

BHP

Ministers North Aquifer Numerical groundwater modelling

6 May 2024



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Introduction

Background

Ministers North is located approximately 280 kilometres south-east of Port Hedland and 100 kilometres north-west of Newman. It is located south of the Jugari (BHP) and Jugaricoogina (RTIO) mines, and north of the Mining Area C (BHP) and Hope Downs (RTIO) mines (Figure 1).

The Ministers North aquifer is hosted in mineralised Dales Gorge Member of the Brockman Iron Formation and supports the Jugaricoogina Gorge Groundwater Dependent Ecosystem (GDE). Groundwater levels within the gorge naturally occur either at or close to the surface of the creek bed resulting in the presence of groundwater dependent vegetation, groundwater seepage and permanent and perennial surface water pools. These groundwater levels are maintained by flow from the adjacent local (Ministers North orebody) aquifer.

However, groundwater levels in the Ministers North aquifer have been declining since approximately 2018 and if the decline continues, ecosystem damage or loss could occur very rapidly and potentially irreversibly.

The reason for the declines is unknown, although two possible explanations have been identified:

- The annual rainfall in 4 out of the 6 years between 2018 and 2023 have been lower than the long term average. Groundwater continues to discharge from the system at the gorge but is not being replenished in the main aquifer system by rainfall recharge.
- The decline is caused both by the lower than long term average rainfall and by drawdown from dewatering at one or more of the surrounding mines (BHP Jugari and RTIO Jugaricoogina, Mining Area C and/or Hope Downs 1) spreading into the Ministers North aquifer.

Groundwater Consulting Pty Ltd (GWC) was engaged by BHP to undertake numerical groundwater flow modelling to investigate how well the groundwater level observations could be replicated with a rainfall only scenario (i.e. without any drawdown from nearby dewatering included).

Objectives

The objectives were to:

- Produce a model that includes the main characteristics of the site conceptual model.
- With this model, reproduce as closely as possible the historical observations (especially the water level decline from 2018).

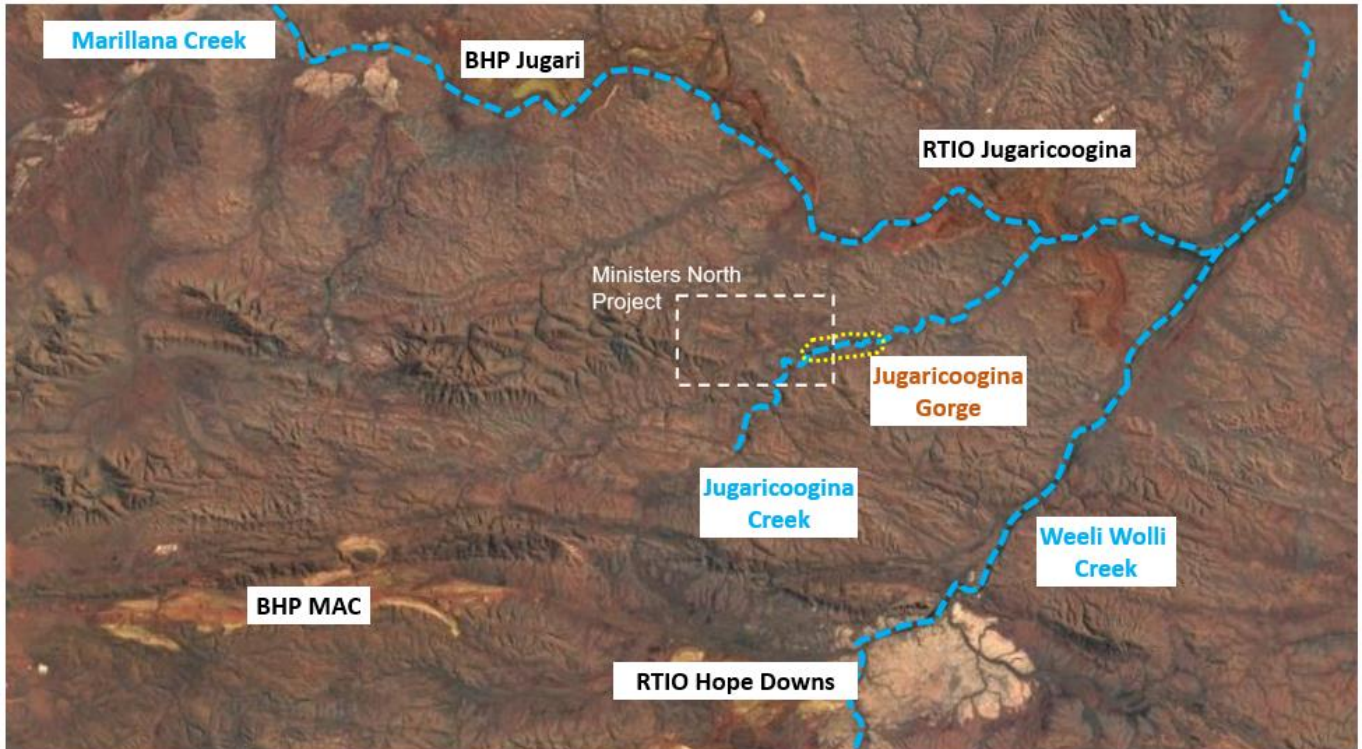


Figure 1 – Jugarioogina Gorge Location

Conceptual model

The Ministers North orebody is located within the mineralised Dales Gorge Member of the Brockman Iron Formation (BHP, 2022). Groundwater is present in sufficient quantity within and surrounding the Ministers North orebody to designate the area as a hard rock aquifer and groundwater resource (referred to herein as the Ministers North aquifer). Figure 2 shows the approximate extent of the Ministers North orebody and the Dales Gorge Member which hosts the Ministers North aquifer.

The Mt McRae Shale Member divides the Ministers North orebody aquifer which has resulted in a preferential flow path forming along-strike of the orebodies controlled by the lower permeability units (i.e. McRae Shale, unmineralised Joffre and Weeli Wolli formations) that sit adjacent to the Dales Gorge members.

The Keystone Fault is a prominent structural feature that propagates NE-SW through the projects and has displaced the stratigraphy up to 60 m along the fault plane.

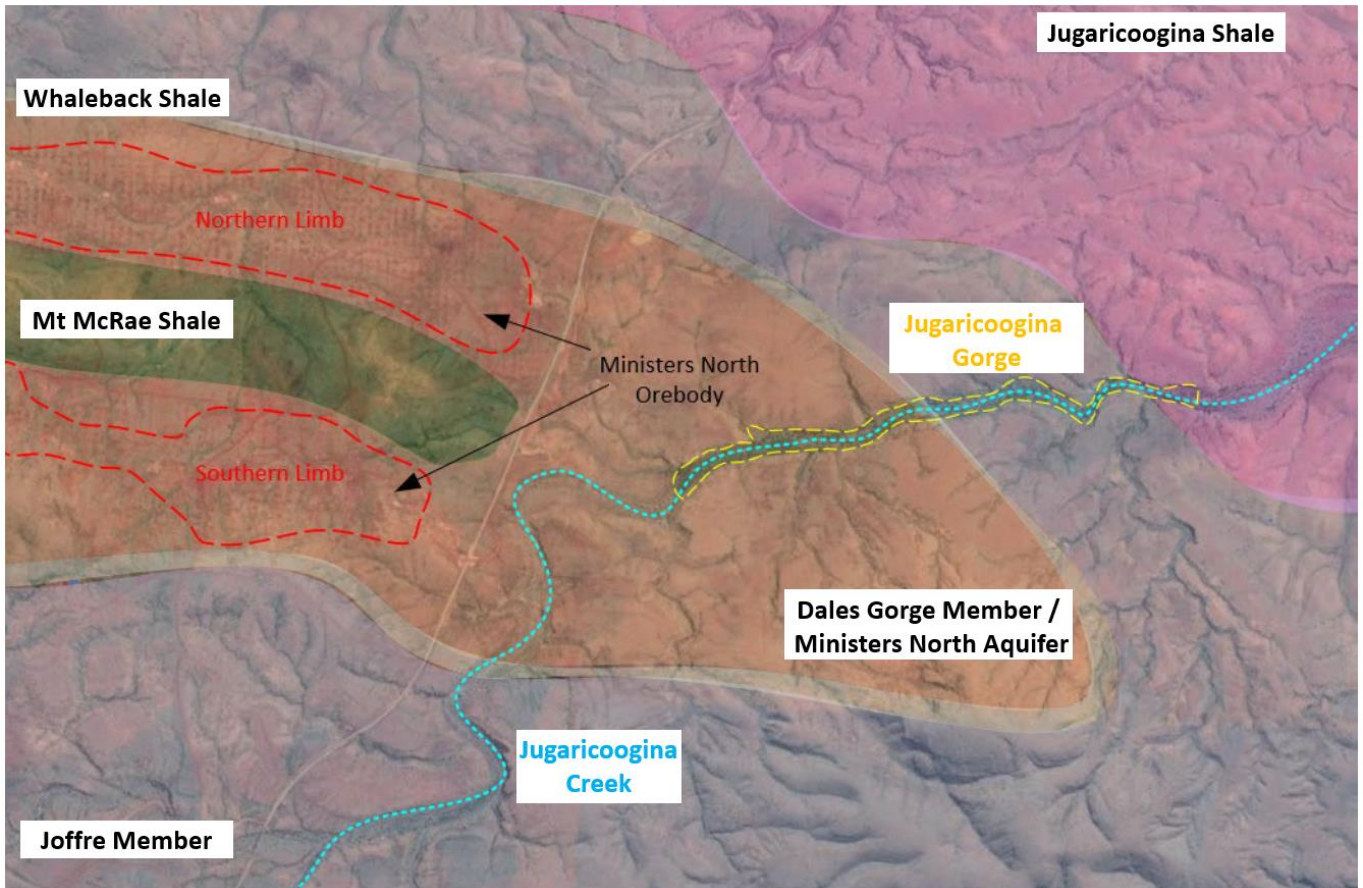


Figure 2 – Geological setting – Ministers North area

In the eastern area of the project and roughly to the east of the Jugari/MAC rail corridor, the Mount McRae Shale is no longer present, and in this area, the north and south limbs of the Ministers North aquifer are directly connected. Further to the east, Jugaricoogina Creek is incised into the Dales Gorge Member to an elevation close to the regional groundwater level in the Ministers North orebody aquifer (~561 mRL). Groundwater has been observed at shallow depths within the creek and zones of seepage have been recorded indicating that groundwater from the Ministers North orebody aquifer discharges into the gorge.

Groundwater levels across the Ministers North aquifer are shown in Figure 3. Monitoring bores with greater than 10 manual dips are shown. There are 37 individual bores which are made up of:

- A long term dataset, with observations from 2002 (the two “rail” bores)
- A medium term dataset, with observations from either 2015 or 2017.

Levels have fluctuated since the first measurements in 2002. However, since 2018 there has been a steady and mostly consistent decline (at roughly 0.6 m/yr). During this time, periods of groundwater level rise are observed following rainfall events, however these seasonal peaks do not interrupt the long-term declining trend.

The cumulative rainfall departure (CRD) curve for rainfall from the SILO database (point 22.85 - 119.10) is shown in Figure 4. This shows that the years from 2018 to 2024 have been drier than the average between 1980 and 2024. This period includes the extremely high rainfall experienced during the 1999/2000 wet season. The groundwater levels in the two rail bores roughly match the variation in CRD between 2002 and 2018, but then diverge, with the groundwater level falling at a greater rate than would be predicted by the CRD. There is no reason however why the groundwater level should follow the CRD trend, and this should be taken as a guide only.

