "level of fit" setting in the PEST control file. A very low value of PHIMLIM generally leads to over-fitting and amplification of measurement noise. The parameter estimation process was then repeated with PHIMLIM set at a value 10% greater than the previous minimum to reduce the propensity for fitting structural noise. This is the recommended strategy in the PEST manual to avoid overfitting when using pilot points.



(a)



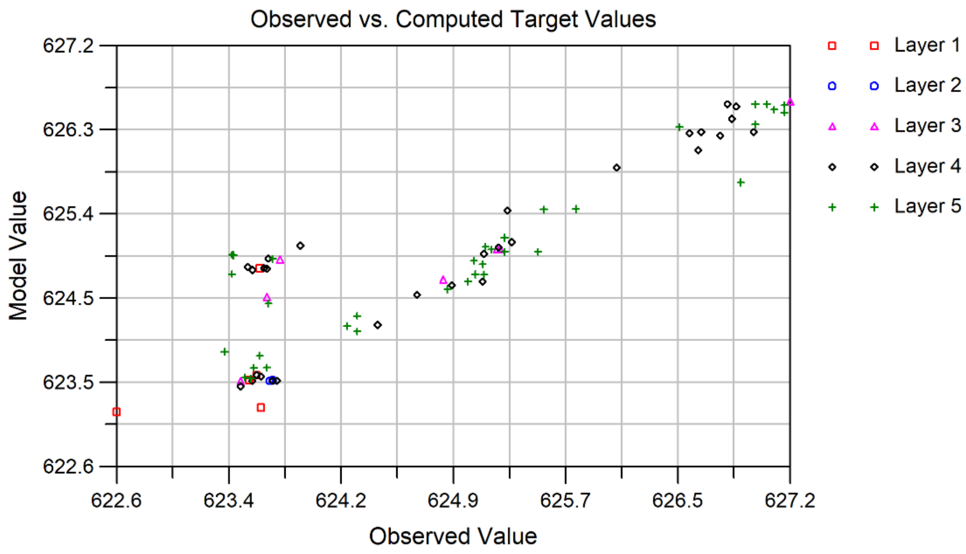
(b)

Figure 18. Pilot point distributions used in the regional groundwater flow model for (a) steady state calibration and (b) transient calibration to the MAR trial data. Red dots = pilot points (applied with same distribution in all model layers) and white dots = locations of steady state head data for all model layers.

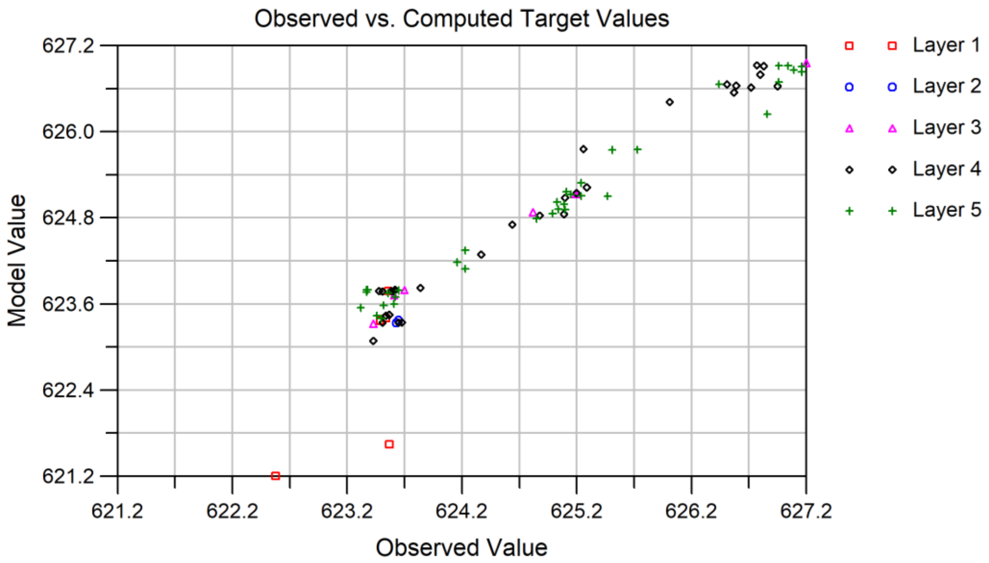
4.2.2. Results

The parameter set results of the different zoned steady-state model calibration approaches carried out in Stage 1 are shown in Table 4. The adopted parameter set includes those parameters observed in all calibration attempts, including the AEM model, that are best aligned with field-tested values and most likely to be representative at the sub-regional to regional scale. Of note, vertical and horizontal hydraulic conductivity values for each unit are similar despite being calibrated as independent parameters. This is not a surprising result, given the relatively shallow gradient in the area, the small volume of recharge and that all aquifers are considered unconfined. The zone representing the combined Nammuldi/ Fortescue Group was identified as insensitive during the parameter estimation process and was subsequently removed from further calibration with parameters fixed at the values presented in Table 4.

Figure 19(a) depicts the model to measurement misfit when using the best zoned parameter set. An SRMS error of 13% results from the 78 steady-state observations, which was considered acceptable given an associated RMSE of 0.6 m. The maximum and minimum residuals were 1.16 m and -1.56 m respectively.



(a)



(b)

Figure 19. Modelled heads (m) versus observed heads for the model using (a) the best zoned parameter set and (b) sparse pilot points.

The results of the steady state calibration with pilot points, using the preferred zone parameters as initial values, are presented in Figure 19(b). For this method, most of the domain has calibrated hydraulic conductivities between 0.1 and 1.0 m/d, with the exception of the calcrete and the Mt Newman/ Macleod Formations (Figure 20). An improved SRMS error of 7.3% was obtained. Two observations with the largest residuals in Layer 1 are located within the KNP near the potential GDE. The mismatch is considered acceptable given their distance from the area of interest. The spatial distribution of residuals is presented in Figure 21.

The raised hydraulic conductivity estimated for the Mt Newman/Macleod Formations in Layer 5 is explained by the over predictions of steady state heads observed in the zoned model (Figure 19a) which were translated to preferred values for the pilot points. Mineralization altering the formation properties could also be responsible for the estimated shift in conductivity but there is insufficient evidence to support this over a large area. Consequently, a review of the conceptual model and model design for the area around Deposit C is recommended prior to any simulation of drawdown or dewatering from this region.

The interpolated fields show some kriging artefacts in Layer 5 attributed to the sparse pilot point distribution, however this is unlikely to influence the results of the MAR simulations as these will primarily affect Layers 1, 2 and 3 that host the water table. Moreover, the resultant hydraulic conductivity fields presented below provide a suitable starting point for subsequent modelling experiments that will also account for, amongst other things, predictive uncertainty associated with uncertainty in aquifer parameters.

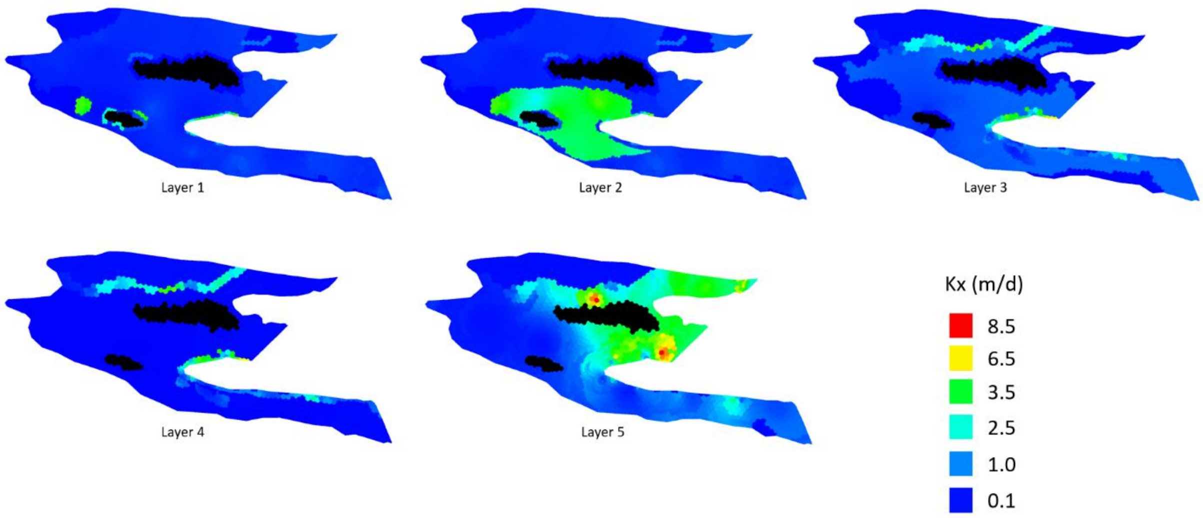


Figure 20 Steady-state calibrated horizontal conductivity fields derived using a sparse pilot point distribution and aquifer property zones.

The simulated steady-state water table contours depict a very shallow hydraulic gradient from east to west in both Deposit C and D regions (Figure 22). The hydraulic gradient in the area between the MAR and KNP boundary is even shallower. Model water balance comprises only rainfall recharge (2,495 kL/d) and discharge via the drains representing the potential GDE (2,495 kL/d).

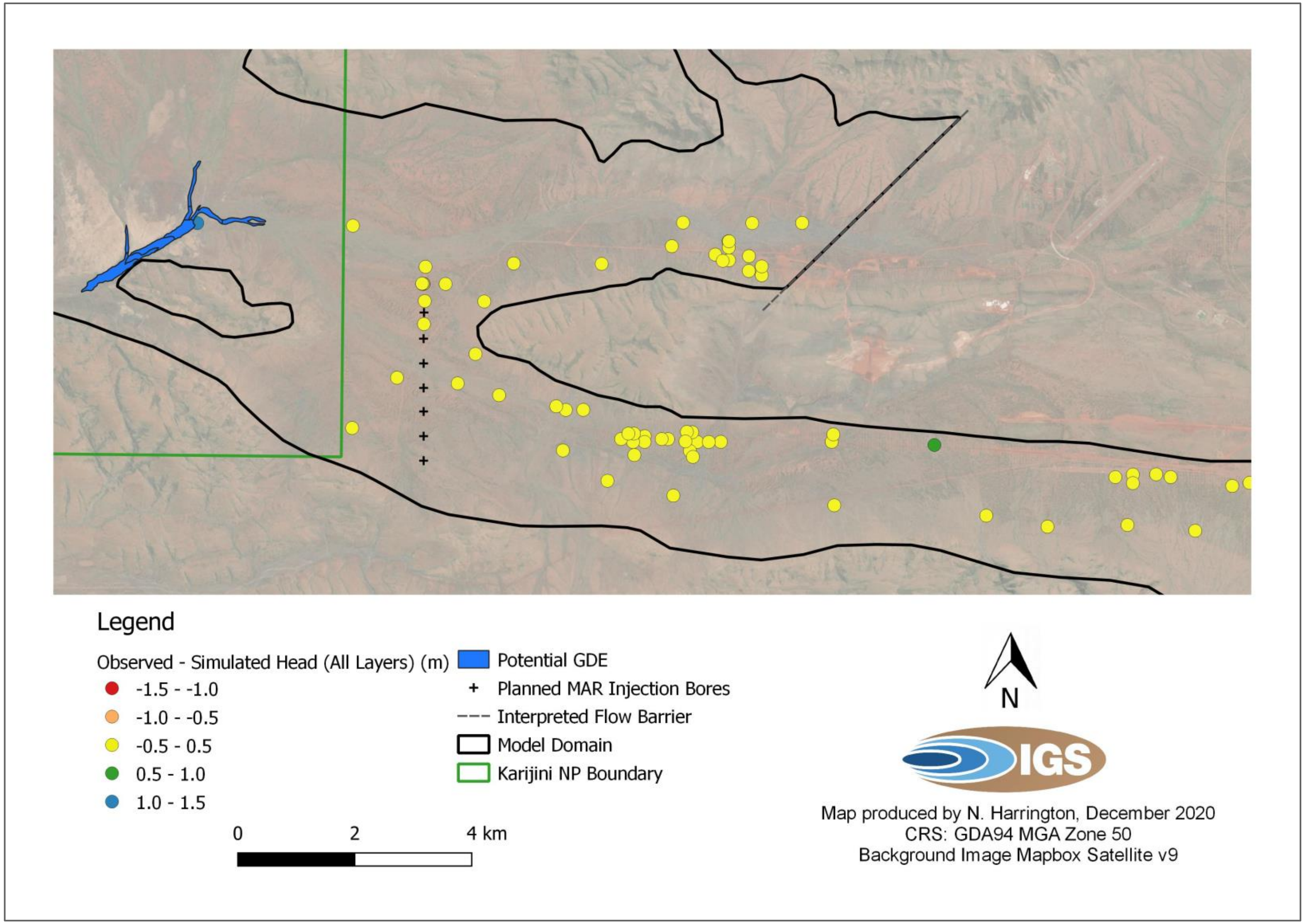


Figure 21. Simulated head residuals (observed head – simulated head) for the steady-state regional groundwater flow model using the hydraulic conductivity distributions shown in Figure 20.

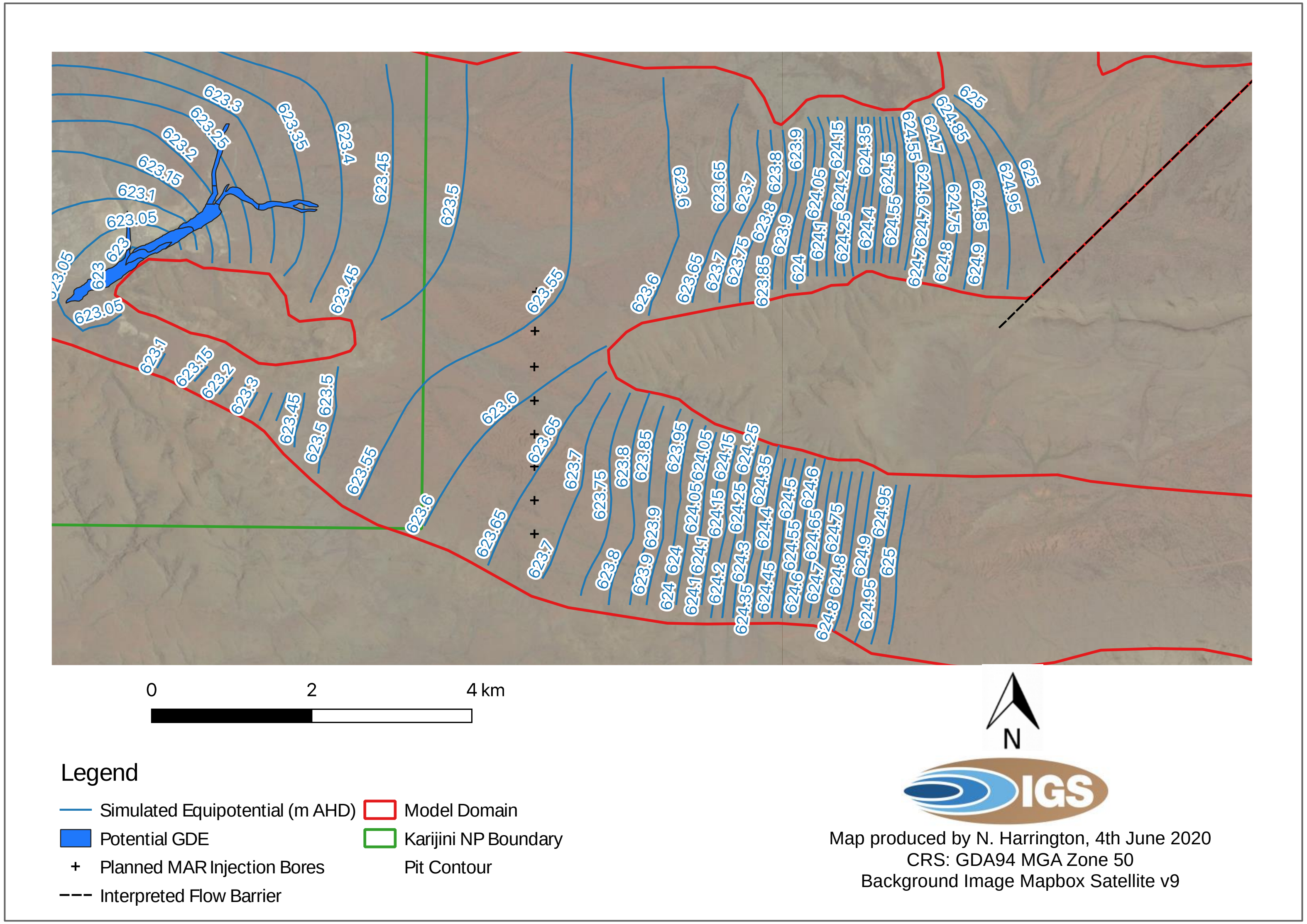


Figure 22. Steady-state water table elevation contours simulated using the calibrated steady state model.

4.3. Transient calibration using MAR trial data

4.3.1. Calibration Methodology

The steady-state regional model excludes any calibration of storage parameters, which is critical for predicting both drawdown from dewatering in Pit D and the likely response of the groundwater system to injection at the MAR bore locations. Additionally, drilling of the MAR injection bores and associated monitoring bores revealed extensive dissolution channel networks present in the calcrete above the water table (pers comm Rob Milton, RTIO). It is doubtful that uncertainty in the calcrete aquifer parameters obtained from the steady-state calibration accounts for these features, which will have a significant impact on the MAR injection. Capturing the plausible range of simulated hydraulic parameters for those formations in the MAR injection region is critical for performing a calibration-constrained optimisation of the injection rates.

