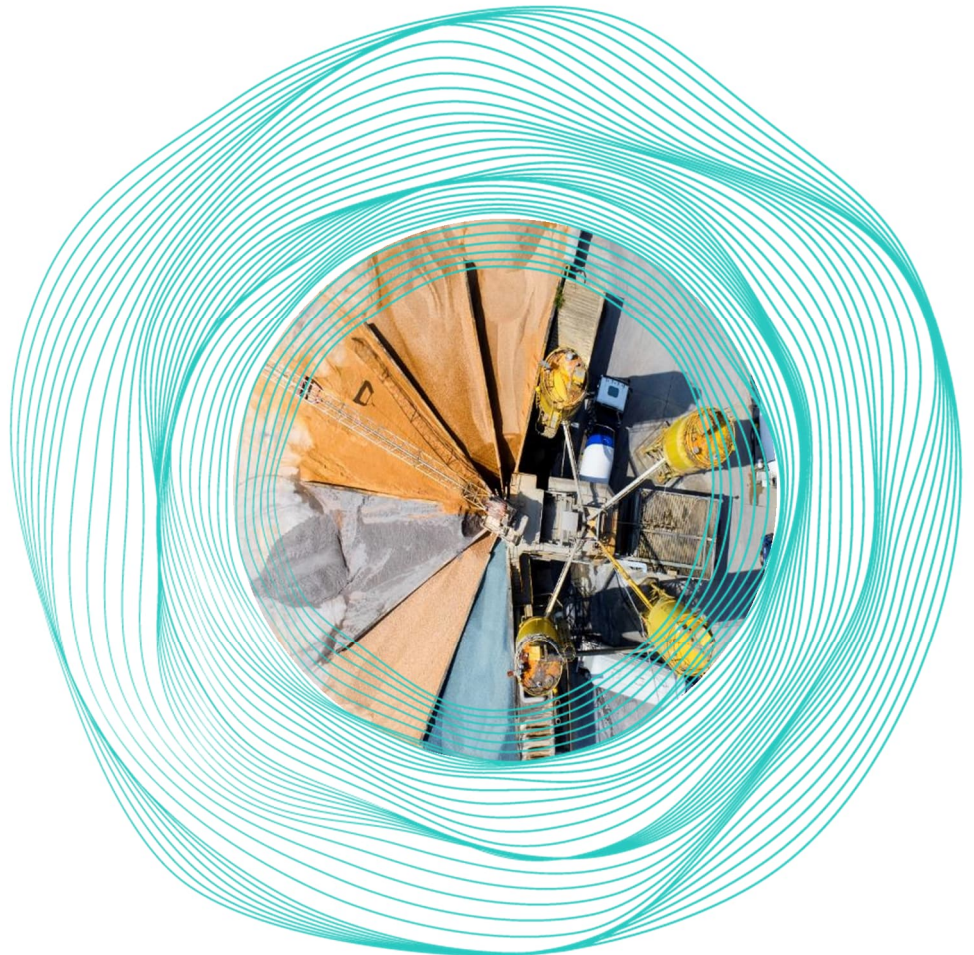


BHP

Northern RAV MAR Modelling Update

Final report

Document no. Rev 1: 311012-01995-HG-REP-00003



16 September 2024

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PROJECT 311012-01995 - 311012-01995-HG-REP-00003: Northern RAV MAR Modelling Update - Final report

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Rev A	Draft for comments	MS			31 May 2024		
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1. Introduction

1.1 Background

BHP has been investigating the MAR option in an area known as Mick Bore in the Runaway Valley situated to the northeast of Mining Area C. As part of this investigation BHP has constructed three injection bores and the associated monitoring instrumentation.

Advisian (2022) developed a numerical model for an initial assessment of MAR capacity which focused on the surficial aquifer system only.

In this report we describe the subsequent modelling work carried out to include the weathered/fractured bedrock aquifer system and evaluate the planned excess water disposal (MAR) into a combination of bedrock and detrital units.

While the natural depth to groundwater is relatively deep (over 40 m BGL in the MAR area), mounding is ideally to be constrained to levels protective of potential vegetation receptors, ie. nominally not within 10 m of ground surface.

1.2 Scope of work

The work tasks for this work included the following:

- Review of the available hydrogeological data for the Runaway Valley, in particular the weathered and fractured basement section not represented in the previous model; and pumping tests recently undertaken that provide information on hydraulic properties of weathered basement. This was based on BHP having collated and reviewed the available information for the area.
- Update of the numerical model by including layer(s) representing the weathered/fractured basement aquifer(s). No changes to the surficial unconsolidated aquifer that was previously represented are required.
- Incorporation of pumping test data in the model to inform model recalibration.
- Calibration of the updated model to the available water level and pumping test data using.
- The model to be used to assess various MAR options and evaluate predictive uncertainty.
- Preparation of a report describing the data available, the conceptual and numerical model updates, the recalibration procedure and results, including the predictive uncertainty analysis (this report)

2. Conceptual model update

2.1 Introduction

The hydrogeological conceptualisation update includes:

- the incorporation of bedrock units,
- the revised geometric delineation of the key hydrostratigraphical units (HSU), both surficial and bedrock, based on:
 - their hydrogeological function using the available geological mapping,
 - geological log information from bores completed by BHP, and
 - the available aerial geophysical products provided by BHP.

BHP has conducted three pumping tests which targeted the more permeable parts of the fractured rock aquifer. Based on the tests BHP interpreted hydraulic parameters using the distance/drawdown method. In addition to that work, Worley Consulting, as part of this work package, also completed a more detailed pumping test analysis.

The spatial model domain has been adjusted (minor changes). The most important model structure change is the incorporation of both the surficial and bedrock units. Aquifer parameterisation is based on bulk properties of the key HSUs informed by the aquifer testing results and a review of values from the broader areas.

The regional water level records and aquifer testing results were compiled to confirm the groundwater flow directions and transient patterns, and to provide the calibration target database.

The minor conceptualisation updates include the specification of recharge and incorporation of evapotranspiration. The latter becomes locally important when mounding results in shallow groundwater levels.

Recognition of the residual uncertainty in model parameterisation is addressed by implementation of a standard Monte Carlo analysis, based on an evaluation of 100 model realisations. It is used to guide the recommendations for further work.

2.2 Supplied information

BHP supplied the relevant hydrogeological information items for the model update (Table 2-1):

Table 2-1 Summary of supplied information for model update

Item	Description
Updated list of bore logs for water bores	Updated dataset of bore logs (pdf and excel) for bores located within Mick Bore tenure; including monitoring and production bores constructed in 2022-2023 as part of the pump testing network. The dataset included construction details and stratigraphy for installed bores.
Exploration drillhole dataset	Excel files for exploration drillhole collars, construction details and intercepted stratigraphy within the Mick Bore tenure.
Pumping test data	Datasets for drawdown and water chemistry measurements collected during step rate test (SRT) and constant rate tests (CRT) at bores HMKB0015P, HMKB0016P, and HMKB0017P, between April to June 2023. Water level logger data for eight regional monitoring bores was also provided for the period in which the CRTs were performed at the three production bores. Includes BHP's Powerpoint presentation summarising the tests and interpreted values of transmissivity.
Water level data	Discrete manual dip measurements from between 2009-2023, for 110 bores within the Mick Bore tenure.
AEM survey data	Data corresponding to an aerial electromagnetic (AEM) survey completed of the Mick Bore tenure area, including grid files, depth slices, and isosurfaces (dxf format) to a depth of 400 m.
Locations of injection bores	In addition to the existing three production (injection) bores, coordinates were provided for three additional locations

2.3 Model domain

The lateral extent of the model domain remains largely consistent with the original model, except for a few refinements to represent the catchment boundaries, as this area is structurally well bounded to the north, east and south by outcropping of the low-permeability McRae Shale Mt Sylvia Formations.

The study domain is presented in Figure 2-2, which shows its position in relation to the existing BHP footprint (Northern Flank, Mining Area C and Yandi), and the Karijini National Park to the west. The study domain covers an area of 234 km².

A more detailed view in in Figure 2-2 also includes ground elevations, injection bores (which were subjected to the aquifer testing), locations of monitoring bores that recorded drawdown during the aquifer testing, and the DEM-derived drainage lines (streams), within the updated domain.

2.4 Hydrostratigraphical units

Hydrostratigraphic units (HSUs) are divided into surficial and bedrock units. (Table 2 1).

HSUs are devised based on:

- the lithology, age, structure of the geological formations, based on borehole logs, surficial and bedrock geological maps and regional reports
- where possible, their hydrological properties such as permeability and porosity which contribute to the control of the groundwater flow

- in case of the surficial HSUs also their potential role in recharge and evapotranspiration processes.

2.4.1 Surficial HSUs

Their spatial distribution is shown in Figure 2-3.

Surface drainage is derived from DEM, mapped as streamlines with a 25 m buffer on both sides. The buffer represents an approximation of the width of alluvial and ecohydrological systems associated with them. Their effective width spatially varies, in reality, but is considered to be acceptable for the scale of this model.

The main surficial HSUs (Figure 2-3) are:

- alluvium and playa
- alluvial fan and slope deposits
- indurated and transported duricrust
- bedrock units in some areas, as outcrops or subcrops (both aquifer and aquitards)

Available bore logs and the existing regolith thickness mapping inform the delineation of the surficial cover thickness. The regolith thickness dataset that provides the template for the entire model domain was “calibrated” using the existing bore logs and adjusted to mirror the major trends.

The resulting surficial (detrital) unit thickness developed for the numerical model is presented in Figure 2-4.

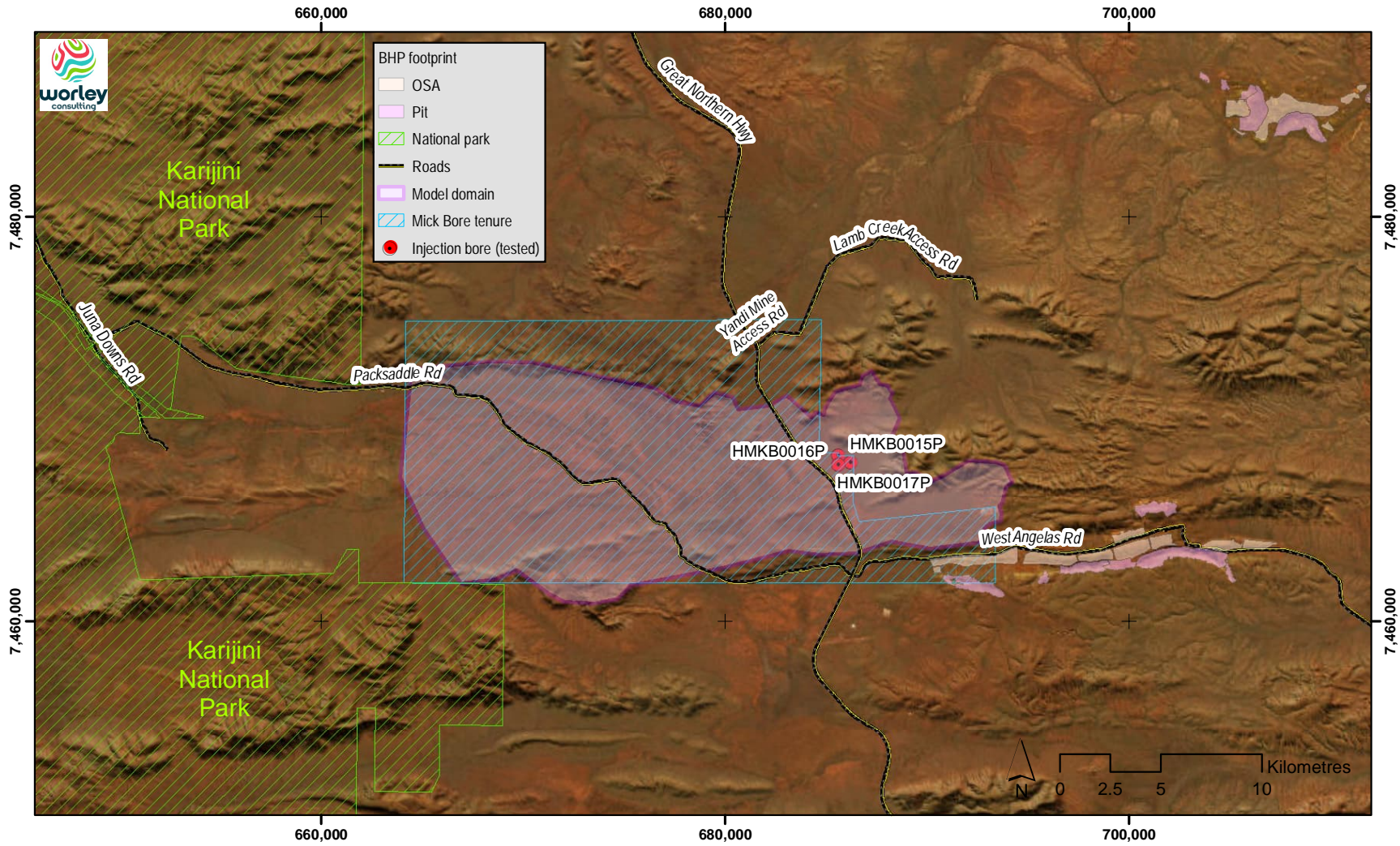


Figure 2-1 Study domain, regional context

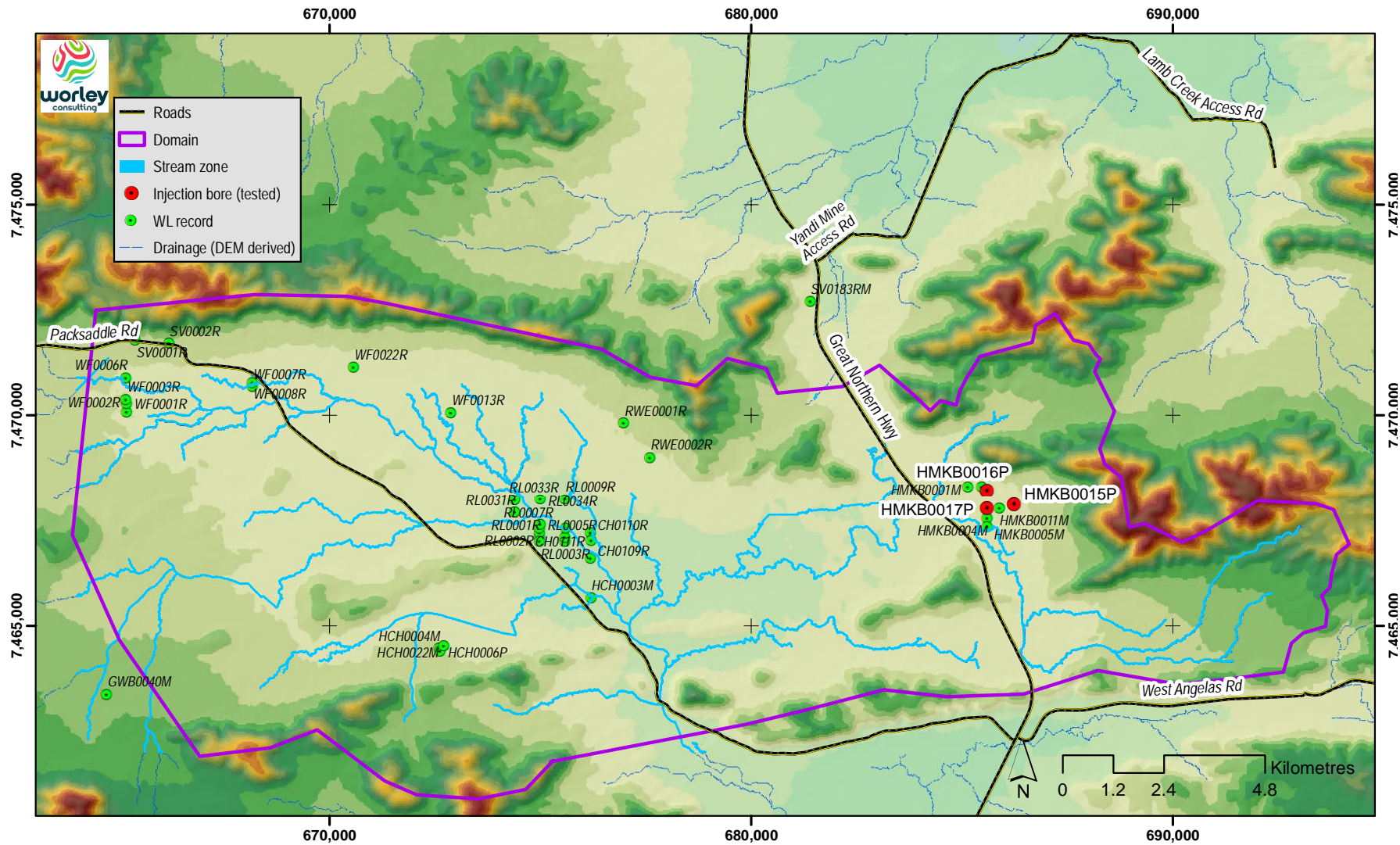


Figure 2-2 Study (model) domain, topography, drainage

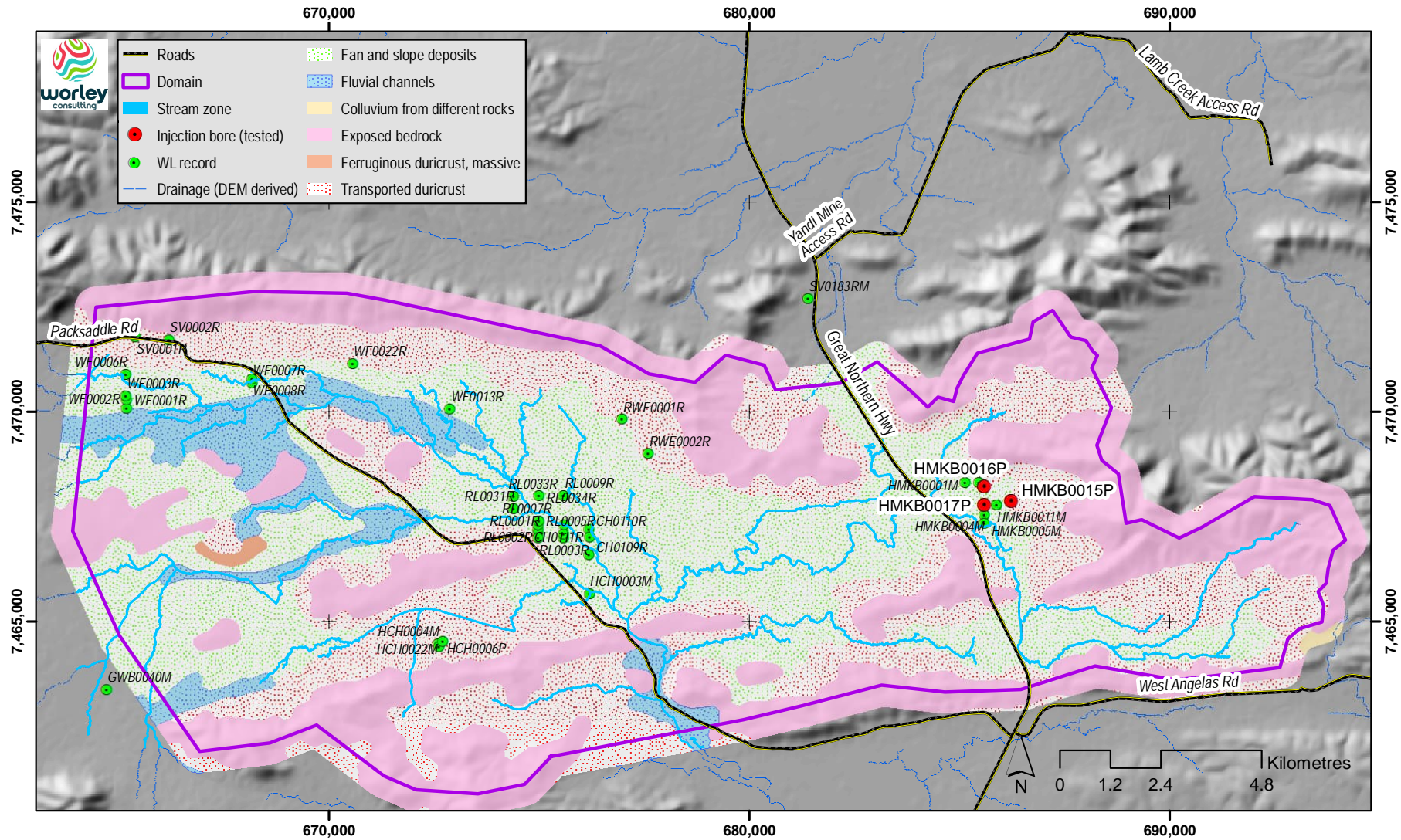


Figure 2-3 Regolith types (surface geology units, Geological Survey of Western Australia) forming the surficial HSUs

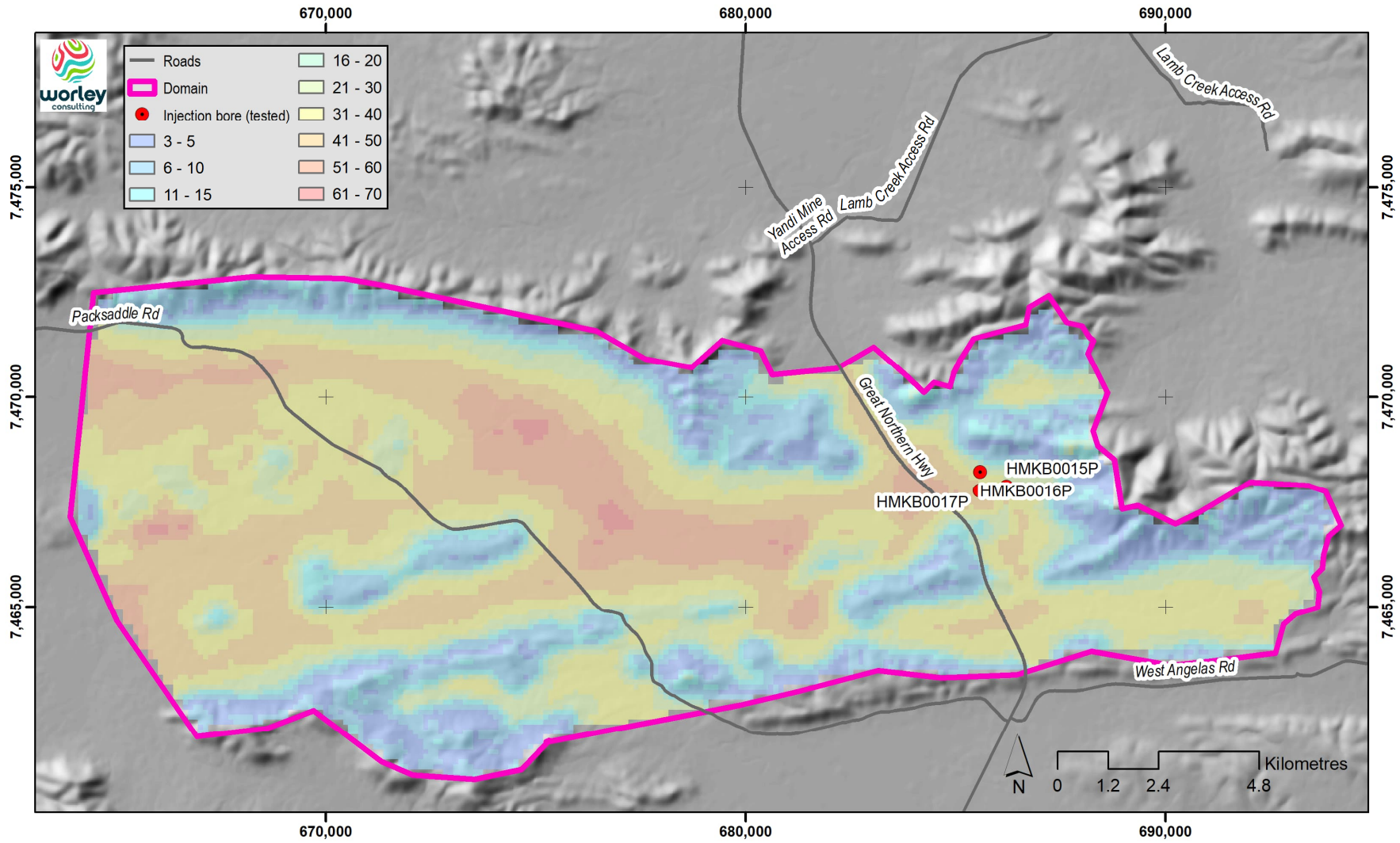


Figure 2-4 Adopted surficial HSU thickness

2.4.2 Fractured bedrock HSUs

Seven fractured bedrock (basement) hydrostratigraphic units are considered for this conceptualisation update (Table 2-4). Some uncertainties are present when evaluating the weathered profile of basement. The reviewed borehole logs from within the model domain showed significant variations in the vertical extent of basement weathering between boreholes in close proximity. This makes it unclear to reliably discriminate between weathered and fresh sections of the different formations.

Table 2-2 Fractured rock HSUs

HSU	Geological member	Lithology	Hydrogeological function
Brockman Formation	Joffre Member	BIF with minor shale bands	Limited aquifer(s) in mineralized zones
	Whaleback Shale Member	Interbedded shale, chert and BIF	Low permeability
	Dales Gorge Member	Interbedded BIF and shale	Aquifer(s) in mineralized zones
Wittenoom Formation	Bee Gorge Member	Graphitic shale with minor sequences of carbonate, chert, volcanoclastic rock, and BIF	Low permeability
	Paraburdoo Member	Dolomite with minor amounts of chert and shale – karstic in areas	Aquifer at regional scale
	West Angela Member	Dolomite, dolomitic shale, and chert	Minor, localized aquifers
Marra Mamba Formation	Mount Newman Member	Chert, banded iron-formation, and shale	Aquifer in mineralized zones
	Macleod Member	Well podded to laminar chert and chert BIF with shale macrobands	Low permeability
	Nammuldi Member	BIF with chert and shale	Aquifer in mineralized zones
Mt McRae Shale and Mt Sylvia Formation	McRae Shale	Interlayered shale, dolomitic shale and chert with minor BIF	Low permeability, potential aquitard
	Mt Sylvia Formation		
Fortescue Group	Roy Hill Shale	Dark-gray to black graphitic shale and chert, locally pyritic	Low permeability
	Warrie Member	Dolomite with inter-bedded chert	Low permeability
Intrusives	Dolerite intrusions	Dolerite	Low permeability, potential hydraulic barrier (when in more permeable bedrock)

2.4.3 Hydrostratigraphic connectivity

Superficial (detrital) units are hydraulically connected with the underlying fractured rock. Regional-scale dolerite dykes are also present in the area and are currently conceptualised, in combination with the low-permeability units, as low permeability barriers to groundwater flow. Regional dykes, adopted from the geological mapping and geophysical interpretation run in a WSW-ESE direction (Figure 2-6).

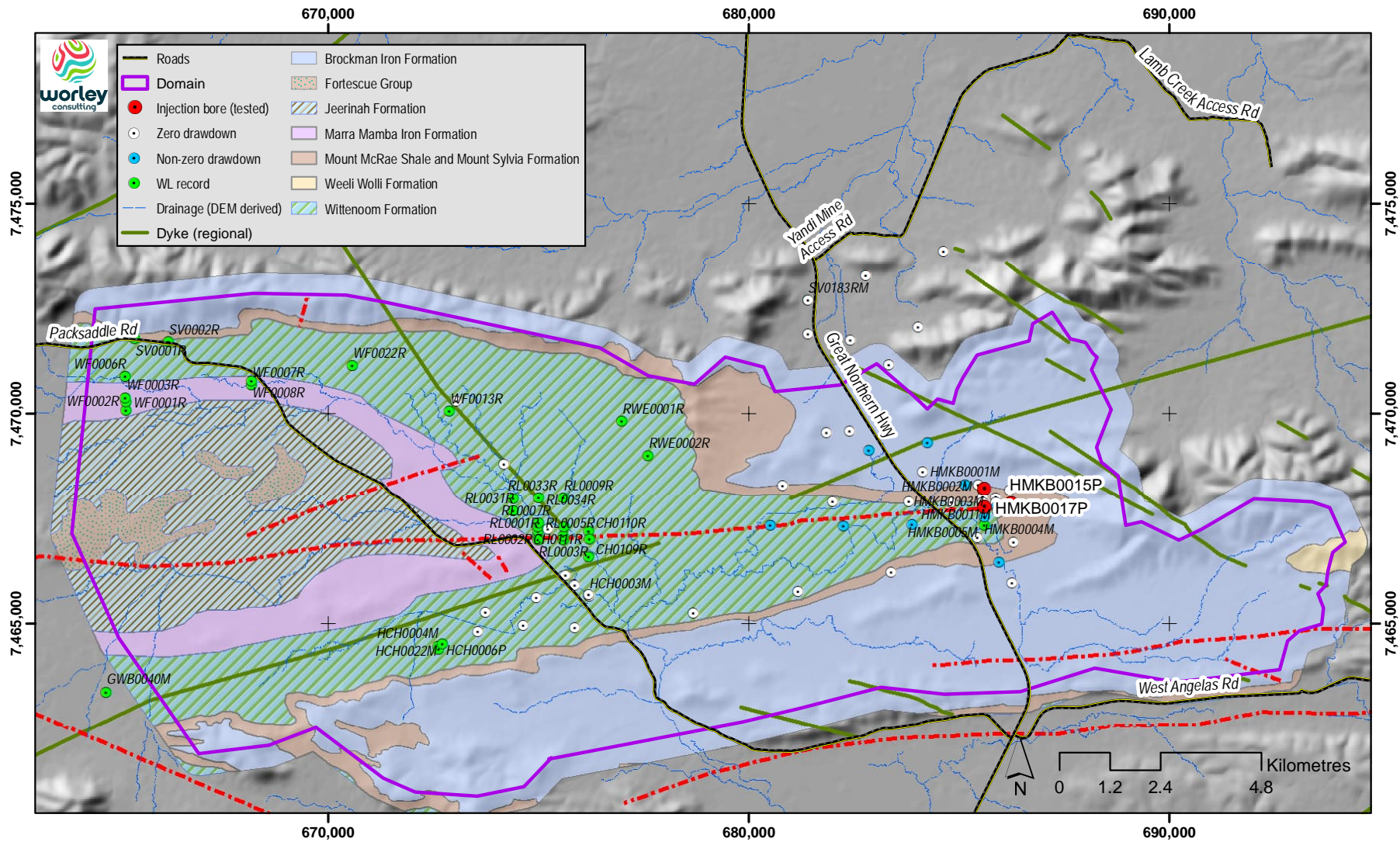


Figure 2-5 Bedrock geology (1: 100,000 mapping)

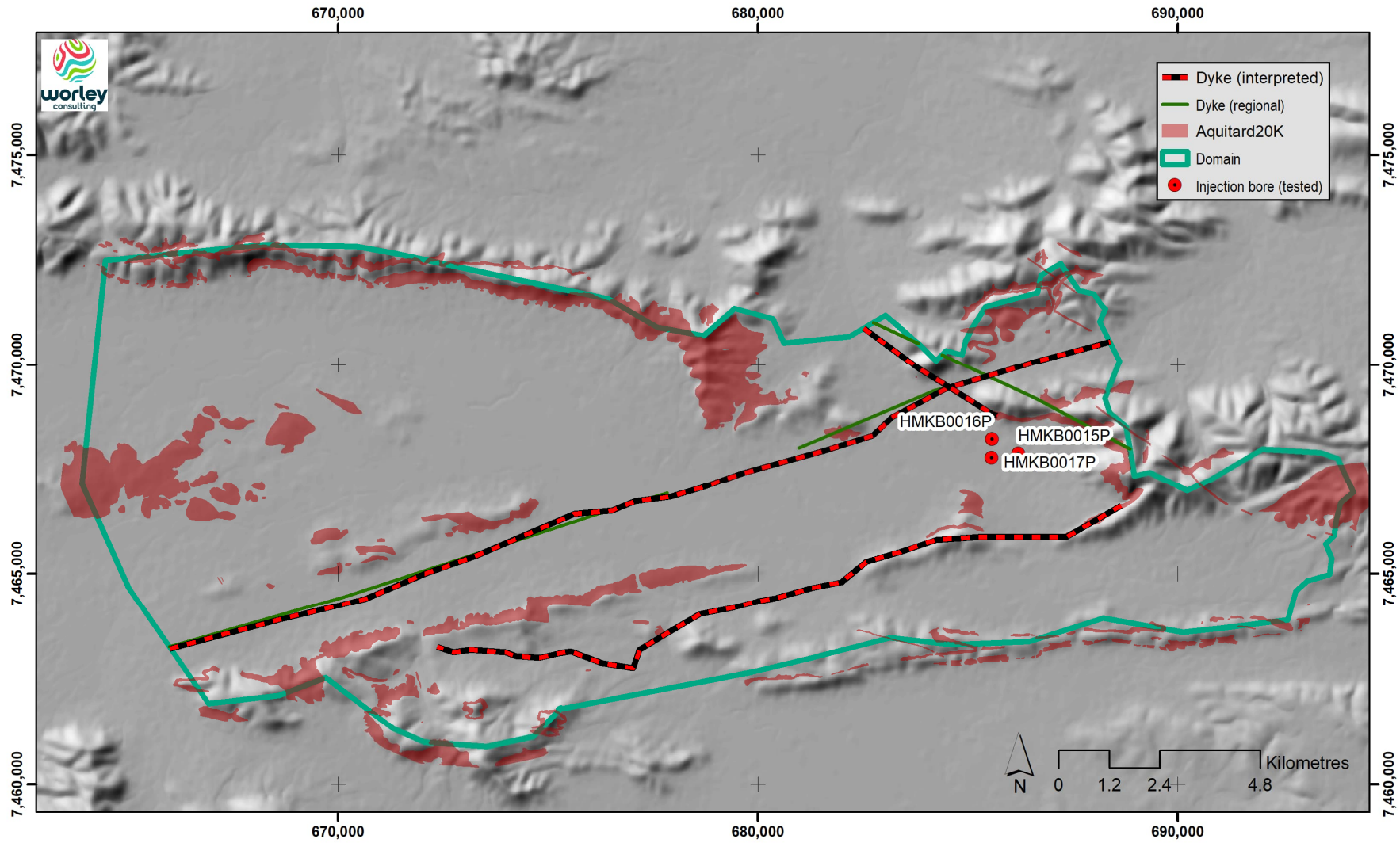


Figure 2-6 Geological features considered functional aquitards (from 1:20,000 geological mapping and geophysical interpretation)

2.5 Aquifer parameters

2.5.1 Aquifer testing

BHP conducted pumping tests on HMKB0015P, HMKB0016P and HMKB0017P in 2023. During testing, the water levels were recorded in the selected monitoring bores (Figure 2-7).