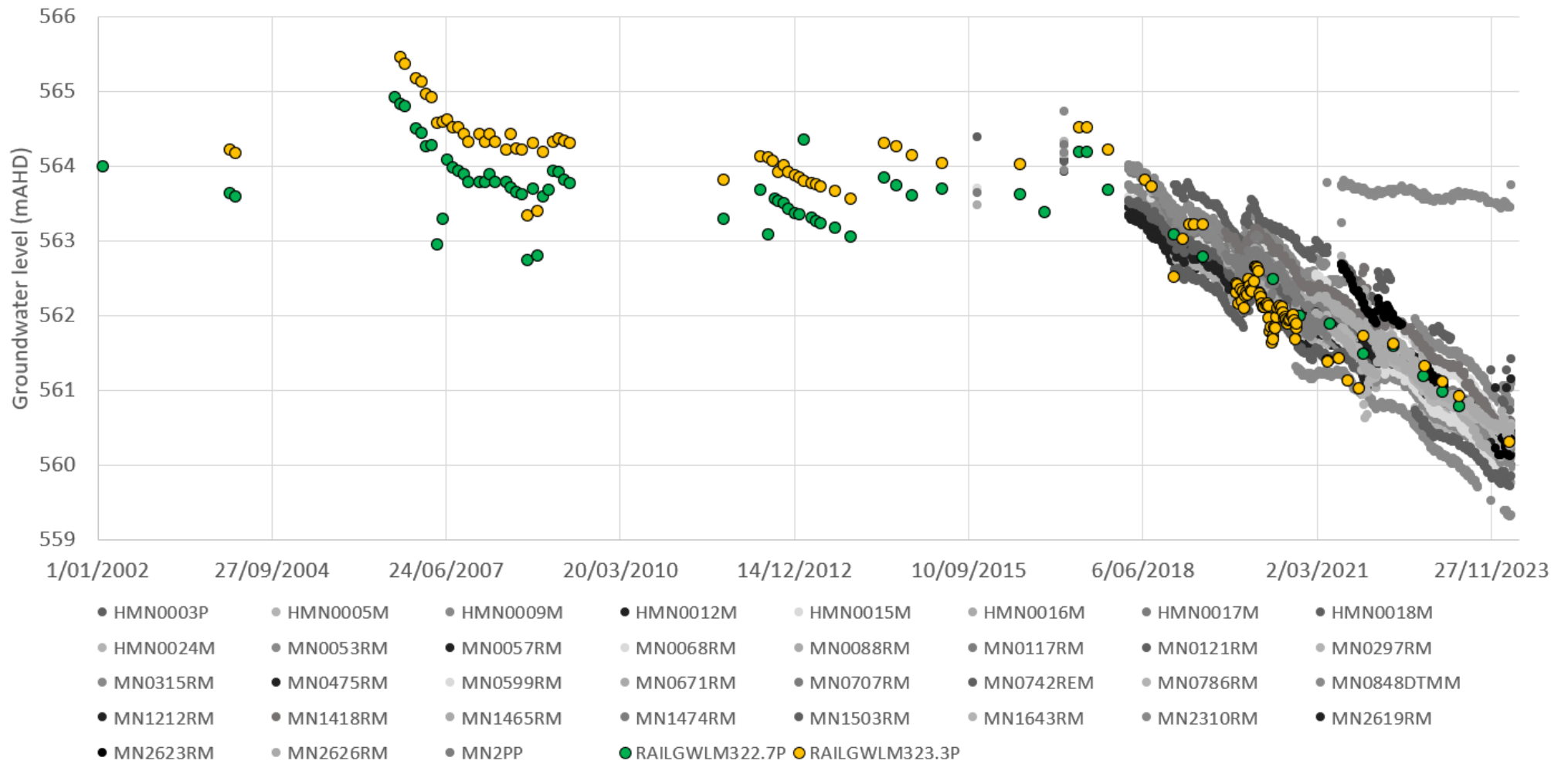


Figure 3 – Ministers North aquifer groundwater level monitoring data

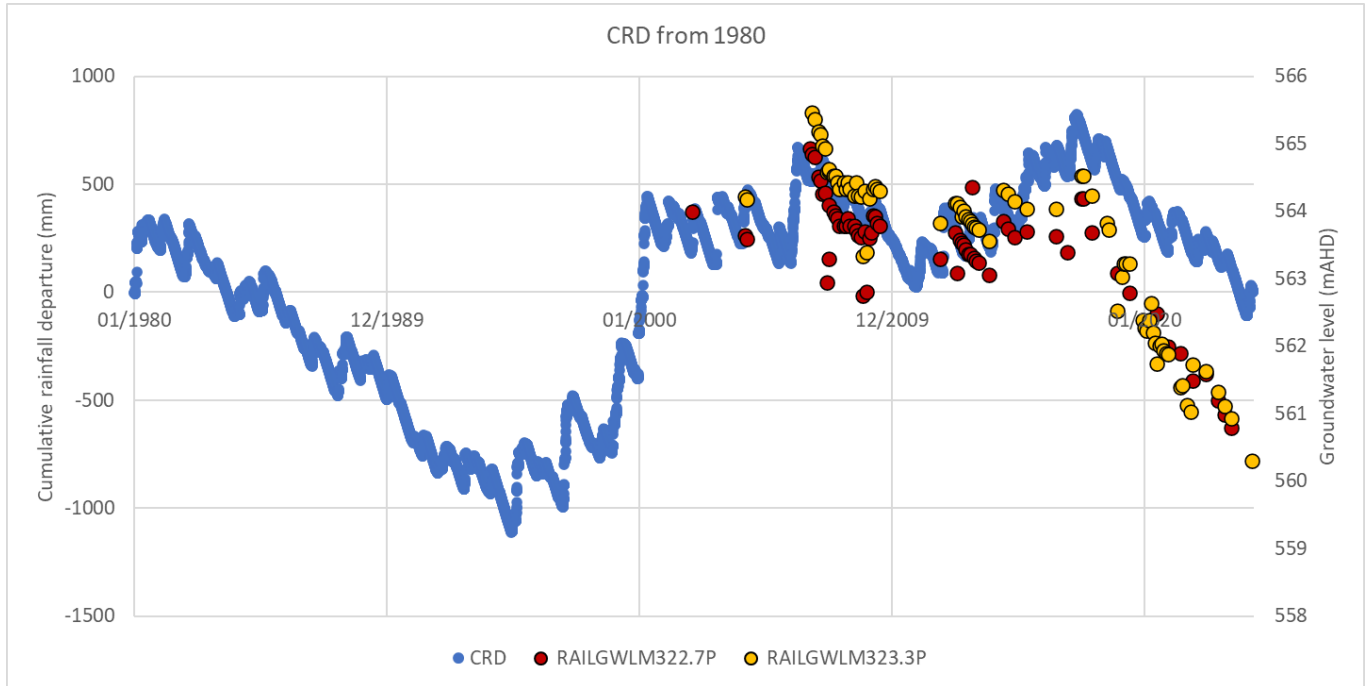


Figure 4 – Cumulative rainfall departure curve and rail bore water levels

Ongoing groundwater level decline in the Ministers North aquifer has been observed to correlate with a similar decline in groundwater levels in the gorge as well as some reduction in the persistence and depth of surface pools, seepage zones and tree health.

Aquifer testing was completed in Q2 FY2022 which involved pumping from a bore in the southern orebody and re-injecting water into a bore in the northern orebody (RPS, 2022). The key objective of this testing was to assess whether groundwater in the aquifer flows into and supports the GDE in Jugaricoogina Gorge.

Preliminary analysis of the regional aquifer response (drawdown and mounding) indicates that groundwater in both the northern and southern orebodies flow towards and into Jugaricoogina Gorge under otherwise undisturbed conditions. The drawdown and mounding response observed confirms that the northern and southern limbs of the Ministers North aquifer are connected to the east of the Jugari/MAC rail corridor.

Analysis of the groundwater level response to the testing indicates a range in possible transmissivities of between 600 and 1400 m²/d and specific yields of between 1 and 5%. These parameters are indicative of a relatively highly transmissive aquifer with moderate to low storage capacity.

Groundwater model construction

Model setup

The groundwater model was developed using the Modflow-USG code developed by Sorab Panday, operating under the Groundwater Vistas graphical user interface. The extent of the model domain was assigned consistent with aquifer extents and the Leapfrog model provided by BHP. The model is setup using the GDA94 Zone 50 coordinate system (Table 1). Figures showing the model domain, boundary conditions and parameter zones are provided in Appendix A.

The model domain covers an area of 9 km west to east and 6 km south to north. The model was rotated 0.8 degrees clockwise to align it with the Leapfrog model and mine grids.

Table 1. Extent of model domain

	Easting (GDA94, MGA, Zone 50)	Northing (GDA94, MGA, Zone 50)
Northwest Corner	711,903	7,477,181
Northeast Corner	724,102	7,477,010
Southwest Corner	711,823	7,471,481
Southeast Corner	724,022	7,471,310

Modflow-USG octree grid refinement was used in the current model. A minimum model grid size of 50 m by 50 m was used to refine the creek and surface water pools that reside along the Jugaricoogina Creek. A maximum cell size of 100 m by 100 m is used everywhere else in the model. The model grid is defined by 31,791 active model nodes over six model layers.

Aside from top of model layer 1, all layers in the model are flat. The groundwater model used a total of six layers to simulate the geometry of the Leapfrog model. Hydrostratigraphic units in the model were assigned consistent with the Leapfrog outputs provided by BHP. The geological units in the Leapfrog model were provided as sub-member units (i.e. Joffre J1-J6, Dales Gorge D1-D4 etc). These units were then grouped to represent formation members (i.e. Dales Gorge, Whaleback, Joffre, etc). In addition to that, BHP provided the extent of the “Ministers North” aquifer which comprises multiple fractured aquifer units including mineralised and sub-mineralised Dales Gorge.

All model layers are 40 m thick, apart from layer 1 which has a thickness dictated by the topography (Table 2).

The hydrogeological units represented in each layer are illustrated in Figures A2 to A7 and a schematic north south cross section is presented in Figure A8.

Table 2. Extent of model domain

Layer	Top (mRL)	Bottom (mRL)	Thickness (m)
1	Topography	560	Variable
2	560	520	40
3	520	480	40
4	480	440	40
5	440	400	40
6	400	360	40

Rainfall Recharge

Inflow to the groundwater system is provided via rainfall recharge to the creek alluvium and Ministers North aquifer (Figure A9). These were represented as separate zones in the model to allow different recharge rates in each.

This recharge is assigned as a proportion of SILO rainfall data. SILO dataset suggests that the average annual rainfall is around 329 mm per year. The percentage of SILO rainfall, applied as recharge in the model, was modified during the model calibration to provide a match to measured water level fluctuations.

Evapotranspiration

Evapotranspiration from phreatophytic vegetation and evaporation from the surface water pools was modelled using the Evapotranspiration package (EVT) in Modflow-USG. This uses a depth dependent relationship to calculate ET such that if aquifer water levels rise to, or above, a specified evapotranspiration surface, EVT occurs at the maximum specified rate. If the aquifer water level falls to below the specified EVT surface, the EVT rate decreases linearly to zero until the water level falls to below an elevation equal to the ET surface minus the extinction depth.

The EVT package was only assigned to a zone where groundwater dependent vegetation reside which coincide with the locations of the surface water pools. The extent of the simulated EVT is presented in Figure A10 and the key settings were:

- Extinction depth: 2 m
- Maximum rate: 1.85 m/year

Throughflow

To simulate outflow from the system where the creek alluvium reaches the model boundary (Figure A1), the Drain (DRN) package of Modflow-USG was used. The elevation and conductance of this boundary were modified during the model calibration to balance the simulated inflows and outflows in the model.

Model calibration

Approach

Model calibration is the process by which the adjustable parameters are adjusted to produce the best match between simulated and observed data. This process typically involves refining aquifer properties and boundary conditions of the model within prescribed limits based on conceptual understanding.

As can be seen from the data, the groundwater levels at Ministers North are in a constant state of flux, reacting to both short-term and long-term changes in rainfall. The groundwater flow model was calibrated to both steady state (or initial groundwater levels) and transient or time varying conditions between January 2000 and March 2024. As the system doesn't really present a steady state condition, the transient calibration was the priority.

The location of monitoring points used in the transient calibration and the results of both the steady state and transient models are shown in Appendix B.

Steady state

The steady state model provides:

- Initial conditions for the transient calibration.
- Quantification of the groundwater flow through the model domain, under average recharge conditions.

The steady state model was designed to replicate observed water levels at rail bores M322.7 and M323.2, as these were the only locations with observations around the year 2000.

The simulated steady state groundwater contours are shown in Figure B1.

As there are only two observations with which to assess the goodness of fit, statistical analyses like the Scaled Root Mean Squared (SRMS) error, are unnecessary.

Aquifer parameters adopted in the steady state model are discussed with the transient calibration (as they are the same). Specific parameter assignment and modifications made during the transient calibration are also discussed in the following sections.

The distribution of recharge included in the steady state model is shown in Figure A9 and summarised in Table 3.

Table 3. Recharge rates (steady state model)

Zone	Recharge Rate (m/d)	Percentage of long-term average rainfall (%)
Jugaricoogina Creek	1.25x10 ⁻⁵	10
Ministers North Aquifer	8.11x10 ⁻⁵	6.5
Basement	0	0

The predicted water balance for the steady state calibration is shown in Table 4. The water balance shows that the only source of inflow in the model is rainfall recharge. Most of the inflow leaves the model via evapotranspiration assigned to simulate the pools and vegetation along the Jugaricoogina creek (i.e., the GDE). The remainder of inflow travels down the creek line and leaves the model via the creek outflow boundary assigned in the eastern end of the model domain. The results show that combined evapotranspiration and creek outflows are approximately 1.6 ML/year.

Table 4. Water balance (steady state model)

Water balance component	Inflow (ML/d)	Outflow (ML/d)
Rainfall recharge	1.6	0
Evapotranspiration	0	1.3
Creek Outflow (DRN)	0	0.3

Transient calibration

The transient model calibration was completed using the entire observation data period (i.e., between January 2002 and March 2024). Other than an assumed small amount of pumping from the two rail bores (which is not included in the model), there are no anthropogenic water inputs or outputs from the system during this time.

The transient calibration was run using a monthly stress period and used the results from the steady state model as the initial conditions. All boundary conditions from the steady state model, other than recharge, were used unchanged in the time variant model.

Recharge was applied using the percentages shown in Table 3, but with the observed monthly averages. Recharge therefore varies significantly throughout the model run time. The water balance averaged over the calibration period is shown in Table 5.

The location of monitoring bores used in the transient calibration are shown in Figure B2. Observed and calibrated simulated water levels are shown in Figures B3-B7.

The observed groundwater level decline from 2018 is well replicated by the model. This match is reproduced purely from the variation in observed rainfall, without any additional inputs from adjacent dewatering operations.

Figures A2-A7 show the distribution of aquifer parameters in each model layer and the calibrated values are summarised in Table 6.

Table 5. Water balance – averaged over the calibration period (transient model)

Water balance component	Inflow (ML/d)	Outflow (ML/d)
Aquifer Storage	1.0	0.9
Rainfall recharge	1.6	0
Evapotranspiration	0	1.3
Creek Outflow (DRN)	0	0.3
TOTAL	2.6	2.6

Table 6. Aquifer parameters

Unit	Hydraulic Conductivity (m/d)		Aquifer Storage	
	Horizontal	Vertical	Confined (1/m)	Unconfined (%)
Creek Alluvium / Detritals	25	25	1x10-6	5
MN Aquifer	20	20	1x10-6	2
Jugaricoogina Shale Member	0.001	0.001	1x10-6	0.1
Joffre Member	0.001	0.001	1x10-6	0.1
Whaleback Shale Member	0.001	0.001	1x10-6	0.1
Dales Gorge Member (Orebody)	20	20	1x10-6	2
Dales Gorge Member (Submineralised)	20	20	1x10-6	2
Dales Gorge Member (Unmineralised)	0.001	0.001	1x10-6	0.1
Mt McRae Shale	0.001	0.001	1x10-6	0.1
Mt Sylvia Formation	0.001	0.001	1x10-6	0.1

Conclusions

The performance of the model, in terms of its ability to reproduce the groundwater level decline observed from 2018, should be judged against the rate of change, rather than the absolute levels. A selection of calibration hydrographs are shown in Figure 5 (the full set are shown in Appendix B). These show that:

- In many locations, the predicted absolute levels are lower than the observed (for example at HMN0009M the difference is approximately 2.5 m).
- The variations observed between 2002 and 2018 are relatively well replicated by the model, including what appears to be the significant jump in water levels in 2006 (for example RAILGWLM322.7P).
- The gradient of decline observed between 2018 and 2024 is replicated by the model. A significant rebound is observed in many, but not all (for example MN0053RM), of the bores in 2021 (for example at MN0707RM and RAILGWLM322.7P). This is not replicated by the model and most likely signifies a mismatch between the SILO data used to set the rainfall recharge rate, and the actual rainfall falling on the catchment feeding the Ministers North aquifer.

The model is therefore able to simulate the groundwater level observations from 2002 based on fluctuations in rainfall only.