Calibration of the AEM to MAR trial data in Stage 1 (IGS, 2020b) revealed that the hydraulic conductivity of the calcrete required to simulate water levels responses to the MAR trial needed to be much greater than the value obtained when performing a steady-state head calibration. Differences in structural uncertainty between the regional MODFLOW-USG model and the AEM precludes direct transfer of aquifer parameter ranges obtained through conditioning. This prompted a more robust interrogation of the MAR trial data by including it in a transient recalibration of the regional model. Details of the MAR trial, including location of the injection and monitoring bores, are provided in IGS (2020b).

The regional model MAR trial calibration adopted the resultant hydraulic conductivity distribution from the steady-state pilot-point calibration initially and featured an irregular array of pilot point multipliers (configured via PLPROC) in all layers. Pilot point placement density increased closer to the injection bore (Figure 18b). Starting storage parameters were uniform in each formation/zone with values based on either literature (Domenico and Schwarz, 1990) and/or pumping test values where appropriate. Preferred value Tikhonov regularisation was adopted with weighting provided by covariance matrices developed using *ppcov_sva* from PEST’s groundwater utilities suite (Doherty, 2020c). PLPROC’s radial basis function (*rbf_sda_interpolate_2d*) interpolator was used instead of kriging to facilitate the inclusion of anisotropy range and bearing in the calibration. A total of five parameters per pilot point were estimated including horizontal and vertical hydraulic conductivities, anisotropy range, anisotropy bearing and specific yield. Values for the storage coefficient in each cell were adjusted to reflect changes in specific yield via a PLPROC script.

The observation dataset comprised two groups of observations namely observed hydraulic heads and processed temporal head differences. Observation weighting was adjusted using PEST’s *pwtadj1* utility (Doherty, 2020e) to ensure three-time greater weighting for temporal head differences, thereby focusing estimation on system response behaviour rather than absolute head observations.

4.3.2. Results

No changes to parameters were necessary for the Detritals, Wittenoom or Newman/McLeod formations. That is, multipliers remained at 1.0 or very close to it. Anisotropy bearing was also found to be insensitive. Consequently, all subsequent conditioning reverted to kriging as the interpolation method. The calcrete, present in Layer 2, required substantial increases in horizontal hydraulic conductivity for some pilot points (up to x100 multiplier) near the injection well (Figure 23). The weathered Wittenoom Formation, which comprises a large portion of Layer 3, required vertical conductivity reductions (down to x0.2 multiplier near the injection well) for some pilot points (not shown). Storage parameters for both the weathered Wittenoom Formation (x0.5 to x1.5) and the calcrete (x0.2 to x1.0) were also altered in the vicinity of the injection well (Figure 24).

These results imply that the bulk of the uncertainty associated with MAR injection response can be attributed to the heterogeneity in model parameters representing the weathered Wittenoom Formation and the calcrete.

Good matches were obtained between observed and simulated heads and drawdowns for the observation bores monitored during the injection trial (Figure 25).

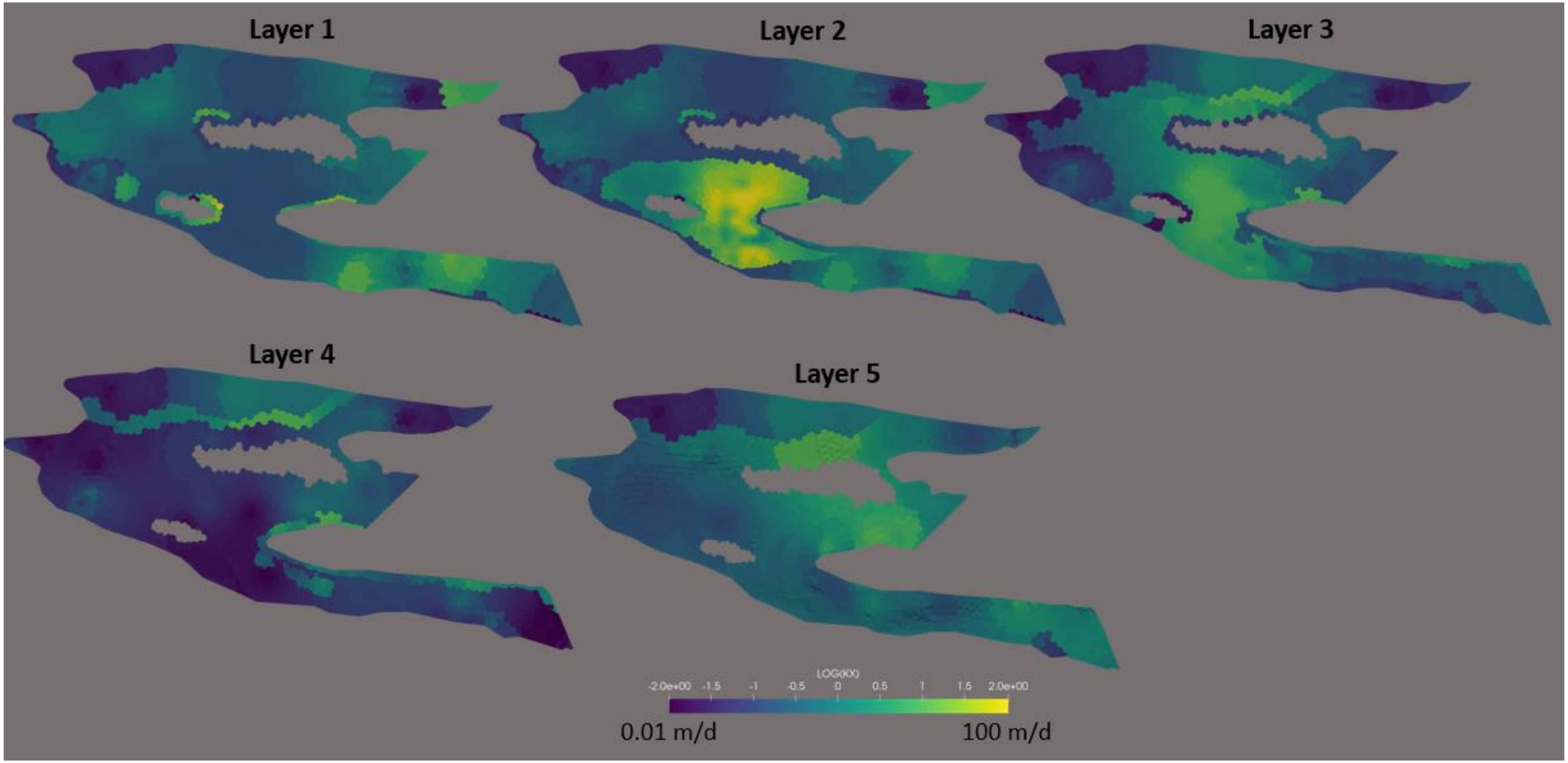


Figure 23. K_H distributions obtained following transient calibration of the regional model to the MAR trial data.

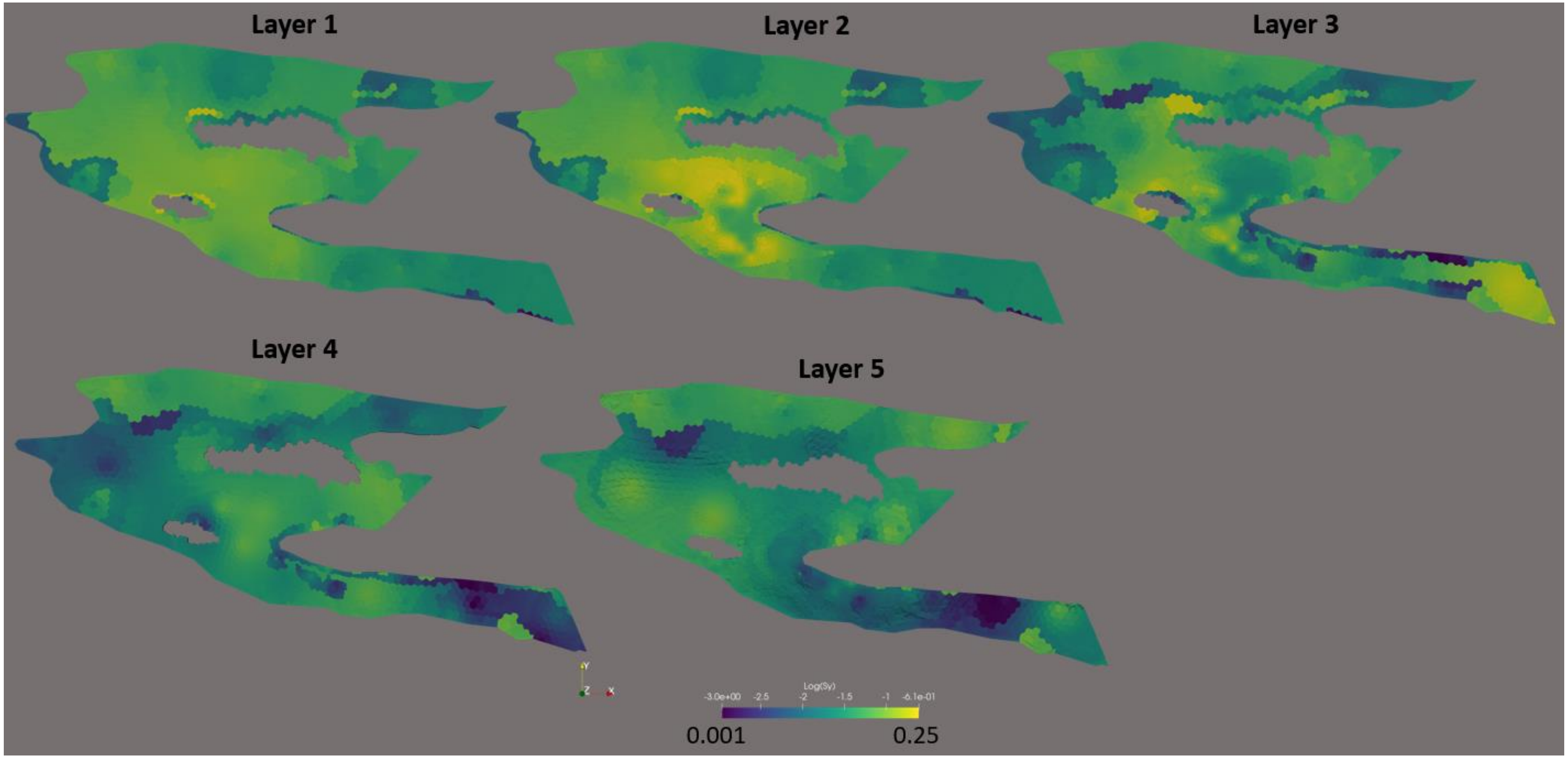


Figure 24. Sy distributions obtained following transient calibration of the regional model to the MAR trial data.

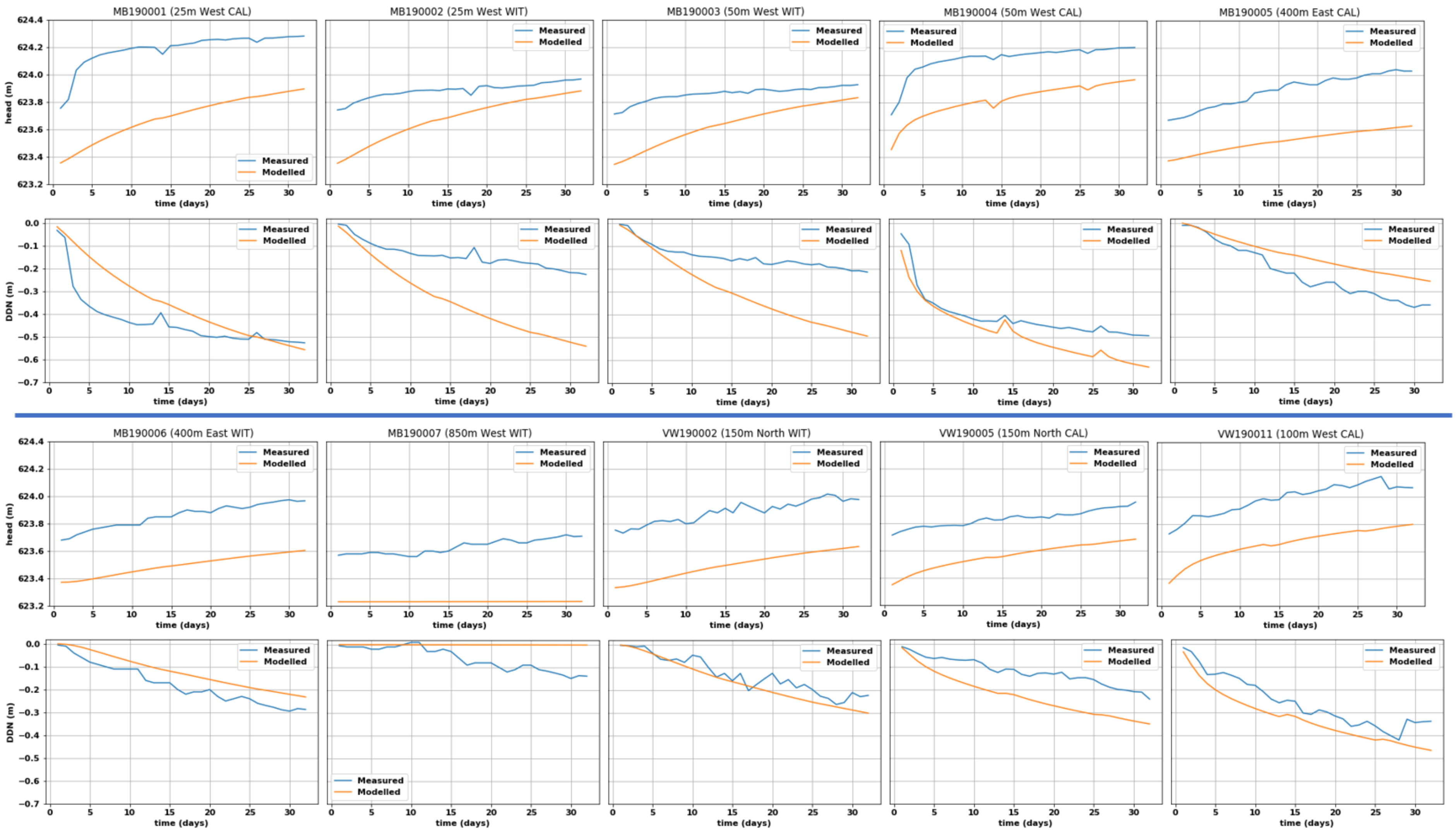

MB190001 (25m West CAL)
MB190002 (25m West WIT)
MB190003 (50m West WIT)
MB190004 (50m West CAL)
MB190005 (400m East CAL)
MB190006 (400m East WIT)
MB190007 (850m West WIT)
VW190002 (150m North WIT)
VW190005 (150m North CAL)
VW190011 (100m West CAL)
head (m)
DDN (m)
time (days)
Measured
Modelled

Figure 25. Observed and simulated head (m) and drawdown (DDN, m) for the MAR trial bores. Negative drawdown indicates impress. CAL and WIT are calcrete and weathered Wittenoom Formation. Distance from injection bore is noted in plot titles.

4.4. Conditioning an Ensemble Using Steady-State and MAR Trial Data

An ensemble of models featuring pilot point parameters was conditioned using PESTPP-IES (White, 2018, White et al., 2020). The objectives for developing the ensemble are to (1) assess the range of potential unmitigated drawdown at the KNP boundary from dewatering Pit D, and (2) use the ensemble with PESTPP-OPT (White et al., 2018, White et al., 2020) to obtain an optimised injection sequence for the MAR that also accounts for the uncertainty in the model predictions.

A model was configured with an initial steady-state stress period followed by 31 daily transient stress periods simulating the MAR trial injection. The steady-state dataset included absolute hydraulic head measurements, whilst the MAR trial dataset was converted to temporal difference head measurements minimising potential bias from boundary conditions. The pre-existing pilot point distribution used for the steady state calibration (Figure 18a) was augmented with a 500 m spacing uniform grid of pilot points in the area between the KNP boundary and Pit D (Figure 26).

A parameter uncertainty file comprising the standard deviation for probability of drain conductance and covariance matrices for pilot point parameter groups was included. Sill values for variograms in the pilot point statistical specification files used by *ppcov_sva* were set at log transformed variances corresponding to uniform probability distributions between parameter upper and lower bounds. This results in no increased likelihood for values between parameter bounds whilst maintaining geologically plausible pilot point parameter sampling by PESTPP-IES. Upper and lower bounds for parameters in both the calcrete and the weathered Wittenoom were extended to be commensurate with observed parameter ranges from the previous MAR trial calibration. Use of PESTPP-IES to condition an ensemble sampled in this manner accounts for both expert knowledge and historical system behaviour.

Zone boundaries were enforced by prohibiting kriging between the different geological formations represented in the model. Kriging of pilot point values to the model grid was performed by a combination of PLPROC’s *calc_kriging_factors_auto2D* and *krig_using_file*. Conditioned parameters included drain conductance, horizontal and vertical hydraulic conductivity, and specific yield.

The optimum number of models for the ensemble was 558 identified through eigen analysis of a prior Jacobian matrix using the *matsvd* utility from the PEST suite (see Moore and Doherty, 2005).