The duration of testing varied between the three locations and was partly limited by water disposal capacity (permit to dispose off water from testing required due to the high pumping rates).

The following test durations were achieved before the disposal wetting front constraint was reached:

- 15 days at 70 L/s for HMKB0015P
- 6.3 days 75 L/s for HMKB0016P
- 8.8 days at 75 L/s at HMKB0017P.

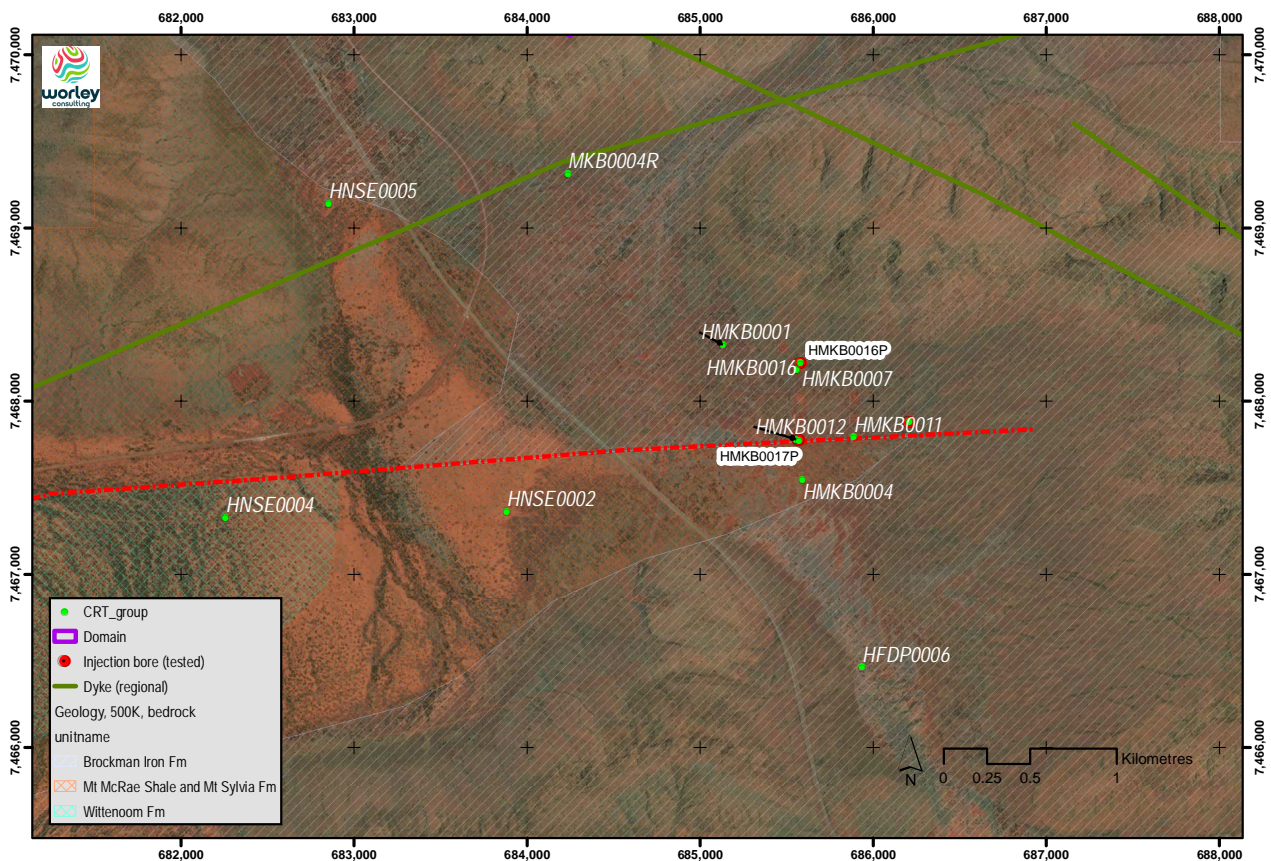


Figure 2-7 Monitoring bores locations observed during CRT

The water level response from regional bores was reported to be relatively small, typically less than 0.5 m, and affected by barometric corrections issues with logger data.

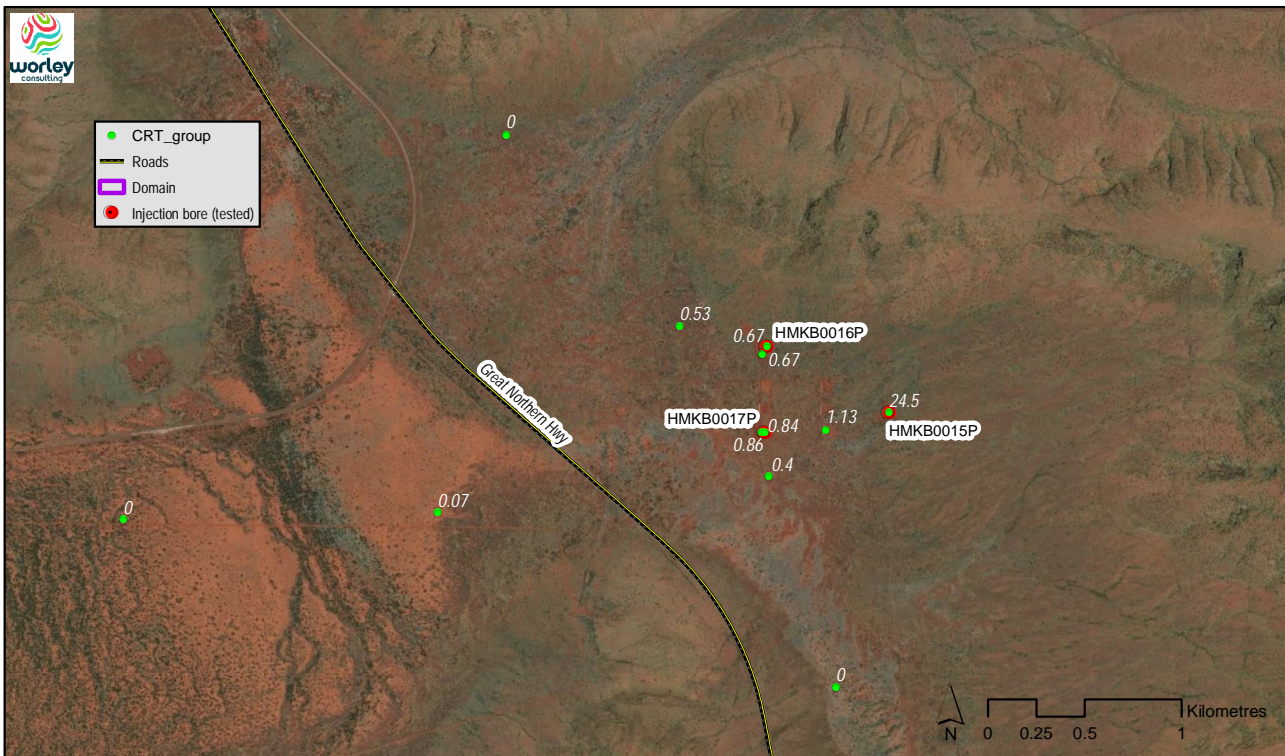


Figure 2-8 Drawdown at the end of CRT on HMKB0015

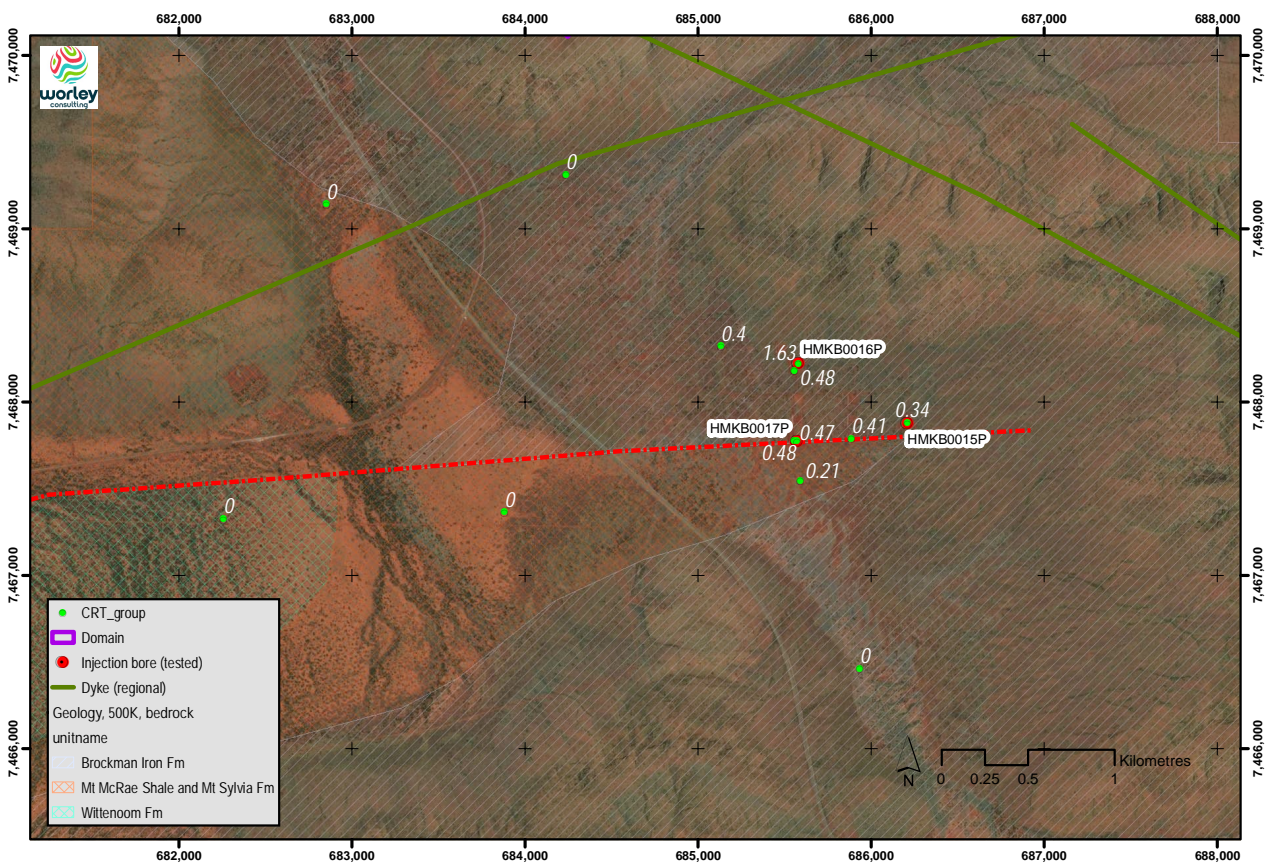


Figure 2-9 Drawdown at the end of CRT on HMKB0016

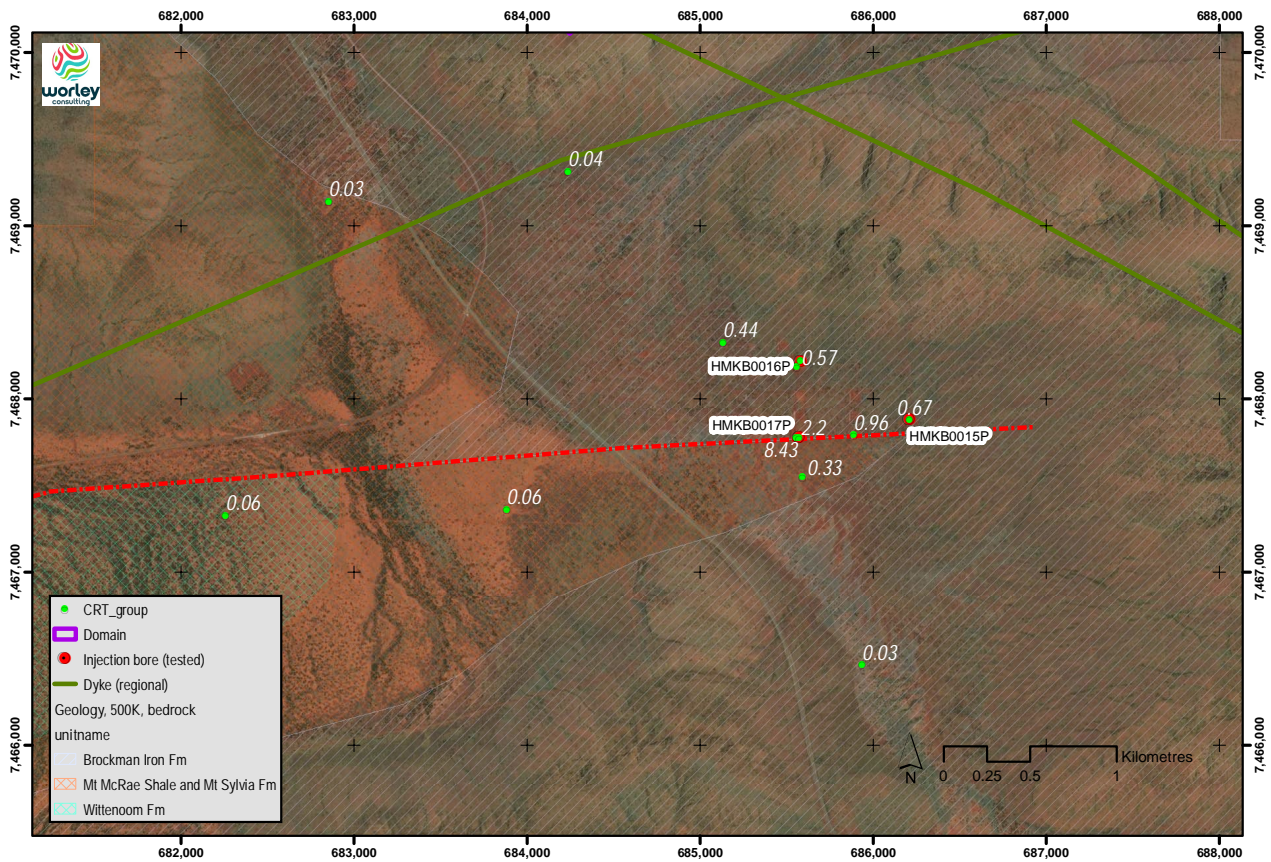


Figure 2-10 Drawdown at the end of CRT on HMKB0017

2.5.2 Aquifer parameters

BHP (2023) interpreted transmissivity and storativity parameters from the three pumping tests using a distance-drawdown method. The interpreted results suggest a large range of transmissivities, between 1,848 to 8,124 m²/d, suggestive of highly permeable conditions, and with storage values ranging between 0.002 and 0.009.

Assuming a nominal aquifer thickness of 100 m these values would correspond to a hydraulic conductivity of 18 to 81 m/d, and specific storage of 2×10^{-5} to 9×10^{-5} (1/m). The high values calculated for the nominal thickness suggest that the effective part of the aquifer system is likely to be thicker than 100 m.

Figure 2-11 Hydraulic parameter values interpreted from drawdown-distance method (BHP, 2023)

Tested bore	Q (L/s)	T (m ² /d)	S	Comments
HMKB0015P	70	1,848 to 2,206	0.008	
HMKB0016P	75	8,124	0.002	
HMKB0017P	75	2,508	0.009	

An analysis of the pumping test results interpreted using the Moench unconfined solution, supported by derivative curves to better constrain the solution, was carried out as part of this study (Table 2-3). The method assumes unconfined conditions.

Table 2-3 Hydraulic parameters interpreted from Moench method (Aqtesolv)

Tested bore	Q (L/s)	T (m ² /d)	Sy	S	Comments
HMKB0015P	70	1,162	0.03	0.0003	HMKB001 monitoring bore; high well losses; Kz/Kr=0.5
HMKB0016P	75	6,087	0.07	0.003	HMKB007 monitoring bore; Kz/Kr=0.3
HMKB0017P	75	1,696	0.08	0.001	HMKB0012 monitoring bore; Kz/Kr=0.2

Transmissivity values estimated by the Moench unconfined solution are about 30% smaller than distance drawdown estimates, with storage parameters also comparatively smaller storage, but typical for this aquifer system. The Moench method also provides specific yield estimates, in the range of 0.03 to 0.08, considered plausible for this aquifer system.

Ranges of hydraulic parameters for other HSUs estimated from available regional reports and hydrogeological summaries are outlined in Table 2-4:

Table 2-4 Summary of typical hydraulic parameters compiled for regional HSUs

HSU	K (m/d): [T (m ² /d)]	Sy	S	Source	Comment
Outcrop (aquitard)	0.1 to 0.5	0.005 to 0.01		Estimate	Mostly unsaturated
Outcrop (BIF)	1 to 5	0.02 to 0.07		Estimate	Mostly unsaturated
Alluvium	5 to 30	0.1 to 0.25		Estimate	Partly saturated
Duricrust	5 to 20	0.05 to 0.2			Mostly unsaturated
Detritals	0.003 to 50	0.001 to 0.2		Golder, 2015	Regional summary
	2.5 to 25	0.05 to 0.1		MWH, 2016	Modelling study
	1.7 to 10	0.06	0.0001	RPS,	Central values
Colluvium	10	0.2		Estimate	Unsaturated
Playa	0.5 to 10	0.15			
BIF	[2,206 to 8,164]			BHP, 2023	Distance drawdown interpretation, some data issues
	[1,162 to 6,057]	0.03 to 0.08	0.0003 to 0.003	This study	Pumping test interpretation
	0.001 to 0.02			Golder, 2015	Regional summary
	3 to 5	0.06	0.0002	RPS, 2015	Central values, ore
Wittenoom Fm	10 to 15	0.02	0.00015	RPS, 2015	Central values
Marra Mamba Fm	0.5 to 12	0.07	0.0002	RPS, 2015	Central values
Mt McRae and Mt Sylvia	0.1	0.001 to 0.003	0.0001	RPS, 2015	Central values
Dolerite dyke	0.1 to 0.2	0.001	0.00001	RPS, 2015	Typical values (much lower in modelling projects)
Weeli Wollli Fm	0.01 to 0.04	0.003 to 0.005	0.0002	RPS, 2015	Central values
Jeerinah Fm	0.3 to 1	0.008 to 0.009	0.00001	RPS, 2015	Central values

2.6 Groundwater recharge

Diffuse recharge and creek recharge are the forms of recharge considered within the model domain. Due to the relatively deep groundwater, which in this region is typically more than 30 m, large soil moisture deficits prevent recharge. Only large rainfall events (including the cyclonic events) overcome those deficits and will result in recharge.

Recharge is more frequent in areas with shallow groundwater which would be associated with drainage lines or intermittent creeks, shown as stream zones in Figure 2-12.

Typical recharge rates in the Pilbara region represent 0.5 to 2% of the mean annual rainfall. With the latter being approximately 533 mm/yr, this would represent a range of 3 to 11 mm/yr, or 0.7 to 2.4 GL/yr for the study domain.

The model domain receives minor throughflow through parts of the western boundary.

2.7 Groundwater levels and flows

Groundwater generally flows in a west to east direction into the central part of the domain which is a regional topographic low. The water levels at the western boundary are about 795 m AHD, decreasing to 693 m AHD the centre.

The potentiometric surface in the MAR area is at 680 m AHD with a flat north-westerly flow gradient, with groundwater likely to flow across the study boundary through an alluvial channel, towards the Yandi area.

The flow directions are affected and partly controlled by the regional dykes crossing the study domain from WSW to ENE.

Regionally, the study domain represents an area that is structurally bound, forming an imperfect bath tub structure.

Groundwater is generally deeper than 30 m BGL.

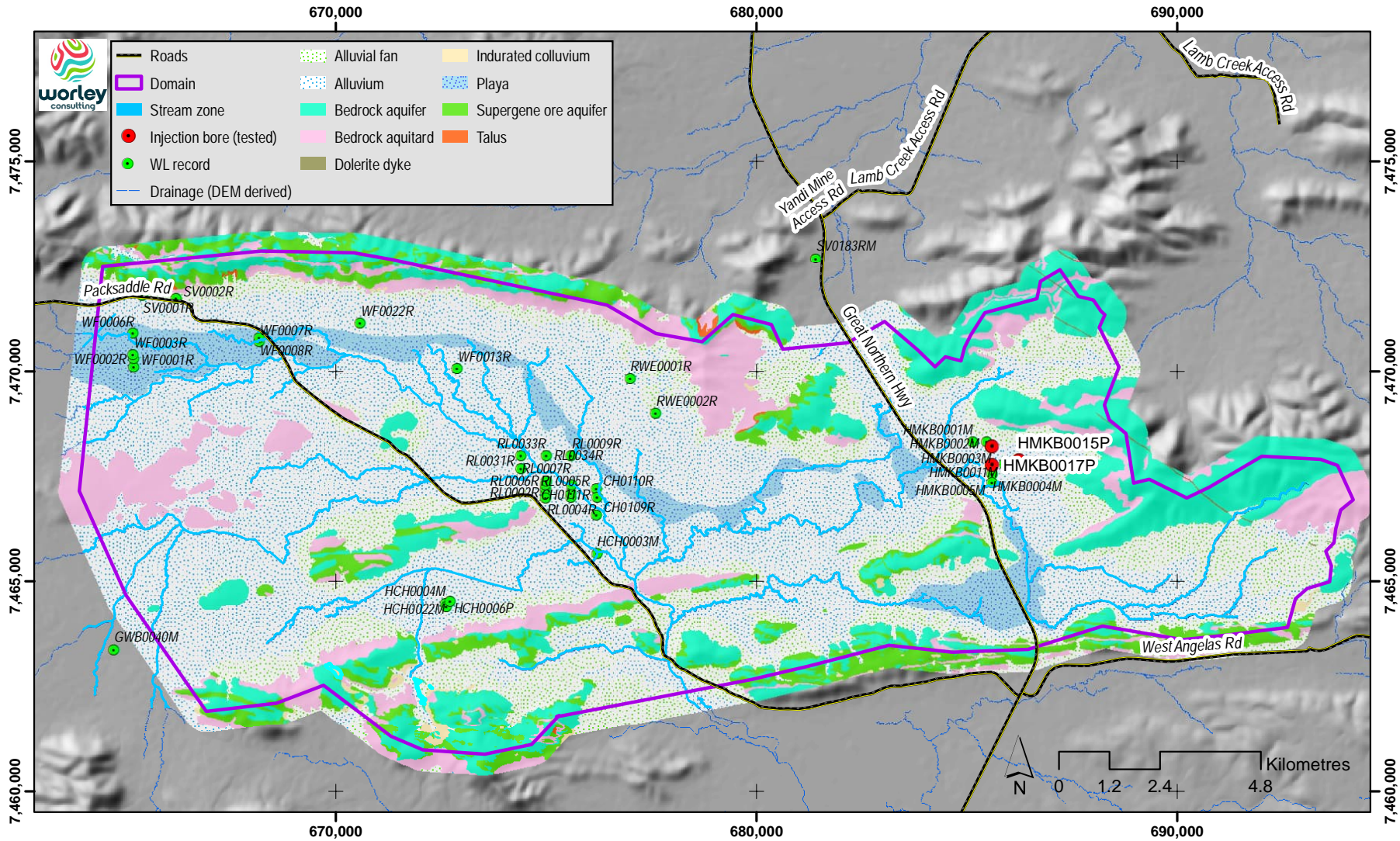


Figure 2-12 Surficial HSUs for recharge zonation

2.8 Groundwater discharge and losses

Limited groundwater outflow, most likely through alluvial channels crossing low permeability subcrops that form the northern and southern boundaries provides a groundwater discharge mechanism from the study area. Limited leakage may occur through low-permeability ridges that characterise the eastern section of the southern boundary.

Evapotranspiration can become a factor during potential mounding associated with the MAR. Its real effect will likely start when depth to water is less than 5 m BGL.

2.9 Surface water groundwater interaction

The potential for surface water groundwater interaction is negligible. Creeks potentially provide recharge to groundwater following periods of high rainfall.

There are no streamflow measurements available for the study area. Several low-elevation locations may pond within the model domain (playa sediments), however it is not due to groundwater discharge.

2.10 Groundwater extraction

There is no licensed groundwater abstraction within the study domain. Groundwater stressors potentially relevant to (but outside of) the study area include:

- Mining Area C situated to the southeast of the study domain is currently being dewatered
- Active MAR schemes to the southwest (Juna Downs) and directly to the east (Runaway Valley)
- South Flank extension under development and subject to dewatering.

Dewatering effects are muted due to the low permeability structural controls along the southern boundary.

2.11 Environmental receptors

There are no recognised protected environmental receptors, such as priority ecological communities (PECs) within the study area.

2.12 Hydrogeological conceptual model

The hydrogeological conceptual model informs the development of the groundwater numerical model. Its important elements are summarised in Table 2-5.

Table 2-5 Hydrogeological conceptualisation summary

Element/feature	Description
Study area and model domain	<p>The study area forms a west to east running region, approximately 30 km W-E and 5 km to 10 km N-S, in total covering 243 km², along the Runaway Valley, to the northwest of the Mining Area C in the central Pilbara region.</p> <p>It mostly mimics the surface catchment boundaries, except for the sections in the west, north and south (towards Lake Robinson) where the boundary crosscuts the interpreted groundwater inflow and outflow paths formed by the detrital channels (inflow from rough Tandanya in the west, outflows towards the Marillana Creek Catchment in the north, and Lake Robinson (Coondewanna Catchment direction to the south).</p>
Hydrostratigraphic units (HSU)	<p><u>Shallow hydrogeological units</u></p> <p>Alluvials, colluvials, duricrust, playa, weathered outcrops</p> <p>Superficial aquifer, generally unsaturated</p> <p>10 to 60 m thick</p> <p><u>Weathered and fractured bedrock hydrogeological units</u></p> <p>Weathered and fractured-rock aquifer (primary and secondary porosity), BIF, dolomite, Marra Mamba Fm</p> <p>Moderately to locally high yielding aquifer, with zones of further increased permeability that coincides with potential mineralisation</p> <p>More than 100 m thick</p> <p><u>Aquitard units</u></p> <p>Low permeability units comprising, Mt Mc Rae Shale and Mt Sylvia Fm, dolerite dykes, Jeerinah Fm, Weeli Wollie Fm</p> <p>Aquitard with low permeability</p> <p>More than 100 m thick, extending to the base of the model</p>
Hydrogeological structures	<p>Structural features within the model domain include:</p> <p>Faults and dykes which have been observed to cause compartmentalisation ie form hydraulic barriers (based on water level observations and aerial geophysics delineation).</p> <p>These structures penetrate weathered and fresh bedrock, but subcrop/outcrop in some areas.</p>
Aquifer system hydraulic properties	<p>Hydraulic parameters for each HSU were derived from field investigations undertaken by BHP. Testing involved SRT and CRT pumping tests, and recovery tests. Where testing was deemed inadequate to accurately estimate hydraulic properties for a specific HSU, parameters were adopted from the regional aquifer parameter overview.</p> <p>The full table of parameters to be used for the numerical model are provided in Table 2-4.</p>
Groundwater recharge rate	<p>Average annual rainfall: 533 mm/yr</p> <p>Recharge rate as a proportion of rainfall – estimated to be 0.5 to 2% (0.6 to 2.6 GL/yr) over the entire domain, based on recharge between 0.5 to 2% mean annual rainfall.</p> <p>Drainage lines provide intermittent focused recharge to the underlying groundwater during short periods of flow following large rainfall events.</p>
Groundwater discharge & abstraction	<p>Groundwater throughflow is the main mechanism of groundwater discharge from the model domain, nominally to the north and south along the main surface water drainage, through the alluvial/detrital cover and/or through the weathered basement.</p> <p>Evapotranspiration is also a means of groundwater discharge, especially during potential mounding associated with the MAR, however due to the generally deep groundwater levels it is not a dominant process within the model domain under natural conditions.</p> <p>There is currently no known groundwater abstraction within the model domain, however the model domain is situated next to Mining Area C (to the southeast) which is subject to large-scale dewatering.</p>

Element/feature	Description
Groundwater flow directions and water levels	<p>Groundwater within the model domain typically occurs 30 m BGL or deeper, which means that the surficial/detrital cover is often unsaturated. The shallowest groundwater occurs in the centre of the study domain, with water levels within a 20 to 30 m BGL range.</p> <p>Watertable elevations within the study range between 660 and more than 700 m AHD in the topographically areas.</p> <p>A west to east trend is evident in the general direction of groundwater flow within the model domain. A southward trend is present in an area along the southern boundary associated with the presumed groundwater (and occasional surface water) outflow towards the Lake Robinson in the Coondewanna Catchment.</p>
Surface water and groundwater interaction	<p>There is limited potential for groundwater interacting with surface water along drainage lines due to known typical depths of regional groundwater being 30 m BGL or deeper. Following larger rainfall events intermittent streamflows provide some recharge in sections of drainage lines.</p> <p>There are no streamflow measurements available for the study area to our knowledge.</p>
Environmental and third-party receptors	<p>There are no reported recognised environmental receptors, such as priority ecological communities within the study domain.</p>

2.13 Volumetric groundwater balance of the study area

The conceptual water balance (with a focus on groundwater) represents average hydrological conditions, not affected by any major artificial stresses. Changes in groundwater storage are likely negligible over the longer periods, hence the presented water balance is representative of a near-steady state.