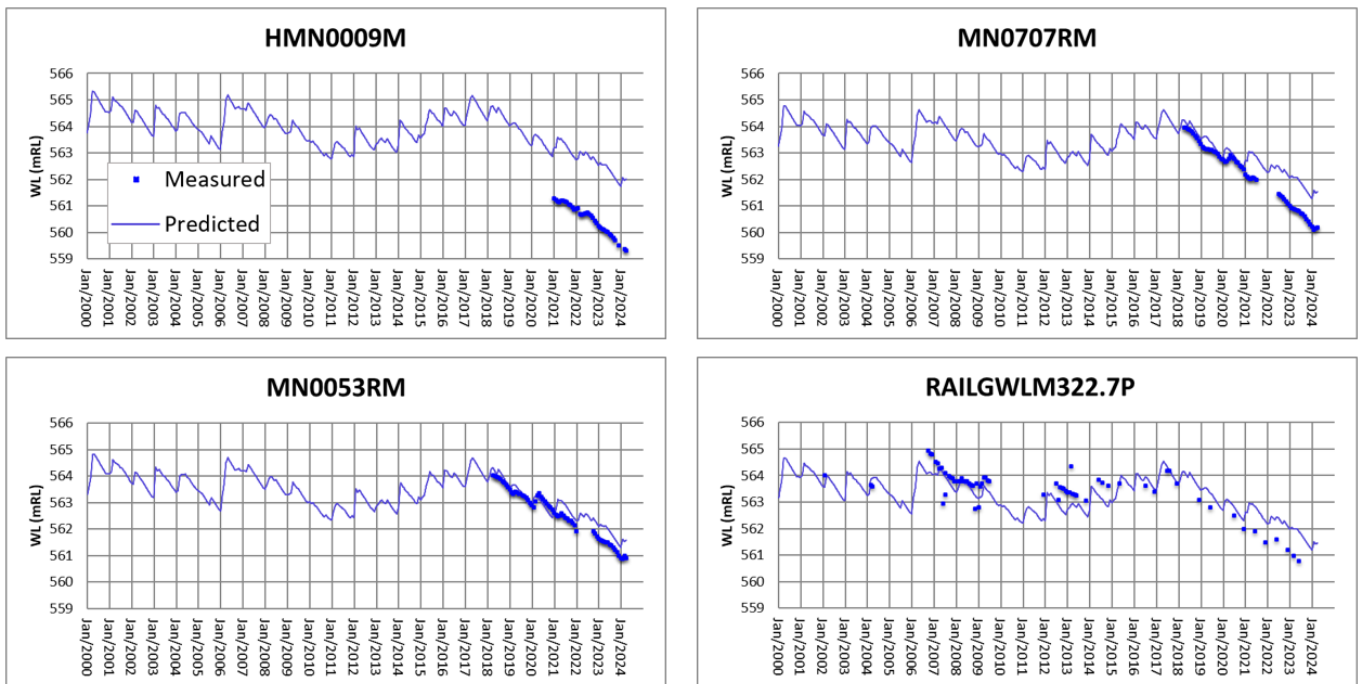


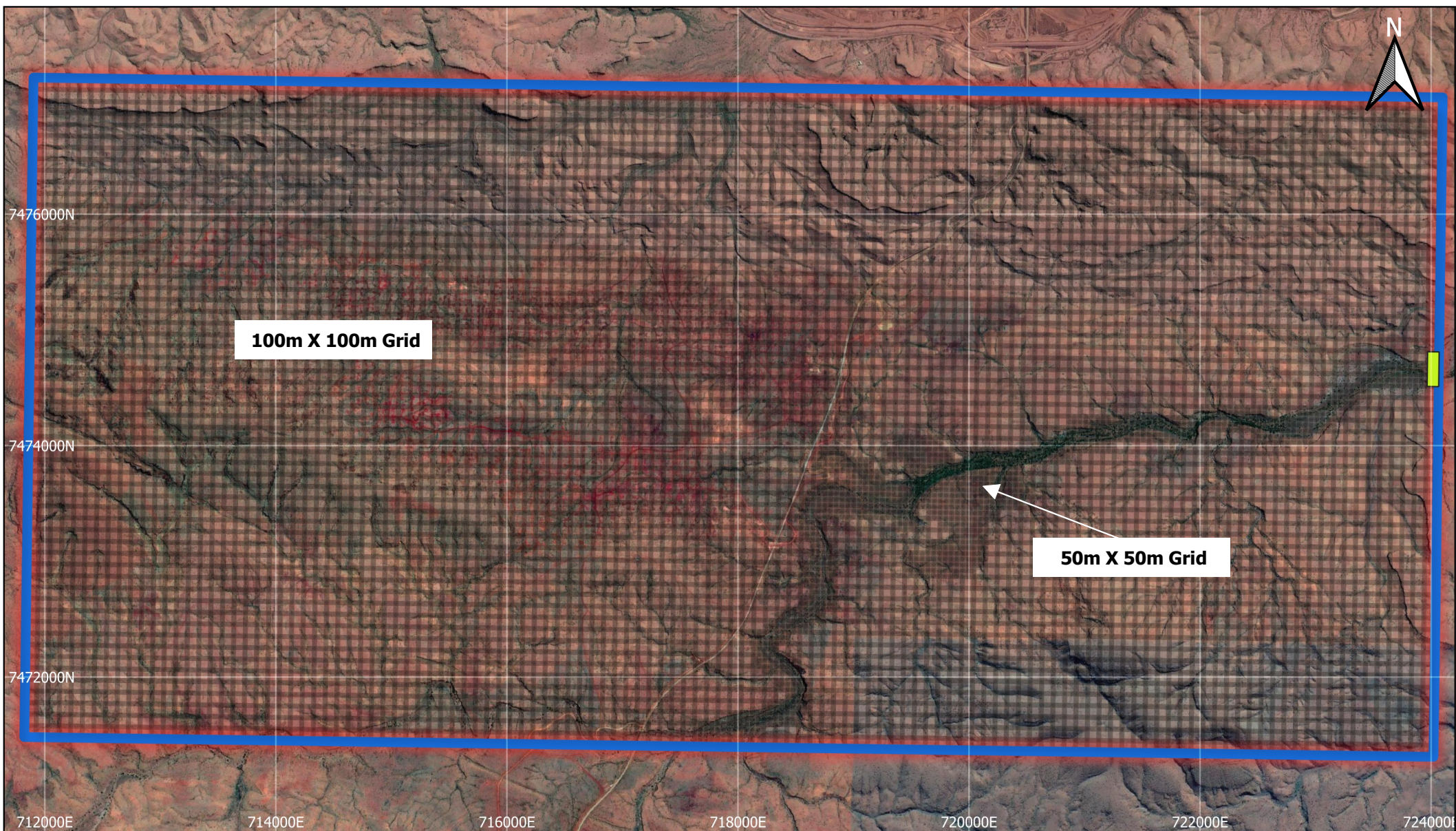
Figure 5 – Observed and simulated groundwater levels at example bores

References

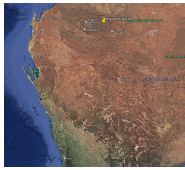
BHP, 2022: Below Water Table Mining Assessment - Ministers North, Draft report, 1 March 2022.

RPS, 2022: Hydrogeological Drilling and Test Pumping Report, Ministers North DEW Phase 1, FY 21, AU213001879.001 Draft A, 28 February 2022



Appendix A

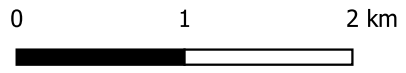


Location Map



Legend

-  Creek outflow boundary (drains)
-  Model Domain



AUTHOR: MP
 DRAWN: SP
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NOTES & DATA SOURCES:
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 ESPG:28350 (GDA94/MGA zone 50)

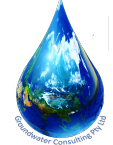
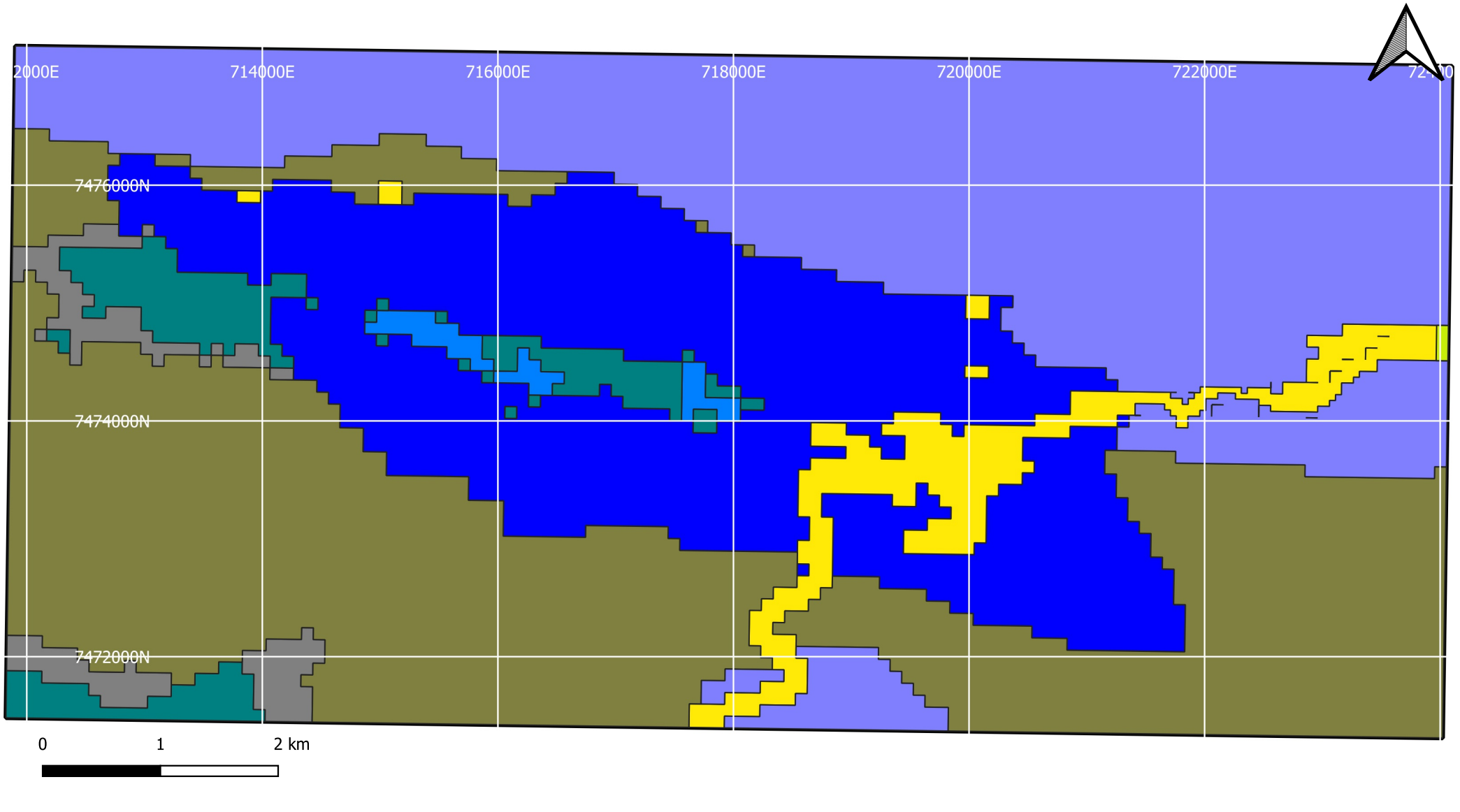


Figure A1
Model Domain



Location Map



Legend

- | | | | |
|------------------------------|---------------------------|------------------------|--------------------|
| Hydraulic conductivity zones | MN Aquifer | Joffre Member | Dales Gorge Member |
| Creek Alluvium / Detritals | Yandicoogina Shale Member | Whaleback Shale Member | Mt McRae Member |

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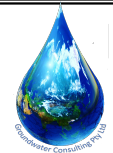
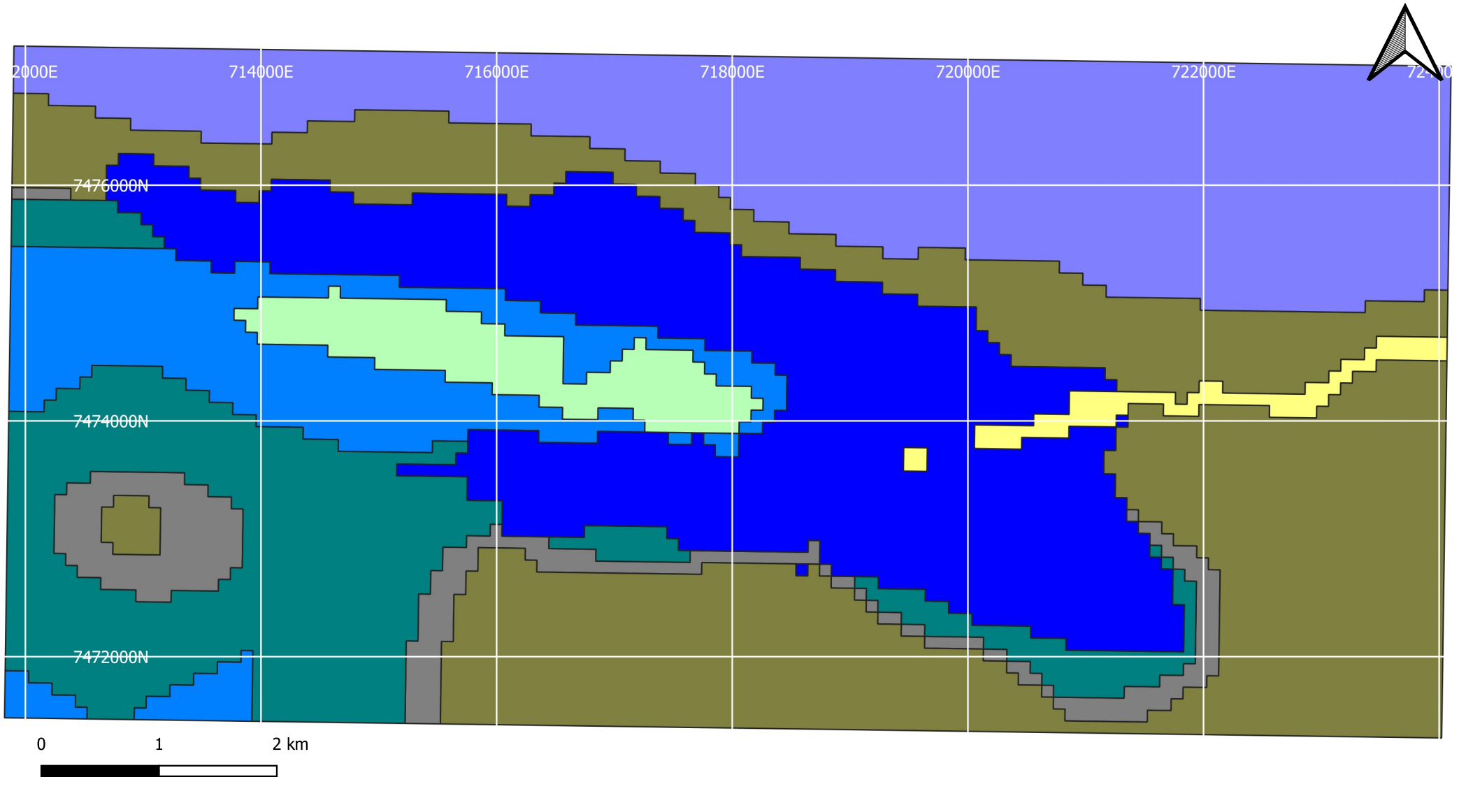