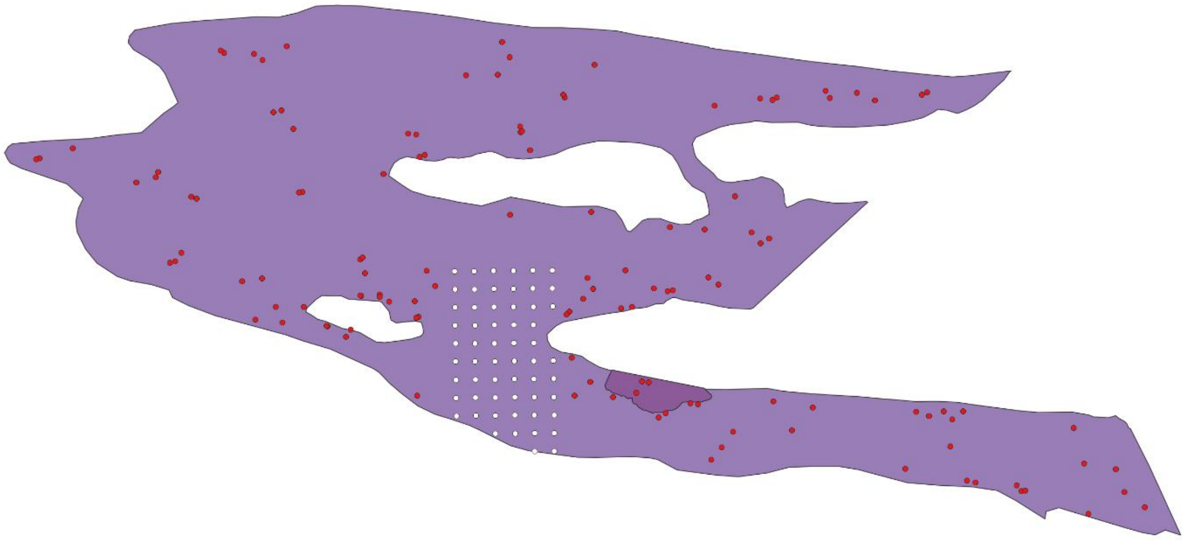


Figure 26 Pilot point distribution used in ensemble conditioning. Red – points from previous steady-state calibration. White – new grid of points added across MAR injection region.

Figure 27 and

Figure 28 summarise the ability of the ensemble of 558 models to simulate both the steady state head dataset and the transient heads and drawdown observed in the MAR injection trial. The range of steady state head values produced by the 558 models for each observation point was less than approximately 2 m (Figure 27). At least 50% of models simulated steady-state head values within 0.5 m of observed for the majority of observation locations. All simulated heads were within approximately 2 m of observed. The ensemble of models also simulates the impress observed at various observation locations during the MAR trial.

Figure 28 demonstrates that the transient system response behaviour, observed as the change in slope of the hydrograph with time, is captured reasonably well by the calibration. However, the absolute hydraulic head values show observation-simulation mismatches that range between 0.0 m and 0.3 m. Some mismatch is expected because higher weighting was given to temporal head differences over absolute hydraulic head for better storage parameter calibration. In addition, the spacing of some of the observation bores are close to a single model cell providing very little opportunity for parameter adjustments in the model to account for the effects of local scale heterogeneity

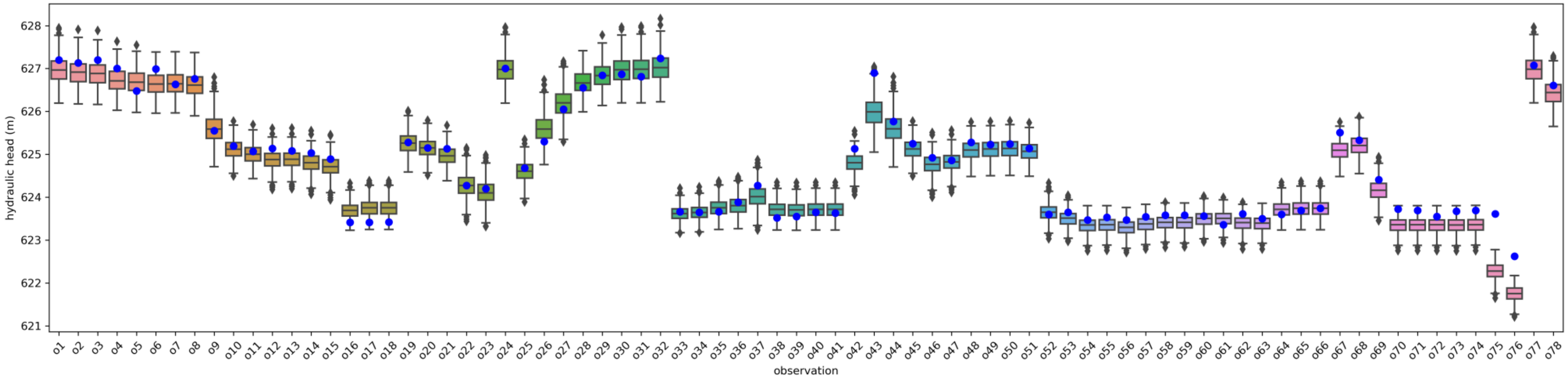


Figure 27. Box-and-whisker summary of steady state calibration results for the conditioned ensemble of 558 models. The blue dot represents the steady state head target. The box in the box and whisker plot represents 50% of the simulation results. The horizontal line represents the mean value for all simulations. The whiskers approximate 100% of all model results after assessing outliers.

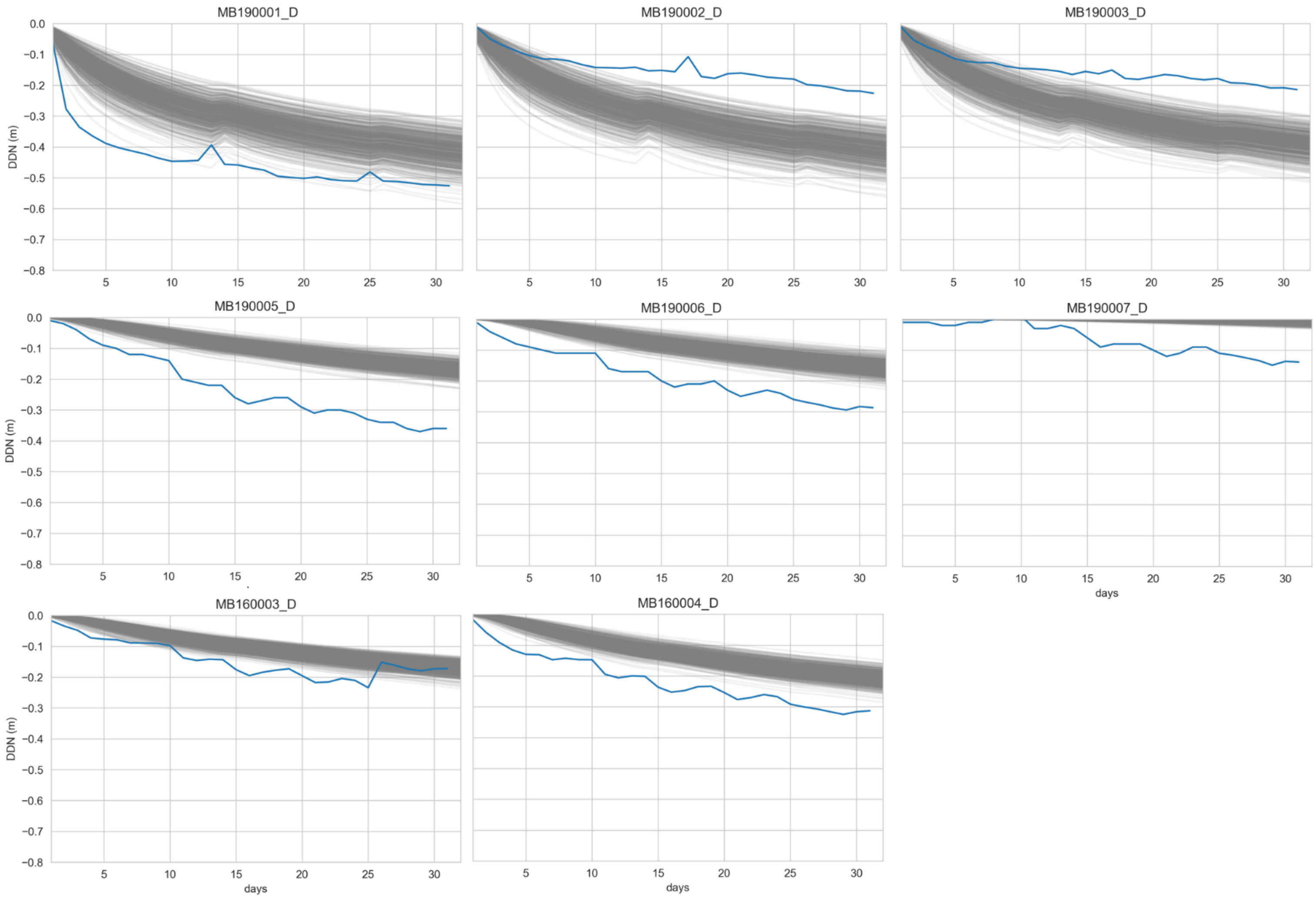


Figure 28. Comparison between observed impress (negative drawdown) during the MAR trial and impress simulated by the ensemble of 558 models.

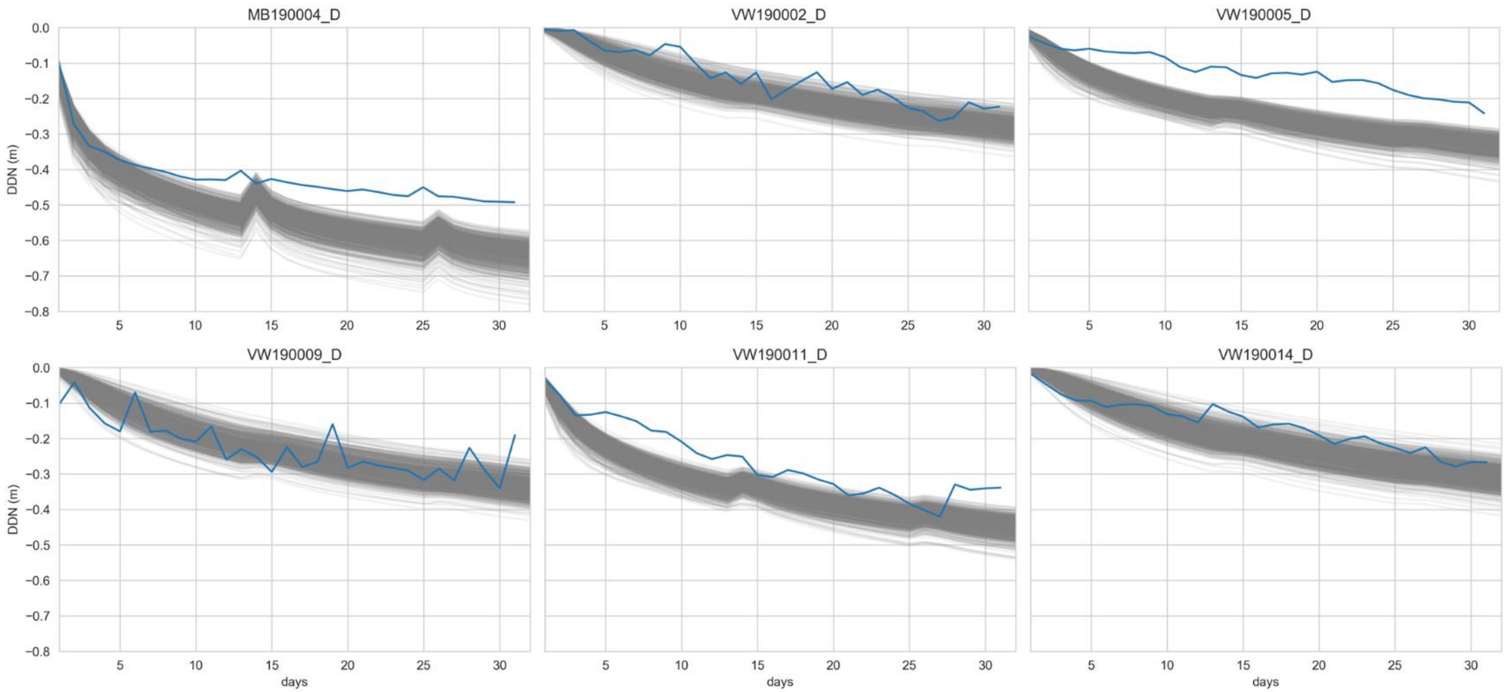


Figure 28 (continued). Comparison between observed impress (negative drawdown) during the MAR trial and impress simulated by the ensemble of 558 models.

5. Transient Simulation of Unmitigated Drawdown: Dewatering of Pit D1

The ensemble of models described in Section 4.4 were then used to simulate unmitigated drawdown impacts from Pit D1. Pit D1 is the current focus as it requires the greatest reduction in groundwater levels Dewatering is implemented in the model via drain cells over the maximum pit footprint.

Fixed fortnightly time steps were used and drain conductance for the pit was set at 100 m^2/d. Details of drain elevations are provided in IGS (2020a). The conductance was selected by trial and error seeking a sufficient rate of water table decline without excessive iterations from the solver or evidence of numerical instability.

Figure 29 shows simulated unmitigated drawdown at 15 different locations along the Karijini National Park boundary and Figure 30 to Figure 32 show contours of the simulated maximum unmitigated drawdown from the ensemble of 558 models at different times. Maximum impacts at the KNP boundary occur within 20 years post-mining (~35 years total simulation time) in the south but in the north, drawdown continues to increase with time beyond 85 years post-mining (100 years of simulation time).

Figure 29 shows that the conditioned ensemble comprises model realizations that simulate drawdown impacts in two distinct bands. The high impact band contains 126 models and the low impact band contains 432 models. This is thought to occur largely due to significant differences between the models in the properties of the Detrital aquifer surrounding the calcrete in Layer 2. The most notable differences are the horizontal hydraulic conductivity and specific yield of the Detrital aquifer adjacent to the calcrete (Figure 33).

Due to their mode of deposition, Detrital aquifers are very heterogeneous, and the prior parameter distribution implemented in PESTPP-IES for the Detritals was broad implying large uncertainty. Additionally, there are only two steady-state head observations in the Detritals and no transient observations from the MAR trial in this unit (the water table remained within the calcrete, which is extensive across the MAR area) to constrain its parameter distribution. Moreover, the lateral boundary between the calcrete and the Detrital aquifer and the degree of connectivity between these aquifers is unconstrained by drilling information.

The current model design features a discrete boundary between the calcrete and Detrital aquifer delineated according to RTIO's geological model. Aquifer properties are interpolated between pilot points within zones/formations only, which results in a number of calibrated models with a definite contrast in properties across the calcrete / Detrital boundary (Figure 33). The magnitude of this contrast influences drawdown propagation resulting in the bimodal distribution of unmitigated impacts observed in Figure 29. There was no indication of a bimodal distribution in the ensemble when assessing model behaviour with the observation dataset used in calibration. (Figure 27 and Figure 28). Regardless, the current model design honours the existing conceptual model, and the resulting two bands of unmitigated impacts provides an appreciation for the influence that uncertainty in Detrital properties has over model predictions.

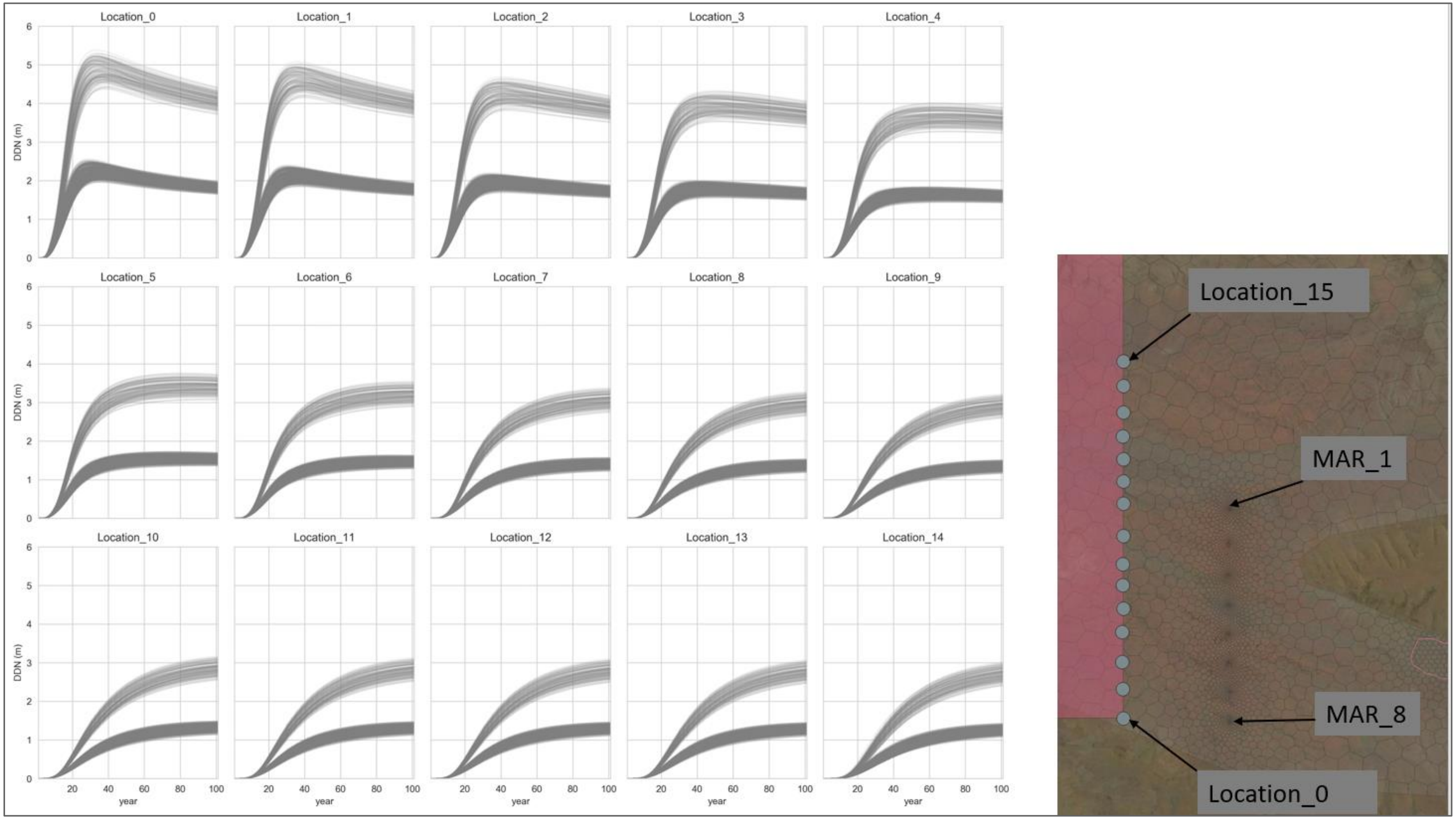

Location_0
Location_1
Location_2
Location_3
Location_4
Location_5
Location_6
Location_7
Location_8
Location_9
Location_10
Location_11
Location_12
Location_13
Location_14
DDN (m)
year
Location_15
MAR_1
MAR_8
Location_0

Figure 29. Simulated unmitigated drawdown at points along the Karijini National Park boundary using the ensemble of 558 models. Model observation locations are shown in the location map relative to the locations of planned MAR bores 1 to 8 (MAR_1 to MAR_8).