The water balance estimates are based on the following assumptions:

- Model domain area 243 km²
- Mean annual rainfall 533 mm/yr
- The study area is a quasi-closed system with limited throughflow outlets
- Potential recharge rate varies between 0.6 to 2.6 GL/yr
- Evapotranspiration is negligible
- Groundwater abstraction is negligible
- Occasional creek inundation events are included in the average recharge estimate (measured flow data is not available)

Aside from an outflow through alluvial channels no other sizeable groundwater discharge processes occur. Any recharge received is balanced out by the existing outflow channels (north towards Yandi and south towards the Coondewanna Catchment).

The study area has relatively deep groundwater levels, consistently more than 30 m BGL, and consequently diffuse recharge through a thick sequence of detritals is likely to be very small unless they are sufficiently pre-wetted. It is possible that the principal contribution to recharge occurs through bedrock aquifer outcrops and shallow subcrops, which is currently difficult to quantify.

3. Numerical model

3.1 Approach to numerical representation of the conceptual model

The current numerical model is built on an updated HSU structure which includes fractured bedrock basement units and development of the new model mesh and parameterisation.

The model is built with several layers to allow for a more appropriate vertical distinction in the key represented lithological units / HSUs.

Model calibration is focused on representing the regional trends of groundwater flow directions within the model domain, acknowledging the likely structural control of the recognised linear geological structures which are currently conceptualised as low permeability flow barriers.

There is therefore the lack of large-scale stresses that the model can be tested on.

3.2 Model structure and parameterisation

3.2.1 Model discretisation

The numerical model is developed in Modflow USG, using the unstructured grid functionality to represent the detail of the MAR area. The model has four layers: the two top layers simulate the surficial, detrital cover; while the underlying two layers represent the fractured bedrock aquifer.

The model consists of 76,012 active (quad) model cells, ranging in size from 12.5 to 200 m. The GDA94 Zone 51 coordinates of the SW corner of the model grid are 664,051E and 7,460,842N.

The implemented model grid is presented in Figure 3-1, and the MAR area detail in Figure 3-2.

The base of surficial HSUs (base of layer 2) is displayed in Figure 3-3. The bedrock (layers 3 and 4) is terminated at a nominal elevation of 550 m AHD. Layer 3 has a nominal uniform thickness of 10 m.

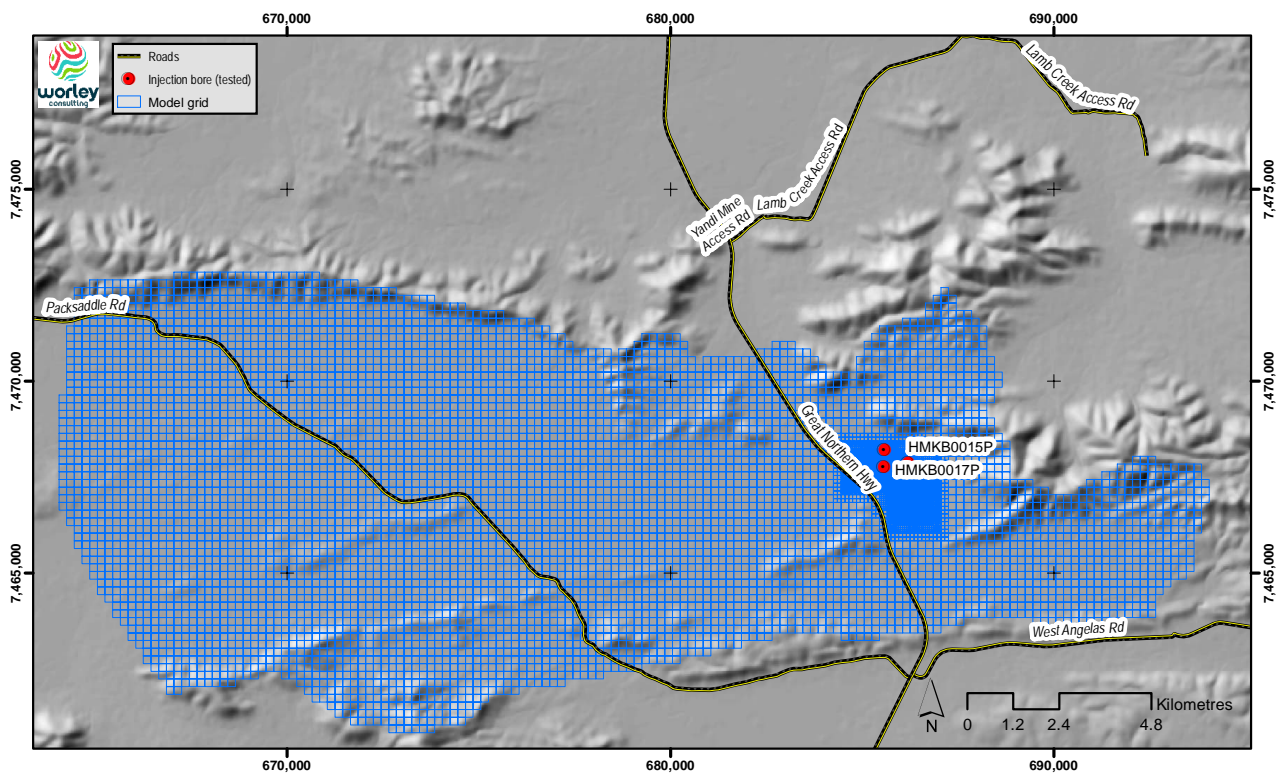


Figure 3-1 Numerical model grid

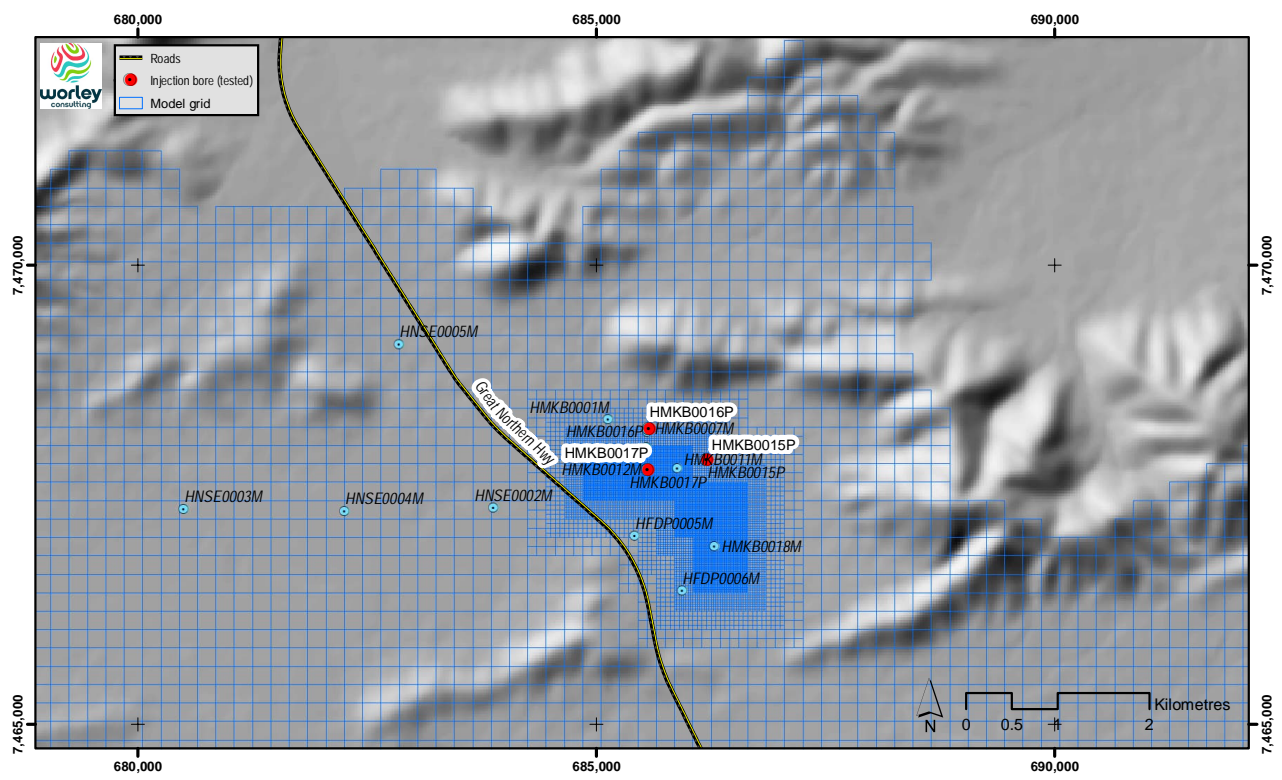


Figure 3-2 Numerical model grid, MAR area detail

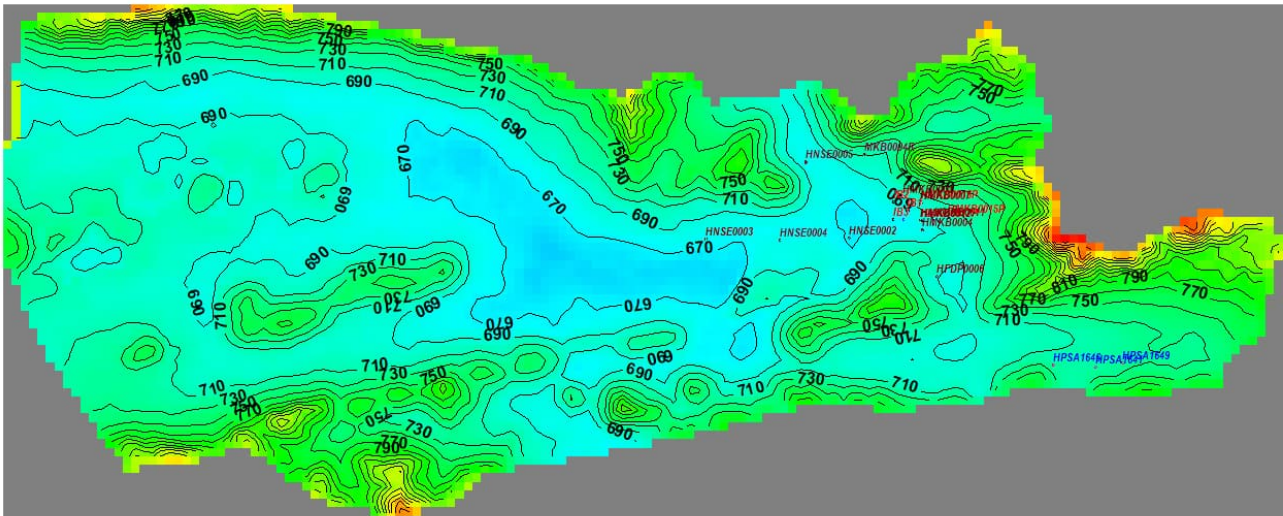


Figure 3-3 Base elevations of the surficial deposits

3.2.2 Parameter zones

Parameter zones reflect the conceptual HSUs. Their spatial delineation is presented in Figure 3-5 (surficial HSUs) and Figure 3-6 (fractured bedrock HSUs).

Their parameter values were initially informed by the conceptual overview shown in Table 2-4, and adjusted during model calibration.

The calibrated values (base case calibration) are shown in Section 4. The effects of varying values of selected parameter zones, deemed relevant for the MAR operation, are also further examined through standard Monte Carlo analysis, covered in Section 5.

3.3 Boundary conditions

3.3.1 Throughflow

Throughflow boundaries are implemented using the CHD/GHB packages as follows (Figure 3-9):

Figure 3-4 Throughflow boundaries

Location	Head (m AHD)
Sections of western boundary	696
Sections of southern boundary	660
Outflow to north	680

The boundaries are set as constant (i.e. no temporal variation is implemented).

3.3.2 Recharge and evapotranspiration

The model area is set to receive nominal recharge at a rate of 6 mm/yr which is within the typical range for this region. This rate is applied everywhere except for the aquitard outcrops, which are set to have zero recharge.

3.3.3 Horizontal barrier

Two linear regional structures, conceptualised as the dolerite dykes, are implemented using the HFB package in layers 3 and 4 (Figure 3-9). They function as low-permeability barriers to groundwater flow, producing partial compartmentalisation of the modelled aquifer system.

Their nominal parameters used (and unchanged) for the HFB package in all simulations are: thickness 5 m and hydraulic conductivity 0.0001 m/d.

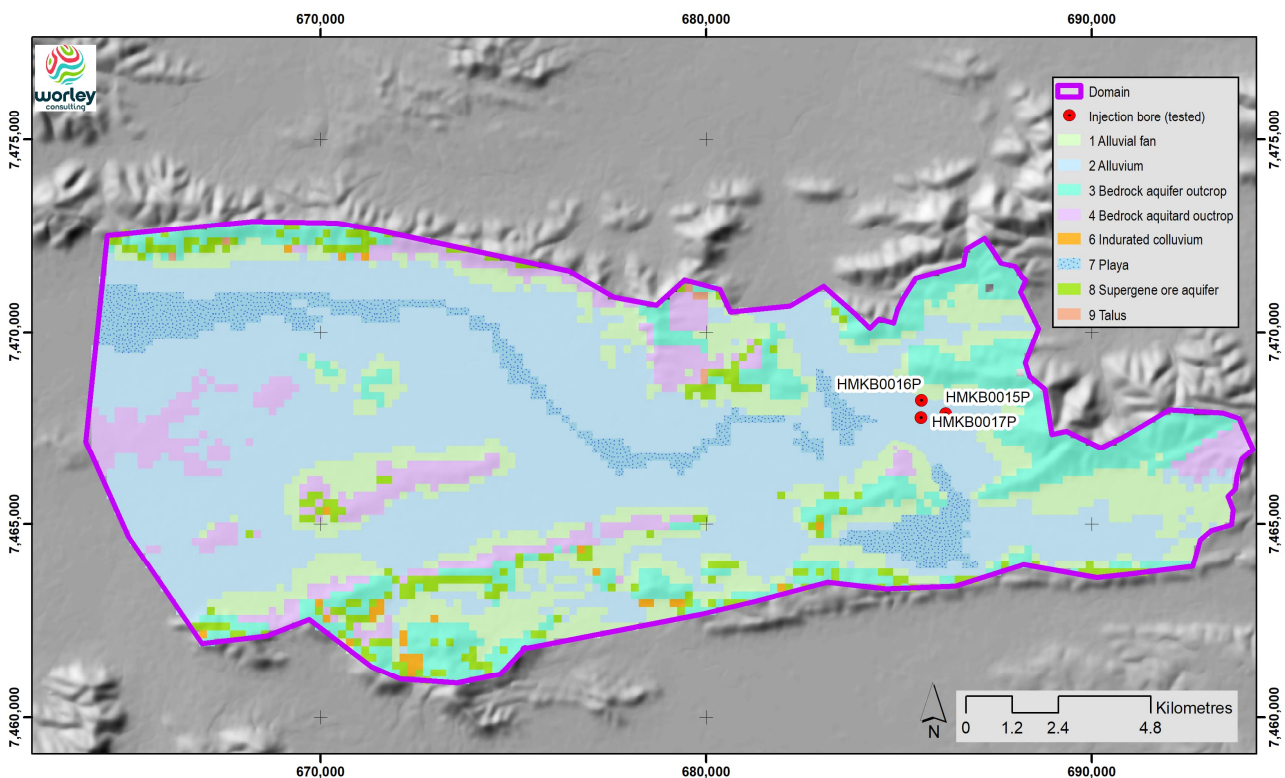


Figure 3-5 Parameter zone distribution – surficial HSUs (model layers 1 and 2)

3.3.4 Groundwater abstraction and injection

Injection and monitoring bores are represented in the numerical model through the WEL package, distributed in the MAR area (Figure 3-9). During calibration, actual testing rates are applied as per Section 2.5.1. In the predictive simulations the total rates is spread among the six locations

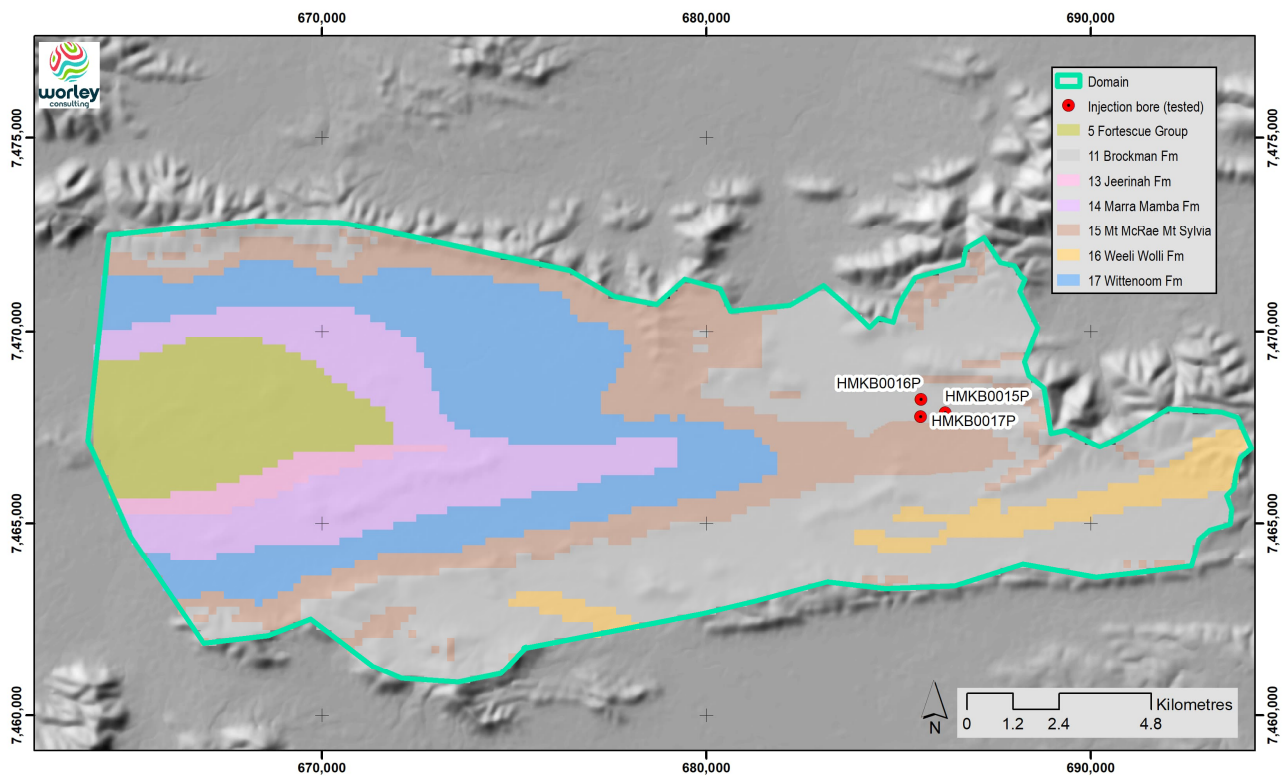


Figure 3-6 Parameter zone distribution – bedrock HSUs (model layers 3 and 4)

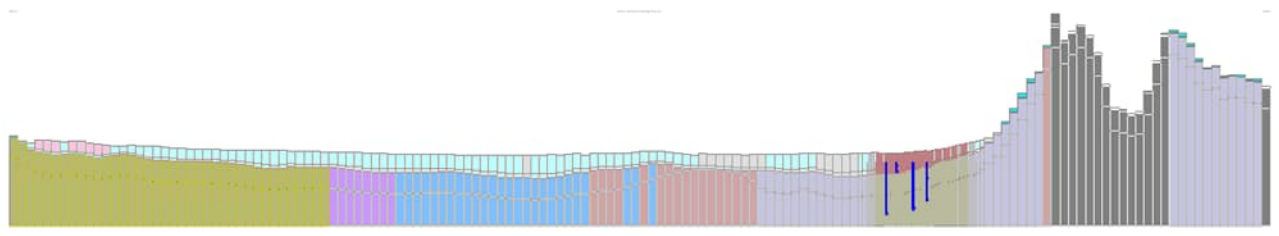


Figure 3-7 WE section through the model grid

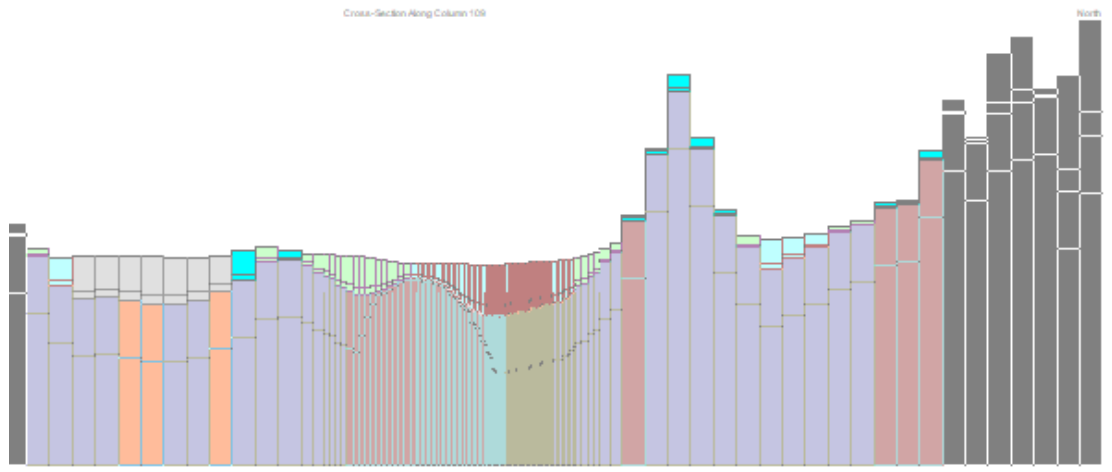


Figure 3-8 S-N section through the model grid

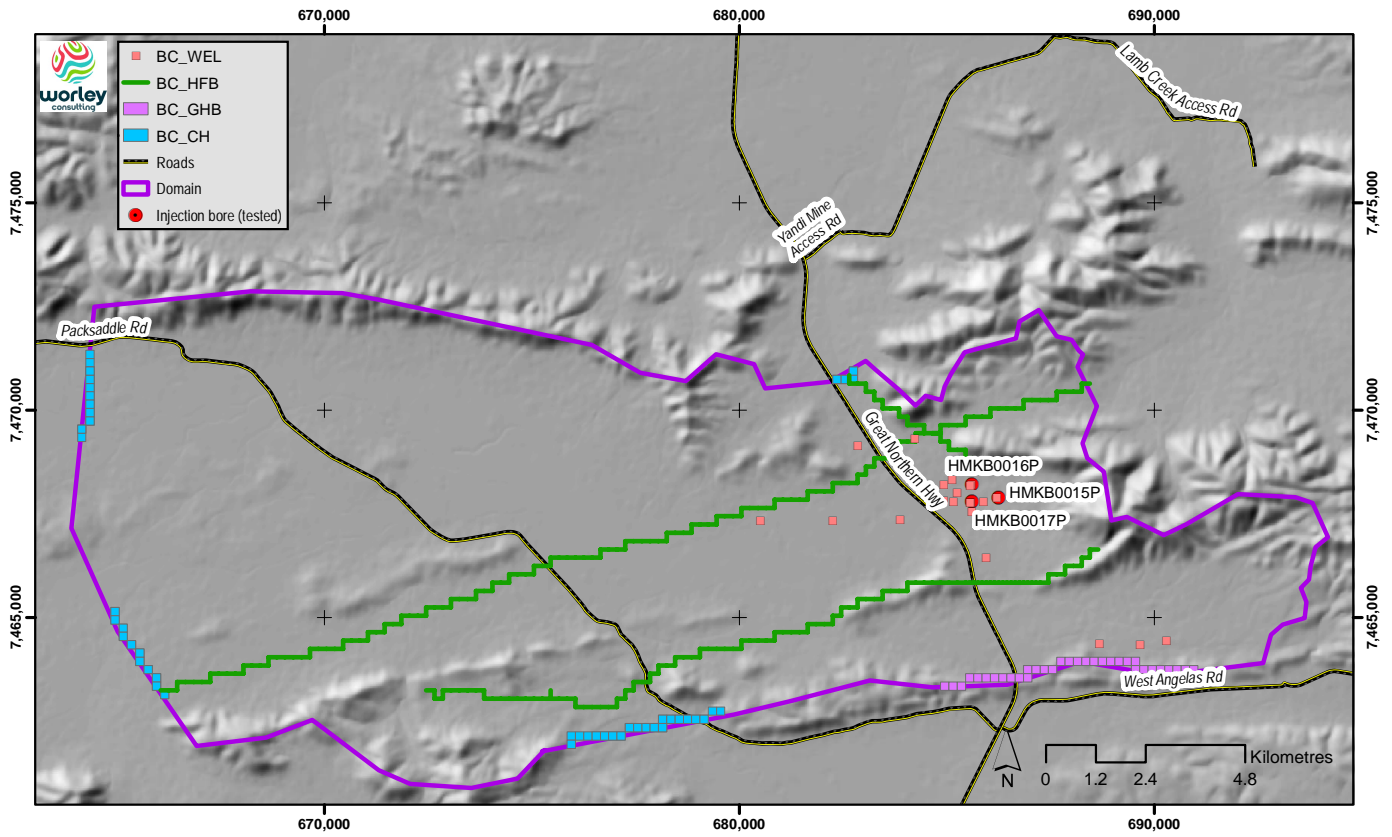


Figure 3-9 Spatial distribution of model boundary conditions

4. Data assimilation (calibration)

4.1 Approach

Data assimilation / calibration applied to the current model included the following steps:

- Steady state calibration to align the groundwater flow directions within the model domain
- Transient calibration to reproduce the water levels measured at observation bores monitored during the pumping tests conducted on injection bores HMKB00015P, HMKB00016P and HMKB00017P

The steady-state representation represents the long-term conditions. A better, more detailed distinction of recharge processes is currently not considered since reliable data representing the aquifer response to potential recharge events such as large rainfall and/or intermittent flow in the drainage lines is not available. Water levels in the area are deep, and would attenuate the signals from individual recharge events.

While the duration of pumping tests is relatively short compared to the eventual MAR operation, they provide a valuable indication of hydraulic parameters for fractured rock aquifer system in this area.

The model is set up as follows:

- Stress period 1 is steady state, intended to represent inferred long-term groundwater flow conditions and provide initial water levels
- Transient calibration (stress periods 2 to 7) – designed to reproduce (using the model) the pumping test behaviour during the three pumping tests carried out in 2023
- Predictive simulation (stress period 8) – set up to represent injection through 6 injection bores over 20 years (transient simulation).

4.2 Targets

Steady state calibration makes use of the measurements from hydrogeological bores which have been monitored at various times. A selection of 37 bores is used for calibration purposes, however there are additional water level observation from the RC and other drilling in the area. Additional observations are largely consistent with the selected set.

Monitoring bores observed during the pumping tests on the three production bores in the MAR area are the focus of transient calibration. Hydrographs compiled of the measured and modelled groundwater level data are used to indicate the calibration performance of the model.

4.3 Calibration results

The calibrated model reflects the key groundwater flow directions and adequately matches observed water level trends.

The distribution of steady-state water levels is shown in Figure 4-1. They show the general west to east gradient, groundwater levels at approximately 680 m AHD in the MAR area, and the compartmentalisation effects of the regional dykes, as per the hydrogeological

conceptualisation. The unsaturated portion of surficial HSUs (shown in light purple), is also shown to highlight their limited overall saturation and the testament to deep groundwater.

