Appendix F

3D Rendered Images of Rehabilitation Concept

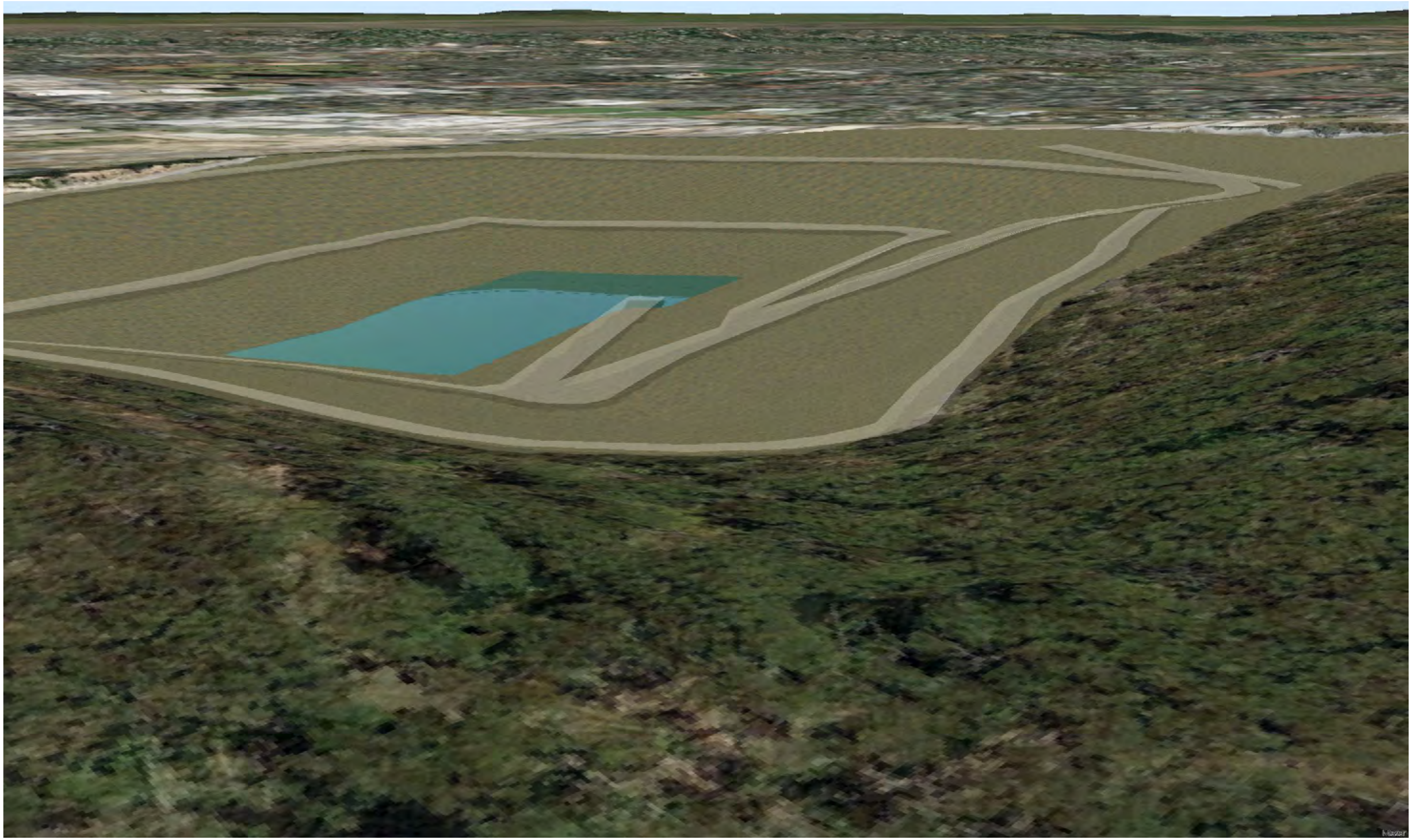


Figure A *Near view, looking northwest from Bungalook Creek*

Figure B *External View, looking southeast to the Dandenong Ranges*