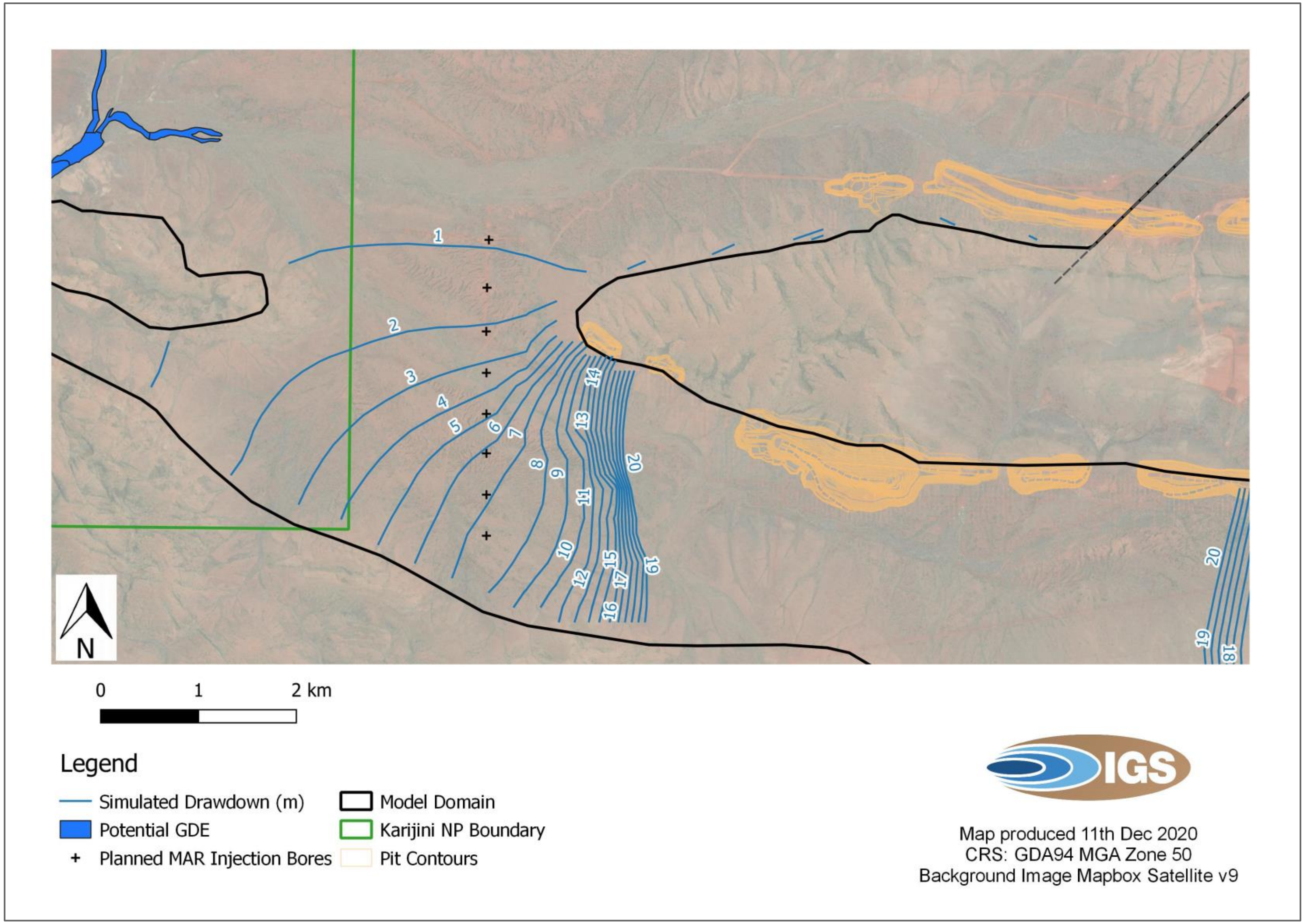

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
19
20
20
19
18
N
0
1
2 km
Legend
Simulated Drawdown (m)
Potential GDE
Planned MAR Injection Bores
Model Domain
Karijini NP Boundary
Pit Contours
IGS
Map produced 11th Dec 2020
CRS: GDA94 MGA Zone 50
Background Image Mapbox Satellite v9

Figure 30. Simulated maximum unmitigated drawdown from the ensemble of 558 models five years after the end of dewatering of Pit D1.

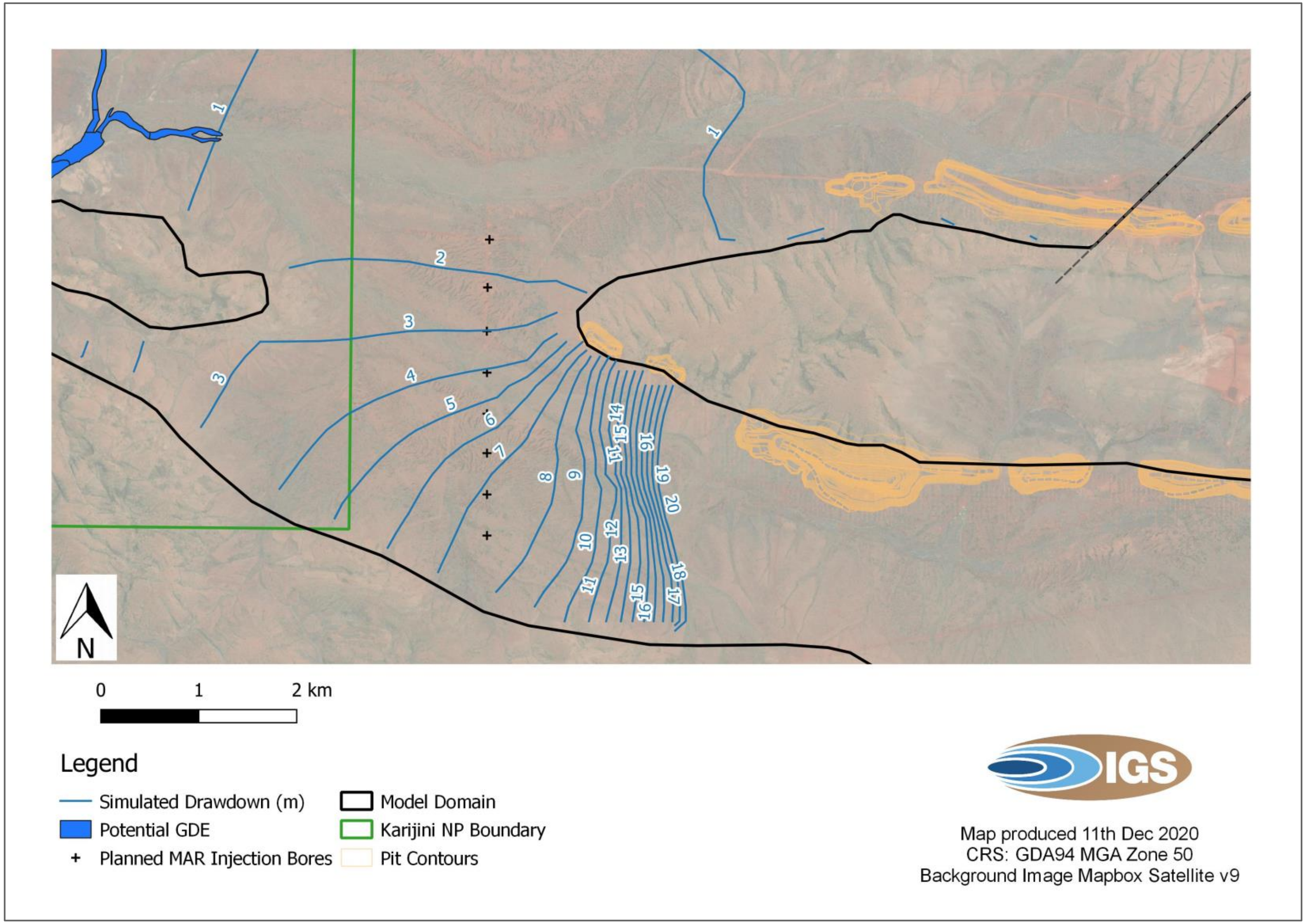


Figure 39. Simulated maximum unmitigated drawdown from the ensemble of 558 models 15 years after the end of dewatering of Pit D1

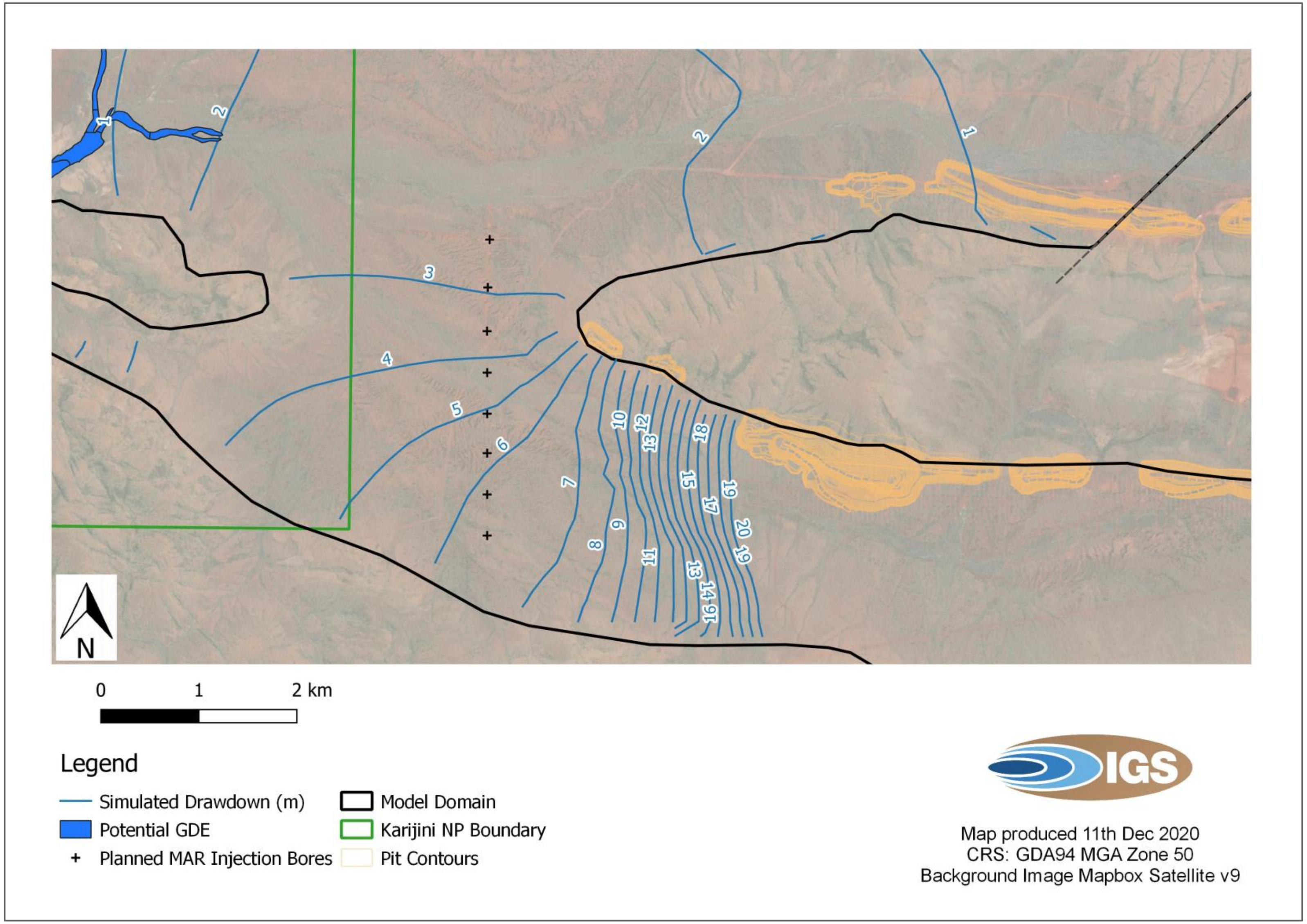


Figure 32. Simulated maximum unmitigated drawdown from the ensemble of 558 models 35 years after the end of dewatering of Pit D1.

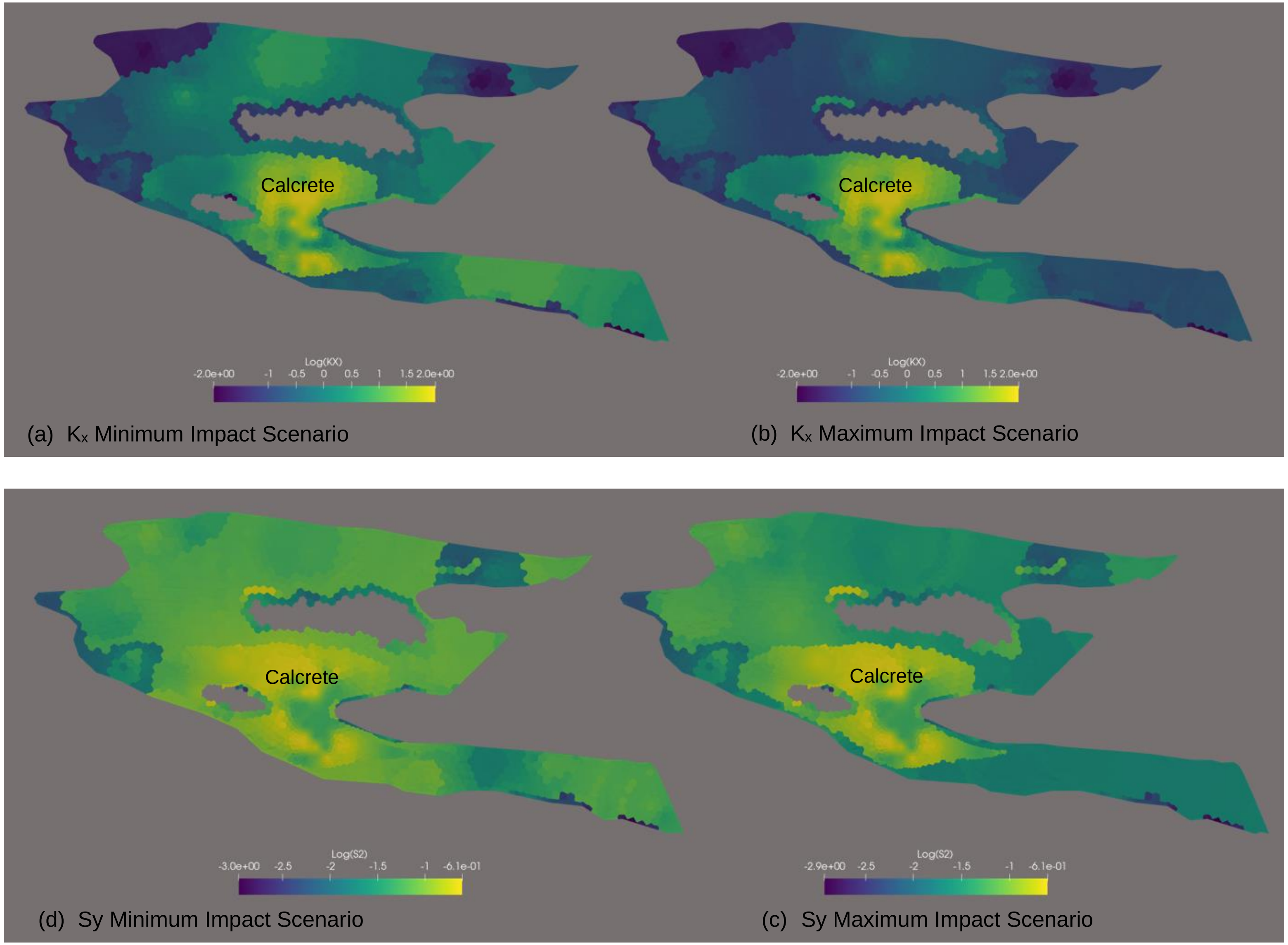


Figure 33. Differences in Kx and Sy for Layer 2 (Calcrete and Detritals) for the minimum and maximum impact scenarios shown in Figure 29.