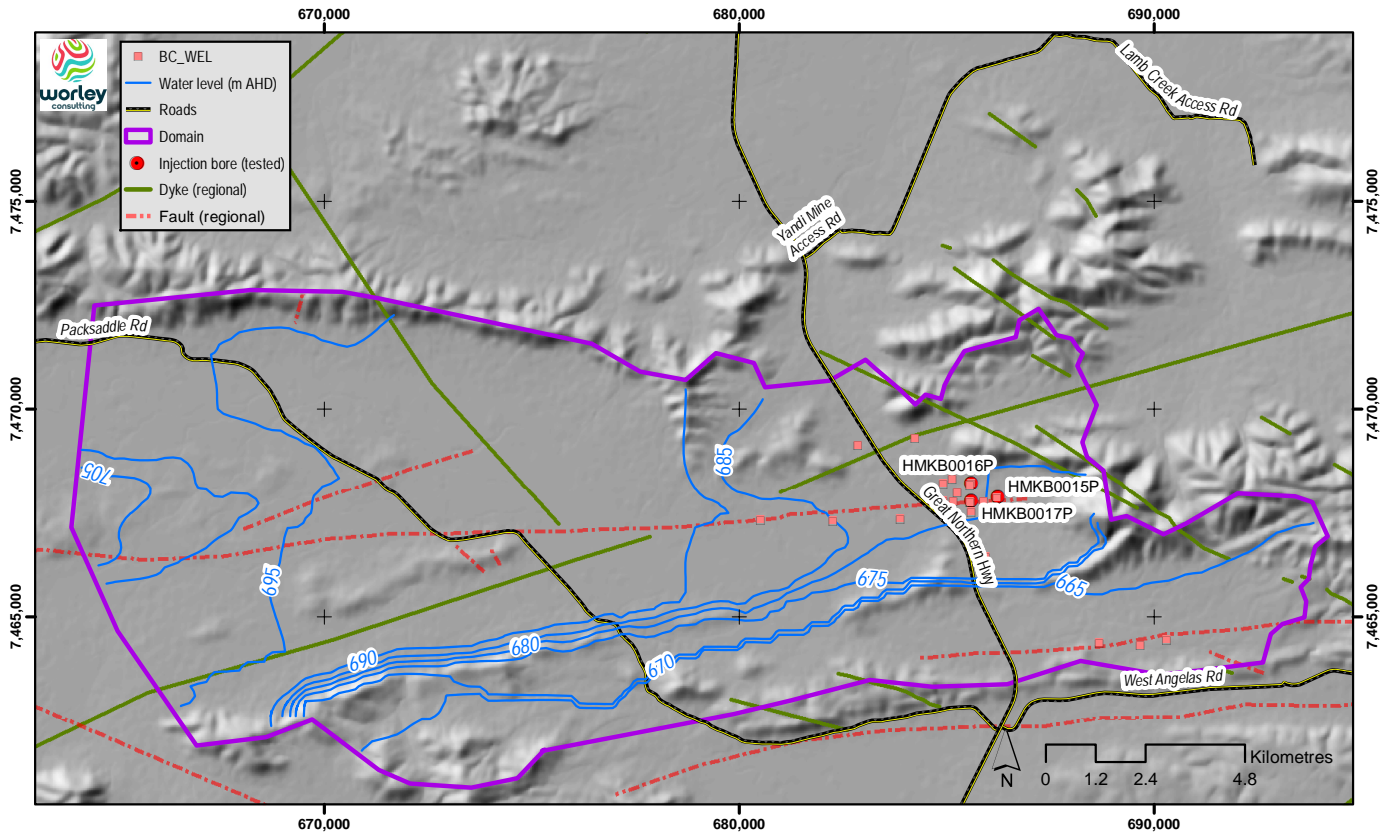


Figure 4-1 Steady state water level configuration

The match between the modelled and observed water levels during the aquifer testing is considered adequate. The proximal locations, shown in Figure 4-2, reproduce the drawdown responses from pumping of individual production bores.

The distal locations (Figure 4-3) display a 50:50 split in over- or underprediction by a few metres between the observed and modelled values.

HNSE0004M and HFDP006M monitoring bores, situated furthest to the west and south of the MAR area, could indicate the need for consideration of potentially lower hydraulic conductivity in their respective areas, requiring potential further spatial adjustment of the aquitard HSU.

HNSE0005M and HMKB0004RM monitoring bores show a slight overprediction, less than two metres, possibly indicating slightly more permeable conditions to the northwest of the MAR.

Recharge rates for important drainage lines have also been tested during the calibration, ie greater rates were applied. Changing the recharge rates along these features was found to have negligible effects on the calibration results.

The calibrated parameter values (eg. hydraulic conductivity), in particular for BIF, are considered to be at a higher end of the range in the region. All parameter values for the calibrated case are presented in Table 4-1 and Table 4-2.

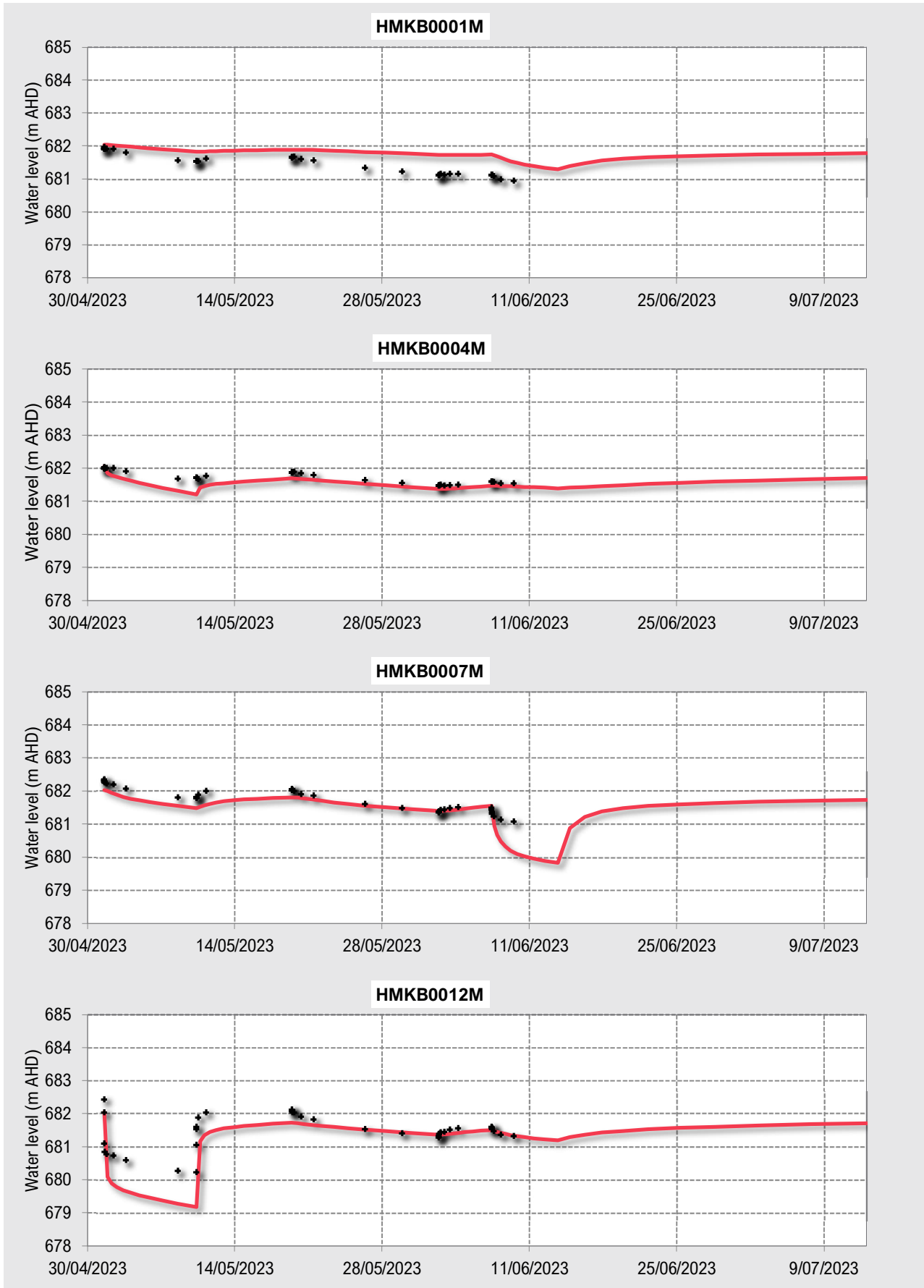


Figure 4-2 Observed and modelled water levels during pumping test simulation – proximal bores

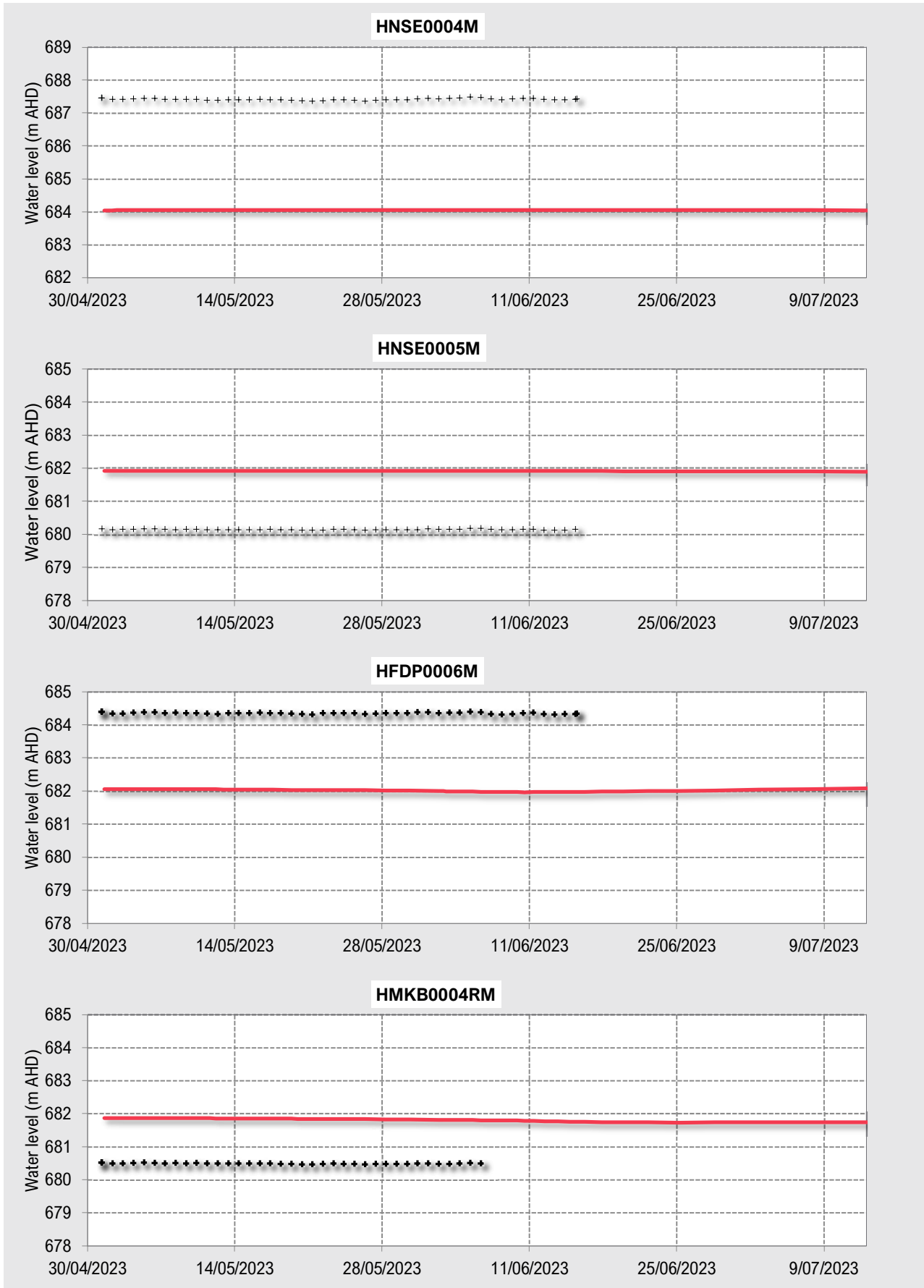


Figure 4-3 Observed and modelled water levels during pumping test simulation – proximal bores

Table 4-1 Zone parameter summary (surficial HSUs) obtained from calibration

HSU	Zone	Kh (m/d)	Kv (m/d)	Sy	Ss (1/m)
Alluvium	2	10	2	0.2	1x10 ⁻⁵
Playa	7	2	0.2	0.15	1x10 ⁻⁵
Alluvial fan (transported duricrust)	1	20	2	0.2	1x10 ⁻⁵
Supergene ore aquifer	8	5	5	0.05	1x10 ⁻⁵
Talus	9	5	0.5	0.2	1x10 ⁻⁵
Indurated colluvium	6	2	0.2	0.15	1x10 ⁻⁵
Bedrock aquitard outcrop	4	0.3	0.3	0.005	1x10 ⁻⁵
Bedrock aquifer outcrop	3	5	2.5	0.05	1x10 ⁻⁵

Table 4-2 Zone parameter summary (bedrock HSUs) obtained from calibration

HSU	Zone	Kh (m/d)	Kv (m/d)	Sy	Ss (1/m)
BIF	11	10	5	0.02	5x10 ⁻⁶
Wittenoom Fm	17	15	3	0.05	1x10 ⁻⁵
Mt McRae Shale and Mt Sylvia	15	0.03	0.03	0.005	1x10 ⁻⁶
Marra Mamba Fm	14	7	7	0.05	5x10 ⁻⁶
Jeerinah Fm	13	0.3	0.3	0.005	1x10 ⁻⁶
Weeli Wolli Fm	16	0.05	0.05	0.005	1x10 ⁻⁶
Fortescue Group	5	0.005	0.005	0.001	1x10 ⁻⁶

5. Predictive simulations

5.1 Approach

The calibrated model forms the basis for setting up the predictive simulations. In addition to predictive simulation based on the calibrated model (which is referred to as base case model, BCM), predictive modelling also includes a standard Monte Carlo (SMC) simulation to help explore the effects of parameter uncertainty.

The predicted groundwater change due to the MAR is reported in terms of predicted depth to water (DTW), recognising that the typical environmental constraints require maintaining the DTW not less than 10 m BGL.

5.2 Groundwater injection

5.2.1 Setup

The predictive model setup comprises of:

- Three additional injection bores to the three existing production bores are added
- The recharge and throughflow rates being constant through the prediction period
- Incorporation of evapotranspiration function (7 mm/d; extinction depth of 1 m)
- Application of two injection rate scenarios, 20 and 30 ML/d, spread among 6 injection bores, to be continuously operated for 20 years.

The MODFLOW model setup consists of an initial steady state stress period, followed by stress periods representing the individual pumping tests and then followed by the 20-year prediction period.

This is to allow for evaluation of standard Monte Carlo realisations, to be able to understand their effects on calibration performance (including calibration statistic), as well as on prediction.

5.2.2 Predicted groundwater level change

Prior to the MAR, groundwater in the MAR area is relatively deep, 40 to 50 m BGL. Injection sustained over time leads to groundwater mounding within the fractured rock aquifer and the overlying detrital sequence, the latter of which is mostly unsaturated under natural conditions.

After 12 years of injection at 20 ML/d, mounding of groundwater above 10 m BGL begins to occur. After 20 years of continuous injection, mounding above the 10 m BGL limit has spread to cover an area that includes three of the MAR bores (Figure 5-1).

After 2 years of injection at 30 ML/d, mounding of groundwater above 10 m BGL begins to occur. The mounding after 20 years of continuous injection is shown in Figure 5-2).

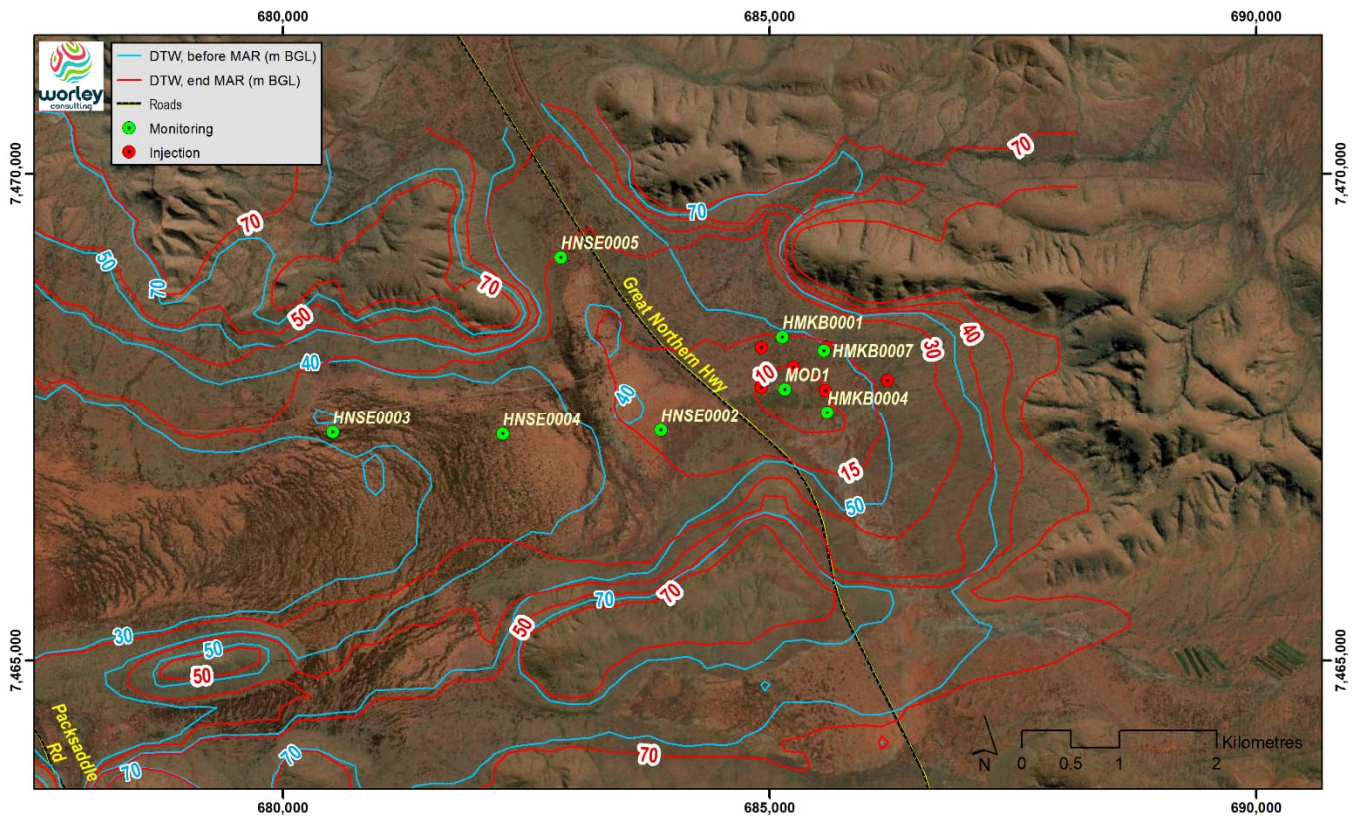


Figure 5-1 Predicted depth to water - before and at the end of MAR; 20 ML/d case

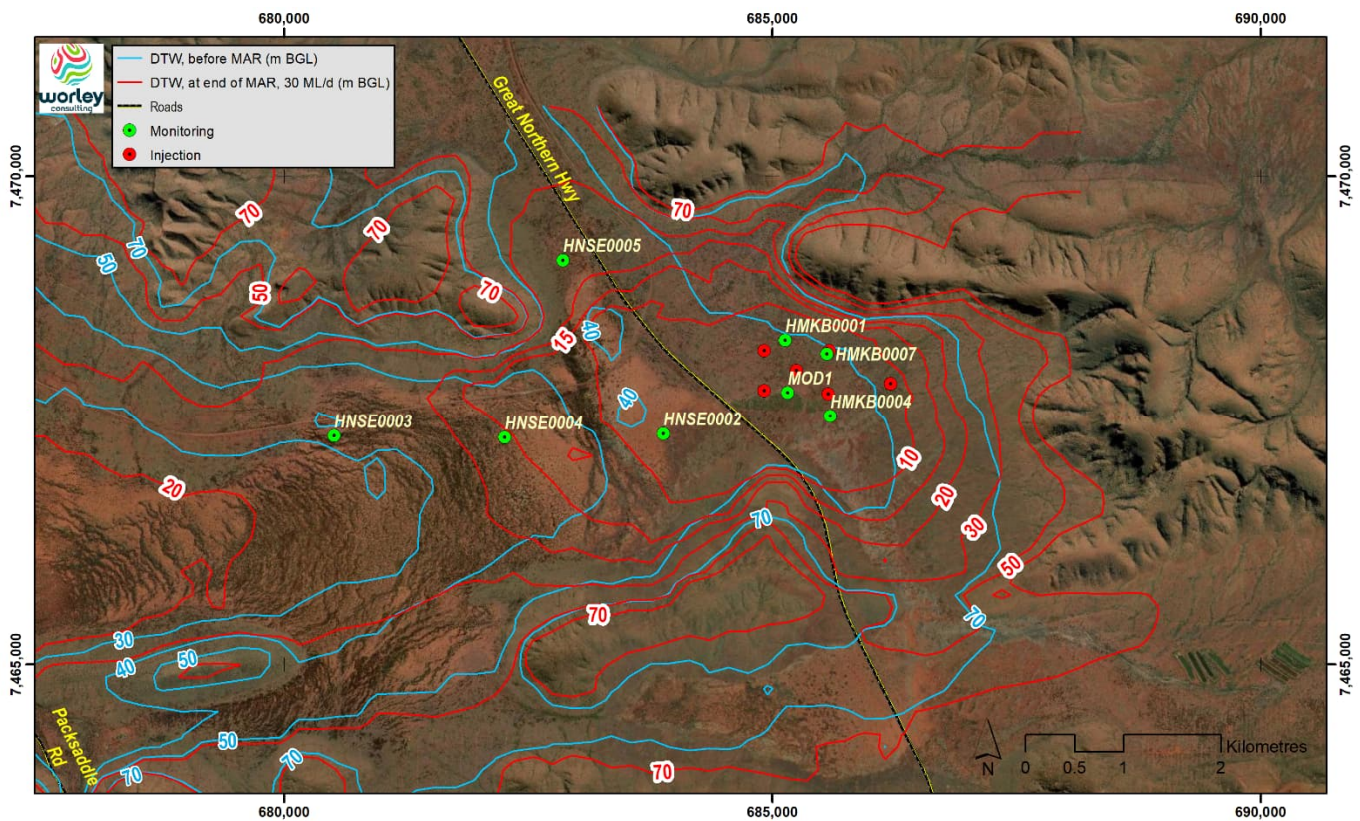


Figure 5-2 Predicted depth to water - before and at the end of MAR; 30 ML/d case

5.2.3 Predictive uncertainty simulations

As with any model, it is a simplification of a complex natural system, with most of its properties and their spatial distribution being uncertain. The aquifer parameters for this system have only been tested for a small part of the model domain.

To explore the effects of some of these uncertainties, a standard Monte Carlo (SMC) simulation is also incorporated into the simulation run. Unlike with the null-space Monte Carlo (NSMC) analysis, the individual realisations do not have to necessarily conform with the calibration criteria, although the ensemble of simulations in this report is checked for the calibration performance post simulation.

An SMC simulation, applied to this study, is based on 100 realisations. Each realisation contains a randomly selected set of parameters which are allowed to vary between each realisation. Although randomly generated, the parameters follow the prescribed lognormal distribution, identified by its mean, standard deviation, minimum and maximum values (Table 5-1).

The parameter zones with perturbed parameters include:

- alluvium (detritals, Zone 2)
- playa sediments (along main drainage lines, Zone 7)
- bedrock aquifer outcrop (Zone 3)
- deep bedrock (BIF) aquifer (Zone 11).

Parameters for the remaining HSUs such as eg. Marra Mamba or Wittenoom Formations remain unchanged in all realisations.

The perturbed parameters include:

- Kh (Kv is tied to Kh, ie the Kv/Kh ratio is preserved)
- Sy
- Ss

The statistical setup implemented in Groundwater Vistas is shown in Table 5-1.

Table 5-1 Statistical ranges used for standard Monte Carlo simulations

	Type	Use	Zone	Minimum	Maximum	Distribution	Mean	Std Dev
1	Kx	<input checked="" type="checkbox"/>	2	5.00000e-01	30.00000	Log-Normal	10.00	5.00
2	Kx	<input checked="" type="checkbox"/>	3	5.00000e-01	10.00000	Log-Normal	5.00	2.50
3	Kx	<input checked="" type="checkbox"/>	7	5.00000e-01	10.00000	Log-Normal	2.00	1.50
4	Kx	<input checked="" type="checkbox"/>	11	5.00000e-01	20.00000	Log-Normal	10.00	5.00
5	Sy	<input checked="" type="checkbox"/>	2	1.00000e-02	2.50000e-01	Log-Normal	1.00000e-01	7.00000e-02
6	Sy	<input checked="" type="checkbox"/>	3	1.00000e-02	1.00000e-01	Log-Normal	5.00000e-02	5.00000e-02
7	Sy	<input checked="" type="checkbox"/>	7	3.00000e-02	2.00000e-01	Log-Normal	1.50000e-01	5.00000e-02
8	Sy	<input checked="" type="checkbox"/>	11	1.00000e-02	7.00000e-02	Log-Normal	2.00000e-02	2.00000e-02
9	S	<input checked="" type="checkbox"/>	11	1.00000e-06	1.00000e-05	Log-Normal	5.00000e-06	2.00000e-06

Parameter frequency histograms, which are designed to follow the lognormal distribution within the ranges in Table 5-1 are presented in Figure 5-3.

All SMC realisations successfully converged and, in addition, comply with the calibration criteria across 37 calibration target locations (Figure 5-4). This means that application of ranges of parameters within the existing SMC setup does not lead to violation of calibration outside of SRMS criterion of 10%, with the majority achieving the SRMS value of 5% or less. As a result, none of the realisations significantly misrepresent the modelled system when compared with all other realisations.

The SMC realisation outputs are available for the calibration period in Appendix C. They indicate that the SMC-generated range is aligned with most observations. A comparison of the observed values and SMC-generated ranges suggests that in some cases the SMC-generated range is biased to values just above, indicating that hydraulic parameters are probably conservative (ie. potentially higher transmissivities are possible).

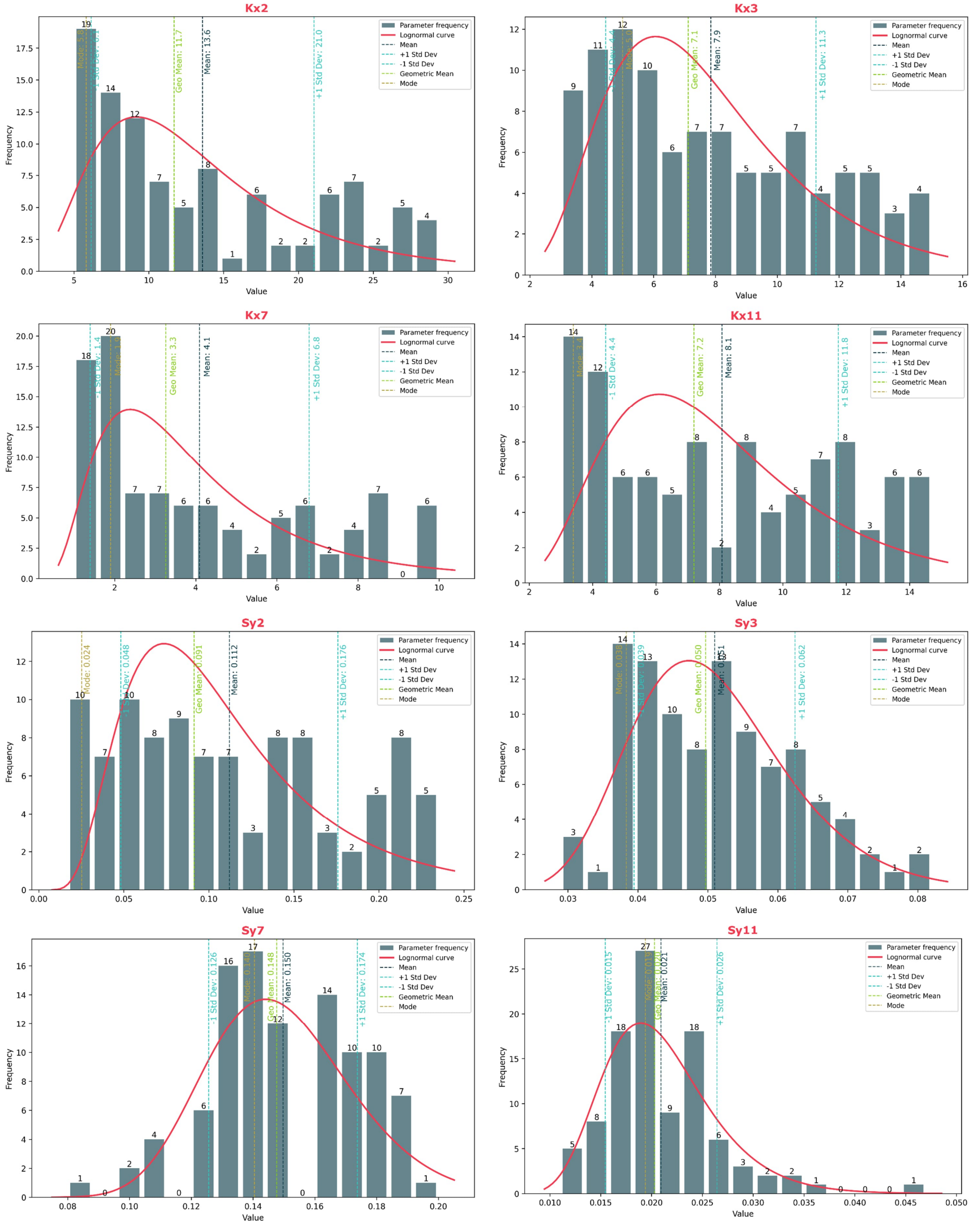


Figure 5-3 Frequency histograms for parameters perturbed in Monte Carlo realisations

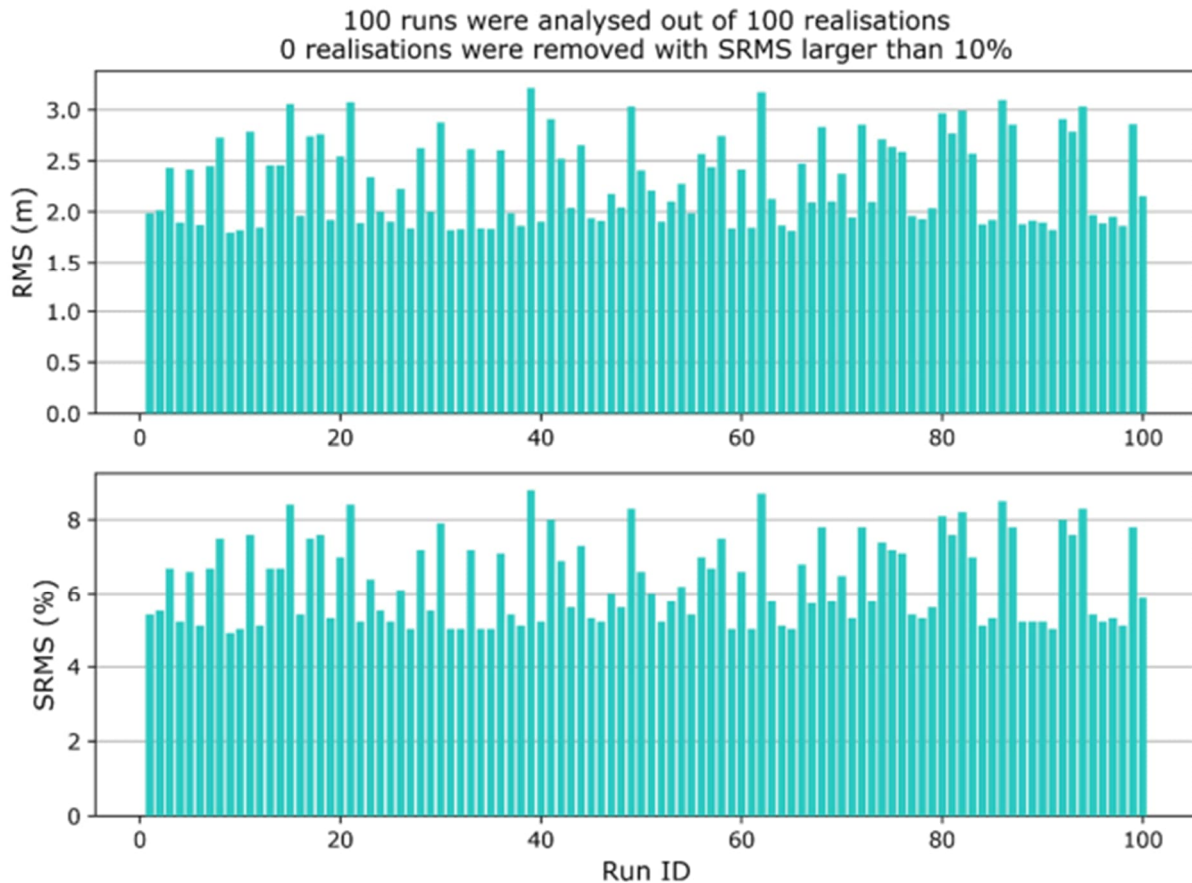


Figure 5-4 RMS and SRMS of 100 SMC realisations (calibration period)

The results of the SMC for both 20 and 30 ML/d cases are provided for easy visualisation as 10, 20 and 30 m DTW contours extracted for 10th, 50th and 90% percentile (P10, P50, and P90 cases), all after 20 years continuous injection. They illustrate the extent of mounding, in particular where groundwater is predicted to rise to less than 10 m BGL (Figure 5-5 to Figure 5-9).