Figure A2
Hydraulic conductivity distribution in Layer 1



Location Map



Legend

Hydraulic conductivity zone

- Creek Alluvium / Detritals
- MN Aquifer

- Yandicoogina Shale Member
- Joffre Member
- Whaleback Shale Member

- Dales Gorge Member (Unmineralised)
- Mt McRae Shale
- Mt Sylvania Formation

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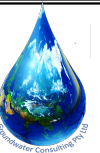
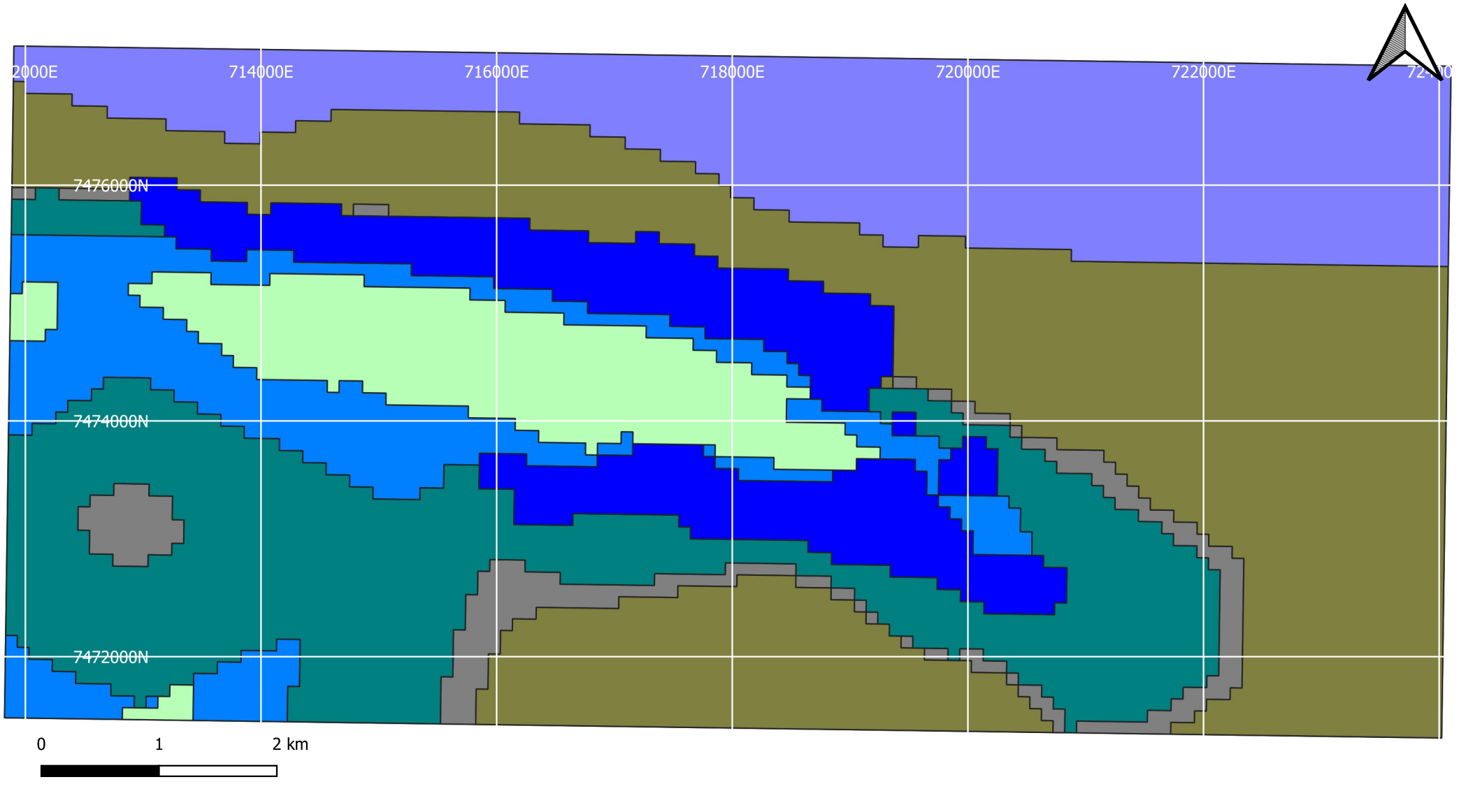


Figure A3

Hydraulic conductivity distribution in Layer 2



Location Map



Legend

Hydraulic conductivity zone

- MN Aquifer
- Yandicoogina Shale Member

- Joffre Member
- Whaleback Shale Member
- Dales Gorge Member (Unmineralised)

- Mt McRae Shale
- Mt Sylvia Formation

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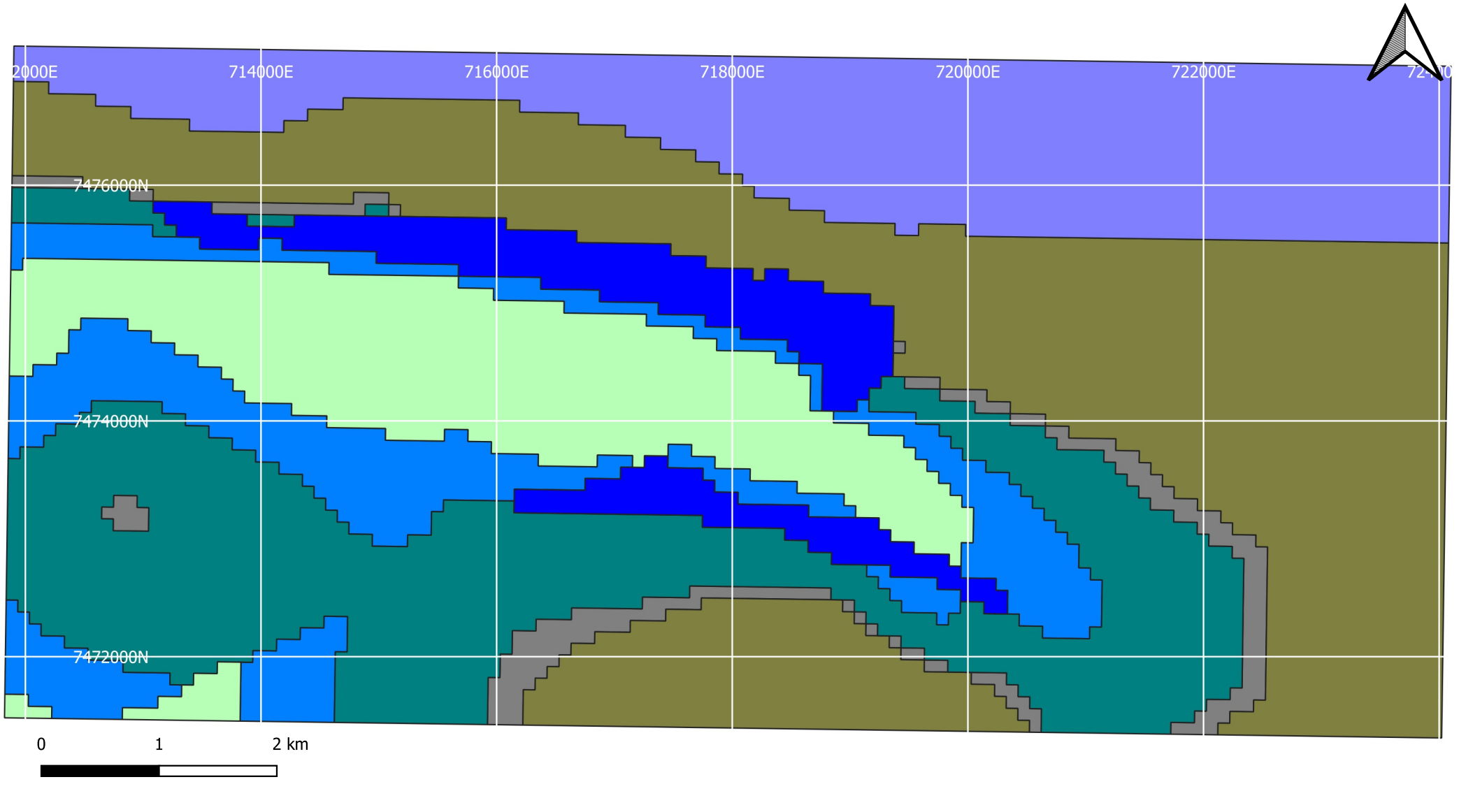
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Figure A4

Hydraulic Conductivity distribution in Layer 3



Location Map



Legend

Hydraulic conductivity zone

- MN Aquifer
- Yandicoogina Shale Member

- Joffre Member
- Whaleback Shale Member
- Dales Gorge Member (Unmineralised)

- Mt McRae Shale
- Mt Sylvia Formation

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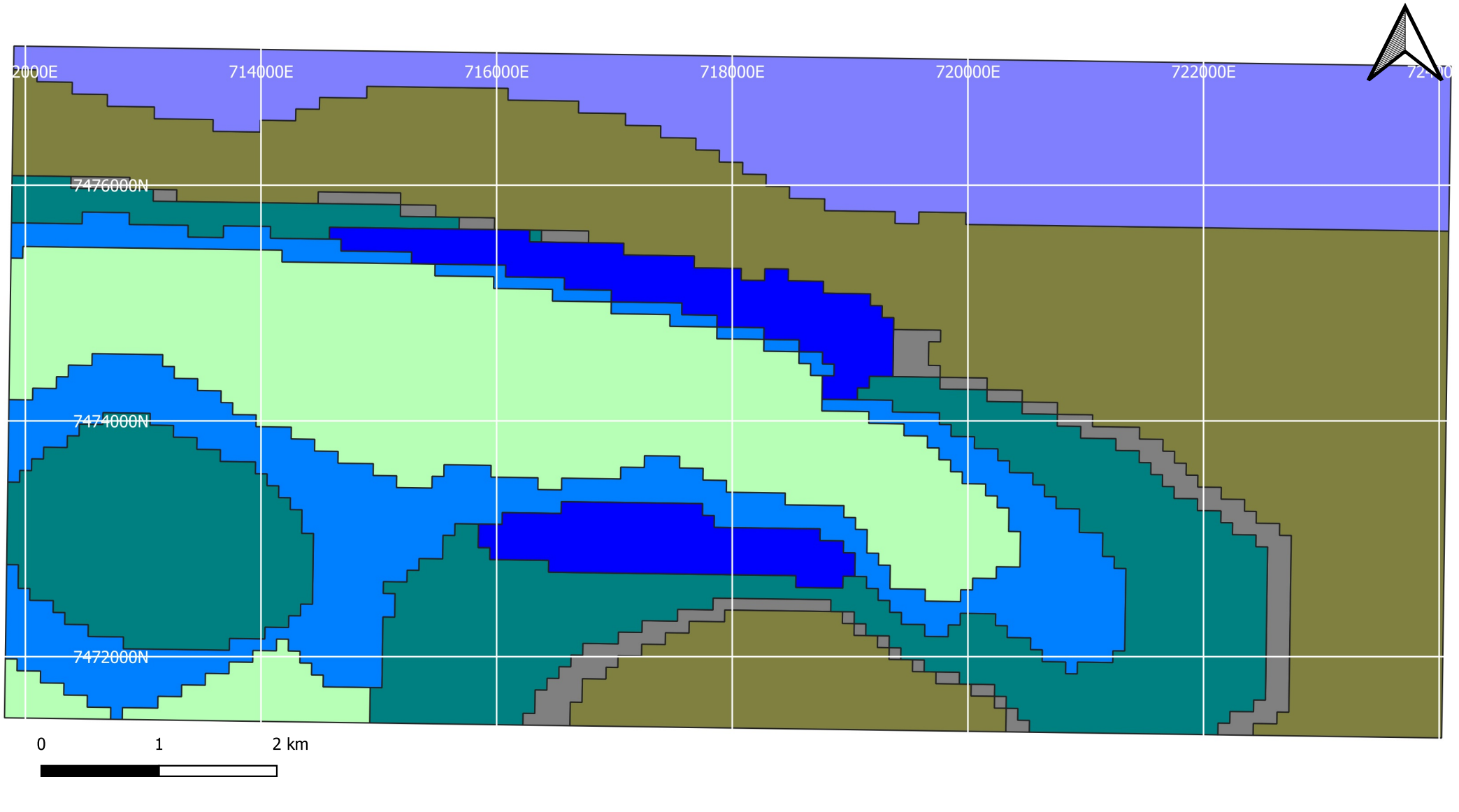
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Figure A5

Hydraulic conductivity distribution in Layer 4



Location Map



Legend

Hydraulic conductivity zone

- MN Aquifer
- Yandicoogina Shale Member

- Joffre Member
- Whaleback Shale Member
- Dales Gorge Member (Unmineralised)