6. Optimization of MAR Injection Rates

6.1. METHODOLOGY

The ultimate objective of the numerical studies described in previous sections was to achieve an appropriate ensemble of plausible models for use in a calibration-constrained optimisation of the MAR injection to achieve zero drawdown at the KNP boundary. PESTPP-OPT (White et al., 2018) was selected as the most suitable application to perform this analysis. The benefit of calibration-constrained optimisation over standard optimisation methods is the inclusion of predictive uncertainty, thus making it ideal for risk-based decision support. Confidence in resource management decisions can be explored with the numerical model synthesizing current system knowledge and behaviour.

A model capable of simulating mitigation of the drawdown via the MAR scheme was developed. It is identical to the model used for assessing unmitigated impacts but includes the MAR injection bores and has yearly stress periods. The approach implemented by PESTPP-OPT requires decision variables and observation constraints. For the present analysis, the decision variables are the injection rates at each MAR bore during each stress period. That is, eight injection rates for each of 100 yearly stress periods totalling 800 decision variables. Cost coefficients are assigned to the decision variables, weighting them according to stress period length. The coefficients are determined by dividing the stress period length of the decision variable by the total simulation time. This effectively creates a pseudo-volume since the decision variable rates are multiplied by coefficients that represent a time period. The optimisation therefore seeks to find the total minimum injection volume that also maintains adherence to the maximum number of observation constraints. Put another way, PESTPP-OPT minimises the cost (pseudo-volume) associated with the parameters (injection rates) while using the observation constraints as guides. This contrasts with a utility like PEST that adjusts the parameters (injection rates) to minimise the mismatch between simulation and observation constraints.

The observation constraints are configured as drawdown impacts at the KNP boundary that must be maintained within a specified margin. These constraints are set for the end of each transient stress period. Constraints of less than 0.1 m drawdown and greater than -1.0 m drawdown were set along the KNP boundary, thereby setting an acceptable water table change as the formal constraint. Note, negative drawdown at the KNP boundary represents an impress, which is implicitly minimised because PESTPP-OPT is targeting the minimum pseudo-volume. A range of injection rates between 0.0 and 40.0 L/s were provided for the decision variables based on advice from RTIO about maximum potential pump capacity. Extra observation constraints were added to (1) prevent the impress head from exceeding surface elevation near the injection bores, and (2) limit total injection within a year to be commensurate with existing capacity to deliver water to the MAR scheme. The latter was implemented to ensure the optimisation doesn’t produce a solution that exceeds the volumetric capacity of the infrastructure piping water from the dewatering scheme to the MAR site. The maximum and minimum bounds on injection rates are also constraints on the solution but these are strictly enforced throughout the optimisation.

The optimisation strategy adopted a “stack based” approach for observation constraint uncertainty. This method assesses the uncertainty in observation constraints via a conditioned ensemble of models. Uncertainty in observation constraints is re-assessed by running the entire ensemble following each update to the decision variables (injection rates in this case).

The confidence percentage metric used by PESTPP-OPT's stack-based methodology is dependent on all the observations in the stack, that is, every observation in every stress period from each ensemble member. For example, a 70% confidence optimised solution translates to 70% of all constraints being respected across all models. This means that some models in the ensemble may, for example, not have any constraints respected, while other models may have all constraints respected. The bimodal distribution of unmitigated impacts (see Figure 29) reduces the feasibility of achieving a risk averse optimised solution (i.e., >50% confidence) and preliminary analysis revealed the full ensemble was only capable of achieving a feasible solution with maximum confidence of 61%. Consequently, the decision was made to split the conditioned ensemble into two separate groups and target two high-confidence risk-averse optimised injection sequences instead of a single low-confidence or potentially risk-tolerant (i.e., <50% confidence) solution. The groups were split according to their unmitigated impact predictions at the southern end of the KNP boundary. Models with drawdown impacts less than 4.0 m were grouped as Stack A (432 models), while those with greater impacts formed Stack B (126 models). Stack A achieved a feasible solution at 91% confidence while Stack B attained 93% confidence.

The solutions provided by PESTPP-OPT do not guarantee perfect adherence to observation constraints and are therefore unable to demonstrate with 100% confidence that the existing MAR infrastructure can prevent drawdown propagation into the KNP. Accordingly, an end member analysis was performed using the maximum and minimum unmitigated impact models of the complete ensemble (Figure 29). The covariance matrix adaptation evolutionary strategy (CMAES_P) global optimiser in the PEST (Doherty, 2020a) suite was used to obtain injection sequences that provide strict adherence to the impact constraints at the KNP boundary. In contrast to PESTPP-OPT, CMAES_P implements an objective function that is observation dependent. CMAES_P was selected because of the non-linear response to drawdown observations at the KNP boundary from injection at the MAR site. Unlike PEST, CMAES_P's performance is not dependent on derivatives of model outputs with respect to adjustable parameters. The decision to use CMAES_P was deemed appropriate when a trial run achieved solution in less than 800 model realisations, which is the minimum number of realisations PEST requires to build its initial sensitivity matrix. While observation constraints in PESTPP-OPT were configured as greater-than or less-than via the control file, producing equivalent constraints for CMAES_P required the use of PEST's observation post-processor, *obs2obs*. Observations were configured for zero contribution to the objective function unless the greater than or less than constraint was violated.

6.2. RESULTS

The optimised injection sequences are provided in IGS (2020a). Figure 42 shows the effects of the optimised injection along the KNP boundary for each member of the ensemble. The impress constraint at the KNP boundary is never transcended in any simulation but drawdown exceeds 0.1 m in all simulations most notably in the southern regions (locations 0 to 4). This is unsurprising given a less than 100% feasibility for the solution. Recall that PESTPP-OPT does not strictly enforce observation constraints but instead uses them to guide a solution and quantify feasibility. It is also seeking a single injection sequence that uses the least injection volume yet meets 91% of the prescribed constraints across all simulations in Stack A.

For Stack B drawdown constraints are exceeded in the southern region of the KNP albeit to a lesser extent and in later years than those observed in Stack A (Figure 43). However, impress along the entire park boundary is noticeably larger in the majority of simulations.

No constraint exceedances are observed for both CMAES_P solutions (Figure 44), which is unsurprising given the constraint focused objective function implemented in CMAES_P. Indeed, the drawdown constraint is maintained at almost 0.0 m for both solutions despite a threshold of 0.1 m. The integrated injection constraint associated with water delivery capacity to the MAR site remains unsurpassed throughout all solutions (conservatively set at 120 L/s).

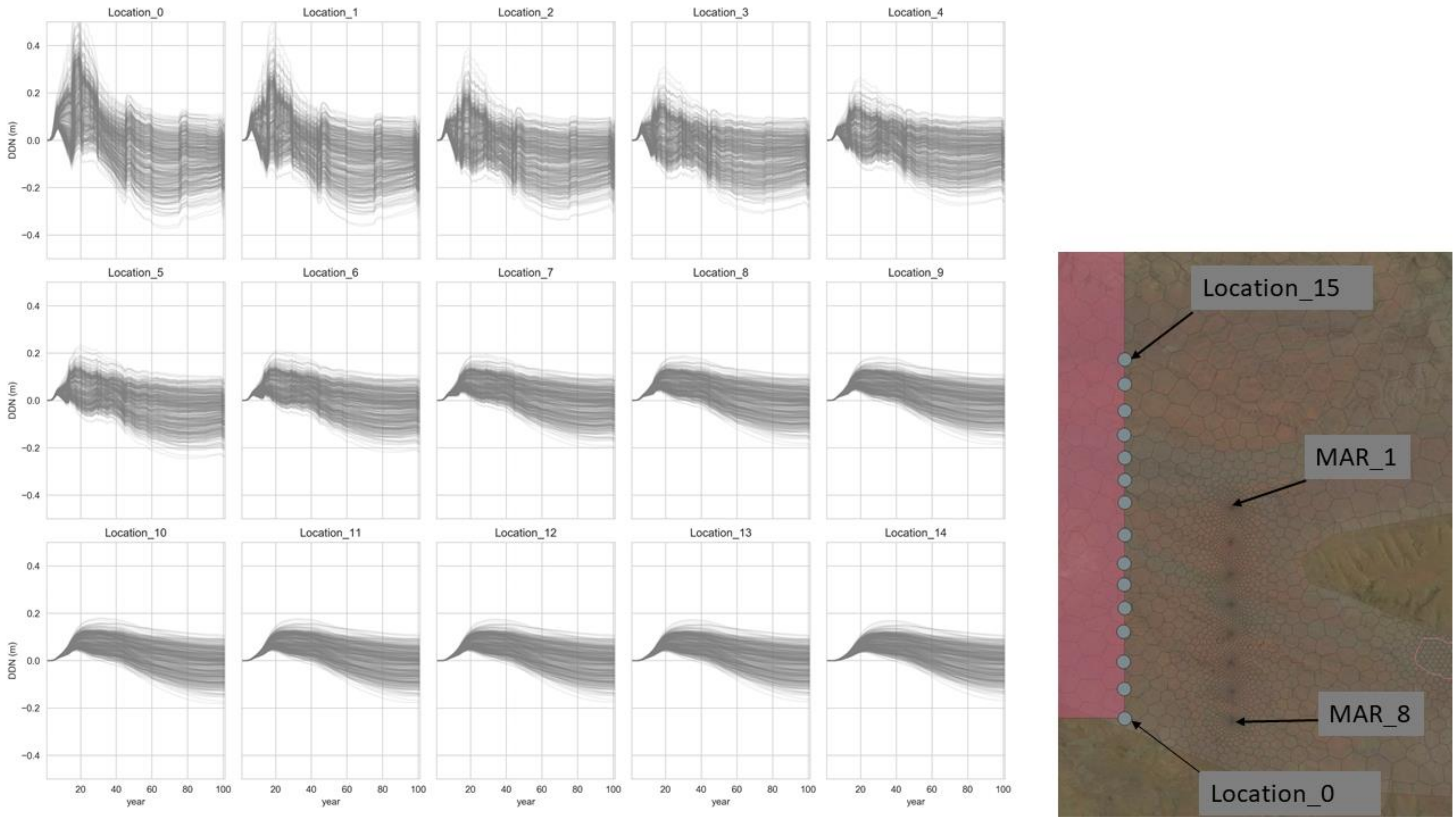


Figure 42. Stack A ensemble mitigated impacts along the KNP boundary. Note negative drawdown indicates impress.

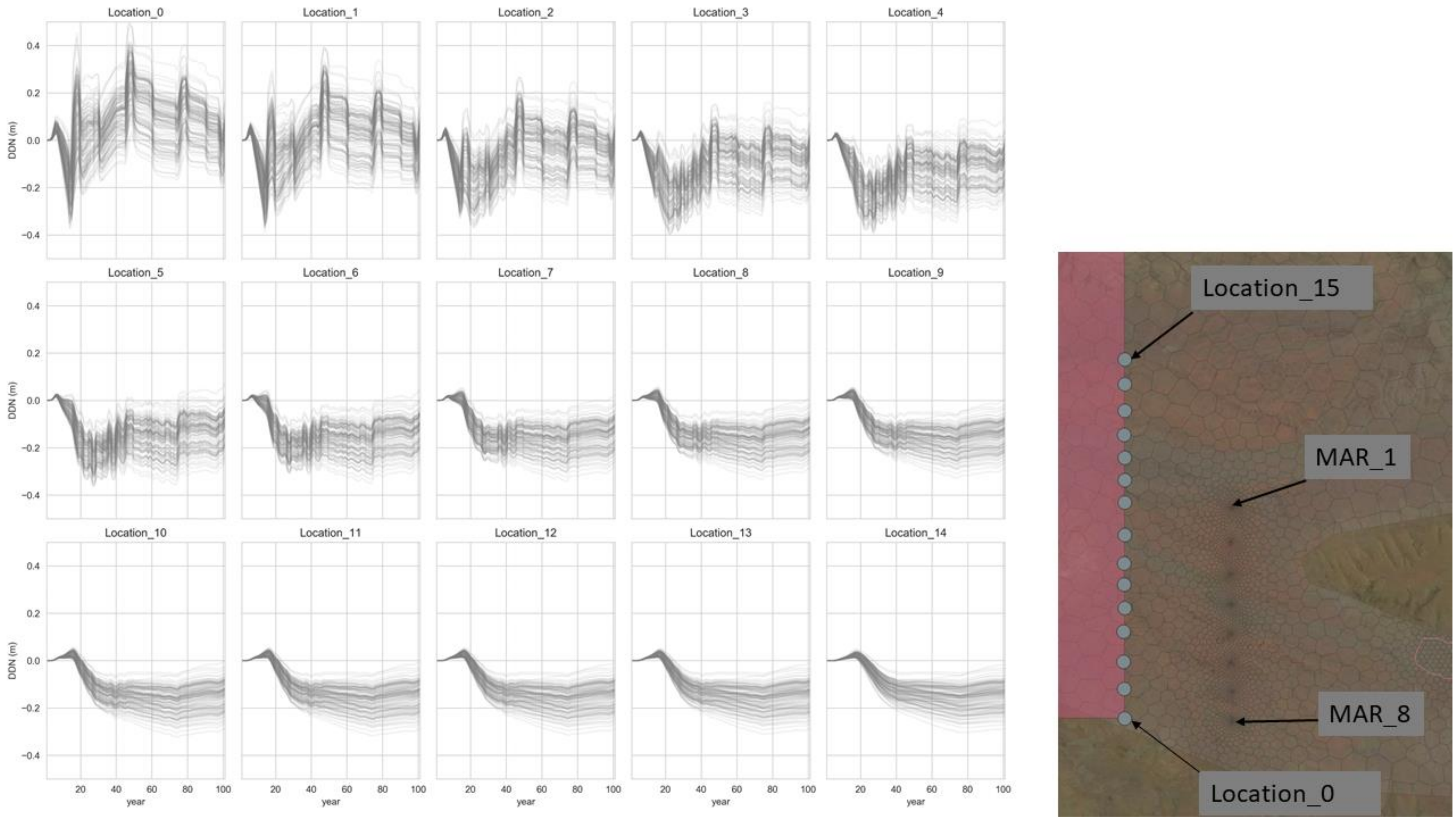


Figure 43. Stack B ensemble mitigated impacts along the KNP boundary. Note negative drawdown indicates impress.

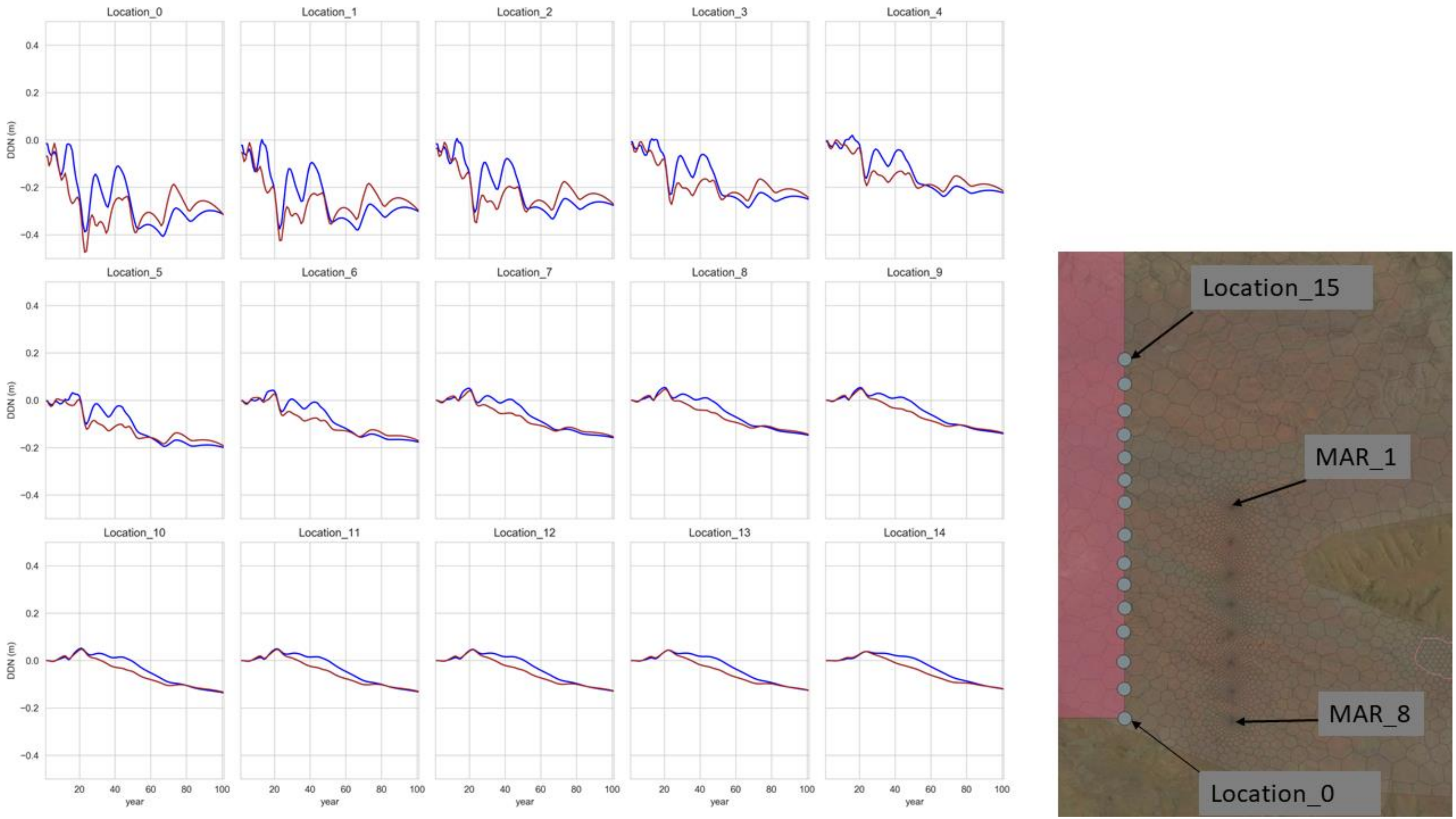


Figure 44. Maximum (red) and minimum (blue) mitigated impact model simulation results along KNP boundary. Note negative drawdown is an impress.