For the P50 case, at 20 years (Figure 5-5) and 20 ML/d rate, the area where mounding reaches within 10 m of ground surface will extend 2 km in E-W direction and up to 1.2 km in N-S direction and would be even larger for the P10 case (2.7 x 2.2 km; Figure 5-7).

For the 30 ML/d rate, and the P50 case, the area with predicted groundwater being shallower than 10 m BGL will cover a footprint of 3 km by 2 km.

A location with the shallowest groundwater resulting from mounding is referred to as MOD1 (not an existing bore). It is central to the area where mounding occurs. The groundwater level at this location (Appendix D) is predicted to rise to 10 m BGL and less after about five years for the P50 realisation and the 20 ML/d case, and within two years for the 30 ML/d case (Appendix E).

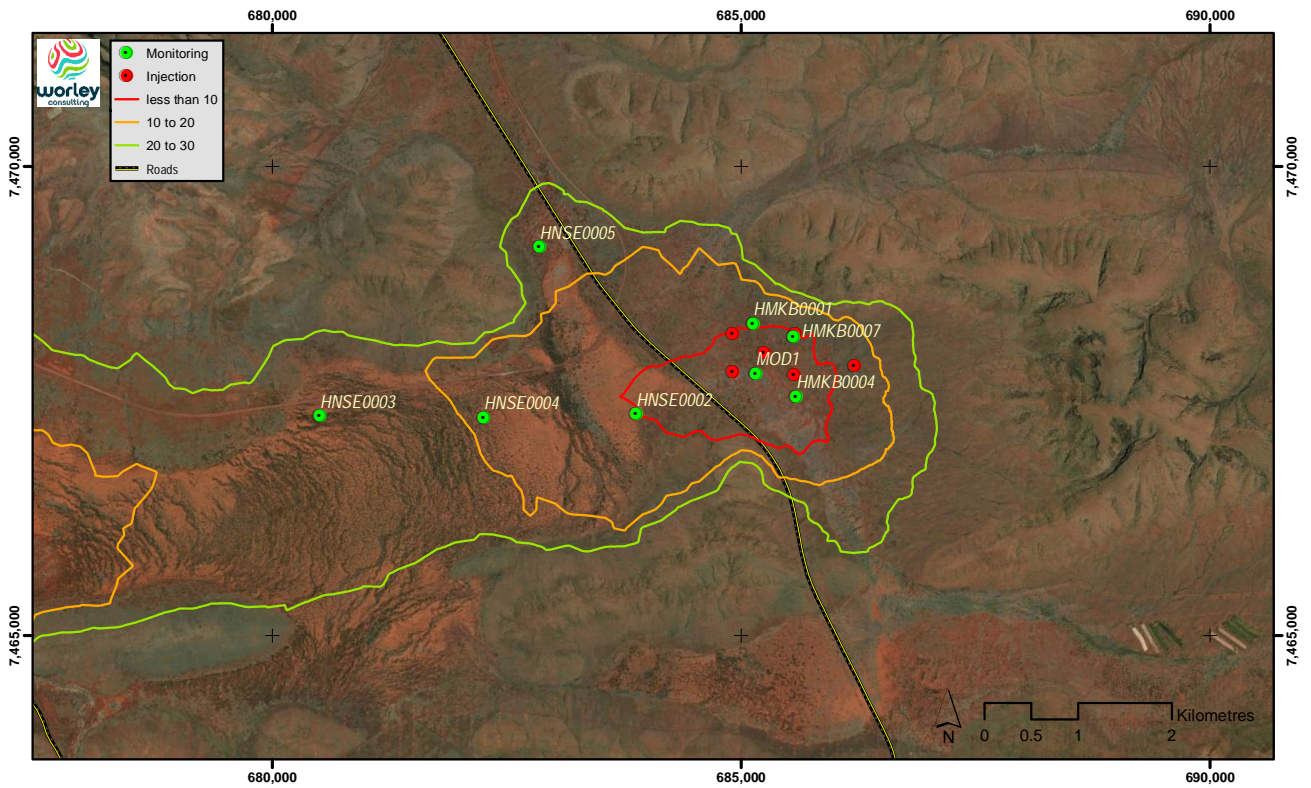


Figure 5-5 P50 MC realisation, predicted depth to water, 20 ML/d

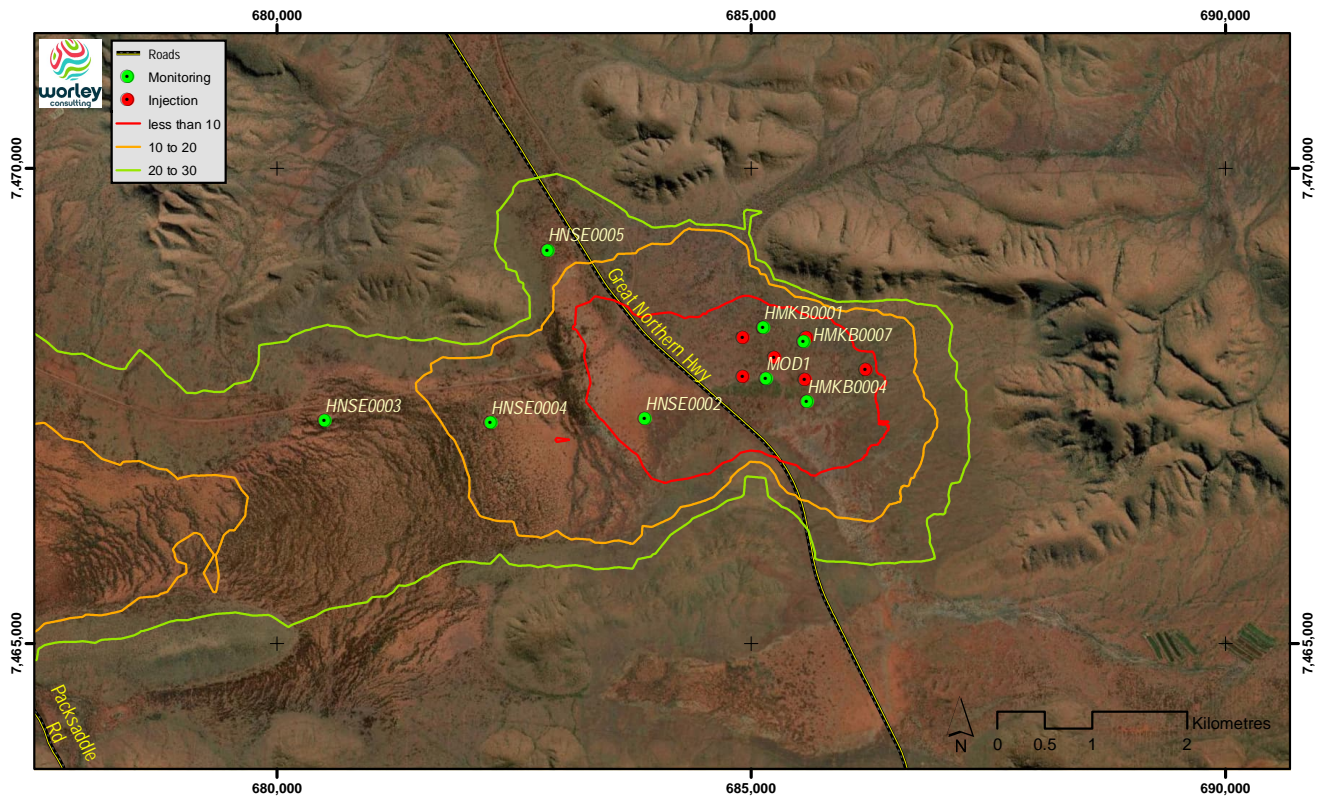


Figure 5-6 P50 MC realisation, predicted depth to water, 30 ML/d

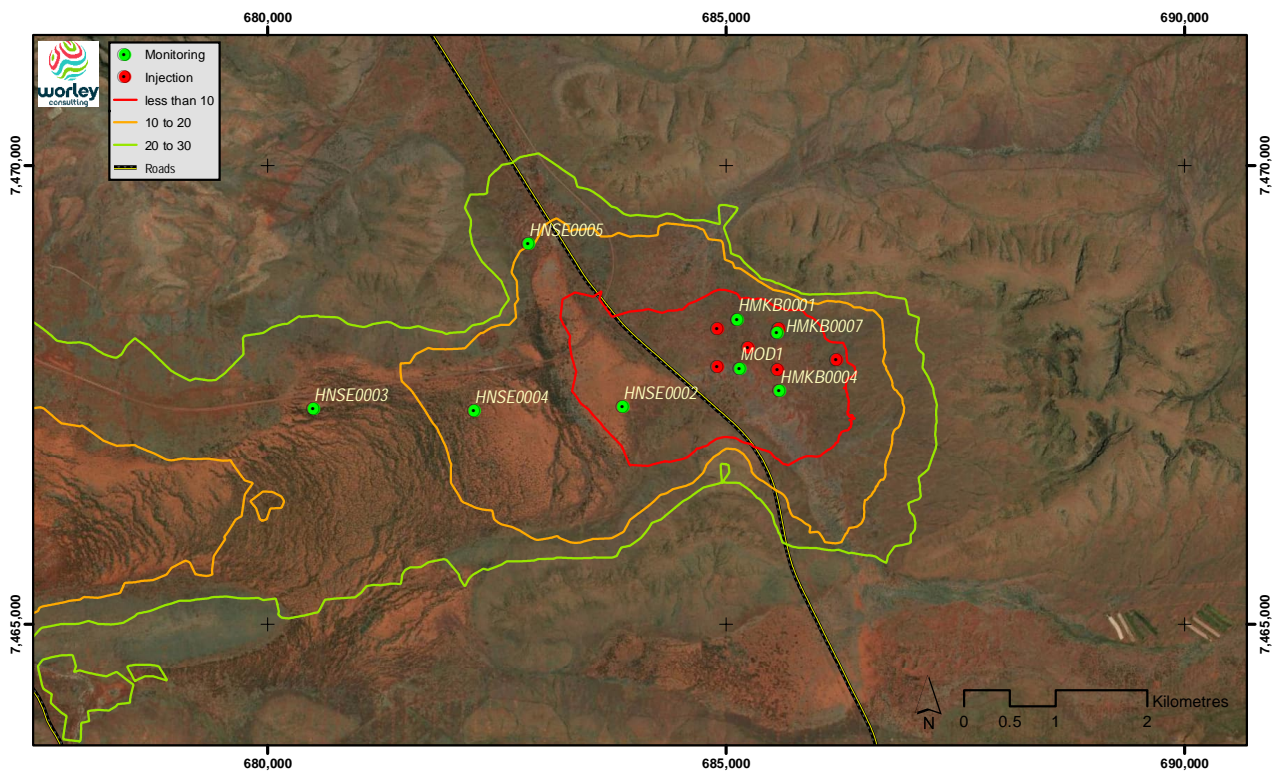


Figure 5-7 P10 MC run, predicted depth to water, 20 ML/d

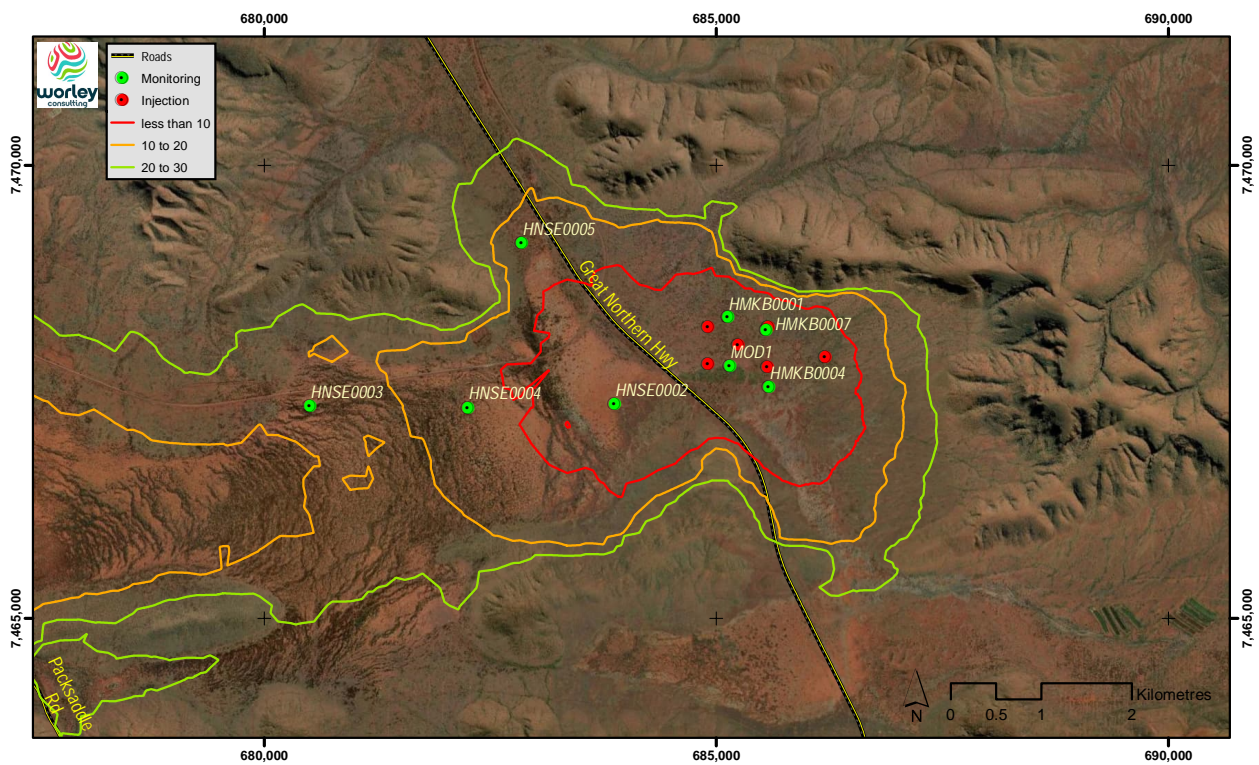


Figure 5-8 P10 MC run, predicted depth to water, 30 ML/d

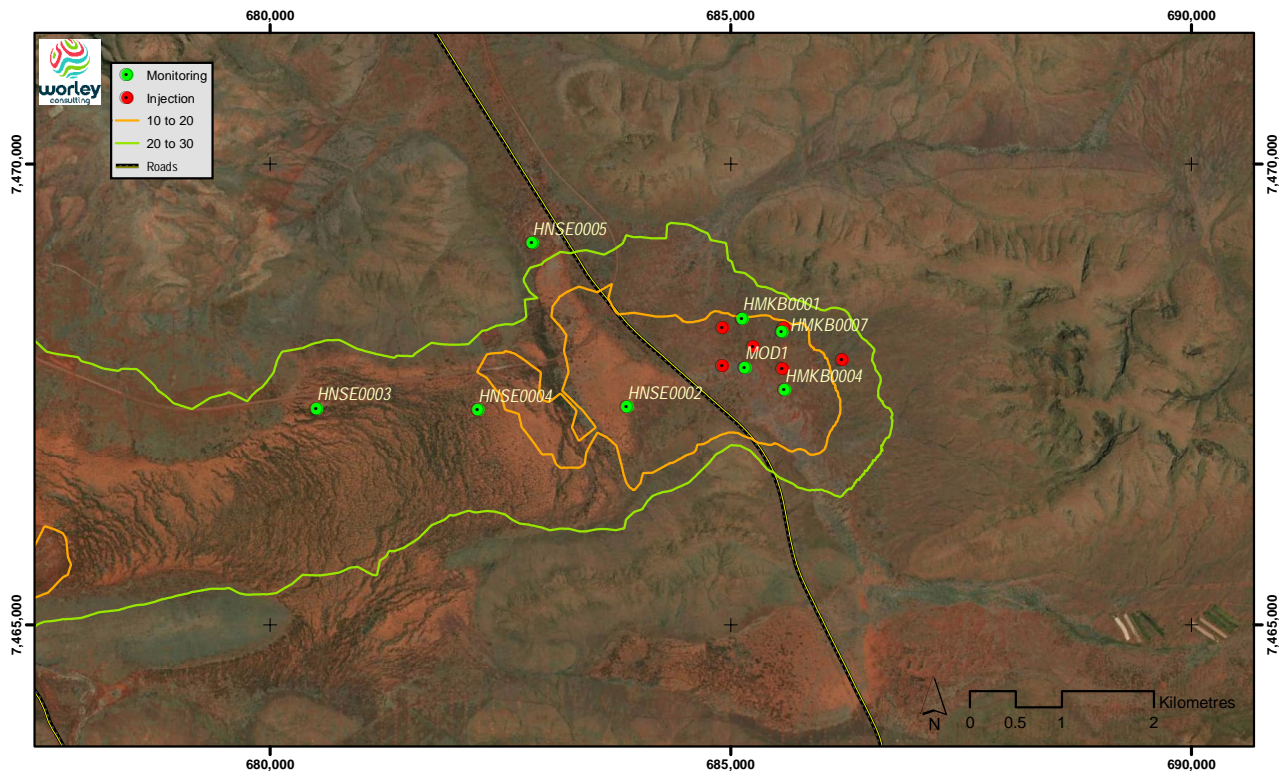


Figure 5-9 P90 MC run, predicted depth to water, 20 ML/d

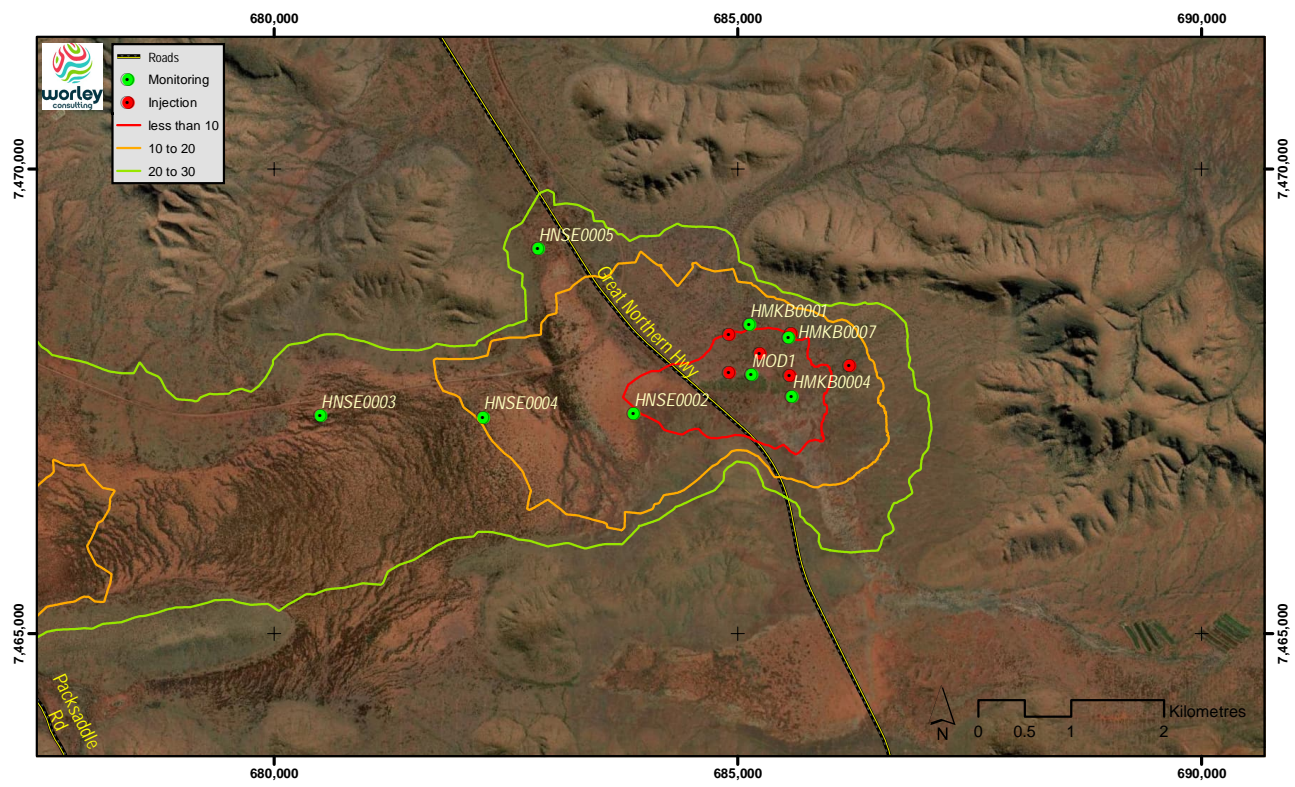


Figure 5-10 P90 MC run, predicted depth to water, 30 ML/d

5.3 Summary of predicted groundwater change

Predictive modelling and standard Monte Carlo analysis support the following:

- Sustained injection of 20 ML/d or 30 ML/d through six nominated injection bores in the MAR area will result in groundwater mounding
- Under the base (deterministic) case groundwater levels rise above 10 m BGL after 12 years at a continuous injection rate of 20 ML/d
- The probabilistic analysis (using 100 realisations of standard Monte Carlo) suggests that at P50, the groundwater level increases above 10 m BGL after five years for 20 ML/d injection rate, and two years for 30 ML/d rate
- Comparison of the SMC-generated ranges with the calibration dataset suggests there may be a slight conservative bias in the analysis, which may lead to potentially lower predicted mounding.

6. Conclusions and recommendations

BHP has been developing an MAR scheme in the Mick's Bore area of the northern Runaway Valley. They have executed an initial investigation program, with installation and testing of three production bores and monitoring instrumentation.

This study developed a new groundwater numerical model with both fractured rock and surficial (detritals) units. The revised hydrogeological conceptualisation results in an updated hydrostratigraphical unit delineation and geometry, based on geological and aerial geophysical mapping and exploration drilling. Evaluation of pumping tests conducted in the MAR area provides an indication of aquifer parameters to inform the model parameterisation.

The four-layer numerical model is built on Modflow USG platform with quad mesh which simulates a semi-closed aquifer system with structural compartmentalisation. The model is calibrated to regional groundwater levels and adequately reproduces the regional groundwater flow directions and water levels. Transient calibration is focused on reproduction of pumping test results with good matches between observed and modelled water levels achieved.

Predictive modelling carried out on the calibrated model extends also to initial predictive uncertainty analysis to partly address residual uncertainty associated with aquifer parameterisation. The prediction results of two injection rate scenarios, at 20 ML/d and 30 ML/d, over a 20-year period, are provided.

Sustained injection over 20 years will cause groundwater mounding around the zone of injection bores. The zone with groundwater shallower than 10 m BGL at the end of 20 year injection is predicted to cover an area of 2 to 5.5 km², based on analysis of modelled groundwater levels for the two rates of 20 ML/d and 30 ML/d, respectively.

Under the base case (deterministic scenario based on calibrated model), the scheme can be operated at 20 ML/d for at least 4.5 years before groundwater levels rise above 10 m BGL (assumed to be a limit to mounding). At 30 ML/d groundwater will rise above 10 m BGL within two years. These results are broadly consistent with P50 case from probabilistic uncertainty runs.

The probabilistic analysis suggested that at 20 ML/d there is a:

- 50% chance that injection will cause groundwater levels to reach 10 m BGL after five years
- 75% chance that injection will cause groundwater levels to reach 10 m BGL after 14 years

And at 30 ML/d a:

- 50% chance that injection will cause groundwater levels to reach 10 m BGL within two years
- 75% chance that injection will cause groundwater levels to reach 10 m BGL within three years

The numerical model and its results should be periodically updated once additional relevant information is collected and made available, and/or hydrogeological conceptualisation is further refined; as well as during the detailed design and operation of the MAR.

7. List of references

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BHP, 2023. Mick Bore Test Pumping. Powerpoint summary

DMIRS, 2018. 1:500,000 State Interpreted Bedrock Geology (DMIRS-016). Government of Western Australia, Department of Mines, Industry Regulation and Safety.

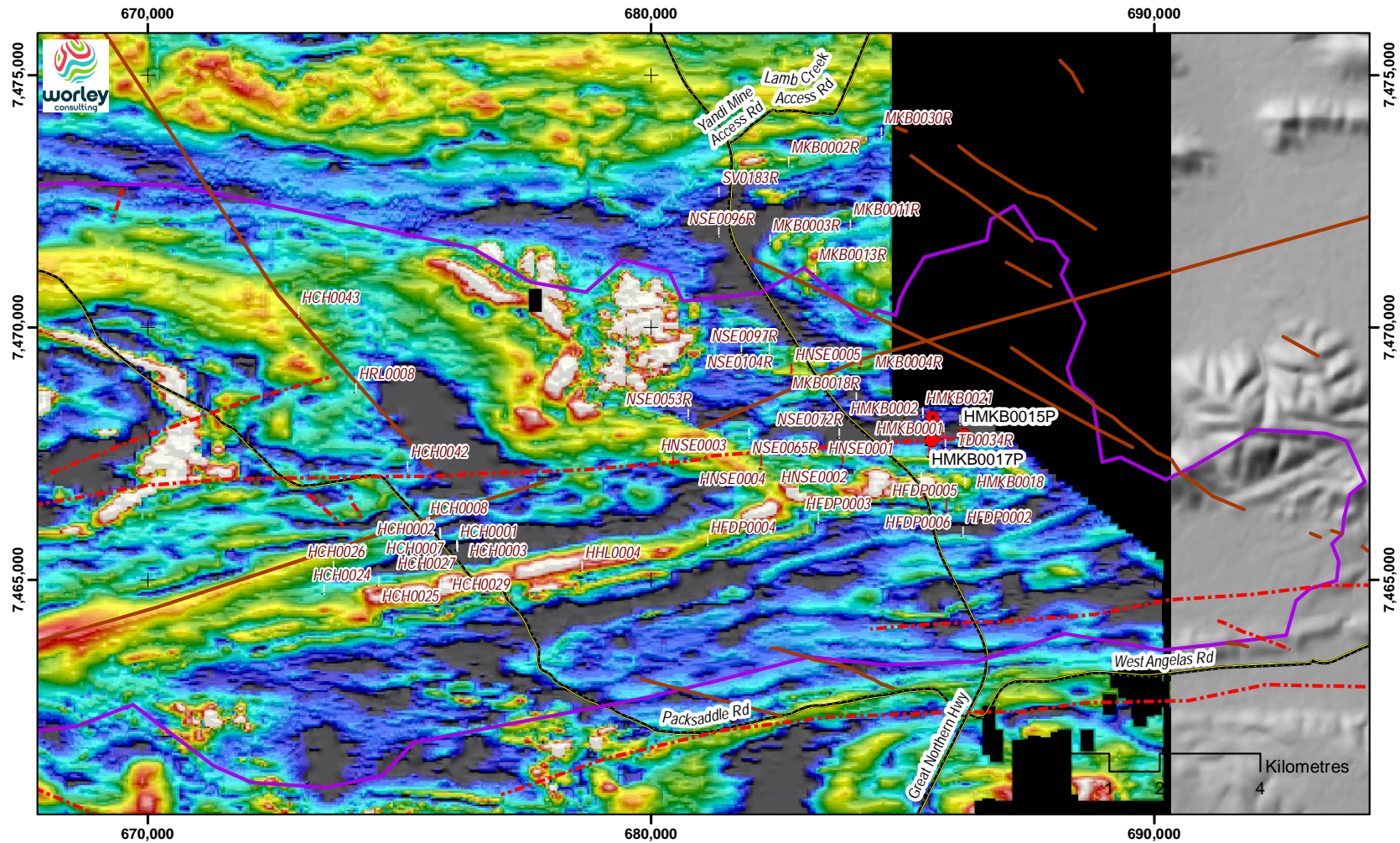
Golder, 2015. Ecohydrological Conceptualisation of the Marillana Creek Region. Report by Golder prepared for BHP Billiton Iron Ore.

Jakica, S., de Souza Kovacs, N., Hogen-Esch, J., Granado, I.M.T., 2020. 1:500 000 State regolith geology of Western Australia — compilation methodologies. Geological Survey of Western Australia, Record 2020/10, 22p.