- Mt McRae Shale
- Mt Sylvia Formation

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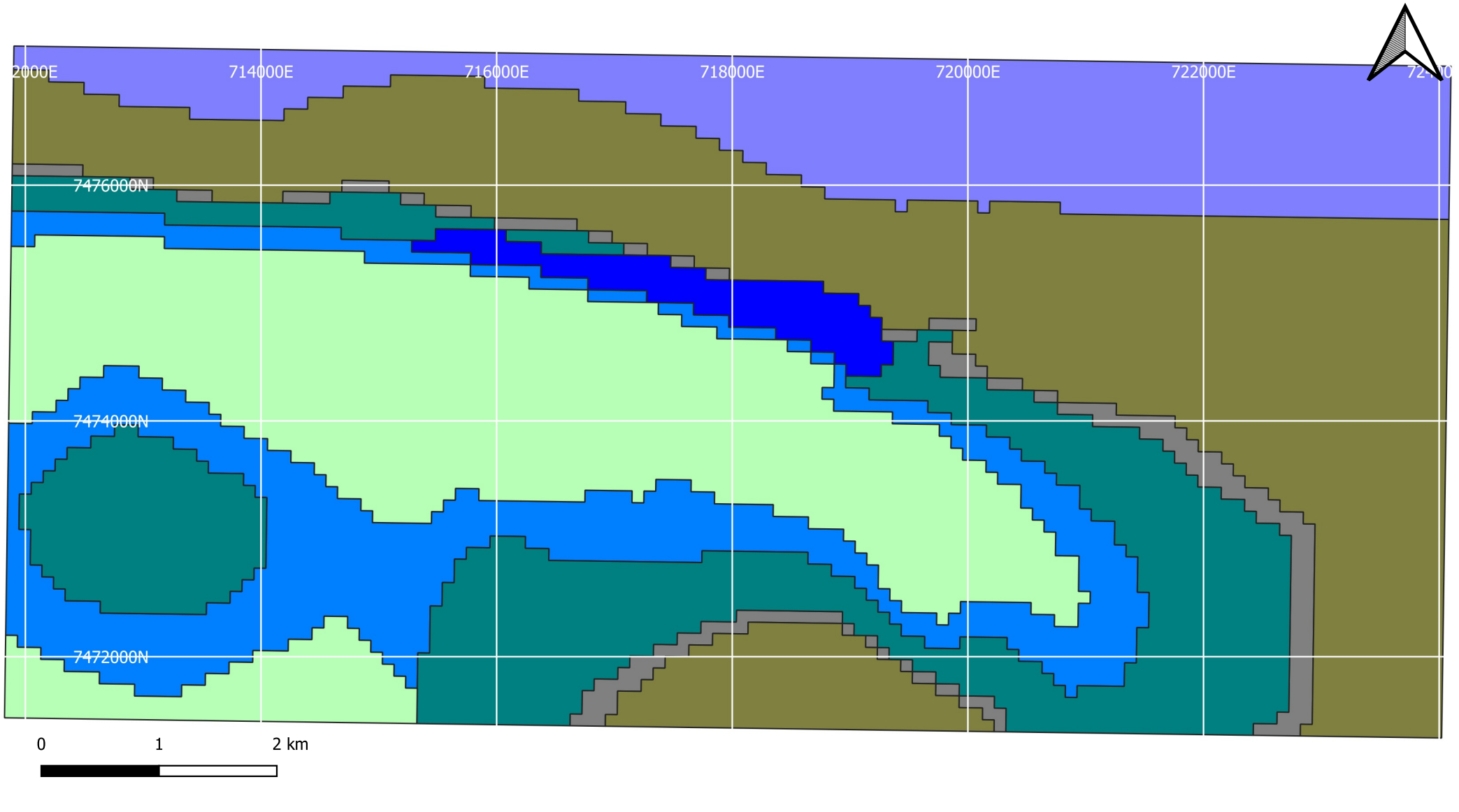
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Figure A6

Hydraulic conductivity distribution in Layer 5



Location Map



Legend

- | | | | |
|-----------------------------|------------------------------------|---------------------|----------------|
| Hydraulic conductivity zone | | Joffre Member | Mt McRae Shale |
| MN Aquifer | Whaleback Shale Member | Mt Sylvia Formation | |
| Yandicoogina Shale Member | Dales Gorge Member (Unmineralised) | | |

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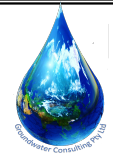
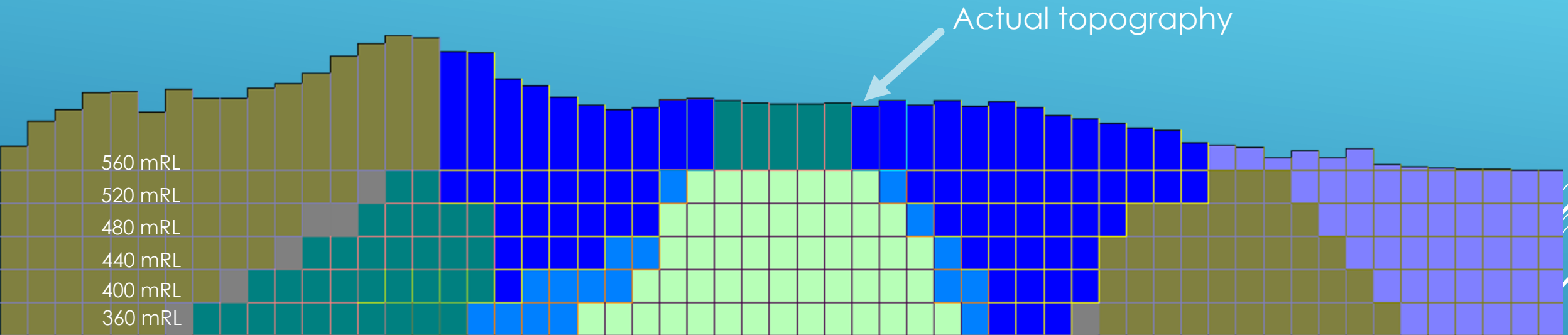
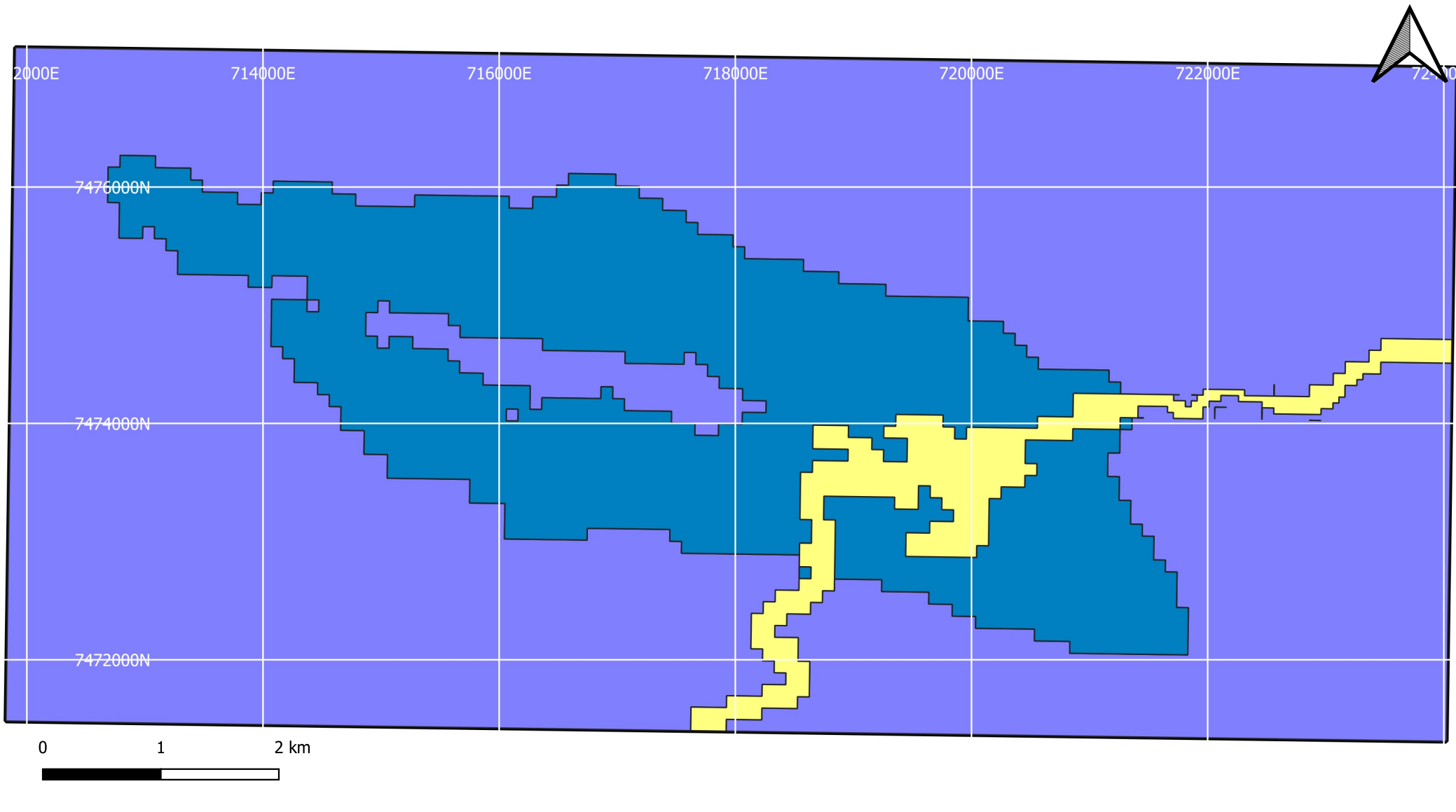


Figure A7
Hydraulic conductivity distribution in Layer 6

FIGURE A8 – NORTH – SOUTH MODEL SECTION TROUGH NORTHERN AND SOUTHERN LIMBS





Location Map



Legend

- Recharge zone
- MN Aquifer Recharge
- No Recharge
- Creek Zone Recharge

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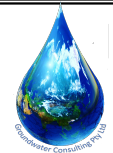
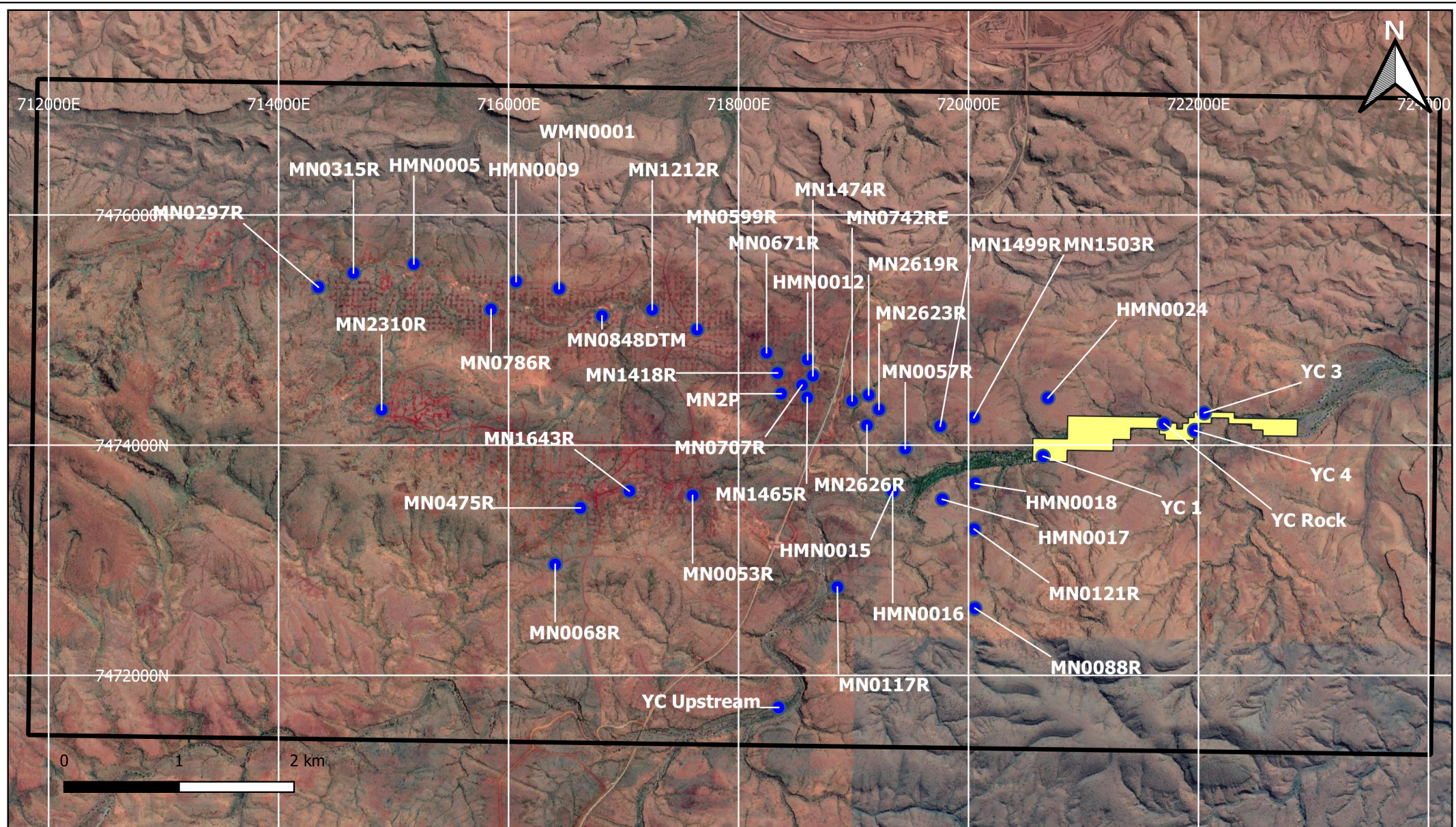


Figure A9
Modelled recharge distribution



Location Map



- Legend**
- Evapotranspiration Zones
 - Monitoring Bores
 - Modelled EVT Zone

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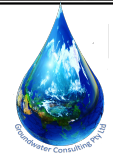
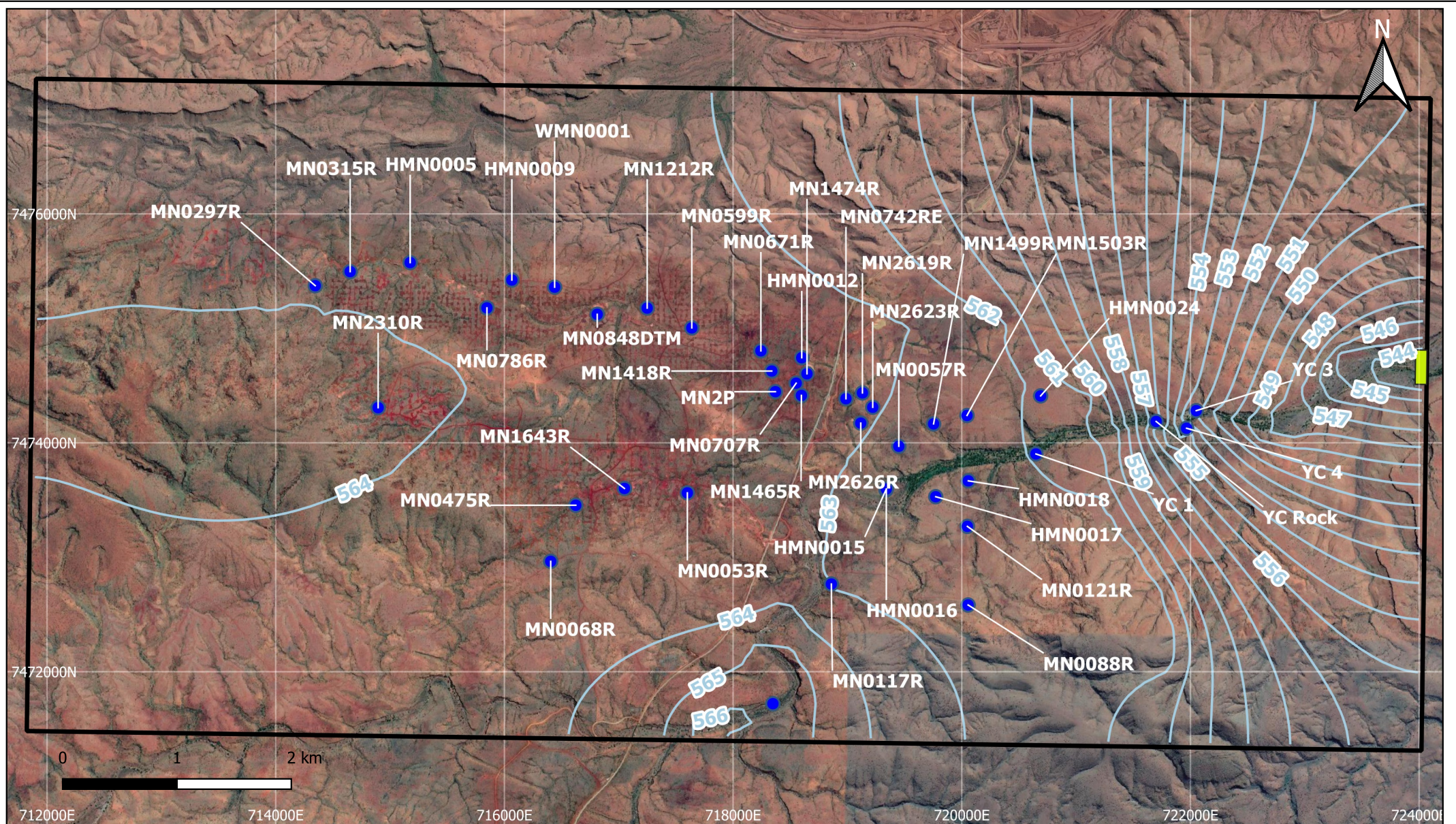