6.3. DISCUSSION

The end member analysis demonstrates the capacity for the present MAR infrastructure to mitigate the likely propagation of drawdown to the KNP boundary associated with dewatering in Pit D. The CMAES_P simulations implicitly account for uncertainty because they represent the two extreme impact prediction models derived from the conditioned ensemble. The differences in the solutions between CMAES_P and PESTPP-OPT are expected because of the differences in the objectives between the two methods. PESTPP-OPT accounts for uncertainty in its optimisation while simultaneously minimising the amount of injection required. CMAES_P solves the optimisation problem framed by the constraints for a specific model without accounting for uncertainty or seeking to minimise the total volume of injection. Nevertheless, the solutions share several common characteristics. The smaller impact models require a greater amount of injection over the peak period, which is likely related to the differences in parameters discussed previously (IGS, 2020a). High specific yield values combined with high hydraulic conductivity requires a greater volume to change hydraulic head. The larger impact models have the opposite combination of parameters that is lower specific yield and lower hydraulic conductivity, which increases the sensitivity of hydraulic head response to a given stress. The locations and timing of the peak injection is consistent across all models and solutions (IGS, 2020a). This reflects the results from the unmitigated impact simulations using the complete ensemble where drawdown was observed to propagate faster in the south than the north. The configuration of the numerical model is for a single injection rate per bore per year. In reality, this can be varied at a much smaller temporal scale. For example, injection rates at different bores can be varied fortnightly or monthly providing significantly finer control of mitigation measures. The implication here is that the simulated impacts are undoubtedly exacerbated due to the lack of fine temporal resolution in the simulated MAR operation. Additionally, the solutions are only representative of the plausible timing of injection volumes that will be required.

7. Preliminary Risk Assessment for Contaminant Transport to Karijini National Park

7.1. METHODOLOGY

Particle tracking was implemented in forward mode with both the maximum and minimum CMAES_P models, which represent the end members of the conditioned ensemble. Forward particle tracking involves using particles placed in the aquifer at a specific time and tracing their movements forwards in time throughout the numerical simulation until they either reach a receptor or exit the model via an external boundary. The objective of this work is to assess the likely pathways and conservative travel times of injected water focusing on impacts at the KNP boundary. Accordingly, the particles are placed in the model at the screen locations of the MAR injection bores within the calcrete at the start of the simulation. The particle tracking code mod-PATH3DU (SS Papadopoulos and Associates, 2014) was selected for the analysis primarily because of its compatibility with MF-USG and the Voronoi grid used in the present model.

Both the maximum and minimum impact mitigated models featuring the injection sequence solutions from CMAES_P were used. Recall that both models demonstrate strict adherence to the impact thresholds with virtually zero drawdown and minimal impress impact at the KNP boundary over a 100-year period. Particle tracking results depict advective transport and are consequently dependent on the porosity or more specifically effective porosity, assigned to the aquifers. For the present analysis conservative values were selected that promote greater advection in the calcrete (porosity = 0.05) and weathered Wittenoom Formation (porosity = 0.05) through which the particles flow. An effective porosity of 0.05 for the calcrete is very conservative (i.e., will result in most rapid particle migration in the aquifer) given the evidence for dissolution channels. This porosity is also conservative for the weathered Wittenoom Formation as it is less than half of the calibrated specific yield value (approximately 0.11) from the MAR trial.

7.2. RESULTS

Particles are plotted once every 365 days along their tracks with a graduated colour scheme starting at white for year 1 and finishing at red for year 100. Tracking in both simulations (Figure 45 and Figure 46) demonstrate that particles primarily migrate towards Pit D because of the gradient induced by dewatering, which is further enhanced at bores 7 and 8 when they are injecting. Accordingly, particles originating from those bores have the greatest travel distance over time. Both scenarios have little to no injection from the rest of the MAR scheme which results in significantly less particle advection from these locations. The migration of particles to the north-west from MAR bore 1 is consistent in both simulations and is representative of the prevailing flow field in this region and not a response to injection.

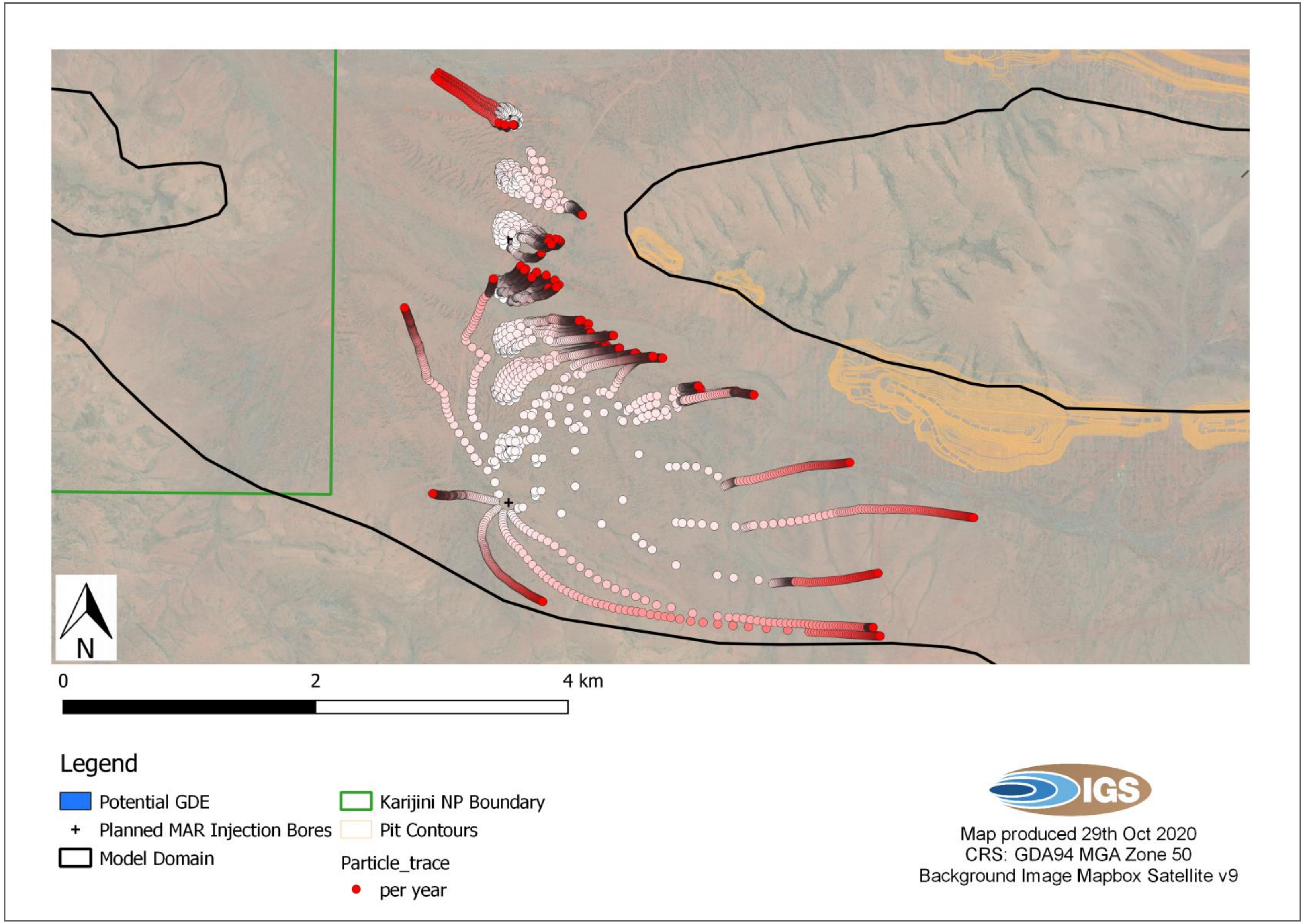
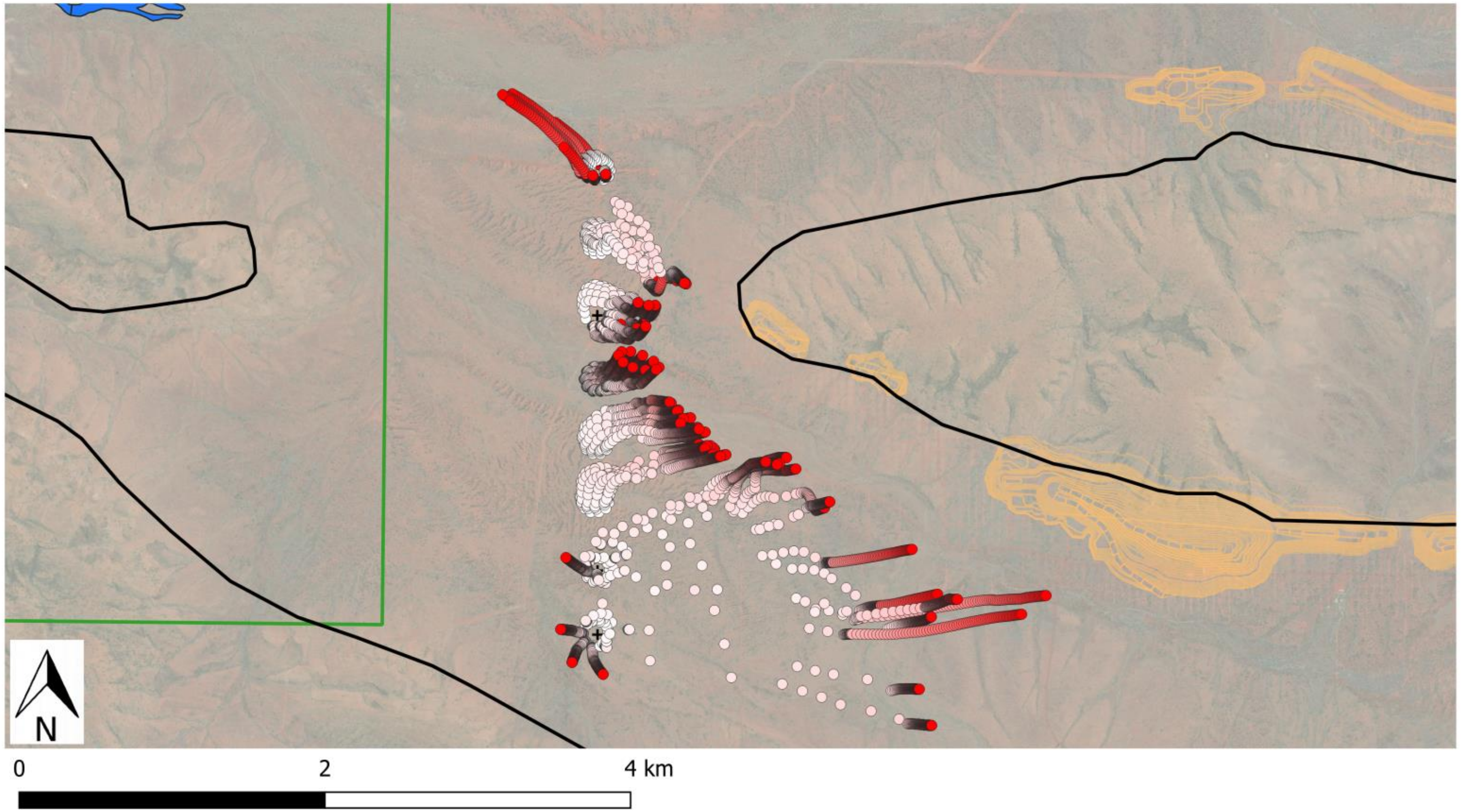

N
0
2
4 km
Legend
Potential GDE
Planned MAR Injection Bores
Model Domain
Karijini NP Boundary
Pit Contours
Particle_trace
per year
Map produced 29th Oct 2020
CRS: GDA94 MGA Zone 50
Background Image Mapbox Satellite v9

Figure 45 Particle tracking solution of mitigated maximum impact model for 100 years. Note each subsequent point is location after +1 year.



Legend

- Potential GDE
- + Planned MAR Injection Bores
- Model Domain
- Karijini NP Boundary
- Pit Contours

Particle_trace

- per year

Map produced 29th Oct 2020
CRS: GDA94 MGA Zone 50
Background Image Mapbox Satellite v9

Figure 46 Particle tracking solution of mitigated minimum impact model for 100 years. Note each subsequent point is location after +1 year.

7.3. Discussion

The results of the particle tracking simulations suggest that water quality impacts at the KNP boundary are unlikely to occur as a result of injection at the MAR scheme. However, it should be noted that particle tracking represents the centre of mass of the injectant and thus does not include mechanical dispersion. On the other hand, use of overly conservative porosities greatly enhances the advective flow velocity, thereby potentially overestimating the migration of injectant centre of mass away from the MAR bores. Simulations featuring less conservative, more realistic porosities in conjunction with dispersive effects will still yield injectant fronts that migrate shorter distances than the centre of mass presented in the results.

8. Hydrograph Analysis and Grey Box Modelling to Support Trigger Development and Assessment

8.1. Observed Historical Ranges of Water Level Declines

In order to develop appropriate water level triggers for both operation of the MAR scheme and regulatory purposes, it is necessary to investigate the natural ranges of water level declines in the area around the proposed MAR scheme and Karijini National Park. This is important to ensure that water level declines that are caused by natural climatic factors and that fit within natural system behaviour are not attributed to mine impacts. The approach adopted here attempts to synthesize information contained in hydrographs by providing statistical metrics of “normal system behaviour”. The focus is on rates of water level decline because the primary concern is avoiding drawdown impacts at the KNP boundary associated with mine dewatering.

Declines in water level over specific time frames at each location and then between locations were recorded. For a single hydrograph the procedure was as follows:

1. Obtain water level of hydrograph on day 1
2. Skip forward a fixed number of days and obtain water level
3. If the difference is a decline, record the change/rate otherwise do nothing
4. Move to day 2 in the record and repeat steps 1 to 3 until the end of the record
5. Plot a histogram of the observed declines
6. Select new number of fixed days and repeat steps 1 to 5

The procedure was automated with a Python script using monitoring bore hydrographs with continuous records for the last four years. A similar Python script was developed to assess hydraulic gradients between monitoring bores across the West Angelas region. This required first developing a table of monitoring bore combinations and the distance between them. The assessment the procedure was as follows:

1. Obtain first monitoring bore combination
2. Get first recorded date in hydrograph of monitoring bore 1
3. Check for a record on the same date in hydrograph of monitoring bore 2
4. If there is a common date, calculate the gradient and record the value
5. Move on to the next date and repeat steps 3 and 4 until the hydrograph ends
6. Plot a histogram of the observed gradients
7. Move on to next monitoring bore combination and repeat steps 2 through 6.

It is considered that a head change of more than 10 cm could be confidently measured using standard monitoring techniques. Anything less than this could be attributed to equipment and/or human error. Statistics show that, for time periods less than approximately 60 days, most historical head declines recorded in the monitoring bores to the east of Karijini National Park (MB16WAW0001 to MB16WAW0010) have been less than 10 cm, i.e. within the range of possible error (IGS, 2020a). For time periods between 90 days and 360 days, head declines between 10 and 25 cm become more common. These trends are variable between bores and it should be noted that the analysis is based on approximately four years of data only.

Based on the above assessment, any observed head declines in the MB16-series monitoring bores of more than 10 cm over 30 to 60 days, or more than 25 cm over 90 to 360 days may warrant further investigation.

The above is also generally true for bore WANG14, which is situated adjacent a potential GDE within Karijini National Park. However, the hydrograph for this bore shows the occurrence of occasional rapid water level rises associated with preferential recharge due to surface water flow events. These rapid water level rises are also followed by rapid declines in water level, which correspond to water level declines of up to approximately 0.85 m over 30 to 360-day periods (IGS, 2020a). Therefore, any observed head declines up to 0.85 m (and greater) at this bore require confirmation that they are not associated with recovery of the water levels following a rapid recharge event prior to being attributed to mining impacts.

8.2. Historical Ranges of Hydraulic Gradients

As well as changes in water levels at individual points, mine dewatering impacts may be observed as an increase in hydraulic gradient towards the mine pit. Frequency analysis of hydraulic gradient between individual monitoring points have been developed. Historical measured hydraulic gradients between all MB16-series monitoring bores (for all times when there were head measurements available for both bores) range between -500μ and 450μ but are most commonly between -50μ and 50μ (IGS, 2020a) . Negative values indicate gradients approximately towards the pit, whilst positive values indicate gradients approximately towards KNP (i.e. depending on the orientation of the bore-pair). A value of 50μ corresponds to a gradient of 5 cm in 1 km. Historical gradients can be used to identify the magnitude of a negative gradient for each bore pair that would be considered outside the normal.

8.3. Grey Box Modelling to Assess Mine Contributions to Hydraulic Head Declines or Increased Hydraulic Gradients

8.3.1. Overview

Time series (TS) analysis of groundwater monitoring bore hydrographs can be used to assess the effects of climate variability, groundwater pumping, river stage variation and tides. It's application to identify the effect of land use change or engineering works has been minimal despite the development of sophisticated monitoring networks and analysis software. TS models are much simpler and give better fits than typical groundwater models. The inclusion of response functions with a TS model provides valuable insight into why heads vary at a specific location. This is preferable to using black-box modelling based on artificial intelligence. Accordingly, the term grey-box model is used synonymously with TS models that include response functions. Unlike the governing equations for a typical groundwater model (or white-box model), the response functions in a grey-box model do not explicitly represent physical processes. Nevertheless, there is always some physical basis for the inclusion of the response function/s. Grey-box modelling is therefore characterised as a semi-physical data-driven approach to find the relationship between input and output signals.