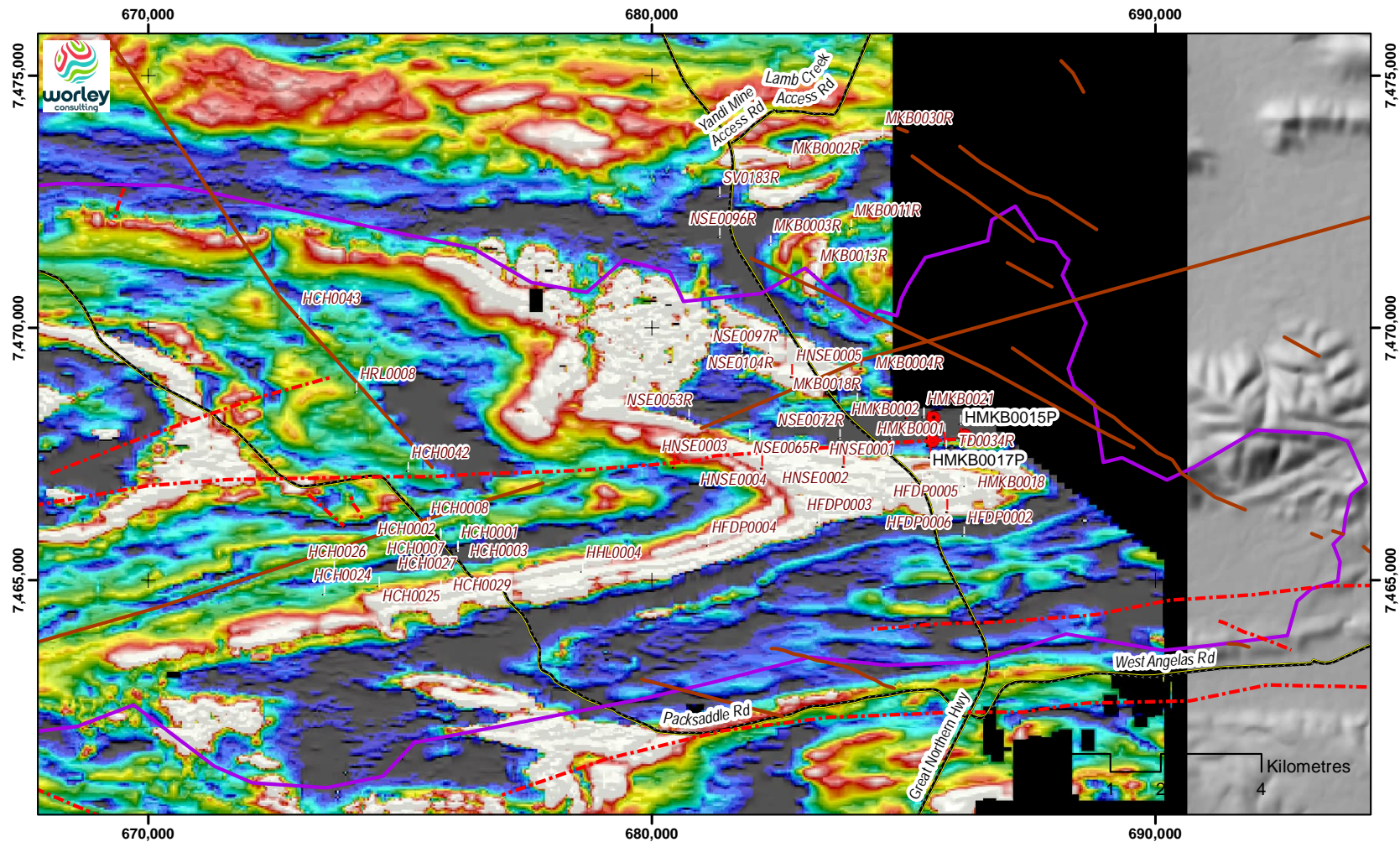
RPS, 2015. Ecohydrological Conceptualisation of the Central Pilbara Region. Technical report for BHP

Appendix A. Aerial geophysics imagery

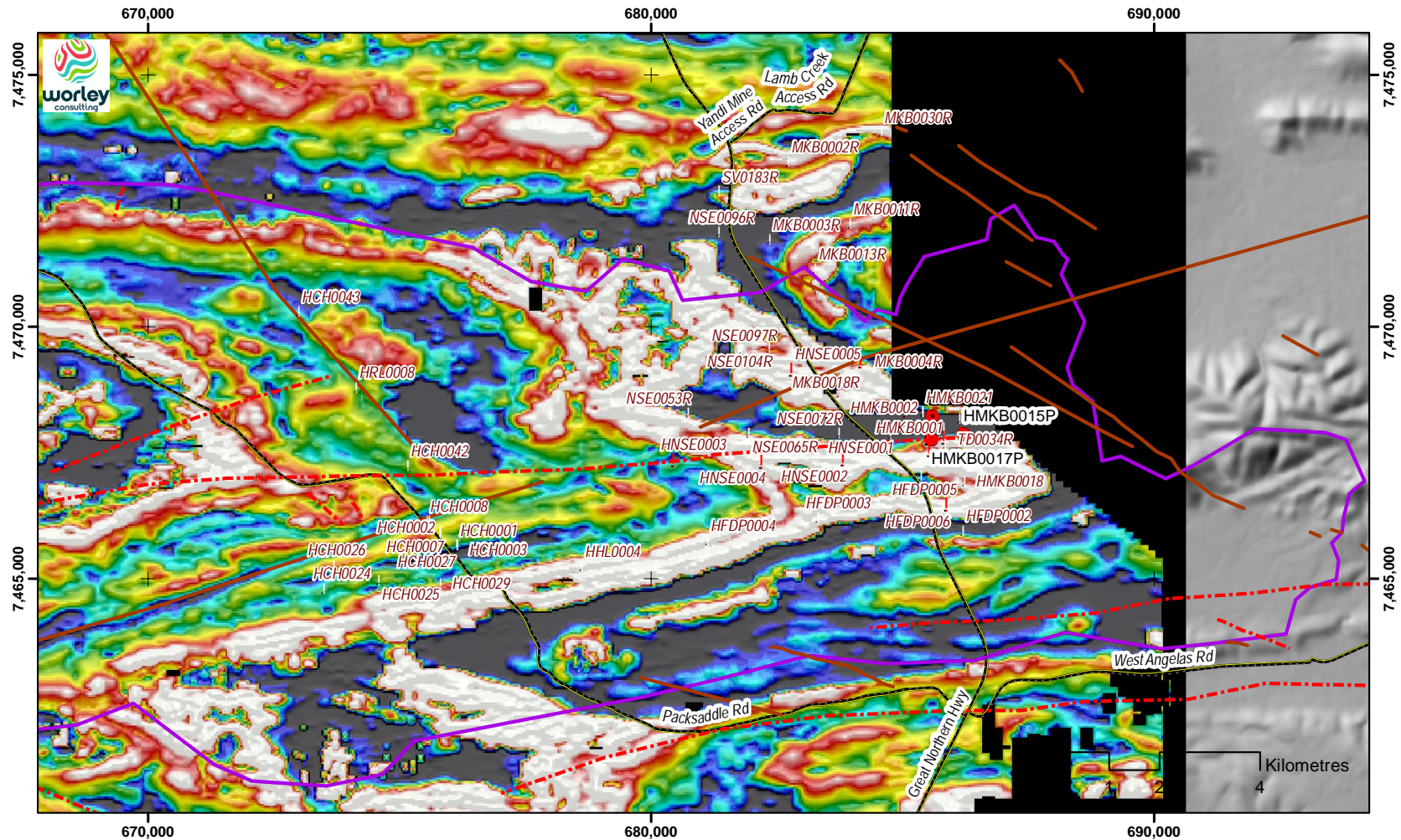
Airborne geophysics – conductivity, depth 60 m



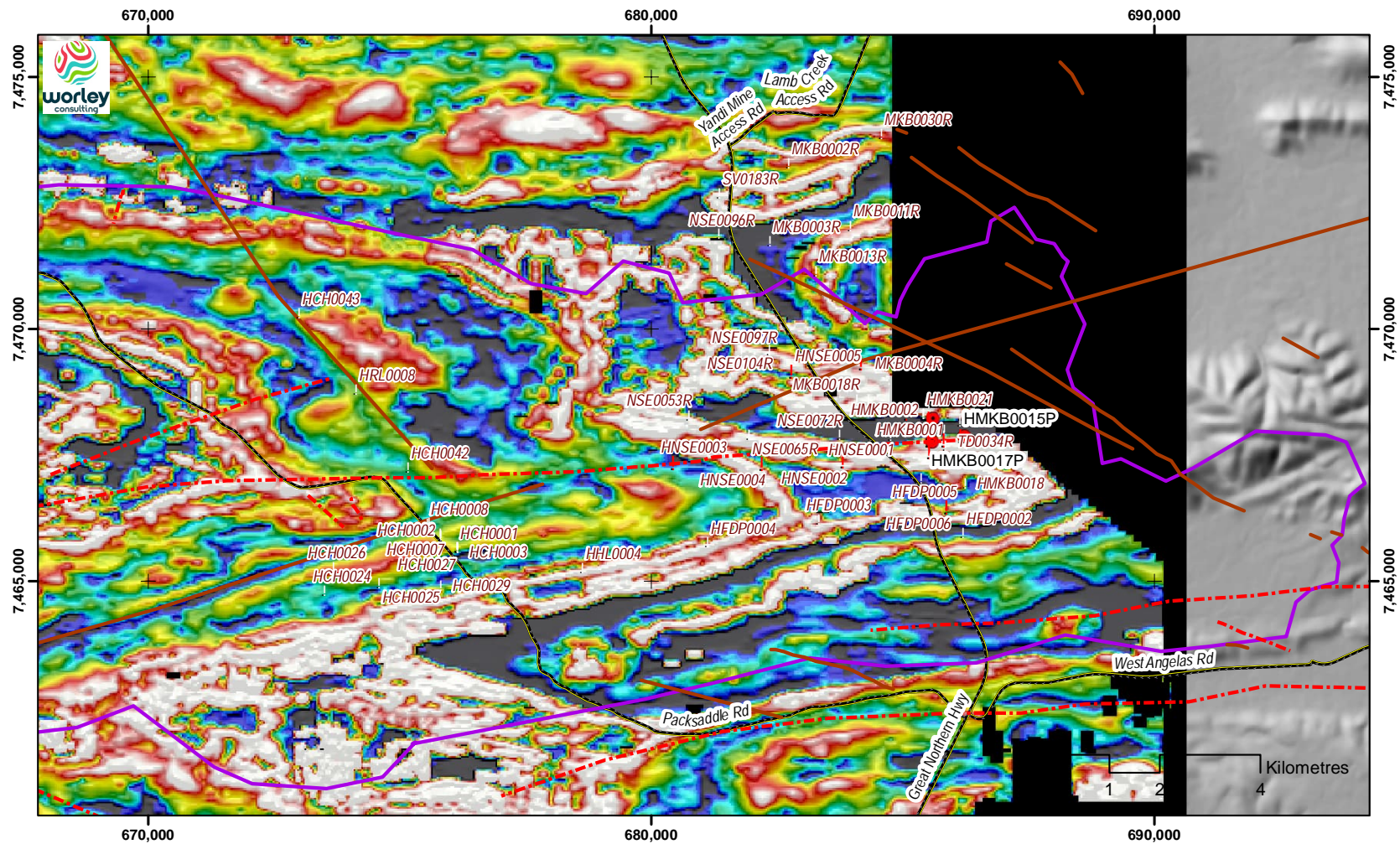
Airborne geophysics – conductivity, depth 100 m



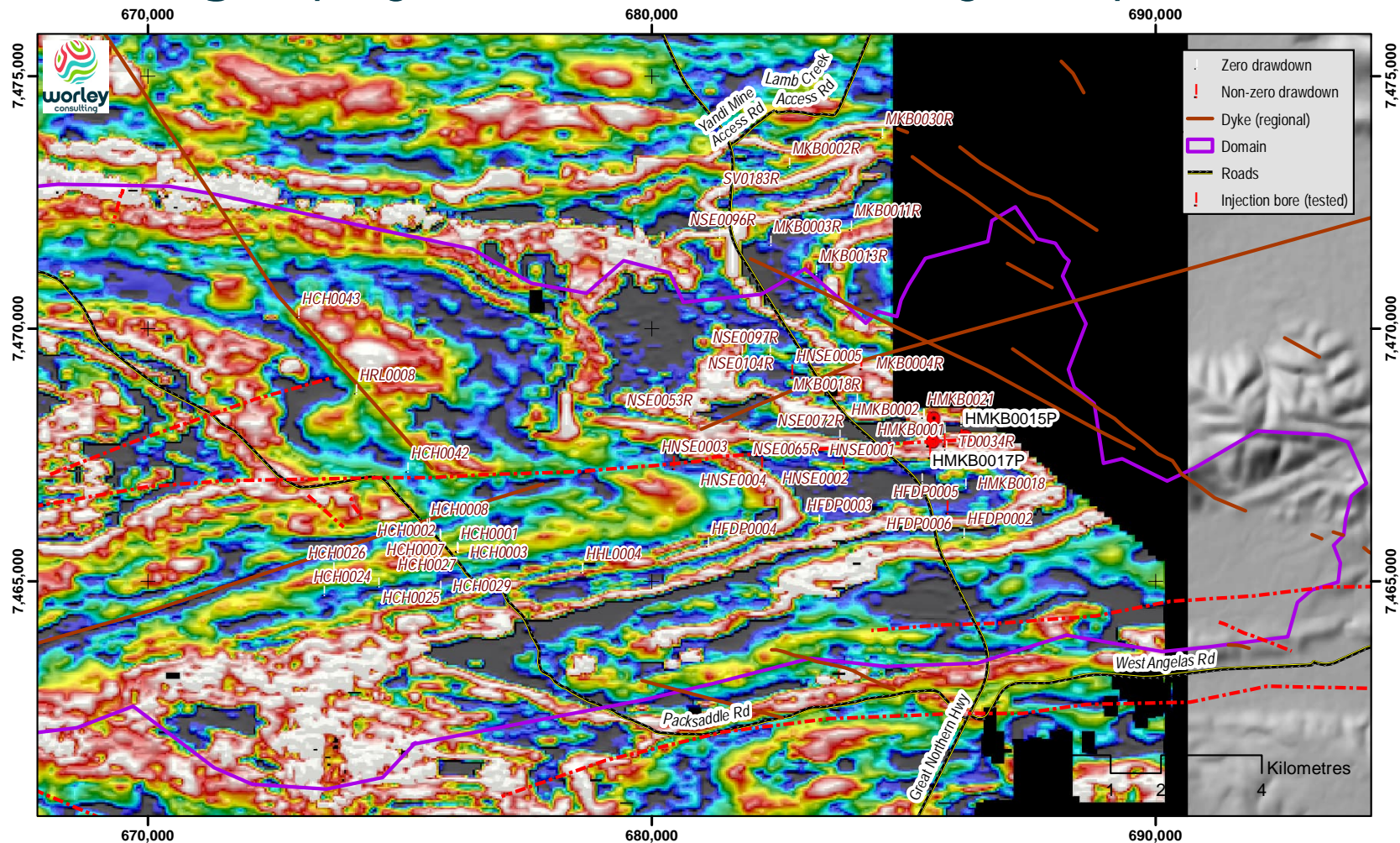
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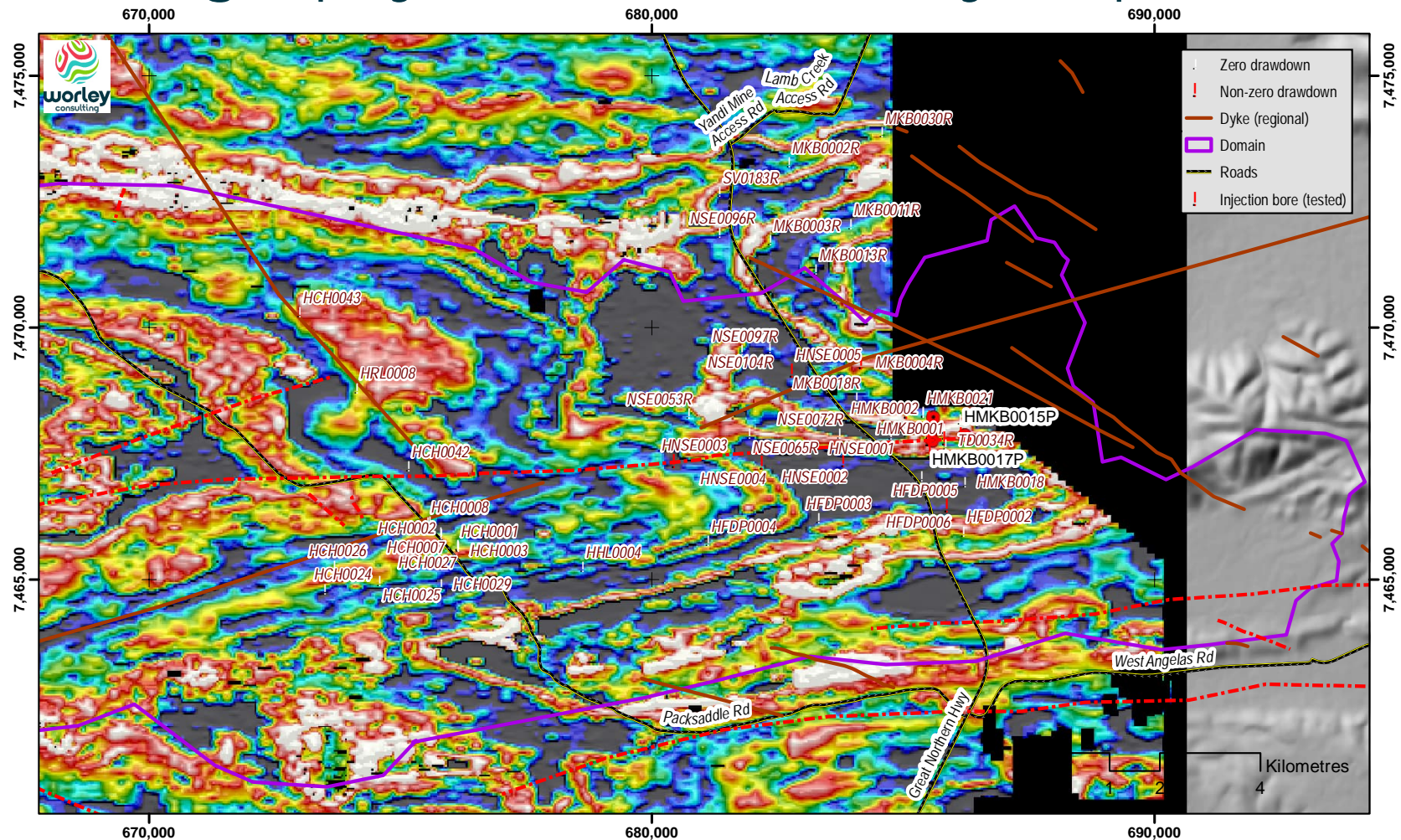
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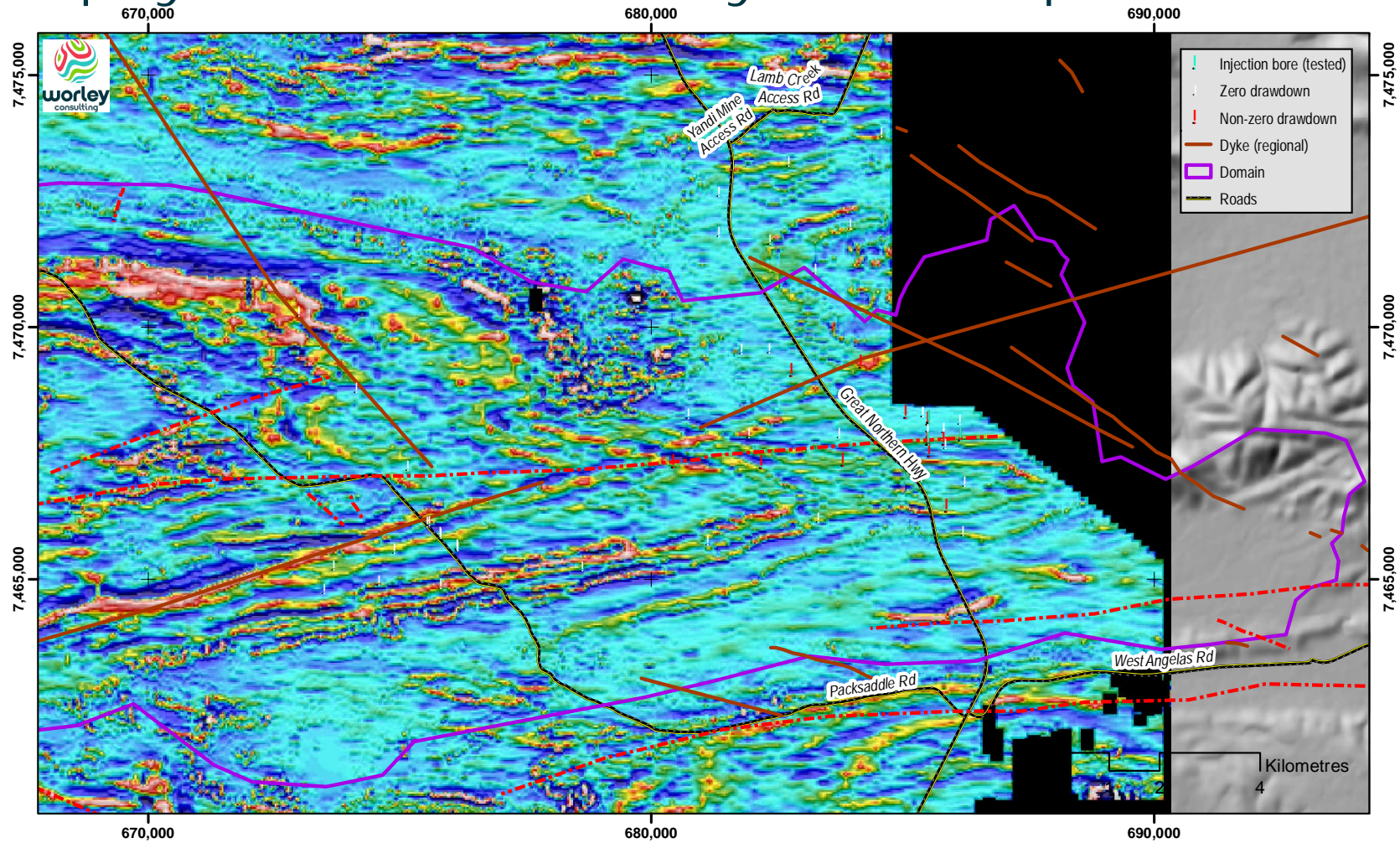
Airborne geophysics – conductivity, depth 250 m



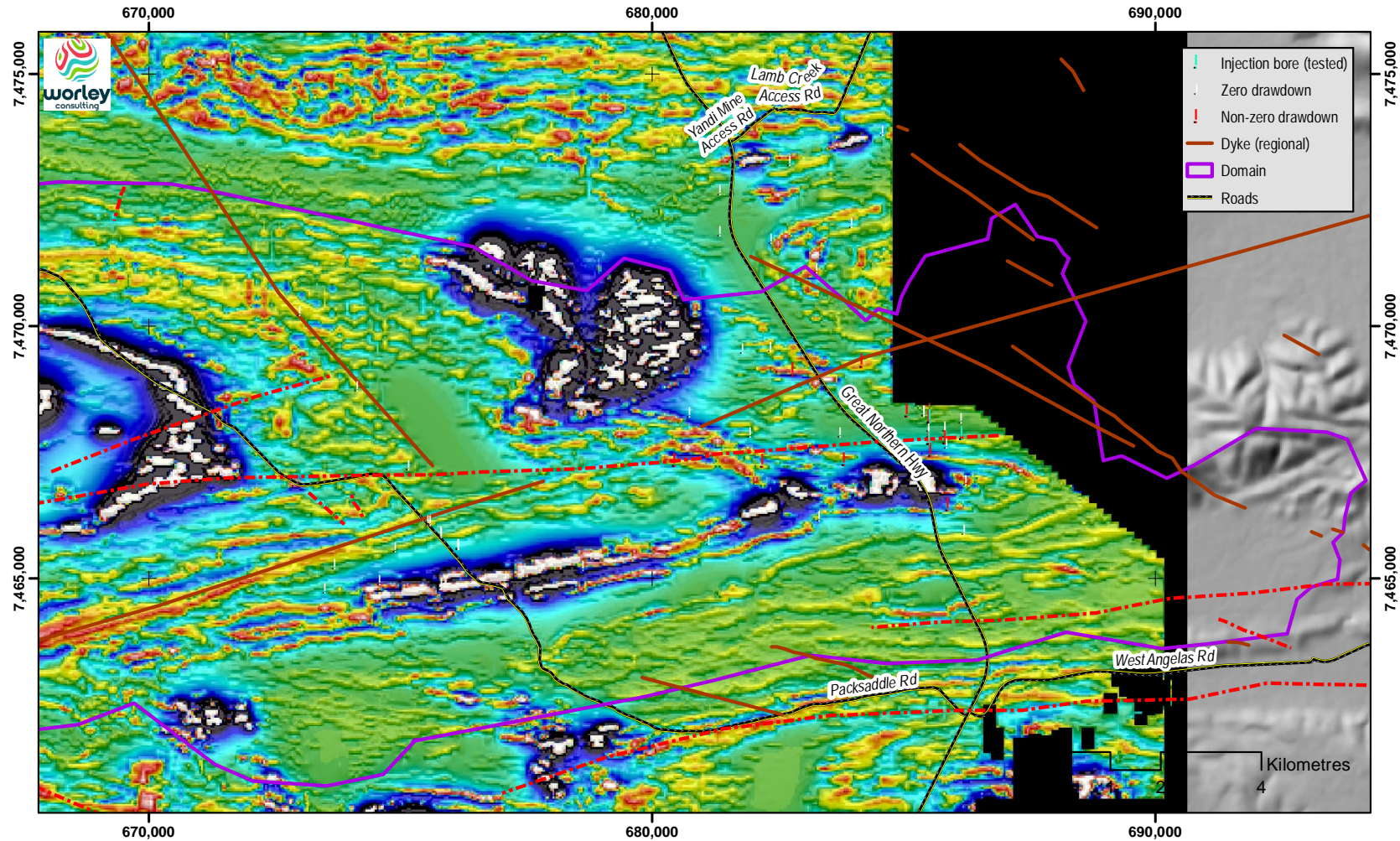
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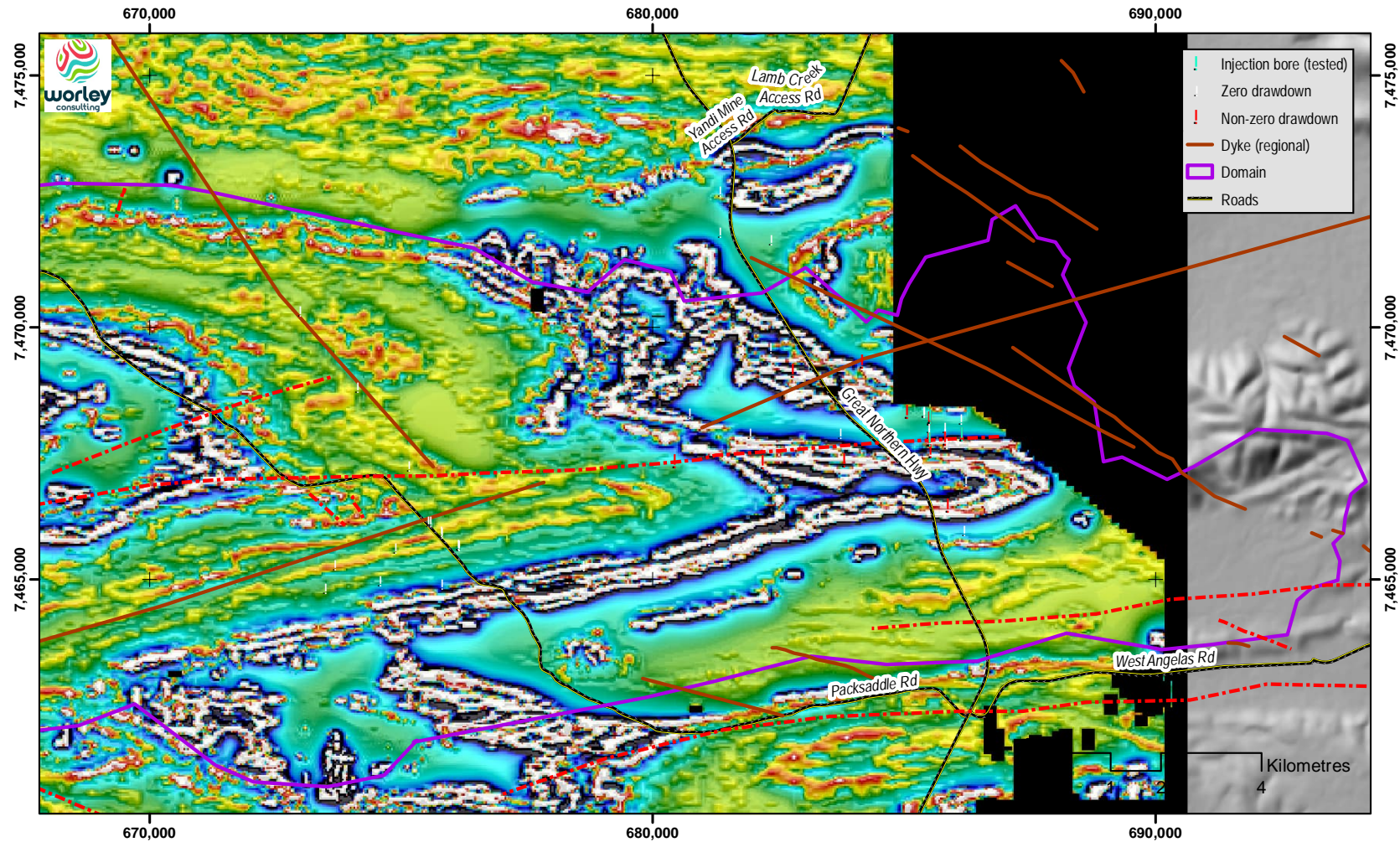
Geophysics – conductivity, VD1, depth 20 m



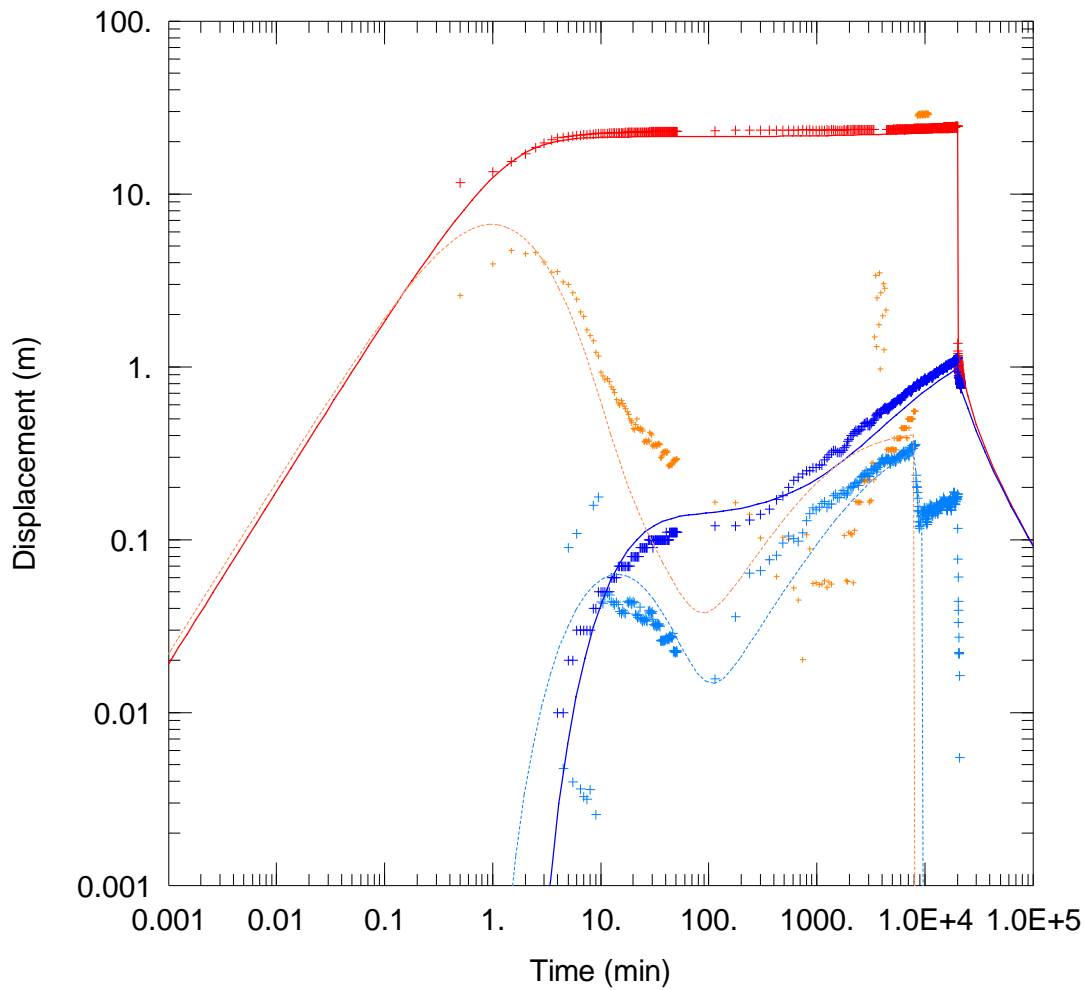
Geophysics – conductivity, VD1, depth 60 m