Figure A10
Modelled evapotranspiration distribution

Appendix B



Location Map



Legend

- Outflow Boundary (Drains)
- Predicted steady state groundwater contours
- Model extent
- Monitoring Bore

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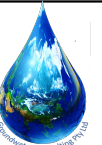


Figure B1
Predicted steady state groundwater contours

FIGURE B2-MONITORING BORE LOCATIONS

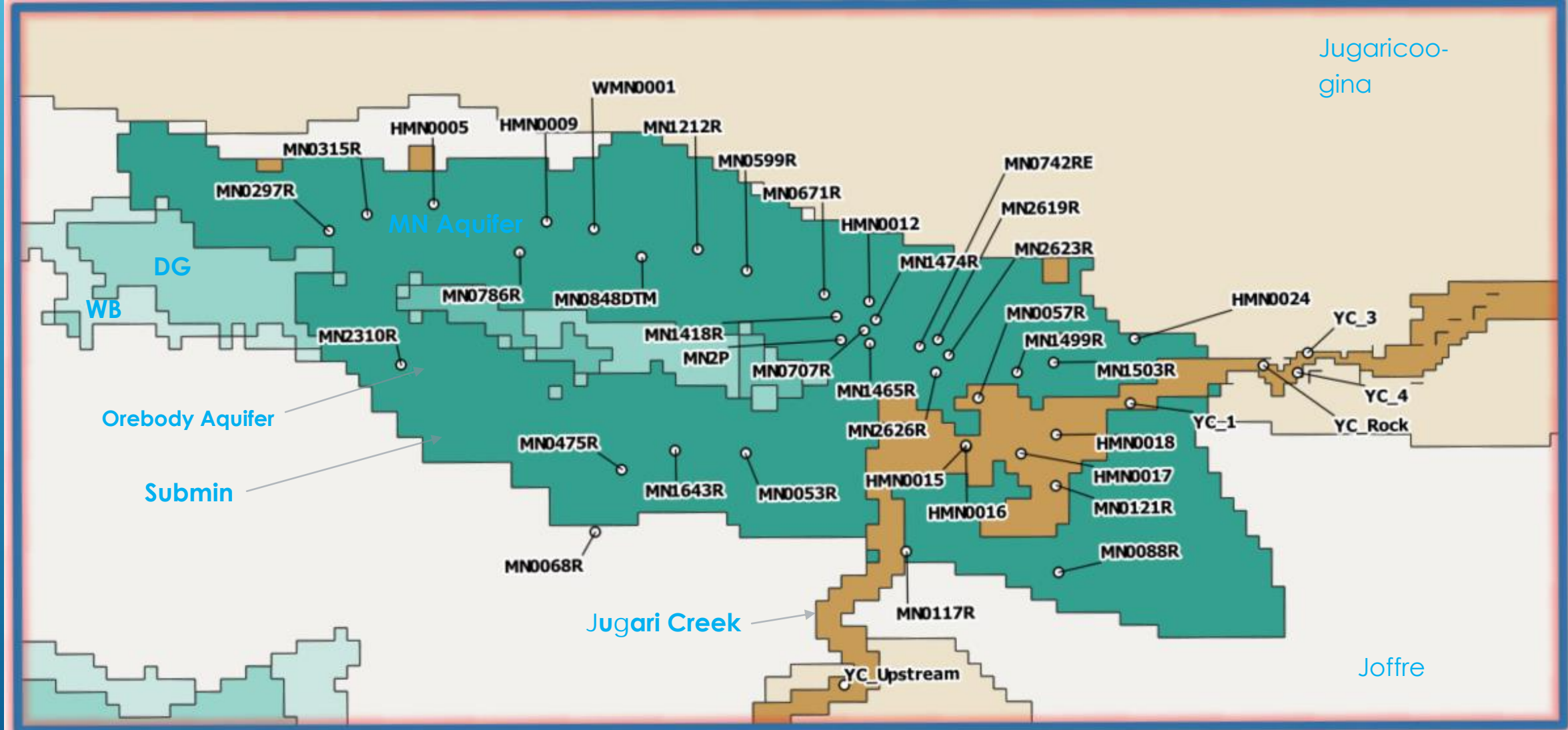
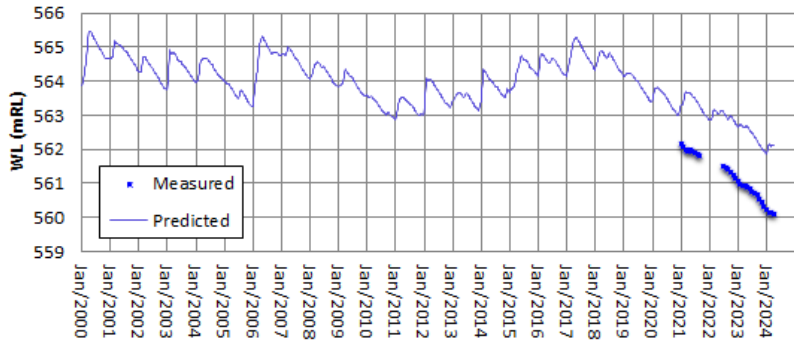


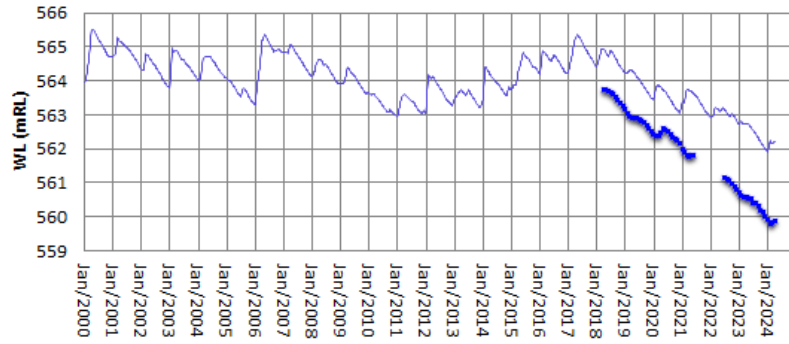
FIGURE B3 - CALIBRATION HYDROGRAPHS 2000 - 2024



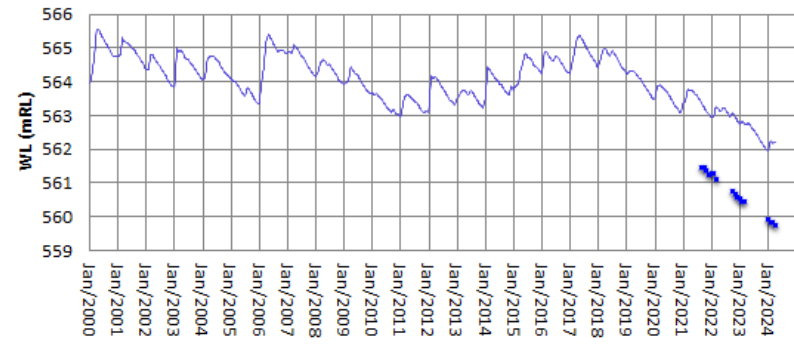
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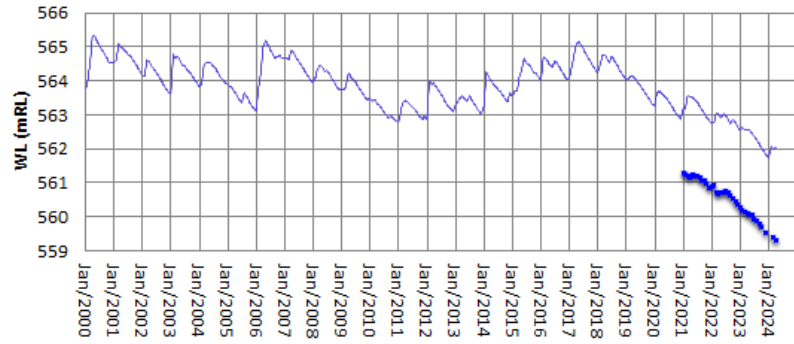
MN0315R



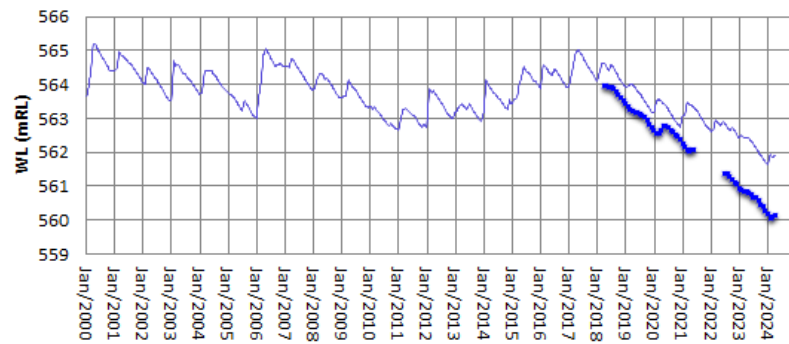
MN0297R



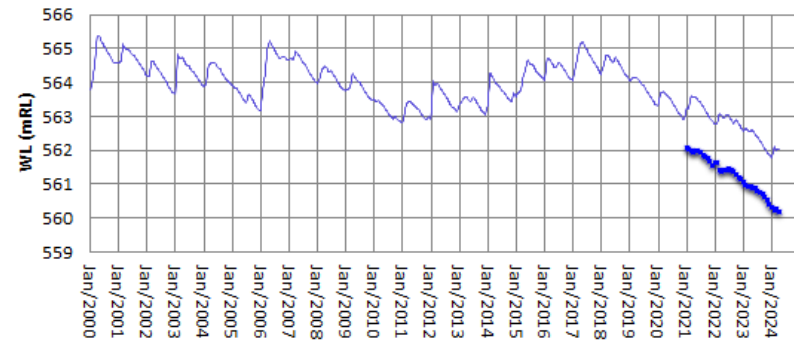
HMN0009



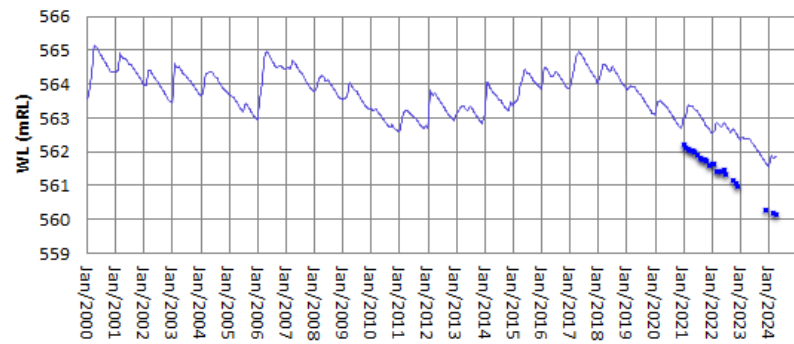
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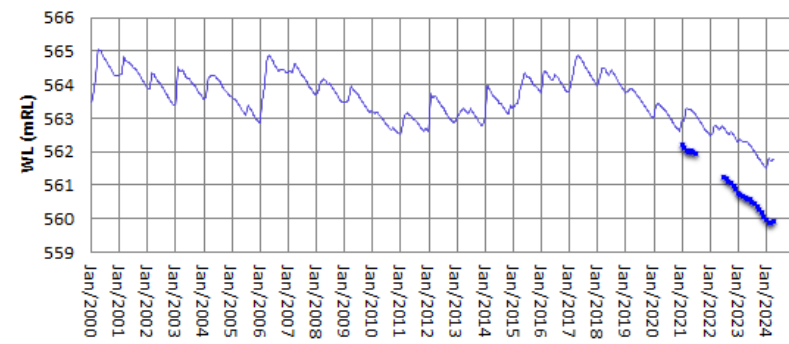
MN0786R



MN1212R



MN0599R



MN0671R

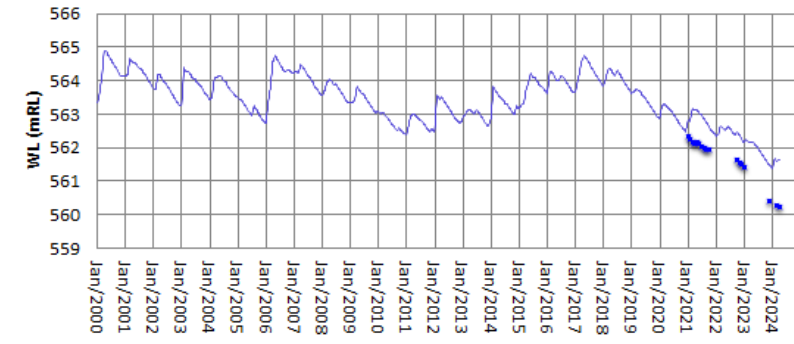
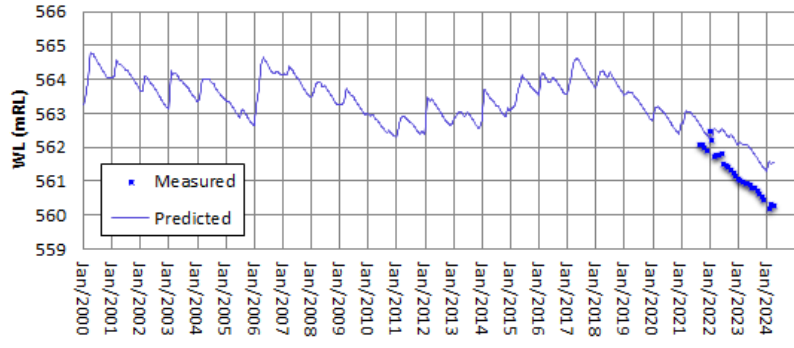