Figure C *External view, looking southwest from Mount Evelyn*

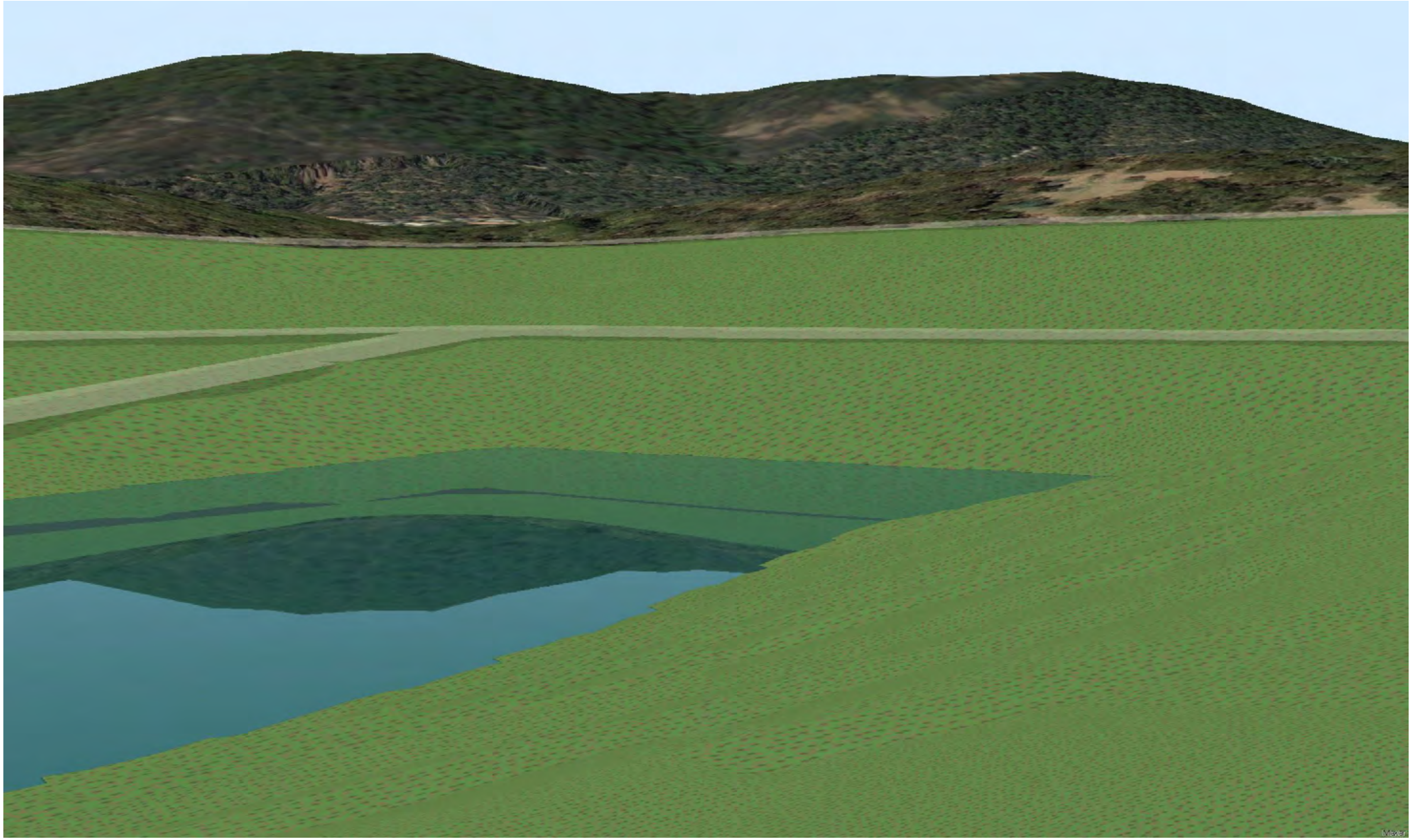


Figure D *Internal view with grass cover, looking southeast towards Dandenong Ranges*