Geophysics – conductivity, VD1, depth 150 m



Appendix B. Aquifer testing analysis plots (Aqtesolv)



WELL TEST ANALYSIS

Data Set: I:\...\HMKB0015P_CRT.aqt

Date: 05/30/24

Time: 16:58:03

PROJECT INFORMATION

Test Well: HMKB0015P

Test Date: 19/05/2023

AQUIFER DATA

Saturated Thickness: 100. m

Anisotropy Ratio (Kz/Kr): 0.2518

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
HMKB0015P	686211.4097467880.596	

Observation Wells

Well Name	X (m)	Y (m)
+ HMKB0015P	686211.4097467880.596	
+ HMKB0011	685886.7227467792.265	

SOLUTION

Aquifer Model: Unconfined

Solution Method: Moench

T = 1162.8 m²/day

S = 0.00031

Sy = 0.03153

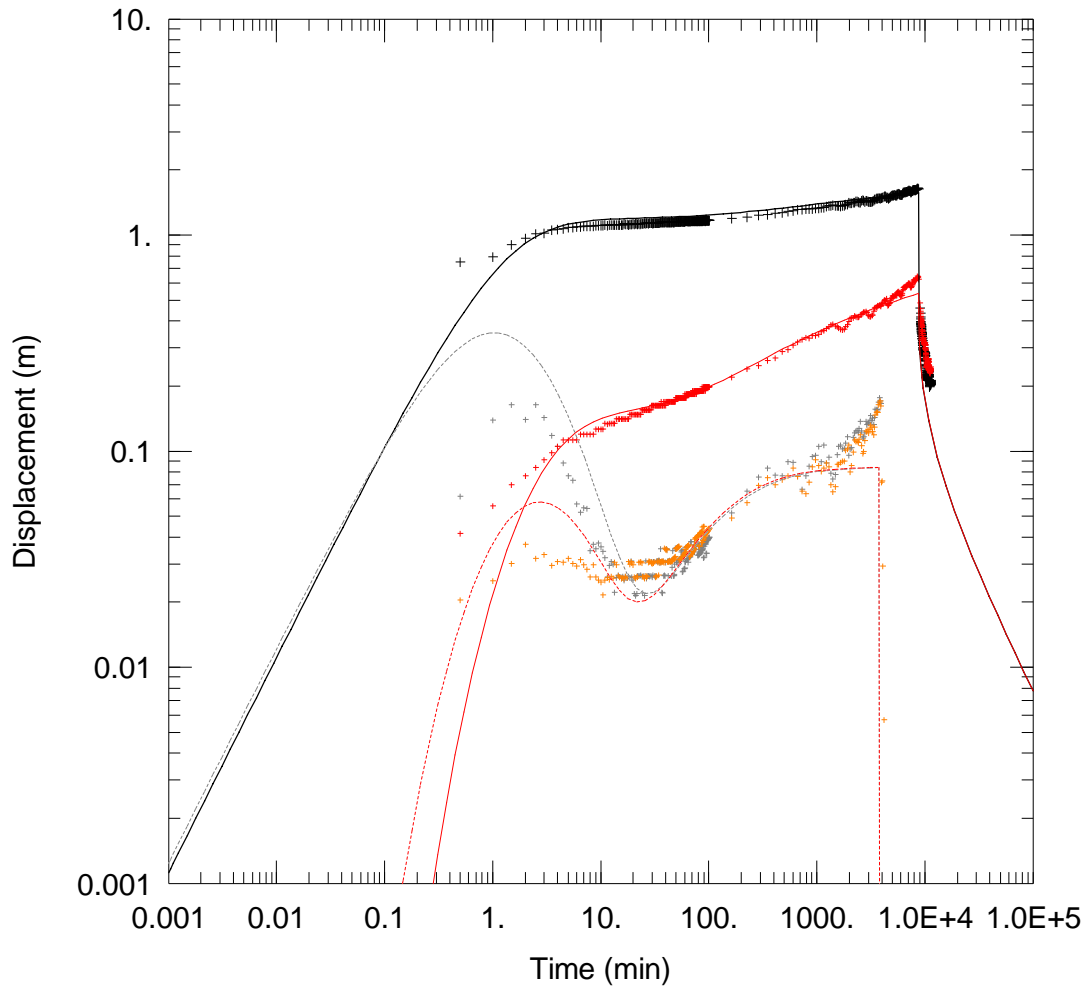
Kz/Kr = 0.2518

Sw = 19.15

r(w) = 0.2583 m

r(c) = 0.2641 m

alpha = 0.001 min⁻¹



HMKB0016P CRT

Data Set: I:\...\HMKB0016P_CRT.aqt

Date: 05/30/24

Time: 17:11:21

PROJECT INFORMATION

Company: BHP

Project: 311012-01995

Location: Runaway Valley

Test Well: HMKB0016P

Test Date: 7/06/2023

AQUIFER DATA

Saturated Thickness: 74. m

Anisotropy Ratio (Kz/Kr): 0.3088

WELL DATA

Pumping Wells

Observation Wells

Well Name	X (m)	Y (m)	Well Name	X (m)	Y (m)
HMKB0016P	685582.8997	468221.743	+ HMKB0016P	685582.8997	468221.743
			+ HMKB0007	685558.9227	468184.585

SOLUTION

Aquifer Model: Unconfined

Solution Method: Moench

T = 6087.5 m²/day

S = 0.003444

Sy = 0.0727

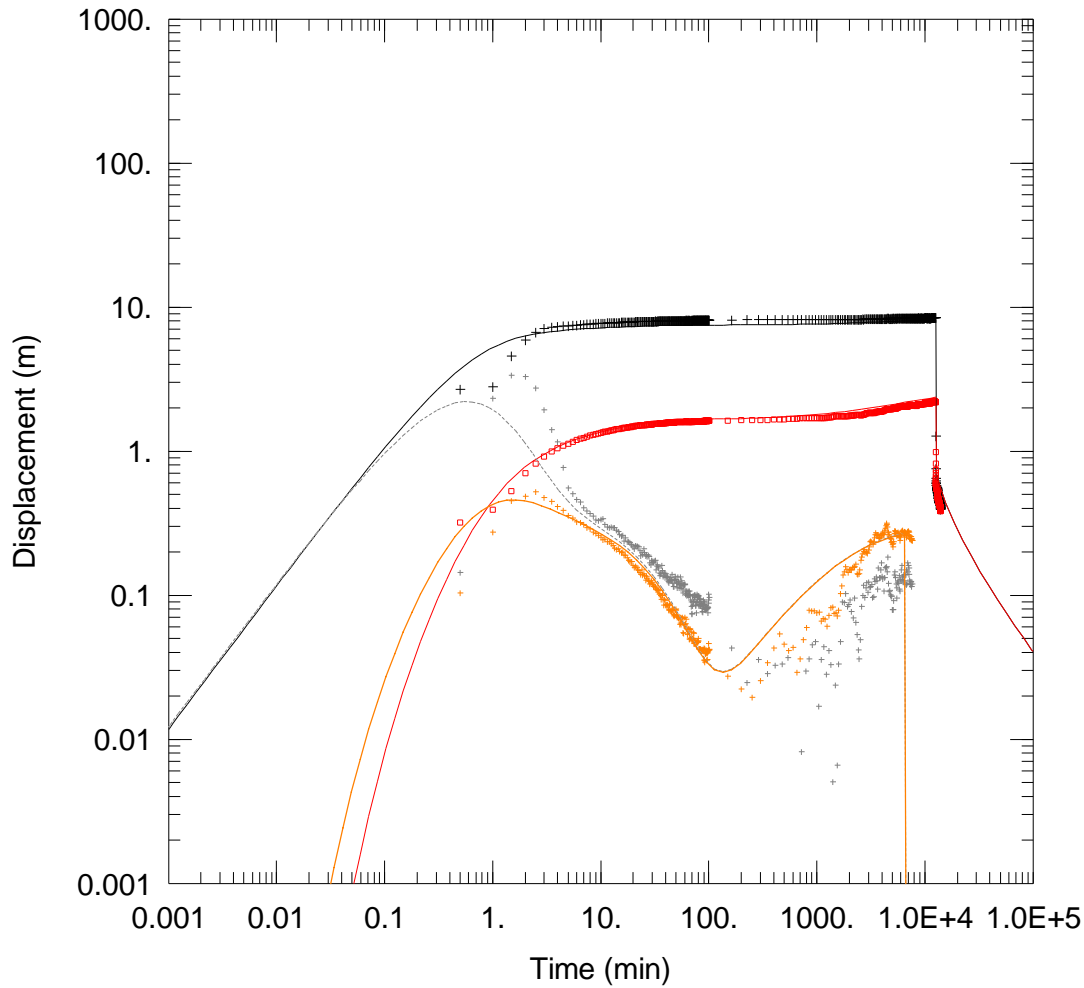
Kz/Kr = 0.3088

Sw = -0.45

r(w) = 0.1829 m

r(c) = 1.13 m

alpha = 10000 min⁻¹



HMKB0017P CONSTANT RATE TEST

Data Set: I:\...\HMKB0017P_CRT.aqt

Date: 05/30/24

Time: 17:23:20

PROJECT INFORMATION

Company: BHP

Project: 311012-01995

Location: Runaway Valley

Test Well: HMKB0017P

Test Date: 19/05/2023

AQUIFER DATA

Saturated Thickness: 110. m

Anisotropy Ratio (Kz/Kr): 0.204

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
HMKB0017P	685571.9727467776	7467776.326

Observation Wells

Well Name	X (m)	Y (m)
+ HMKB0017P	685571.9727467776	7467776.326
◻ HMKB0012	685555.026	7467779.34

SOLUTION

Aquifer Model: Unconfined

Solution Method: Moench

T = 1696.3 m²/day

S = 0.001331

Sy = 0.07799

Kz/Kr = 0.204

Sw = 3.55

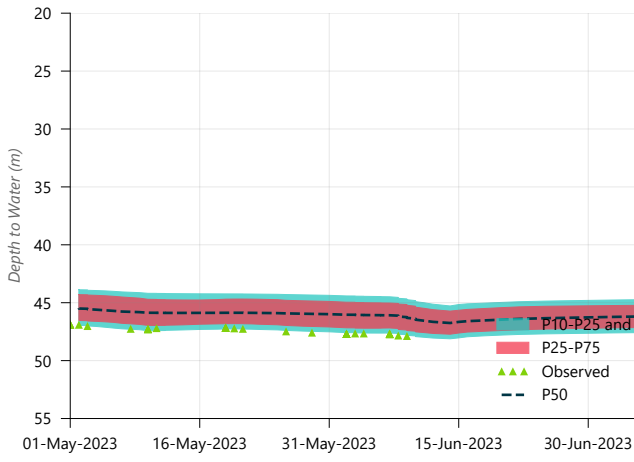
r(w) = 0.225 m

r(c) = 0.3494 m

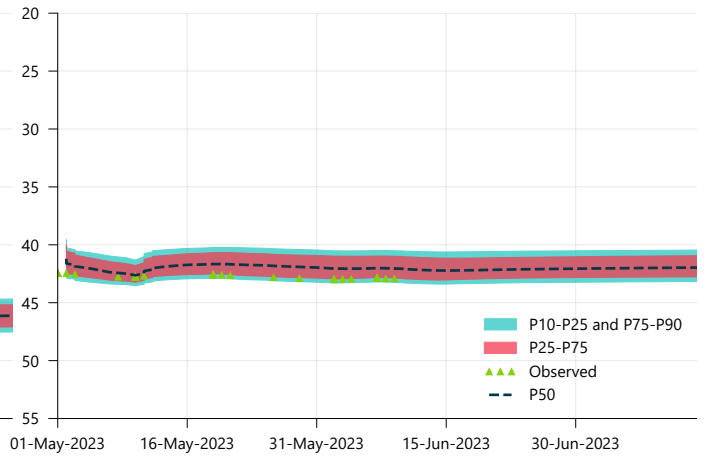
alpha = 0.00631 min⁻¹

Appendix C. SMC hydrographs, history matching part

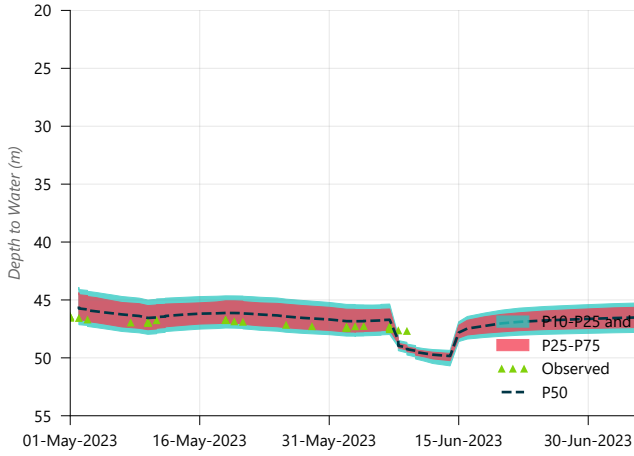
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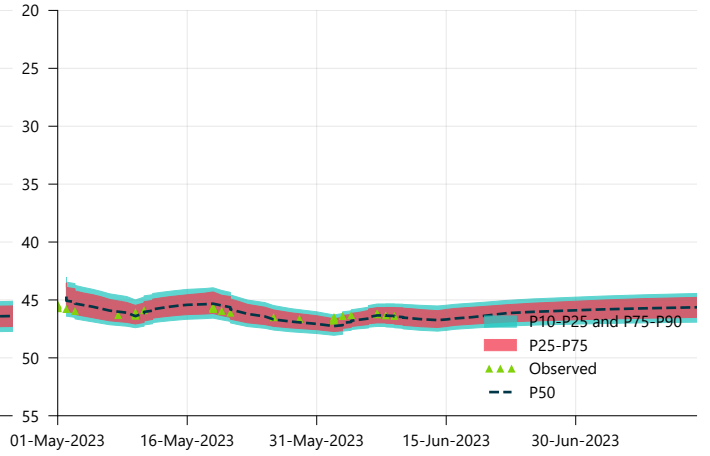
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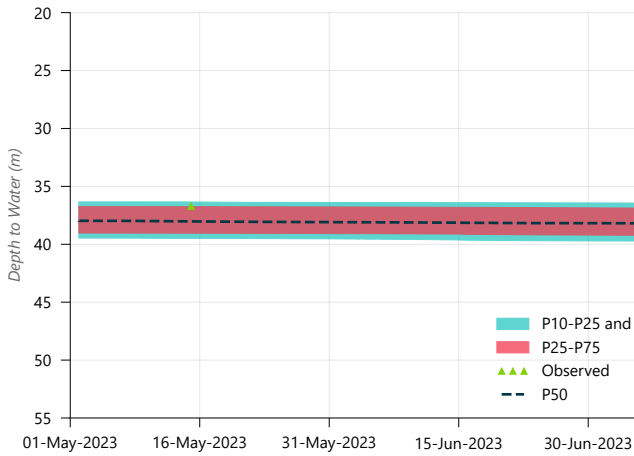
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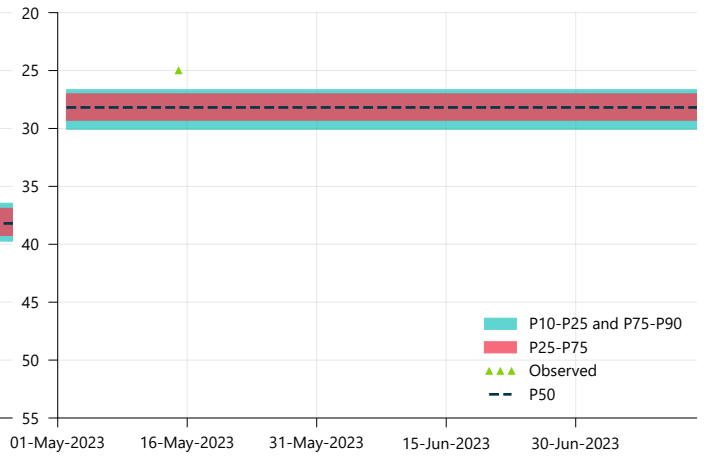
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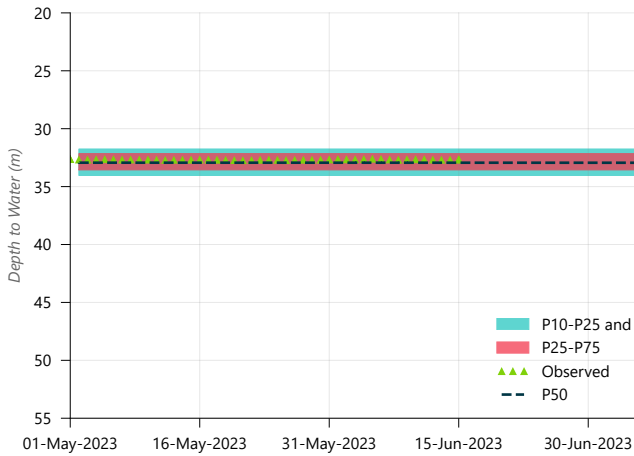
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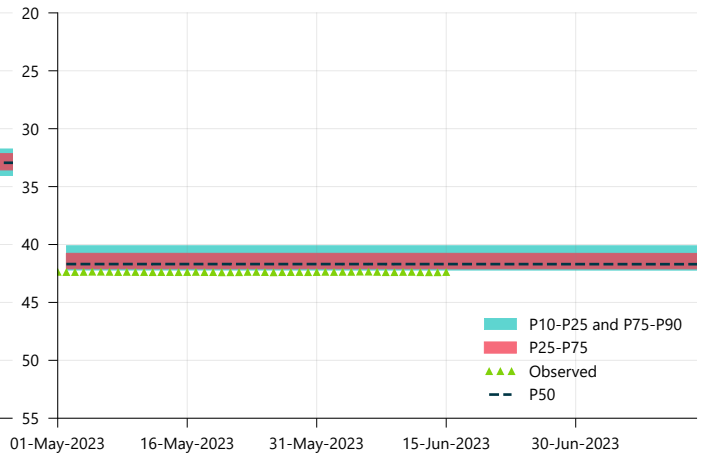
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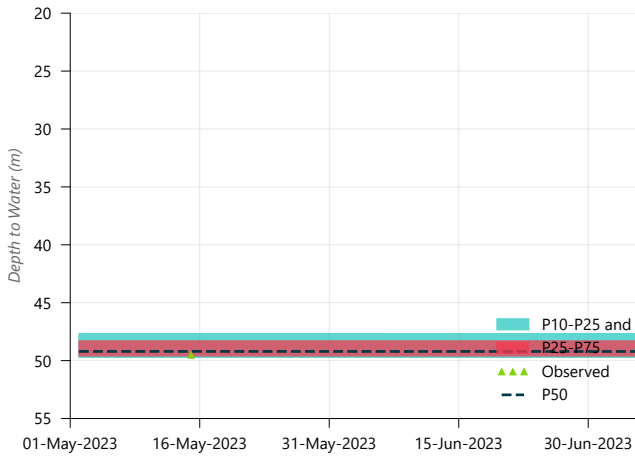
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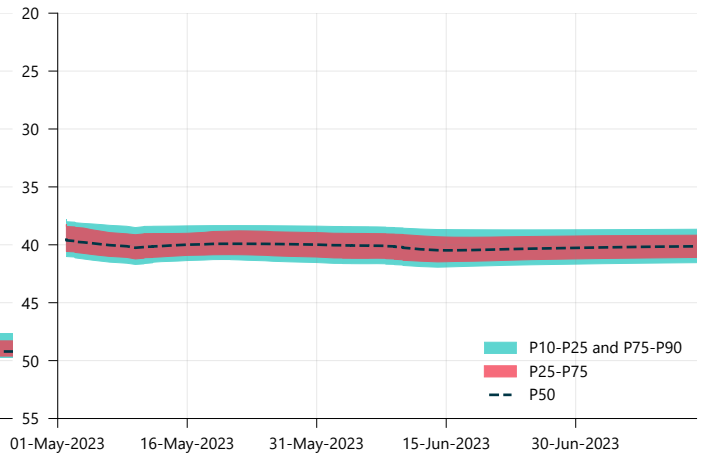
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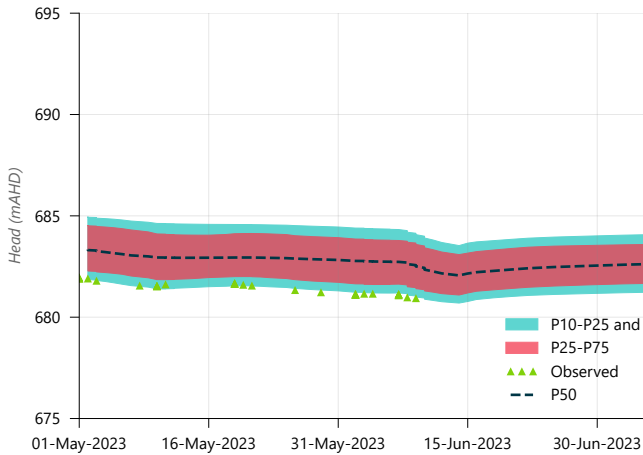
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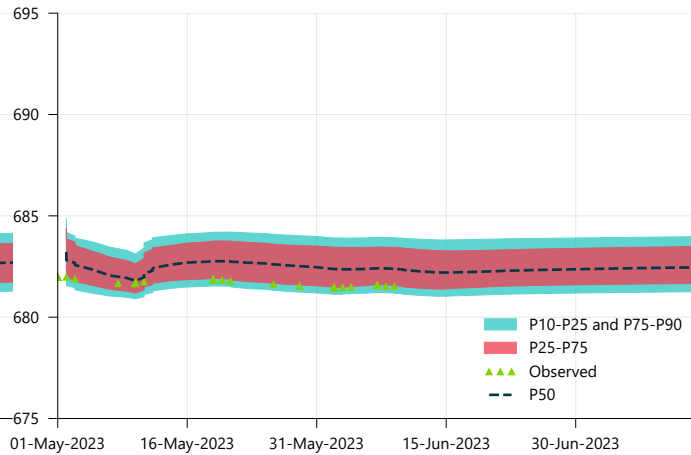
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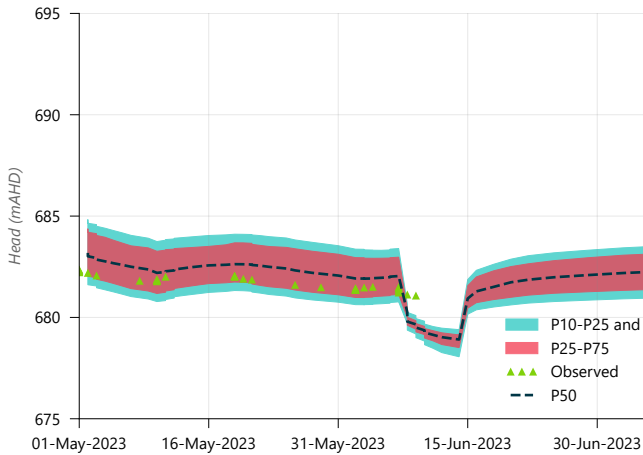
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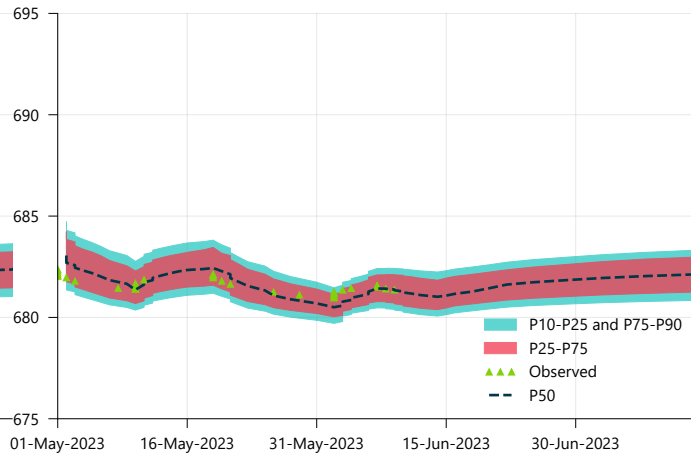
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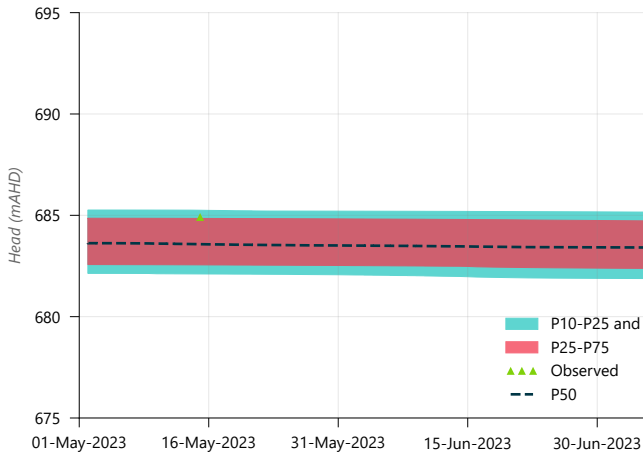
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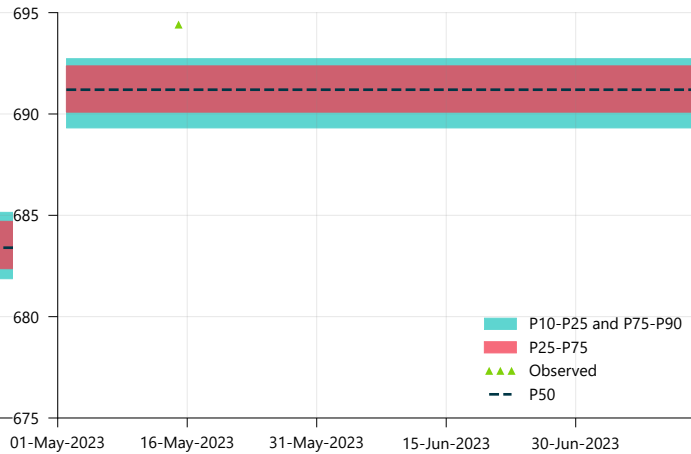
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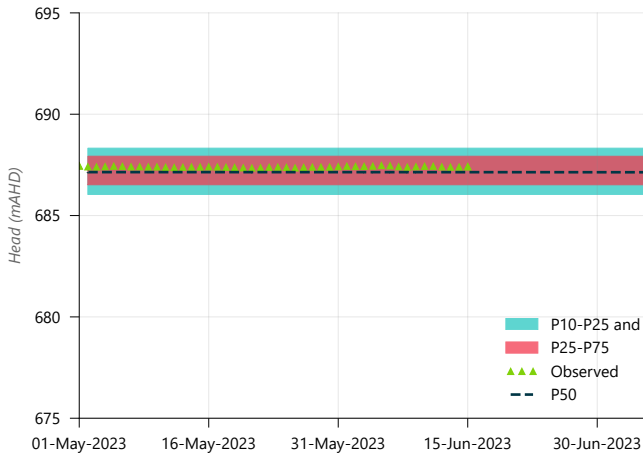
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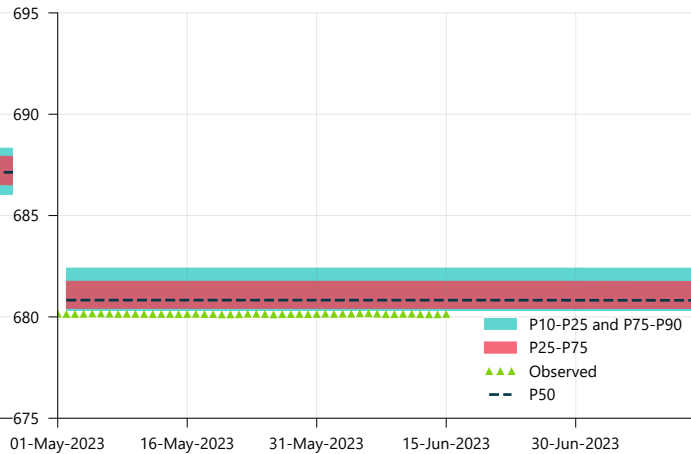
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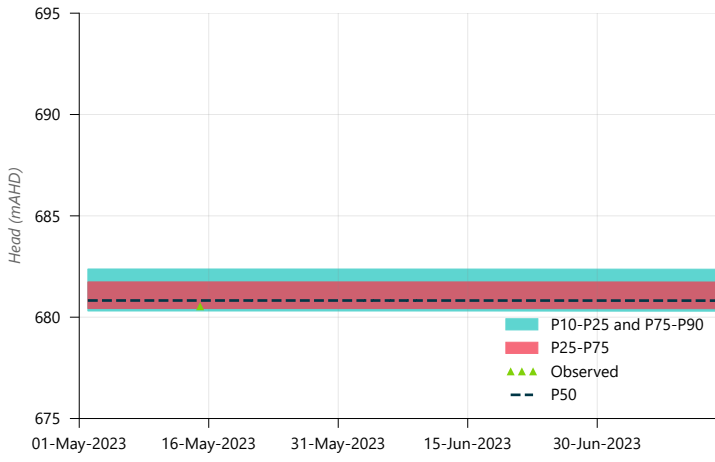
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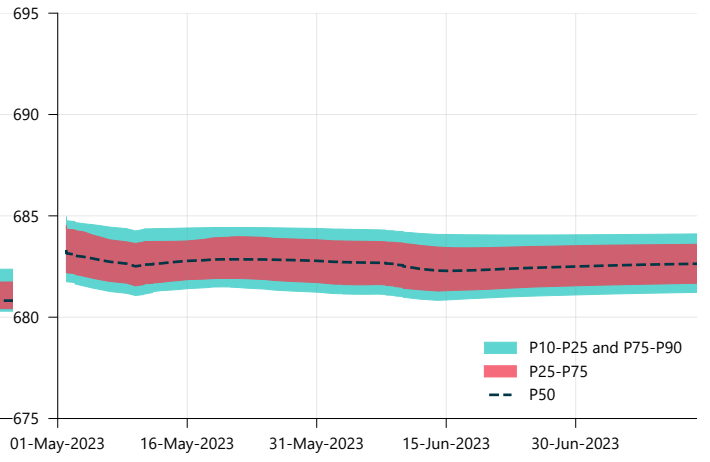
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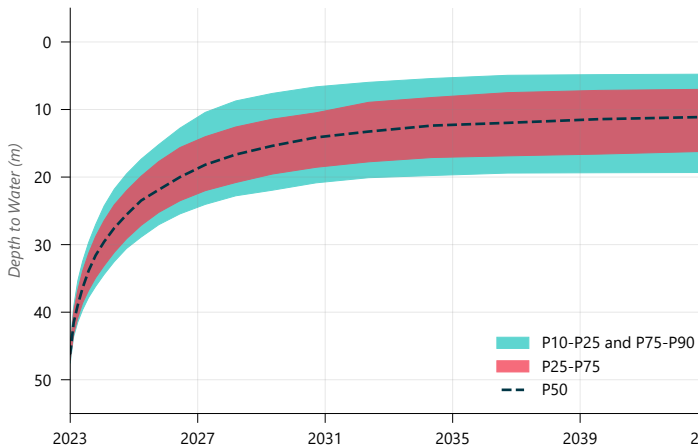