8.3.2. Methodology

The Pastas Python library (Collenteur et al., 2019) was used to perform the TS analysis and produce Grey Box models for a number of locations in the West Angelas region. Pastas is open source software for the analysis of groundwater time series and uses transfer function noise modelling to perform time series analysis. Inputs for the present analysis are:

1. an observation time series (usually the head observation hydrograph for a location)
2. stress time series such as precipitation, potential evaporation or pumping

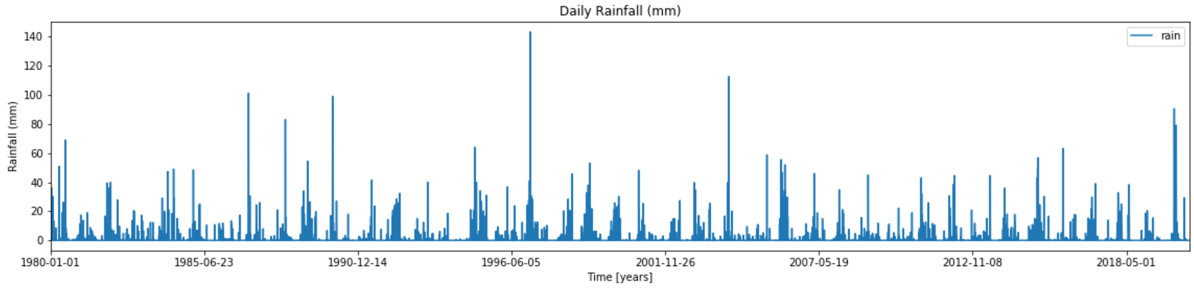
3. response functions assigned to the stresses (i.e., Gamma, Hantush or Exponential)

The Grey Box model parameters are then estimated using a non-linear least squares algorithm to minimize the sum of weighted squared noise. Models have been developed in this project for the following bores:

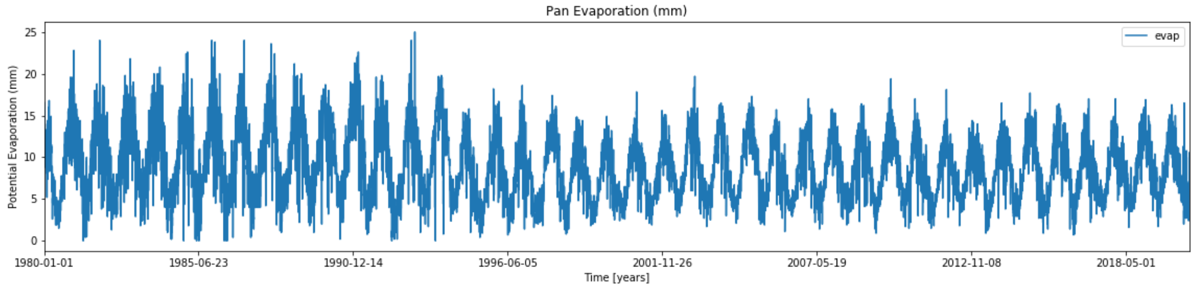
1. WANG14
2. MB16WAW0001 to MB16WAW00010

The input stresses comprise a combination of raw and processed rainfall and evaporation data from Paraburdoo weather station (

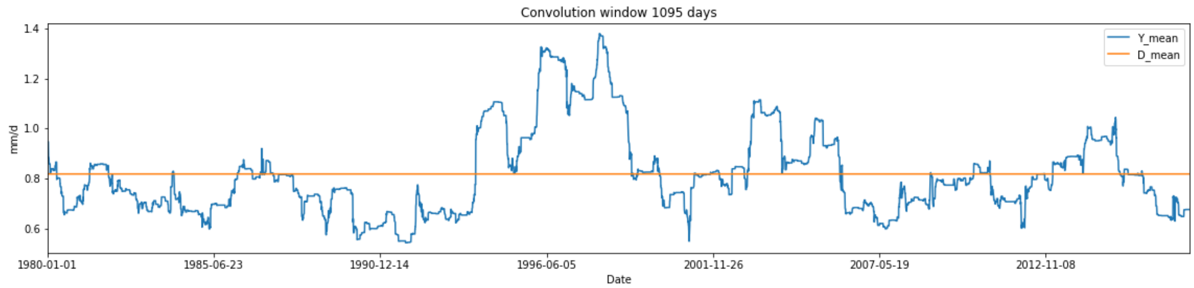
Figure 47). Response functions were trialed to ascertain those that produce the best fit to the observation datasets in each case. This includes multiple step functions for flow events in the ephemeral creek where groundwater levels are influenced by episodic recharge, and linear trends for wetter/dryer than long-term average periods (Figure 48). Steps and linear trends are linked to observations arising from processed rainfall data.



(a) Daily rainfall record.



(b) SILO interpolated pan evaporation data.



(c) 3-year rainfall running mean (blue line) compared to long-term mean (orange line).

Figure 47. Climate data for Paraburdoo (BoM station #7185).

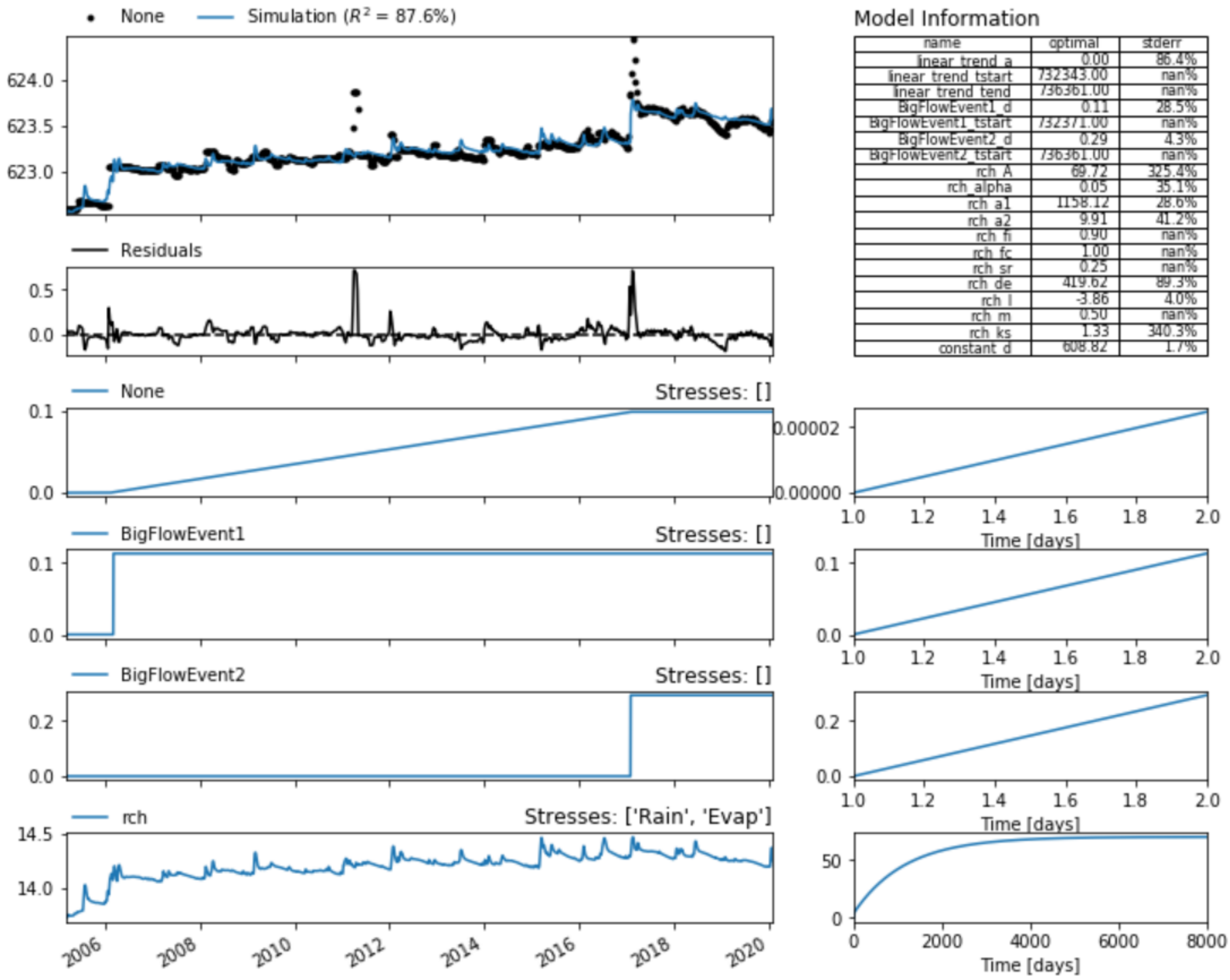


Figure 48. Examples of input stresses and final Grey Box Model (top graph) for observation bore WANG14, located near the potential Groundwater Dependent Ecosystem inside Karijini National Park.

8.4. Results

The Grey Box Model developed for bore WANG14 is shown in Figure 48. Grey Box models have similarly been developed for bores MB16WAW0001 to MB16WAW0010 (IGS, 2020a). The graph plotted at the top of Figure 48 depicts the simulated (pale blue line) model results overlying the observation time series. An R^2 value of 87.6% was achieved with the parameter set listed in the model information table to the right of the plot. A plot of the residuals is located below the simulated output. The stresses used as inputs are then plotted sequentially below the residual plot. These include in descending order, a linear trend, two step stresses and a combined precipitation and potential evaporation stress (combined as precipitation subtract potential evaporation). To the right of each input stress is a plot of their calibrated response functions that ultimately translates the input stress to the simulated hydrograph. The step stresses were necessary to capture the effects of large macropore recharge events that result in long term increases to water table elevation. The combined precipitation and potential evaporation stress captures the increasing trend between 2006 and 2017 but to a lesser degree than what is observed in the hydrograph prompting the inclusion of a linear trend stress.

8.5. Discussion

Once developed and calibrated, a Grey Box Model can be used as a tool to evaluate observed water levels against impact triggers / thresholds.

First, historical water level trends and historical maximum and minimum levels can be used to develop a set of early warning impact triggers and thresholds, whereby exceedance of these triggers would initiate a review of water level trends using the Grey Box model to determine the contribution of dewatering activities. The calibrated model parameters can be used throughout the life of mine to 'predict' water level responses as a result of trends in rainfall and evapotranspiration and therefore quantify the contribution of natural system responses to observed hydrographs. The Grey Box model is calibrated to natural head decline to assess and isolate non-natural decline associated with mine dewatering. Significant departure from the predicted system behaviour can be ascribed to anthropogenic influence triggering adjustments to MAR scheme operation. A second set of triggers specifically for mine-induced water level impacts would result in a management response.

9. Summary and Conclusions

A Managed Aquifer Recharge (MAR) Scheme is planned to offset drawdown impacts at Karijini National Park (KNP) as a result of dewatering West Angelas Deposits C and D. The West Angelas Groundwater Modelling project described herein includes several modelling tasks aimed at informing the design and operation of this MAR scheme, as well as the development of operational and management triggers. The major conclusions from the project are as follows:

Regional Model Development and Performance

A regional groundwater flow model has been developed to simulate both unmitigated drawdown impacts and the mitigation of these by the proposed MAR scheme.

Multiple calibration techniques were used in combination with both steady-state and transient water level datasets, including high-resolution temporal data from a MAR injection trial, to obtain a calibration-constrained ensemble of 558 plausible models that account for uncertainty in, amongst other things, aquifer hydraulic conductivity and storage properties.

In the ensemble of 558 models, 50% produced steady-state simulated head values within 0.5 m of observed values for the majority of observation locations. All simulated heads were within approximately 2 m of observed values.

The ensemble of models also simulates the system response behavior observed at various observation locations during the MAR trial with accuracy. Absolute hydraulic heads were not matched to the same degree, but this can be attributed to the weighting scheme adopted during the conditioning process and sub-optimal grid resolution between observation points.

Unmitigated Drawdown Impacts

Simulated drawdown impacts from dewatering of Deposit D travel more rapidly in the south of the model domain, reaching a maximum drawdown of between 1.9 and 5.2 metres within 20 years of the end of mining at the southern end of the KNP boundary. The impacts then migrate more slowly to the north, and drawdown continues to develop to more than 3.0 metres with time beyond 85 years post-mining at the northern end of the KNP boundary.

Although the water table occurs in the calcrete and weathered Wittenoom Formation across much of the study area, large uncertainty in the parameters and mode of connection of the Detritals with these formations appears to lead to large uncertainty in the simulation of drawdown impacts. This uncertainty is observed in the results of the current ensemble as two distinct groups of drawdown impacts, a low impact group (443 models) and a relatively higher impact group (115 models).

Simulation and Optimization of the MAR Scheme

The results from the unmitigated impact simulations using the complete ensemble (558 models) showed that drawdown propagates faster in the south than the north. The optimization solutions showed that the drawdown propagation can be mitigated with the southern-most bores providing the most effective use of injectant.

Because of the occurrence of two very distinct groups of ‘impact’ models, i.e. a ‘low impact’ and a ‘higher impact’ group, the ensemble of models was divided into these two groups for the purpose of optimization. This was done in order to achieve injection regimes that can address the full range of plausible scenarios with adequate confidence.

Two optimization methodologies were used to optimize MAR injection rates:

Method 1, PESTPP-OPT, attempts to minimise the injection volume, which is viewed in this method as a ‘cost’. In doing this, the optimized injection regime does not always achieve drawdown less than the imposed constraint of 0.1 m at all observation points along the KNP boundary in all model realizations for the specified group. The optimization derived using Method 2, CMAES_P, which has a more constraint-focused objective function than PESTPP-OPT, resulted in no constraint exceedances. Rather than optimizing the full ensemble of models, this method was used to optimize MAR injection for the maximum and minimum impact models only, a simpler method that still captures the full range of potential impacts.

The bulk of the uncertainty associated with MAR injection response can be attributed to the heterogeneity in model parameters representing the weathered Wittenoom Formation and the calcrete.

The optimization simulations were implemented with annual stress periods in the interest of minimising computation times. However, in reality, injection can be varied at a much smaller temporal scale, e.g. fortnightly or monthly. Use of a finer temporal resolution would undoubtedly result in improved mitigation of drawdown impacts.

Risks of Water Quality Impacts to Karijini National Park

The results of the particle tracking simulations suggest that water quality impacts at the KNP boundary are unlikely to occur as a result of injection at the MAR scheme. While the particle tracking approach does not include the effects of dispersion, the adoption of conservatively low effective porosities for both the calcrete and weathered Wittenoom Formation means the predicted distances of injectant migration are likely overestimated and thus precautionary.

Tools for Accounting for Natural Climate Variability in Setting and Assessing Water Level Triggers

There is no data available on the episodic and spatially variable (preferential) recharge processes in the study area and therefore inclusion of spatially and temporally variable recharge in a numerical groundwater flow model is neither feasible nor would it add any additional confidence to model results. The regional model itself therefore uses a conservative value for long-term annual average recharge and does not account for these processes.

However, robust and scientifically defensible tools are required for assessing the contribution of natural climate variability to observed groundwater level declines in order to confirm the magnitudes of mining-related impacts that require mitigation.

Frequency analysis (histograms) of historical head declines for monitoring bores and historical hydraulic gradients for monitoring bore pairs are used to better understand the groundwater system behaviour and inherent variability. The histogram analysis has identified that any observed head declines in the MB16-series monitoring bores of more than 10 cm over 30 to 60 days, or more than 25 cm over 90 to 360 days may warrant further investigation using Grey Box models. These trends are variable between bores and it should be noted that the analysis is based on approximately four years of data only.

Once developed and calibrated, Grey Box Models similar to the ones described in Section 8.3 can be regularly updated with new data and used as tools throughout the life of mine to determine the relative contribution of mine dewatering to observed changes in groundwater level and/or hydraulic gradient. The Grey Box model is calibrated to natural head decline to assess and isolate non-natural decline from mine dewatering.

10. Limitations

During the process of the current project, the following key limitations of the regional groundwater flow model and MAR optimization have been identified:

Uncertainty in hydraulic properties of the Detritals: The current model design features a discrete boundary between the calcrete and Detrital aquifer delineated according to RTIO's geological model. Aquifer properties are interpolated between pilot points within zones/formations only, which results in a number of calibrated models with a definite contrast in properties across the calcrete / Detrital boundary (Figure 33). The magnitude of this contrast influences drawdown propagation resulting in a very large and bimodal distribution of unmitigated impacts as observed in Figure 29 and provides an appreciation for the influence that uncertainty in Detrital properties has over model predictions.

Dykes: The simulated region presently excludes any effects from intrusive dykes, which could potentially further inhibit drawdown propagation to the KNP boundary given their estimated strike and dip from exploration logs. There is existing evidence of dykes that are effective barriers to flow in the region (presently used as an external boundary in the model). However, the function of dykes as barriers in the region between Pit D and the KNP boundary remains unclear. A dyke may also act as a conduit for flow, but this is expected to have little impact between Pit D and the KNP because the dykes run perpendicular to the direction of drawdown propagation.

Uncertainty in Hydraulic Properties of the Weathered Wittenoom and Calcrete: The bulk of the uncertainty associated with MAR injection response can be attributed to the heterogeneity in model parameters representing the weathered Wittenoom Formation and the calcrete. Therefore, uncertainty in these parameters is a key component of the uncertainty in the optimization process.

References

Arndt, N.T., Nelson, D.R., Compston, W., Trendall, A.E., and Thorne, A.M., 1991. The age of the Fortescue Group, Hamersley basin, Western Australia, from ion microprobe zircon U-Pb results: Australian Journal of Earth Sciences, v. 38, pp. 261–281.