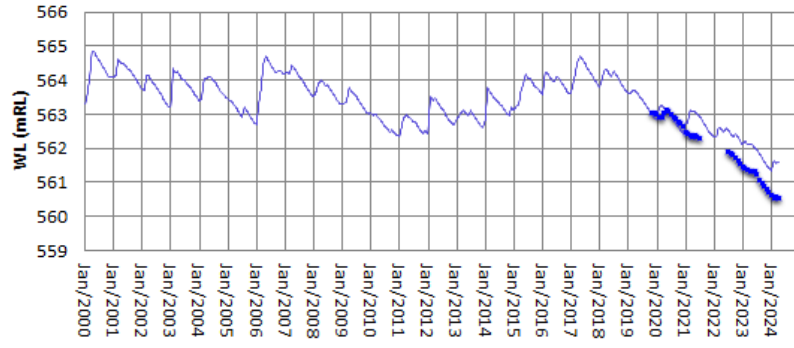
FIGURE B4 - CALIBRATION HYDROGRAPHS 2000 - 2022



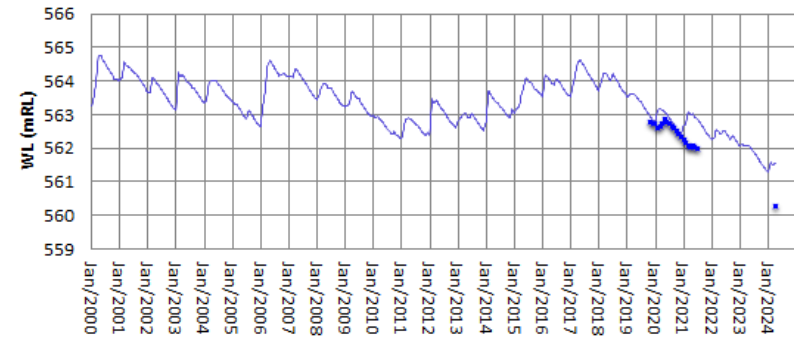
HMN0012



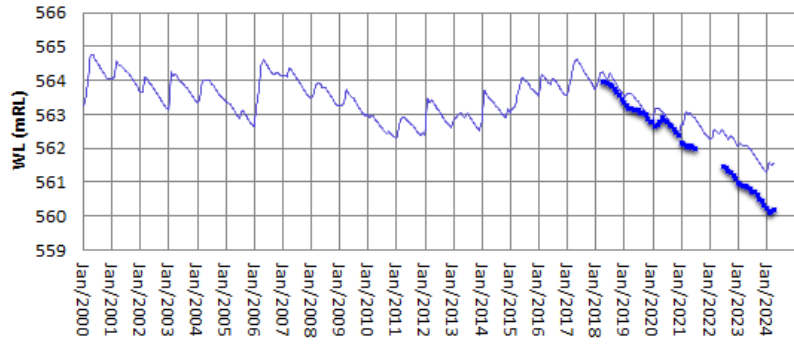
MN1418R



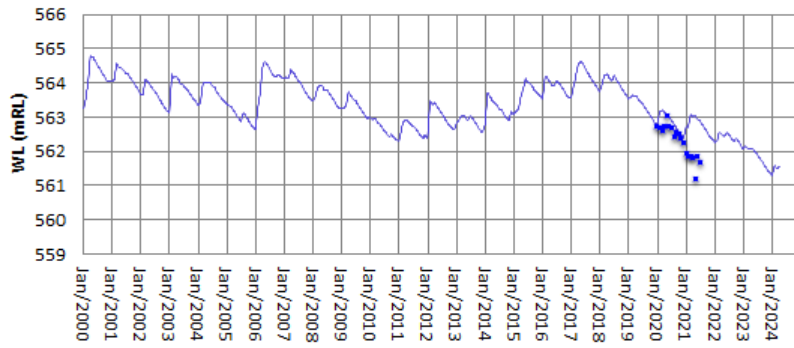
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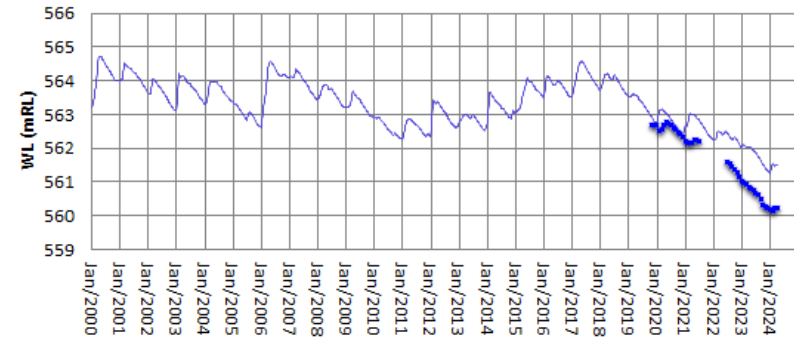
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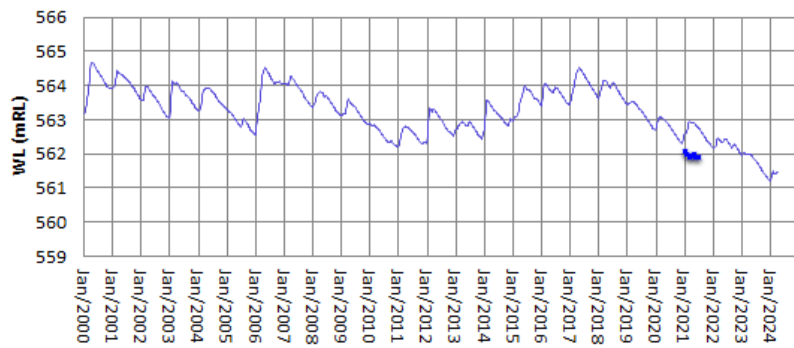
MN2P



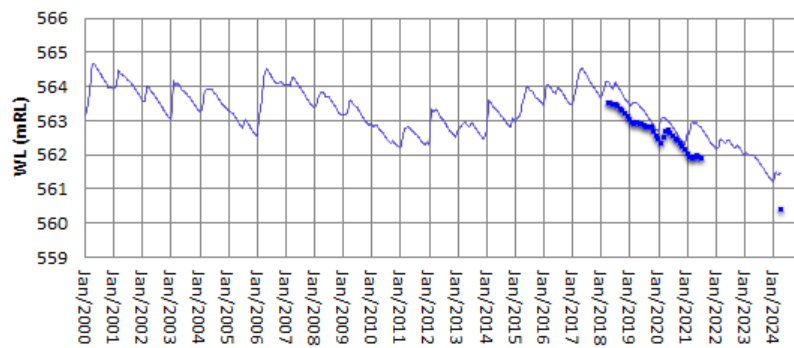
MN1465R



MN2619R



MN0742RE



MN2623R

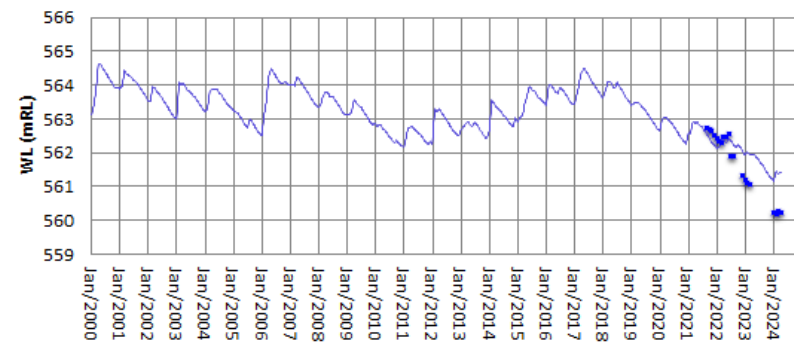
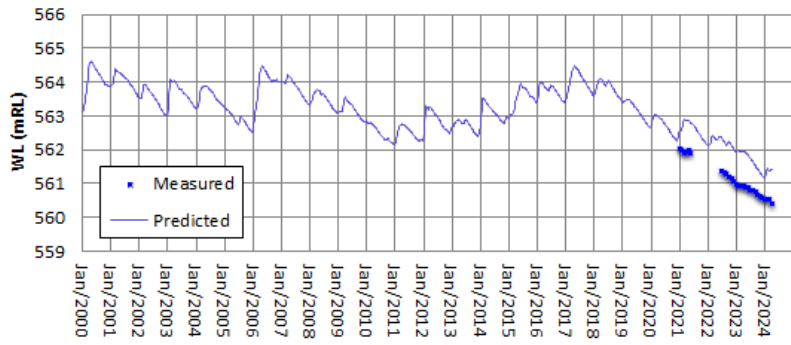


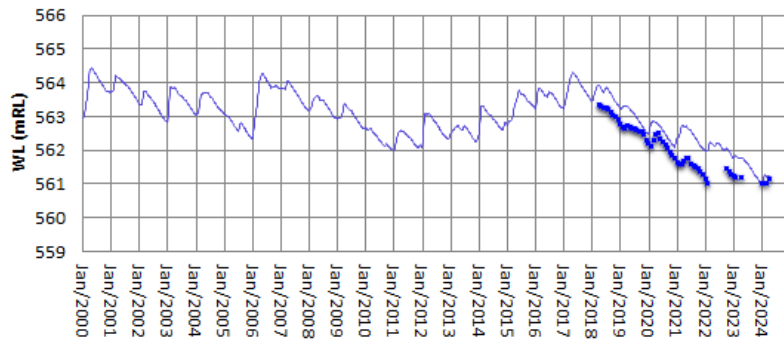
FIGURE B5 - CALIBRATION HYDROGRAPHS 2000 - 2022



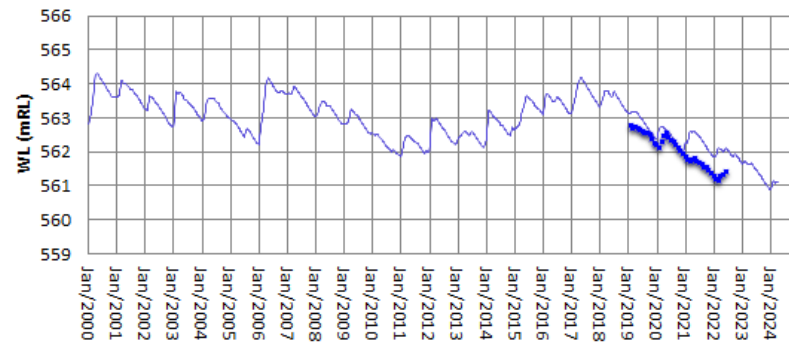
MN2626R



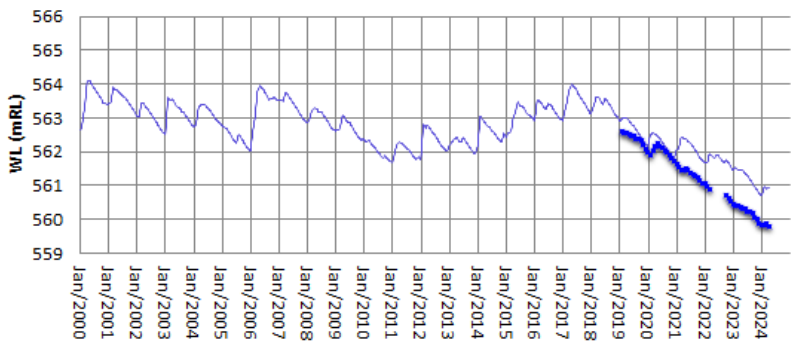
MN0057R



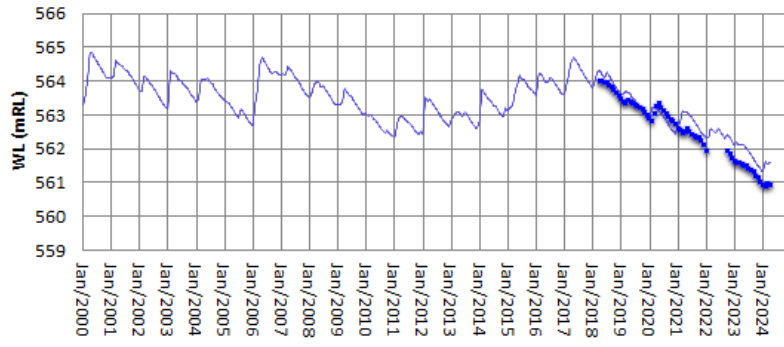
MN1499R



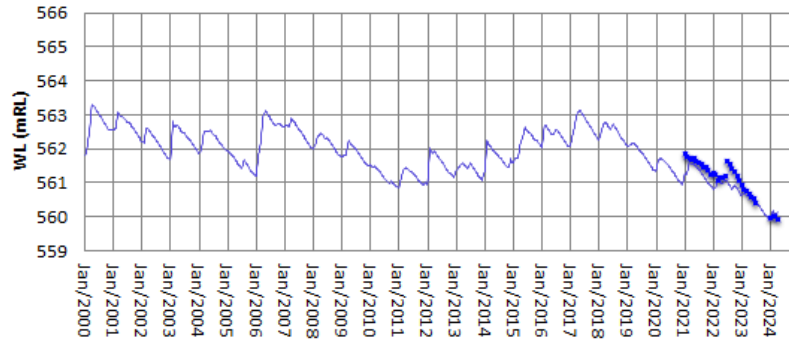
MN1503R



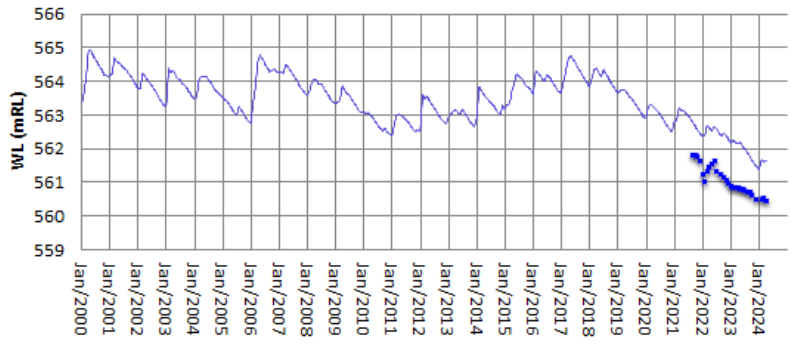
MN0053R



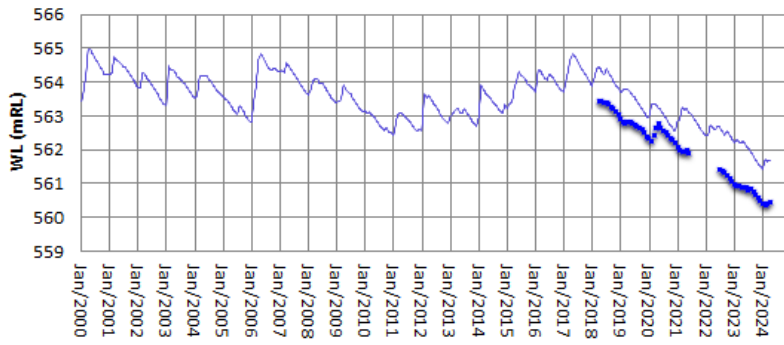
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MN0475R