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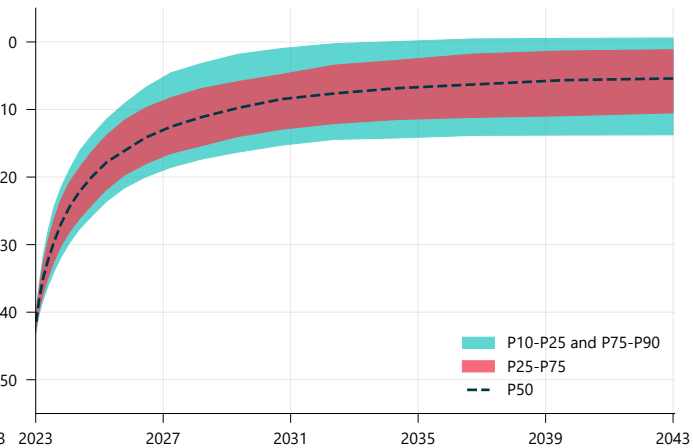


Appendix D. SMC hydrographs, predictions, 20 ML/d

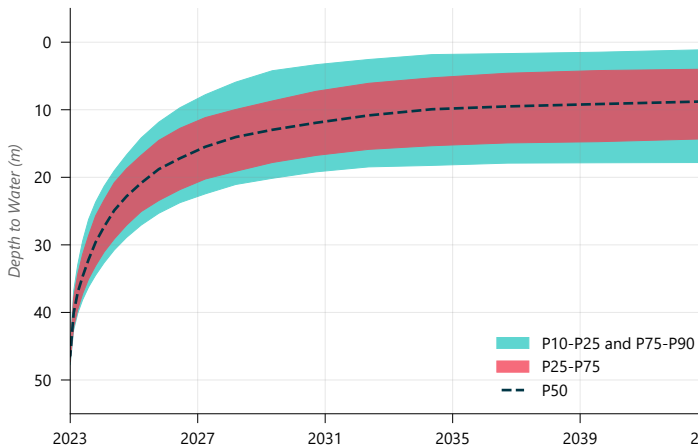
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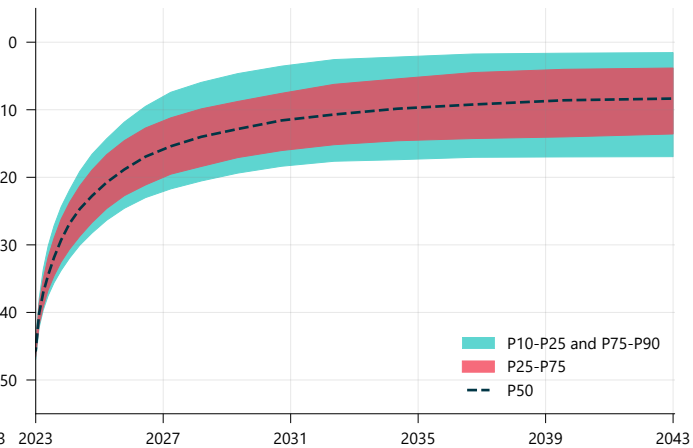
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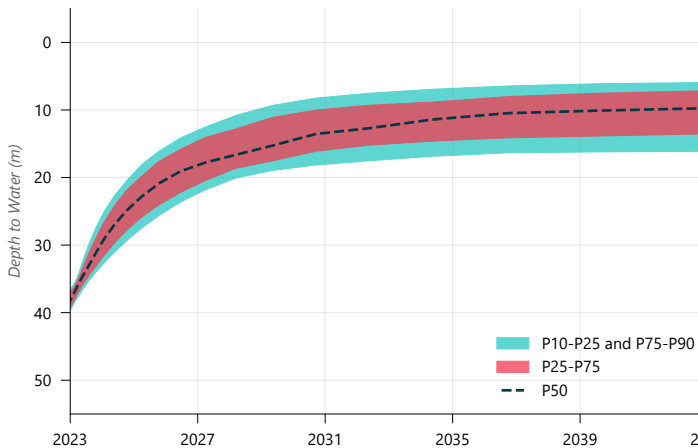
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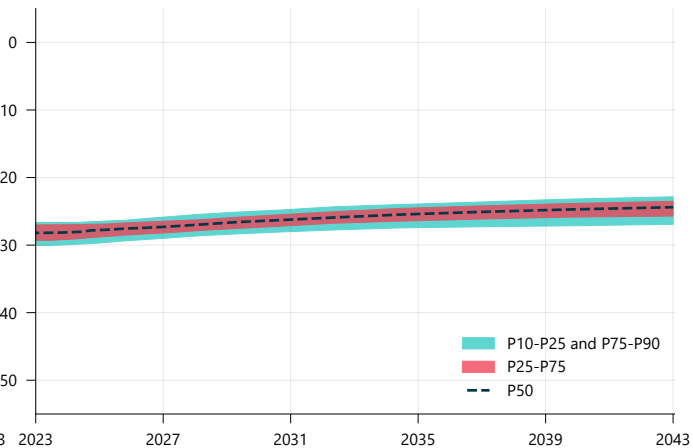
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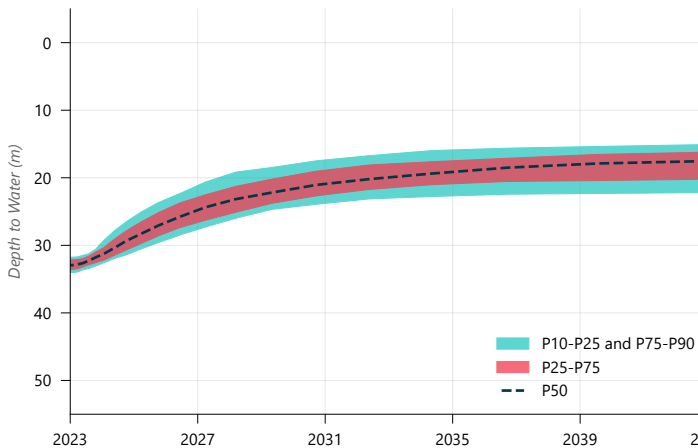
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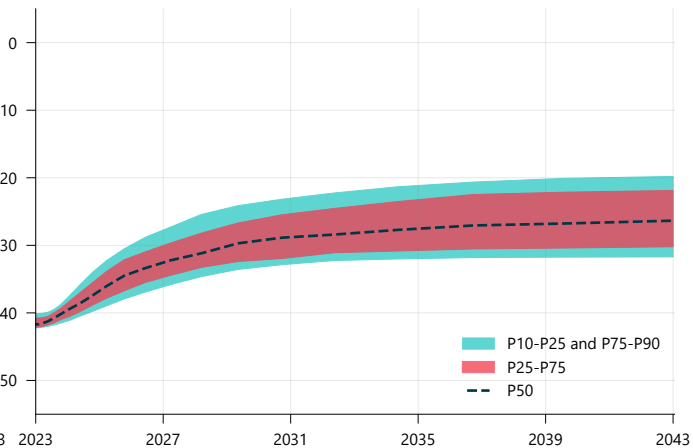
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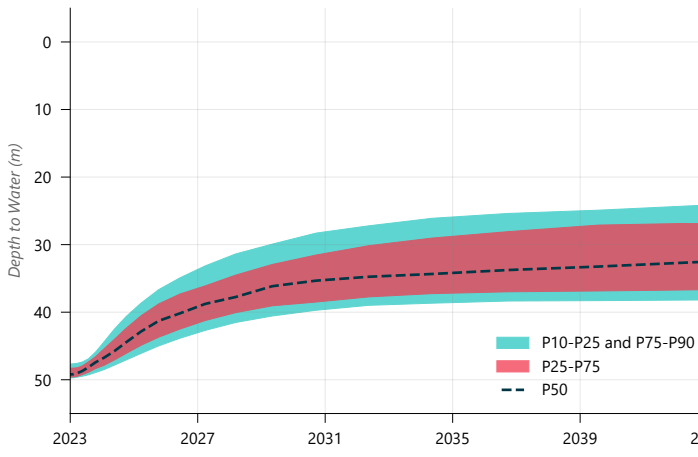
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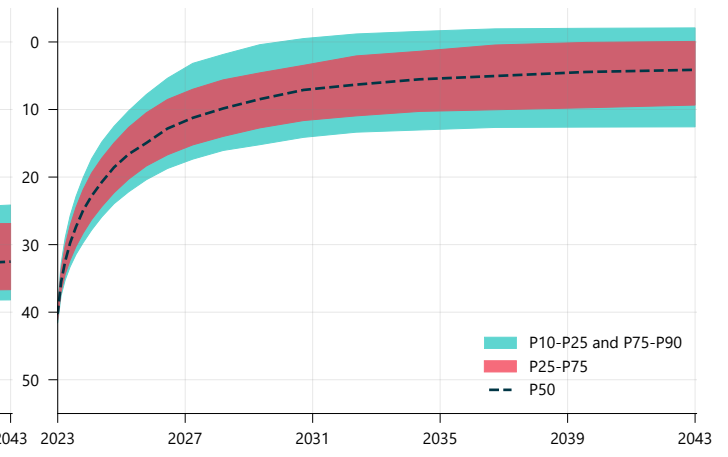
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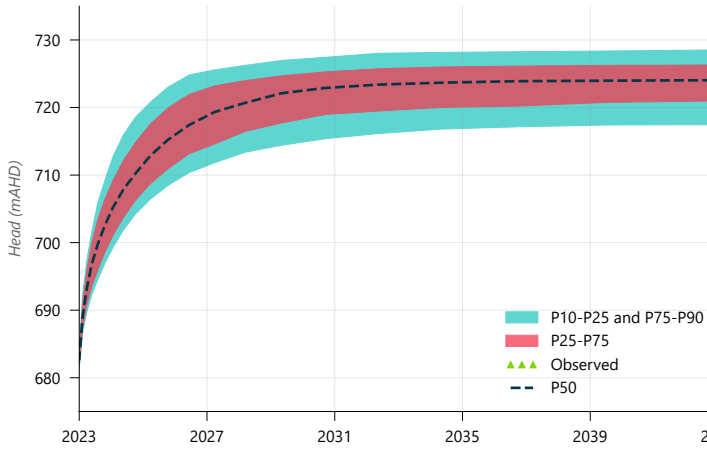


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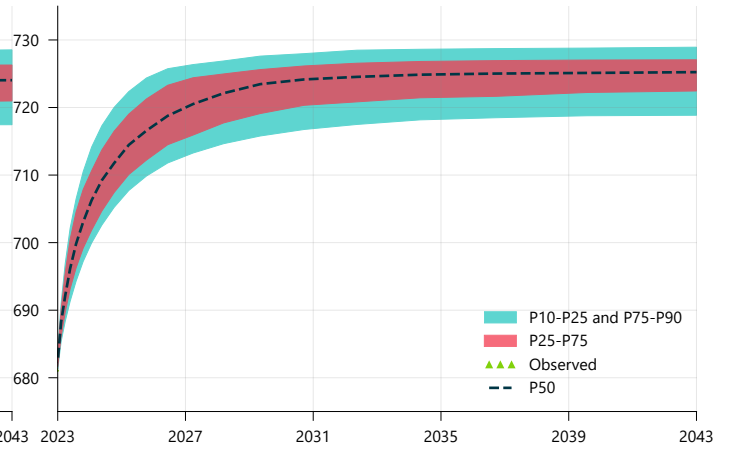


Appendix E. SMC hydrographs, predictions, 30 ML/d

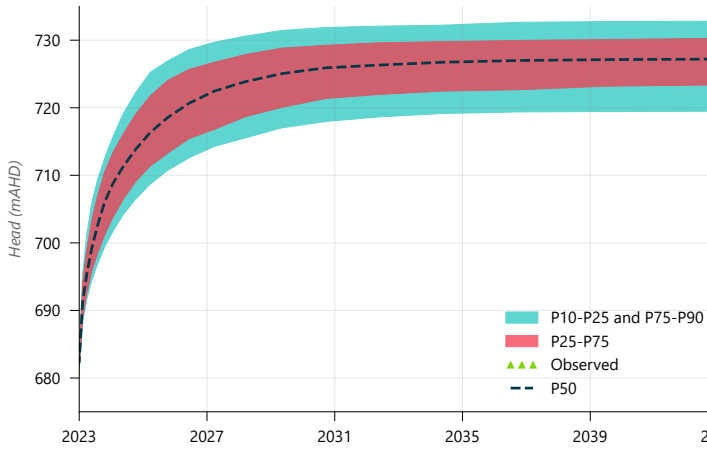
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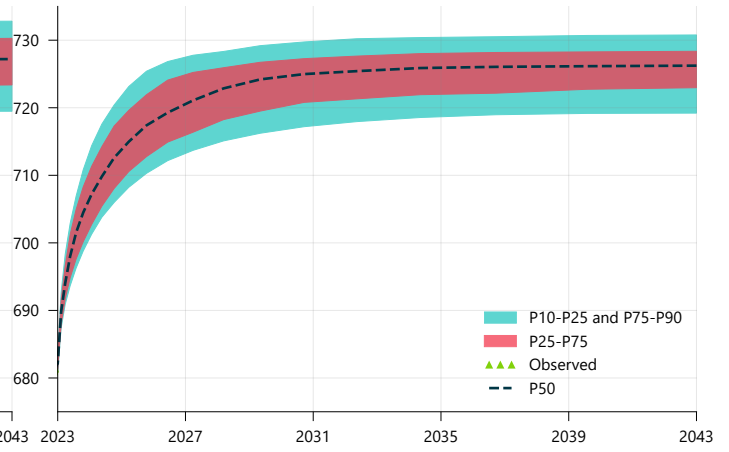
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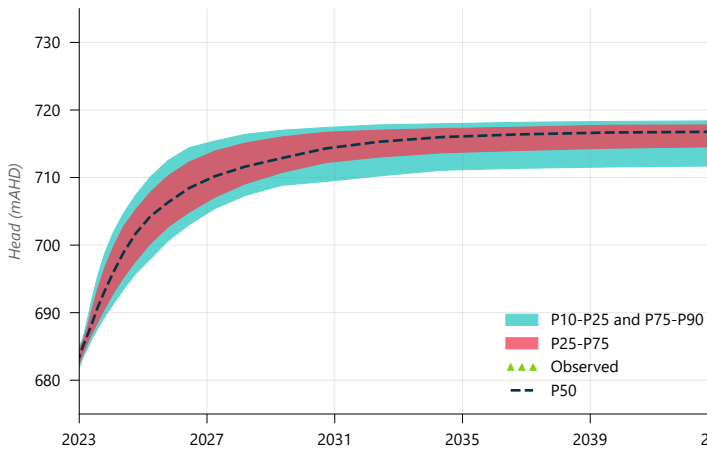
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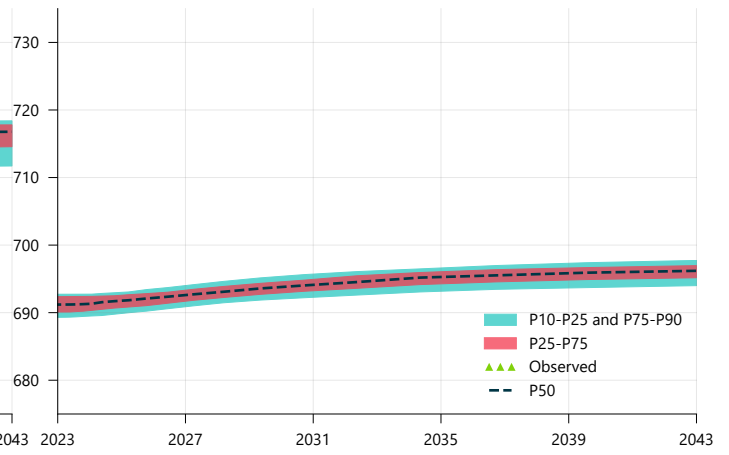
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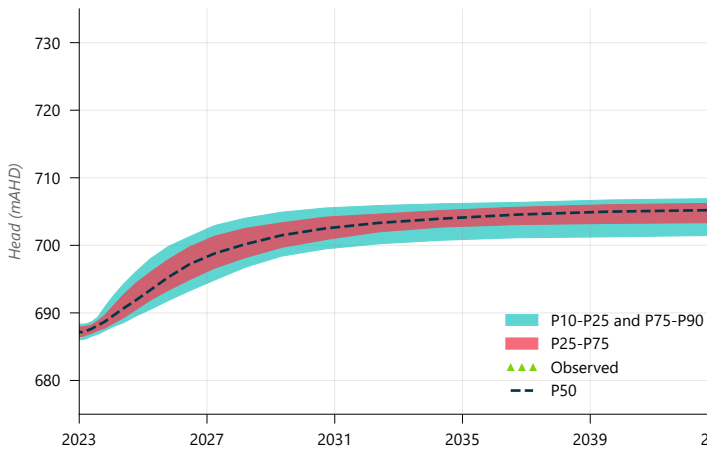
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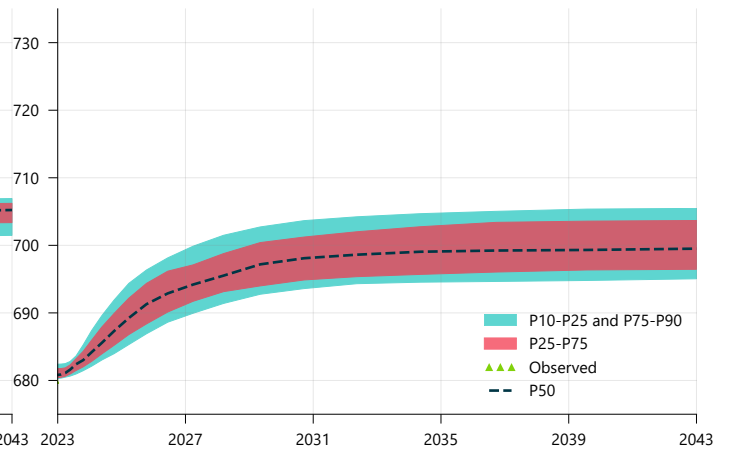
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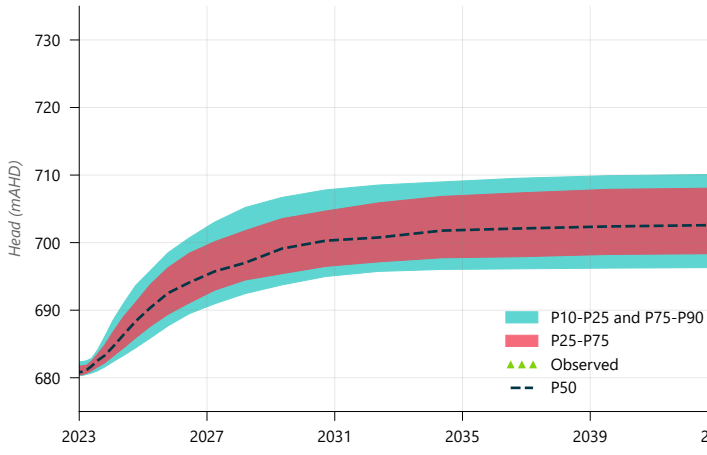
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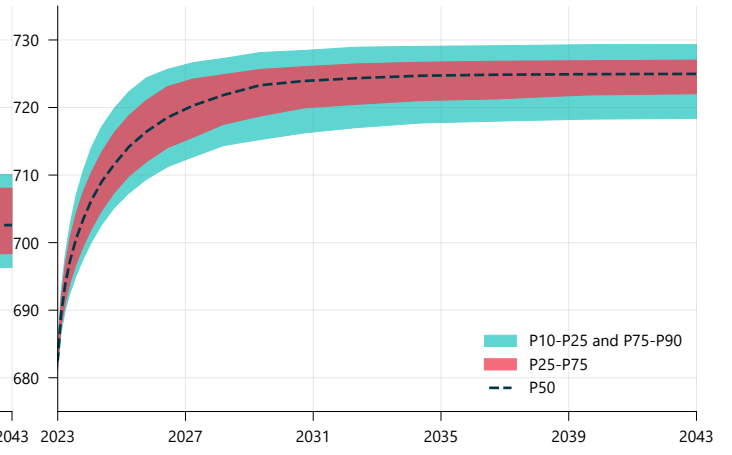
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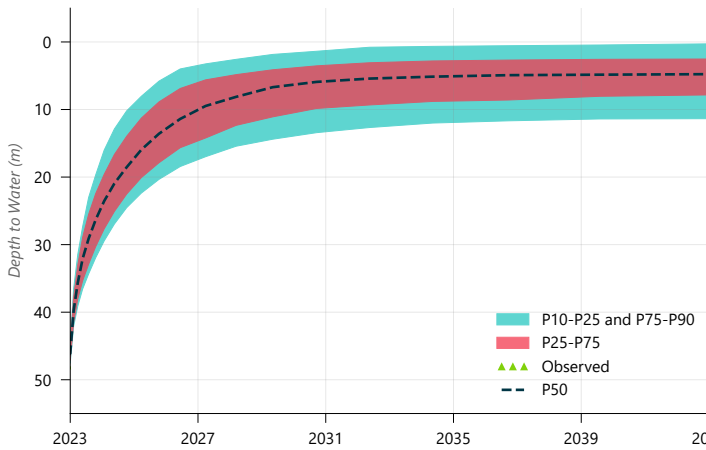
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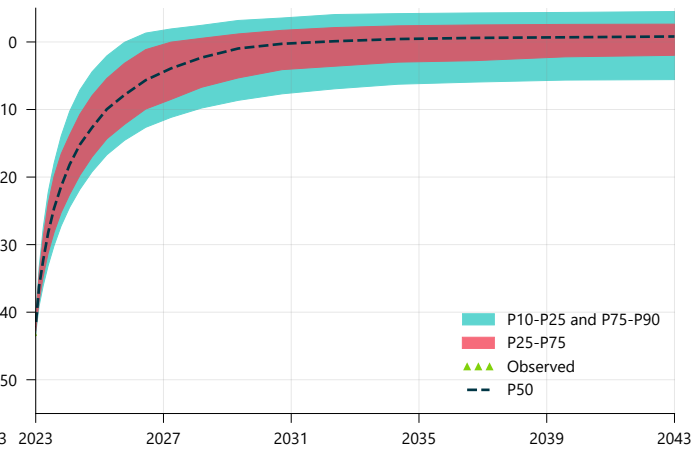
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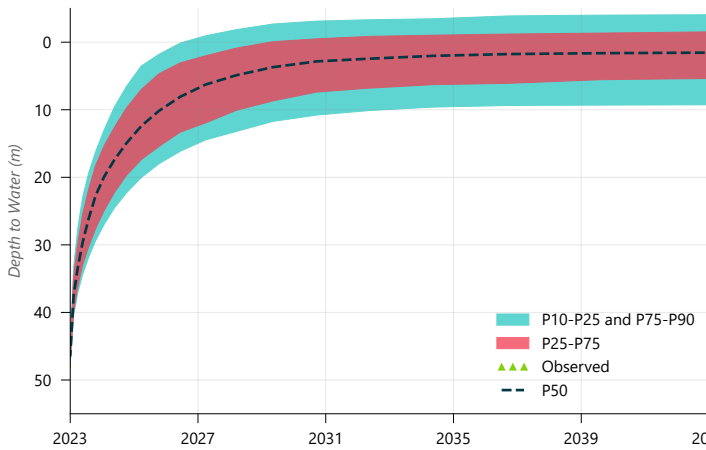
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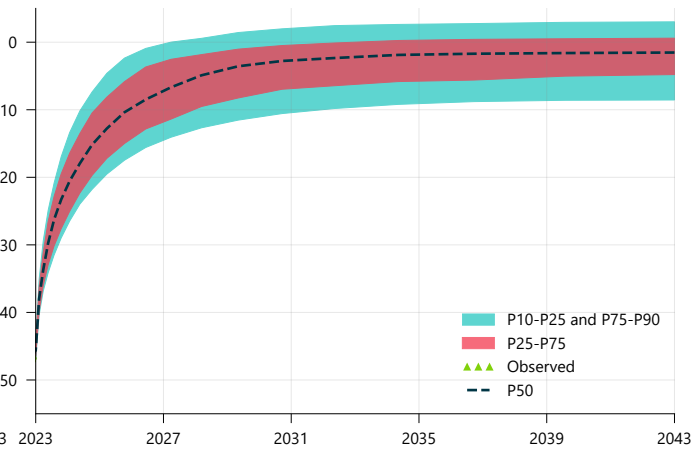
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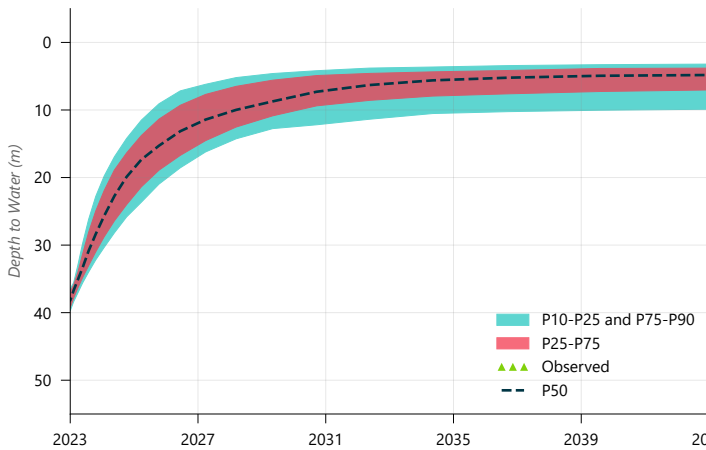
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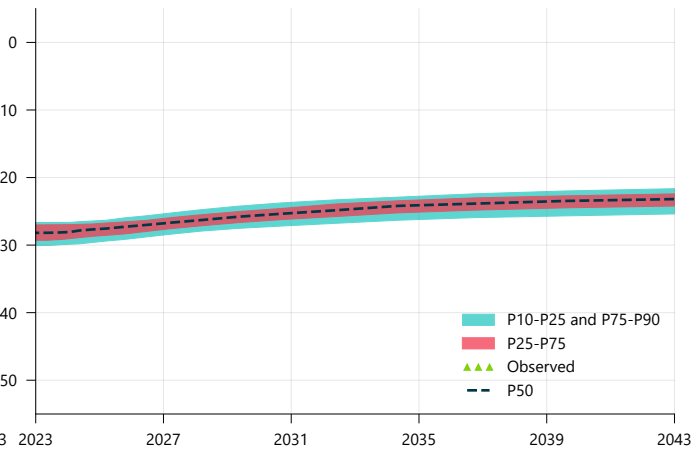
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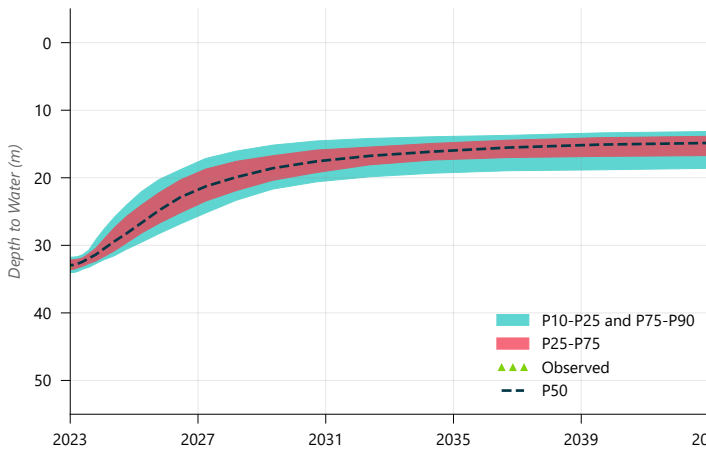
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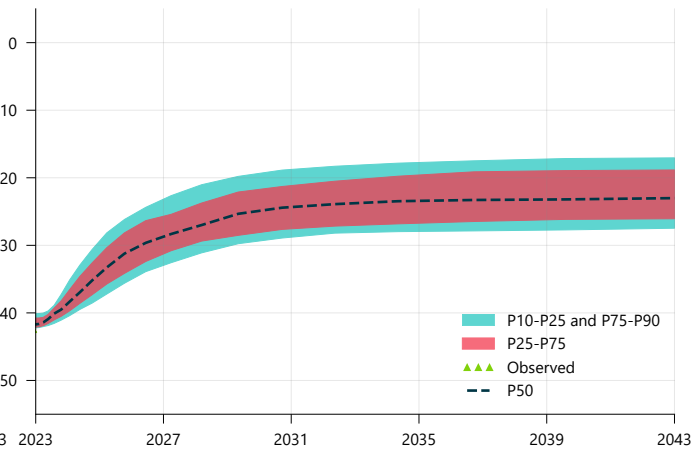
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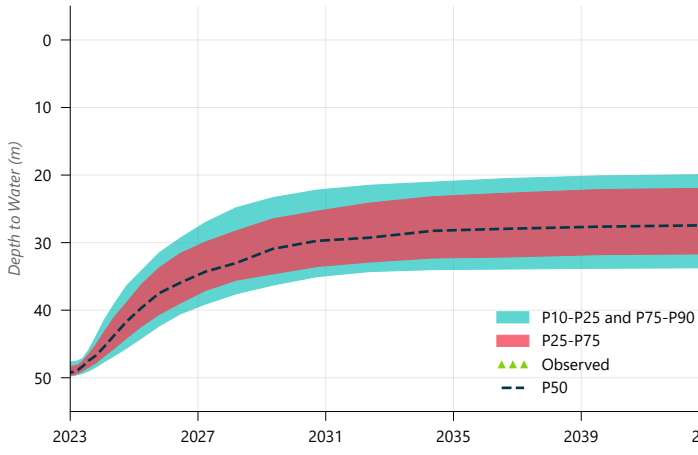
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HNSE0005



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MOD1