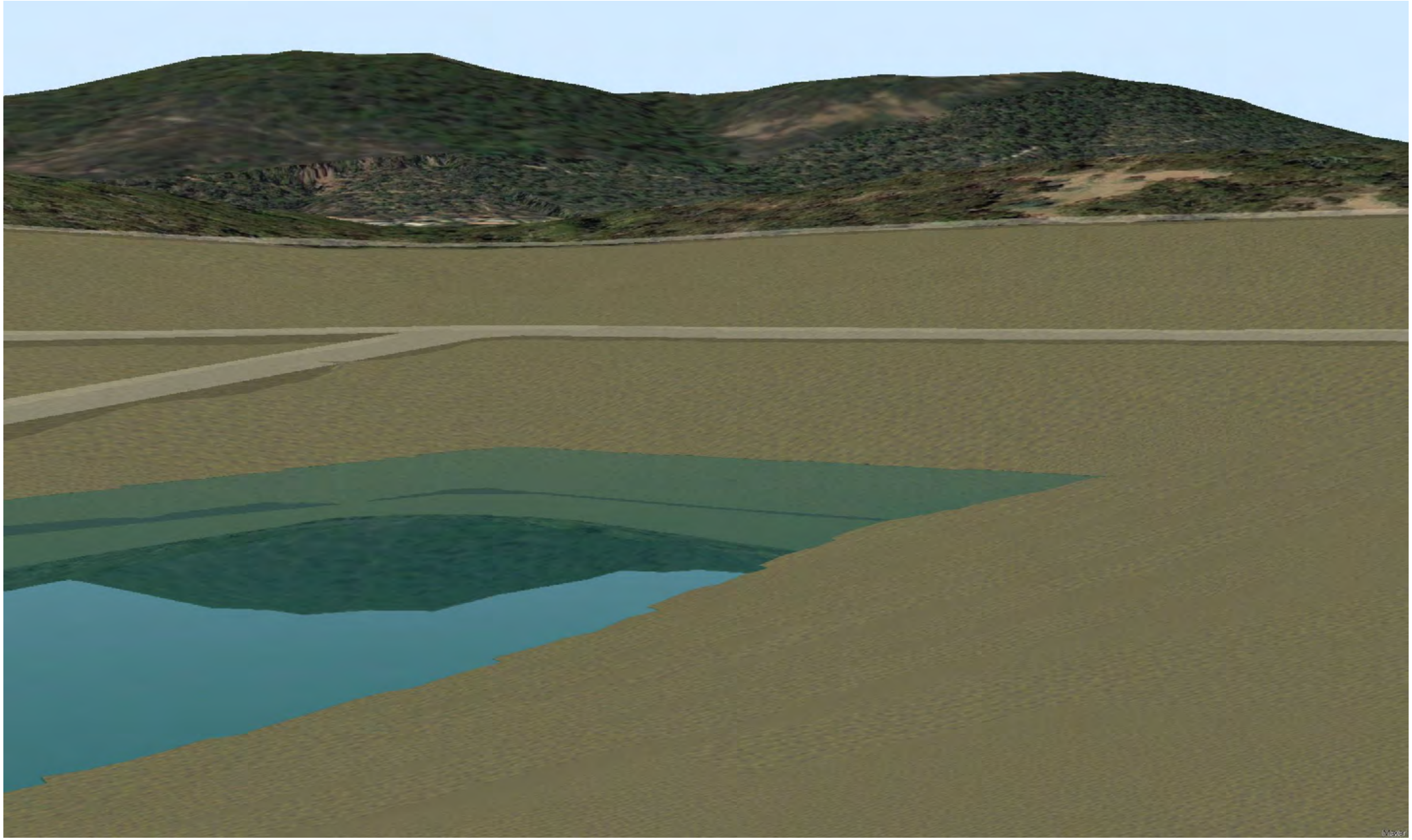


Figure E Internal view with no grass cover, looking southeast towards the Dandenong Ranges