Berendrecht, W. L., Heemink, A. W., van Geer, F. C., and Gehrels, J. C. 2006. A non-linear state space approach to model groundwater fluctuations, Advances in Water Resources, 29, 959–973.

Collenteur, R.A., Bakker, M., Klammler, G., and Birk, S. (in Review) Estimating groundwater recharge from groundwater levels using non-linear transfer function noise models and comparison to lysimeter data. https://doi.org/10.5194/hess-2020-392

Collenteur, R.A., Bakker, M. Calje. R., Klop, S.A. and Schaars. F. 2019. Pastas: Open Source Software for the Analysis of Groundwater Time Series. Groundwater, v. 57 p. 877-885

Dogramaci, S., Skrzypek, G, Dodson, W. and Grierson, P.F. (2012). Stable isotope and hydrochemical evolution of groundwater in the semi-arid Hamersley Basin of subtropical northwest Australia. J. Hydrol., v. 475, p 281-293.

Doherty, J., 2020a PEST Model-Independent Parameter Estimation - User manual Part 1 (7th ed), Watermark Numerical Computing, Brisbane, Australia

Doherty, J. 2020b. A simple lumped parameter model for unsaturated zone processes. Watermark Numerical Computing, Brisbane, Australia

Doherty, J., 2020c PEST Groundwater Data Utilities Part B: Program Descriptions, Watermark Numerical Computing, Brisbane, Australia

Doherty, J., 2020d PLPROC: A Parameter List Processor, Watermark Numerical Computing, Brisbane, Australia

Doherty, J., 2020e PEST Model-Independent Parameter Estimation - User manual Part 2 (7th ed), Watermark Numerical Computing, Brisbane, Australia

Domenico, P.A. and Schwarz, F.W. 1990, Physical and Chemical Hydrogeology, Wiley, New York 824 pp.

ESI (2017). Groundwater Vistas version 7. Environmental Simulations Incorporated. www.groundwatermodels.com.

HydroAlgorithmics, AlgoMesh version 1.2 User Guide 2016 HydroAlgorithmics Pty Ltd http://www.hydroalgorithmics.com/algomesh-version-1-2-released

IGS (2020a). West Angelas Groundwater Modelling to Support MAR Design A report prepared for Rio Tinto Iron Ore. 10 February 2021.

IGS (2020b). West Angelas Groundwater Modelling to Support MAR Design: Stage 1 Progress Report. 8 June 2020.

James H.L., 1954, ‘Sedimentary facies of iron formation’, Economic Geology, 49, pp. 235-293.

James, H.L. 1983. Chapter 12 Distribution of Banded Iron-Formation in Space and Time. Developments in Precambrian Geology, Volume 6, pp. 471-480.

Johnson, S.L. and Wright, A.H., 2001. Central Pilbara Groundwater Study, Water and Rivers Commission, Hydrogeological Record Series, Report HG 8, 102 p.

Krapez, B., 1996., Sequence stratigraphic concepts applied to the identification of basin-filling rhythms in Precambrian successions: Australian Journal of Earth Sciences, v. 43, pp. 355–380.

MacLeod, W.N., de la Hunty, L.E., Jones, W.R. and Halligan, R., 1963. A preliminary report on the Hamersley Iron Province, North-West Division. Geological Survey of Western Australia, Annual Report for 1962, pp. 44-54.

Moore, C. and Doherty, J. 2005, Role of calibration process in reducing model predictive error. Water Resources Research, v. 41-5 https://doi.org/10.1029/2004WR003501

Panday, S., Langevin, C.D., Niswonger, R.G., Ibaraki, M., and Hughes, J.D. 2013, MODFLOW-USG version 1: An unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes using a control volume finite-difference formulation: U.S. Geological Survey Techniques and Methods, book 6, chap. A45

Parsons Brinckerhoff. (2013). Koodaideri Hydrogeological Conceptual Model Report. Document No: 2172670A-DMS-RPT-001 RevB. 20 February 2013.

Richards, J.R. and Blockley, J.G., 1984. The base of the Fortescue Group, Western Australia: Further galena and lead evidence on its age: Australian Journal of earth Sciences, v.31, pp. 257-268.

RTIO (2017). West Angelas Deposits C & D Regional Groundwater Model. RTIO-PDE-0154308.

RTIO (2019). West Angelas. 2019 West Angelas MAR Trial. Powerpoint presentation.

SS Papadopoulos and Associates. 2014, Online user manual for mod-PATH3DU. Accessed at http://www.mp3du.sspa.com on 15/08/2020

Simonson, B.M., Schubel, K.A., and Hassler, S.W., 1993. Carbonate sedimentology of the Early Precambrian Hamersley Group of Western Australia: Precambrian Research, v. 60, pp. 287–335.

Thorne, A. M. and Tyler, I. M., 1997. *Roy Hill, W.A (2nd Edition): 1:250,000 Geological Series Explanatory Notes.* Perth: Western Australia Geological Survey

Trendall, A.F., 1979. Revision of the Mt. Bruce Supergroup. West Australian Geological Survey. Annual Report 1978: pp. 63-73.

Trendall, A.F. and Blockley, J.G., 1990. The iron formations of the Precambrian Hamersley Group, in Eriksson, P.G., Altermann, W., Nelson, D.R., Muellert, W.U. and Catuneanu, O. (eds), The Precambrian Earth: Tempos and events in Precambrian time. Developments in Precambrian Geology 12: Elsevier, Amsterdam, pp 403-421.

White, J. T., Hunt, R. J., Doherty, J. E., and Fienen, M. N. 2020. PEST++ version 5, a parameter estimation and uncertainty analysis software suite optimized for large environmental models. U.S. Geological Survey Techniques and Methods Report

White, J.T., 2018. A model-independent iterative ensemble smoother for efficient history-matching and uncertainty quantification in very high dimensions. Accepted for publication in Environmental Modelling and Software.

White, J.T., Fienen, M.N., Barlow, P.M. and Welter, D.E., 2018. A tool for efficient, model-independent management optimization under uncertainty. *Environmental Modelling and Software*, 100, 213-221.

Appendix 4: Description of Zonal monitoring, data collection and analysis (Note: Red Text is subject to change as bore is yet to be drilled)

Monitoring Bore	Status	Total Cased Depth	Screened Interval	Screened Unit	Abstraction Volume	Injection Volume	Water Level	Water Quality frequency
Zone 1								
WB20WAD 0001	Drilled (Testing to be completed prior to Deposit D dewatering commencement)	72.4	14.2-68.2	Dolocrete/ Wittenoom Fm	Monthly meter reading	Monthly meter reading	NR	Quarterly Manual sampling (at end of Backflush)
WB20WAD 0002	Drilled (Testing to be completed prior to Deposit D dewatering commencement)	75.5	20.7-68.7	Dolocrete/ Wittenoom Fm	Monthly meter reading	Monthly meter reading	NR	Quarterly Manual sampling (at end of Backflush)
WB20WAD 0003	Drilled and Tested	89.7	22.8-82.9	Dolocrete/ Wittenoom Fm	Monthly meter reading	Monthly meter reading	NR	Quarterly Manual sampling (at end of Backflush)
WB20WAD 0004	Drilled and Tested	82	21.2-75.2	Dolocrete/ Wittenoom Fm	Monthly meter reading	Monthly meter reading	NR	Quarterly Manual sampling (at end of Backflush)
WB20WAD 0005	Drilled and Tested	59.5	22.7-52.7	Dolocrete/ Wittenoom Fm	Monthly meter reading	Monthly meter reading	NR	Quarterly Manual sampling (at end of Backflush)
WB19WAC 0001	Drilled and Tested	66	16.6-59	Dolocrete/ Wittenoom Fm	Monthly meter reading	Monthly meter reading	NR	Quarterly Manual sampling (at end of Backflush)
WB20WAC 0001	Drilled and Tested	93.3	20.4-86.5	Dolocrete/ Wittenoom Fm	Monthly meter reading	Monthly meter reading	NR	Quarterly Manual sampling (at end of Backflush)
20WAD-P05	To be drilled and tested prior to Deposit D dewatering commencement	*80*	*20-74*	Dolocrete/ Wittenoom Fm	Monthly meter reading	Monthly meter reading	NR	Quarterly Manual sampling (at end of Backflush)
Zone 2								
MB16WAW 0008	Drilled and Installed	87.5	33.5-81.5	Dolocrete/ Wittenoom Fm	NR	NR	Quarterly manual observation	Quarterly Manual sampling
MB19WAC 0007	Drilled and Installed	70	58-64	Wittenoom Fm	NR	NR	Quarterly manual observation	Quarterly Manual sampling
20WAD-M40	To be drilled and installed in 2021	*120*	*42-114*	*Wittenoom Fm*	NR	NR	Quarterly manual observation	Quarterly Manual sampling
21WAD-M01	To be drilled and installed in 2021	*120*	*42-114*	*Wittenoom Fm*	NR	NR	Quarterly manual observation	Quarterly Manual sampling
WAC_M28	To be drilled and installed prior to Deposit C dewatering commencement	*150*	*42-144*	*Wittenoom Fm*	NR	NR	*Once Drilled - Quarterly manual observation*	*Once Drilled - Quarterly Manual sampling*
WAW_M16	To be drilled and installed prior to Deposit C dewatering commencement	*150*	*42-144*	*Wittenoom Fm*	NR	NR	*Once Drilled - Quarterly manual observation*	*Once Drilled - Quarterly Manual sampling*
WAW_M17	To be drilled and installed prior to Deposit C dewatering commencement	*150*	*42-144*	*Wittenoom Fm*	NR	NR	*Once Drilled - Quarterly manual observation*	*Once Drilled - Quarterly Manual sampling*
Zone 3								
MB16WAW 0005	Drilled and Installed	88	34-82	Dolocrete/ Wittenoom Fm	NR	NR	Quarterly manual observation	Quarterly Manual sampling
MB16WAW 0007	Drilled and Installed	104	26-98	Dolocrete/ Wittenoom Fm	NR	NR	Quarterly manual observation	Quarterly Manual sampling
20WAD-M37	To be drilled and installed in 2021	*120*	*42-114*	*Wittenoom Fm*	NR	NR	*Once Drilled - Quarterly manual observation*	*Once Drilled - Quarterly Manual sampling*
20WAD-M38	To be drilled and installed in 2021	*120*	*42-114*	*Wittenoom Fm*	NR	NR	*Once Drilled - Quarterly manual observation*	*Once Drilled - Quarterly Manual sampling*
20WAC-M07	To be drilled and installed in 2021	*138*	*96-132*	*Wittenoom Fm*	NR	NR	*Once Drilled - Quarterly manual observation*	*Once Drilled - Quarterly Manual sampling*
21WAW-M03	To be drilled and installed prior to Deposit C dewatering commencement	*150*	*42-144*	*Wittenoom Fm*	NR	NR	*Once Drilled - Quarterly manual observation*	*Once Drilled - Quarterly Manual sampling*
21WAW-M02	To be drilled and installed prior to Deposit C dewatering commencement	*150*	*42-144*	*Wittenoom Fm*	NR	NR	*Once Drilled - Quarterly manual observation*	*Once Drilled - Quarterly Manual sampling*
WAW-M01	To be drilled and installed prior to Deposit C dewatering commencement	*150*	*42-144*	*Wittenoom Fm*	NR	NR	*Once Drilled - Quarterly manual observation*	*Once Drilled - Quarterly Manual sampling*
MB17WAW 0001	Drilled and Installed	130	106-124	Brockman Iron Fm	NR	NR	Quarterly manual observation	Quarterly Manual sampling

Monitoring Bore	Status	Total Cased Depth	Screened Interval	Screened Unit	Abstraction Volume	Injection Volume	Water Level	Water Quality frequency
Boundary Bores								
MB18WAW 0003	Drilled and Installed	80	59-77	Wittenoom Fm	NR	NR	Quarterly manual observation	Quarterly Manual sampling
MB19WAW 0006	Drilled and Installed	110	69-93	Wittenoom Fm	NR	NR	Quarterly manual observation	Quarterly Manual sampling
21WAD-M06	To be drilled and installed in 2021	*120*	*84-114*	*Brockman Iron Fm*	NR	NR	*Once Drilled - Quarterly manual observation*	*Once Drilled - Quarterly Manual sampling*
21TURB-M01	To be drilled and installed in 2021	*90*	*72-84*	*Brockman Iron Fm*	NR	NR	*Once Drilled - Quarterly manual observation*	*Once Drilled - Quarterly Manual sampling*
Karijini NP Bores								
WANG14	Monitoring underway	25	22.5-25.5	Detritals/ Wittenoom Fm	NR	NR	Quarterly manual observation	*Once Accessible and Approved - Quarterly Manual sampling*
WANG07	To be accessed and telemetry deployed	65	30-50	Detritals/ Wittenoom Fm	NR	NR	NR	*Once Accessible - Quarterly Manual sampling*
WANG09	To be accessed and telemetry deployed	48	29-48	Detritals/ Wittenoom Fm	NR	NR	NR	*Once Accessible - Quarterly Manual sampling*
WANG10	To be accessed and telemetry deployed	53	46-52	Detritals/ Wittenoom Fm	NR	NR	NR	*Once Accessible - Quarterly Manual sampling*
Water Quality Control Bore								
MB16WAW 0005	Drilled and Installed	88	34-82	Dolocrete/ Wittenoom Fm	NR	NR	Quarterly manual observation	Quarterly Manual sampling
Backup Water Quality Control Bore								
MB16WAW 0007	Drilled and Installed	104	26-98	Dolocrete/ Wittenoom Fm	NR	NR	Quarterly manual observation	Quarterly Manual sampling

Appendix 5: Criteria, Monitoring Zones and Bore Summary

Monitoring zone	Bores	Groundwater Drawdown Criteria	Groundwater Drawdown Threshold	Groundwater Quality Criteria	Groundwater Quality Threshold
1	WB19WAC001	**Early Response indicator 1:** Injection bores non-operational outside of proposed plan for operation of the MAR scheme (more than 1 of a paired set of bores inoperable for more than 1 week).	NA	NA	NA
1	WB20WAC001				
1	WB20WAD003				
1	WB20WAD004				
1	WB20WAD002				
1	WB20WAD005				
1	20WAD-P05				
1	WB20WAD0001				
2	WAW_M17	**Early Response indicator 2:** Two consecutive monitoring periods of drawdown 25 cm greater than Grey Box level for modelled mitigation scenario in Zone 2 monitoring bores. **Criteria Level 1:** Two consecutive monitoring periods of drawdown 50cm greater than Grey Box level for modelled mitigation scenario.		**Early Response Indicator:** Long term pH trend in Zone 2 monitoring bores over two consecutive monitoring periods is not consistent with trend in control bore <u>or</u> proportional change in EC in Zone 2 bores is greater than 20% of proportional change in control bore EC over two consecutive monitoring periods. **Trigger Criteria Level 1:** Long term pH in Zone 2 monitoring bores is not between 6.5 and 8 for two consecutive monitoring periods and trend is not consistent with trend in control bore <u>or</u> proportional change in EC in Zone 2 bores is greater than 50% of proportional change in control bore EC over two consecutive monitoring periods.	
2	WAW_M16				
2	WAC_M28				
2	MB19WAC0007				
2	21WAD-M01				
2	MB16WAW0008				
2	20WAD-M40				
3	MB17WAW0001	**Management Target 2:** Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 3 year, seasonally adjusted water levels (mbgl). **Management Target 3:** Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 5 year, seasonally adjusted water levels (mbgl). **Management Target 4:** Water levels in Zone 3 monitoring bores and modelled are above or equal to rolling 10 year, seasonally adjusted water levels (mbgl). **Criteria Level 2:** Two consecutive monitoring periods of drawdown of 10 cm or greater than the Grey Box level for modelled mitigation scenario in Zone 3 monitoring bores or a single monitoring period of drawdown greater than 10cm in Zone 3 monitoring bores if Trigger Criteria Level 1 exceeded in the current or preceding monitoring period or a single monitoring period of drawdown greater than 10 cm or greater than the Grey Box level recorded in two or more adjacent monitoring bores	**Threshold**: Two consecutive monitoring periods of drawdown associated with the proposal of 20 cm or greater than Grey Box level for modelled mitigation scenario in Zone 3 monitoring bores or a single monitoring period of drawdown exceeding 20cm in Zone 3 monitoring bores if Trigger Criteria Level 2 exceeded in current or preceding monitoring period. or a single monitoring period of significant drawdown (over 40 cm drawdown) and the equipment is not damaged.	**Trigger Criteria Level 2:** Long term pH in Zone 3 monitoring bores is not between 6 and 8.5 for two consecutive monitoring periods and trend is not consistent with trend in control bore pH, <u>or</u> proportional change in EC in Zone 3 monitoring bores is greater than 50% of proportional change in control bore EC over two consecutive monitoring periods.	**Threshold Criteria:** Long term pH in Zone 3 monitoring bores is not between 6 and 8.5 for two consecutive monitoring periods and trend is not consistent with trend in control bore pH as a result of the action or proportional change in EC in Zone 3 bores is greater than 80% of proportional change in control bore EC over two consecutive monitoring periods as a result of the action.
3	WAW_M01				
3	21WAW-M02				
3	21WAW-M03				
3	MB16WAW0005				
3	20WAC-M07				
3	20WAD-M37				
3	20WAD-M38				
3	MB16WAW0007				
Boundary	MB18WAW0003	**Management Target 1:** Water levels in boundary bores to the south and north of the MAR scheme in areas outside of the regional aquifer are above or equal to rolling 3 year, seasonally adjusted water levels (mbgl).	NA	NA	NA
Boundary	MB19WAW0006				
Boundary	21WAD-M06				
Boundary	21TURB-M01				
KNP	WANG10	NA			
KNP	WANG09				
KNP	WANG07				
KNP	WANG14				