MN0068R

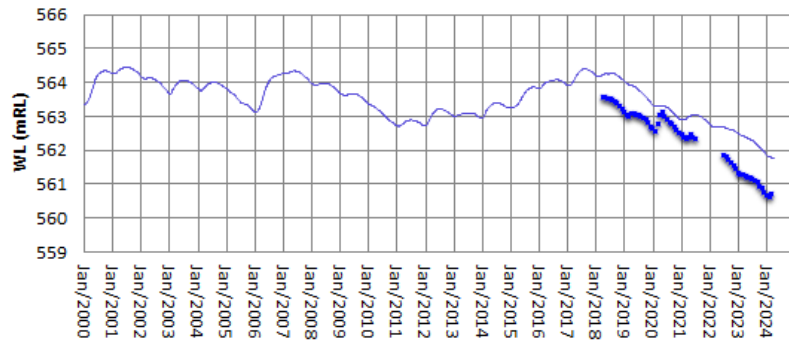
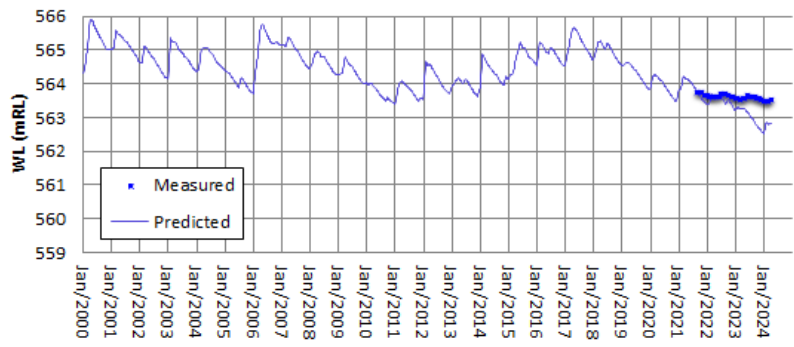


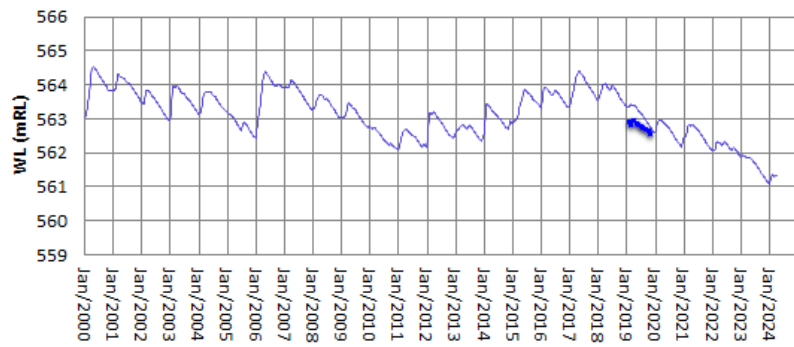
FIGURE B6 - CALIBRATION HYDROGRAPHS 2000 - 2022



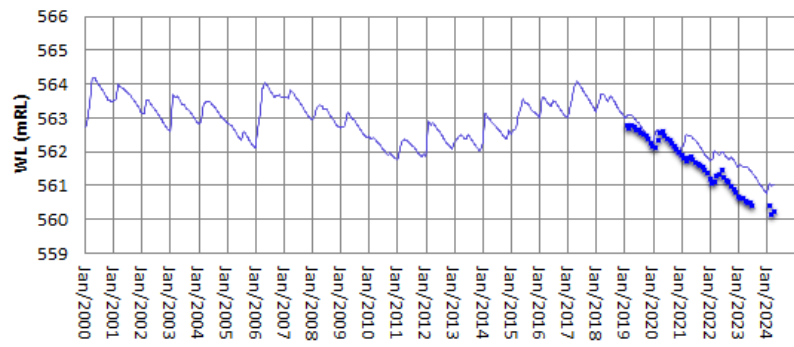
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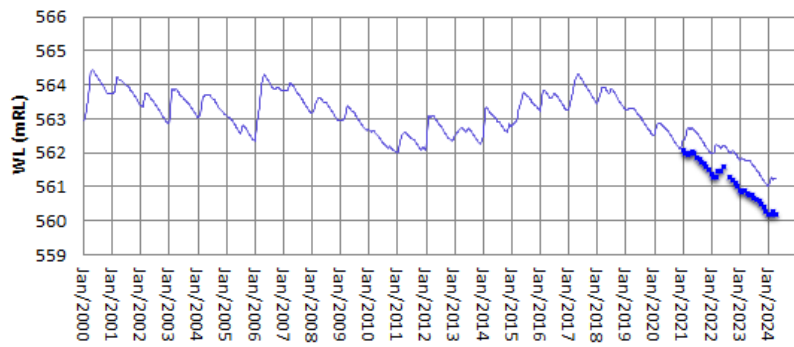
MN0117R



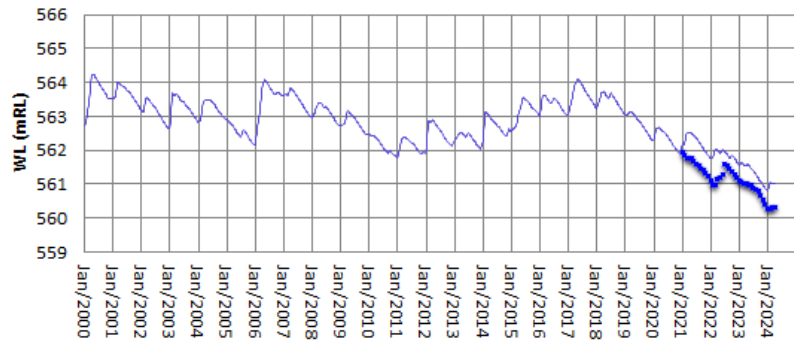
MN0088R



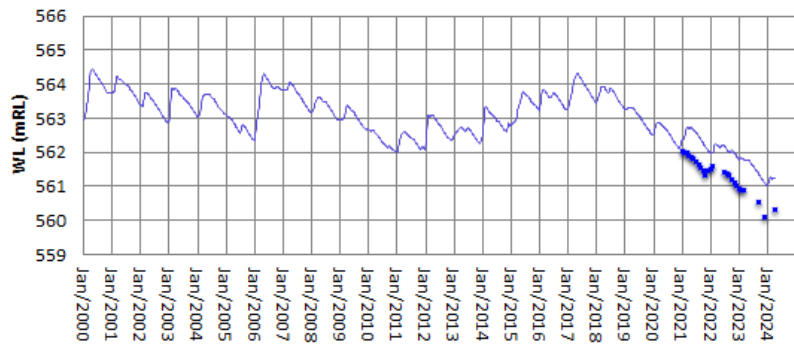
HMN0015



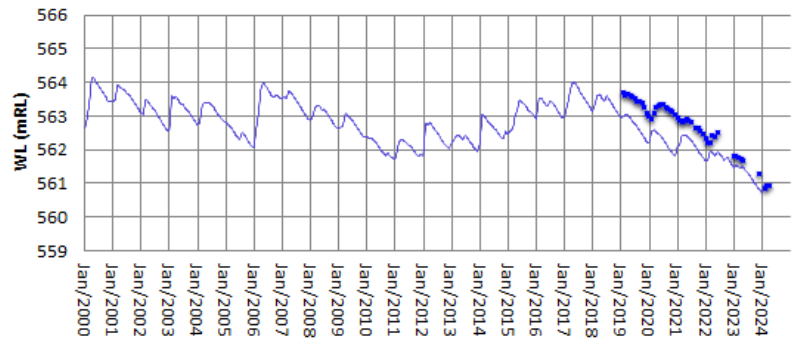
HMN0017



HMN0016



MN0121R



HMN0018

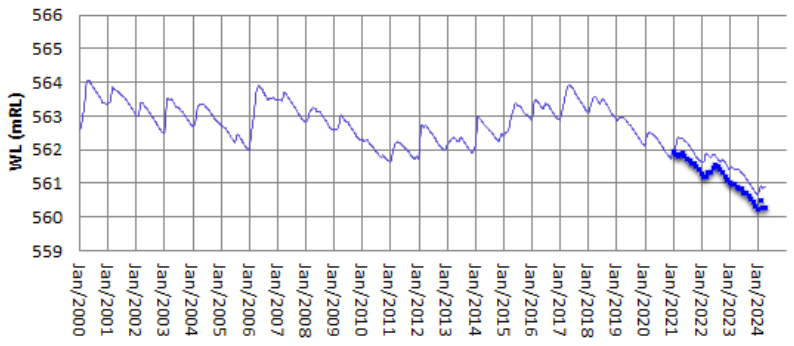
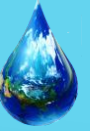
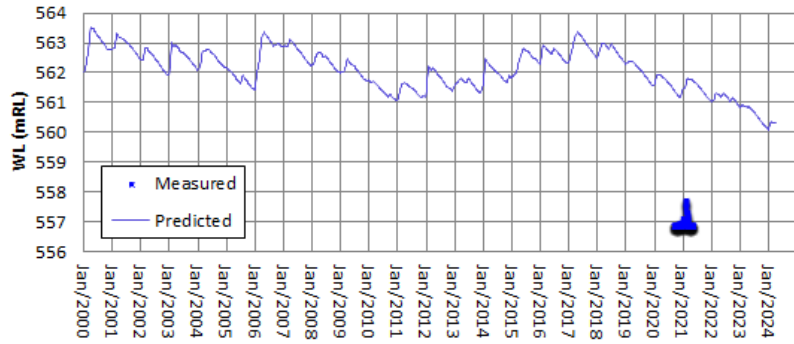


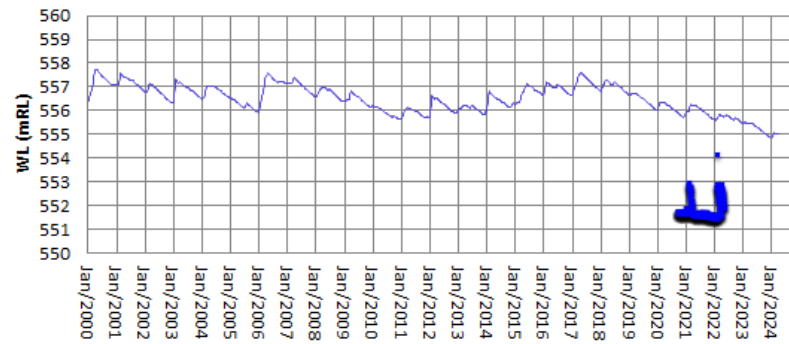
FIGURE B7 - CALIBRATION HYDROGRAPHS 2000 - 2022



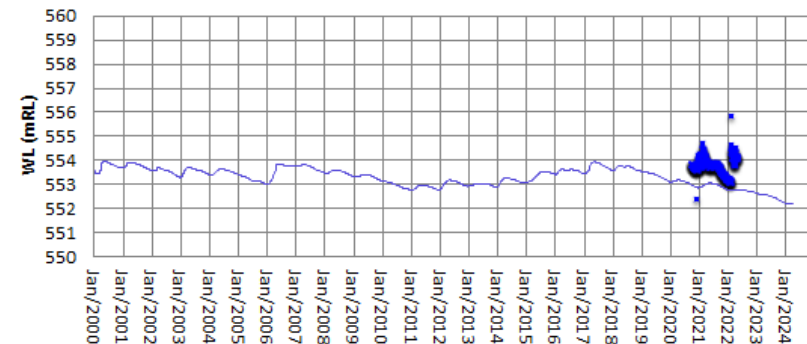
YC_1



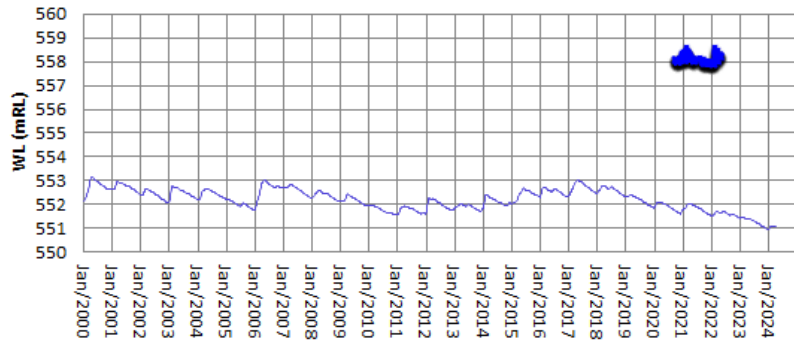
YC_Rock



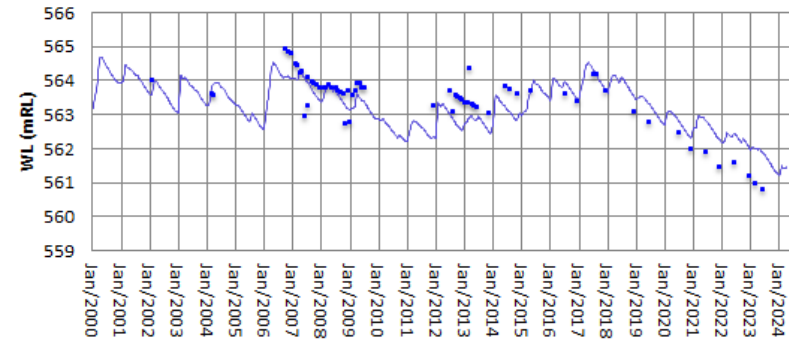
YC_4



YC_3



M322.7



M323.3