Figure F *External view, looking eastward towards Mount Evelyn*

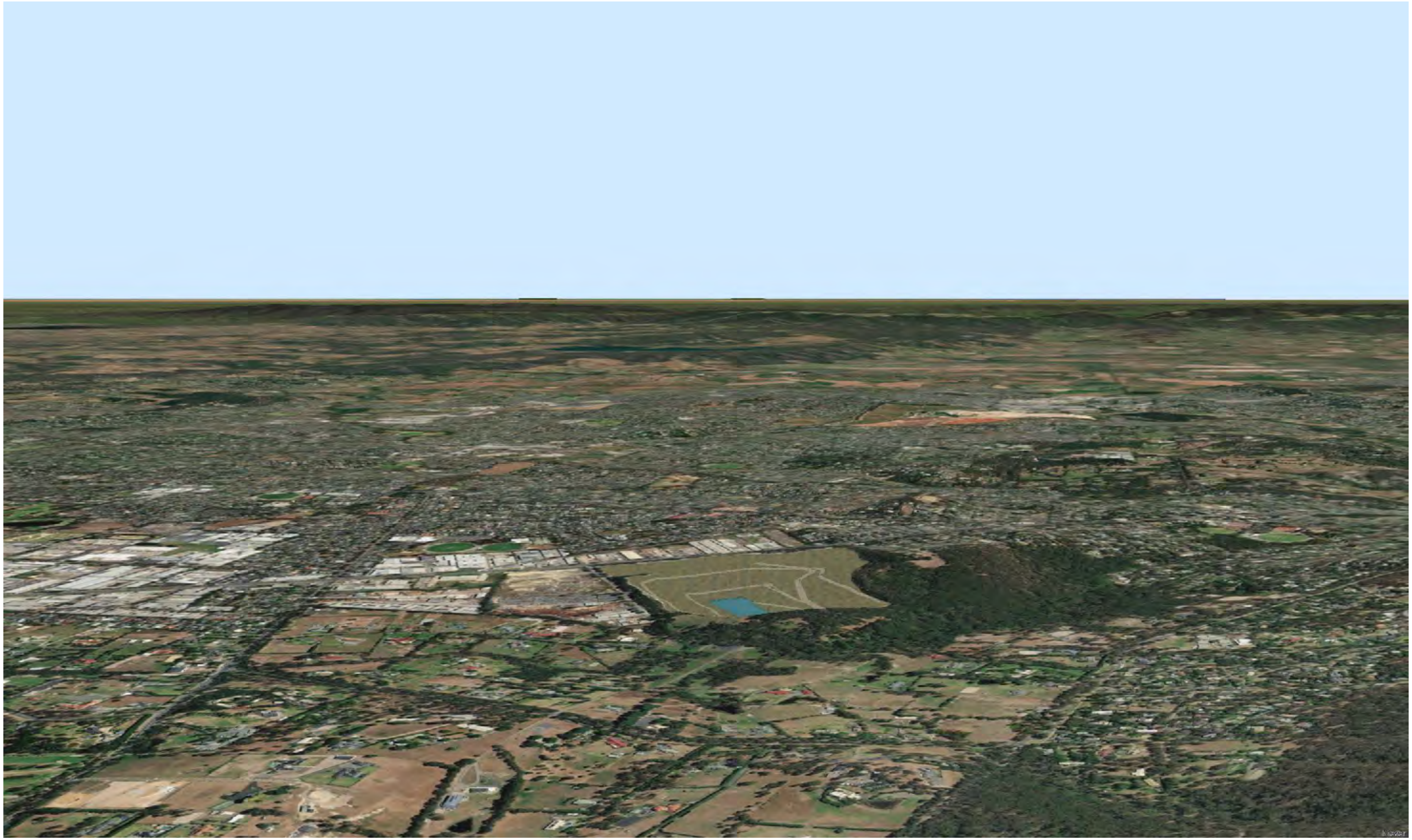


Figure G *External view, looking northwest from the Dandenong Ranges*

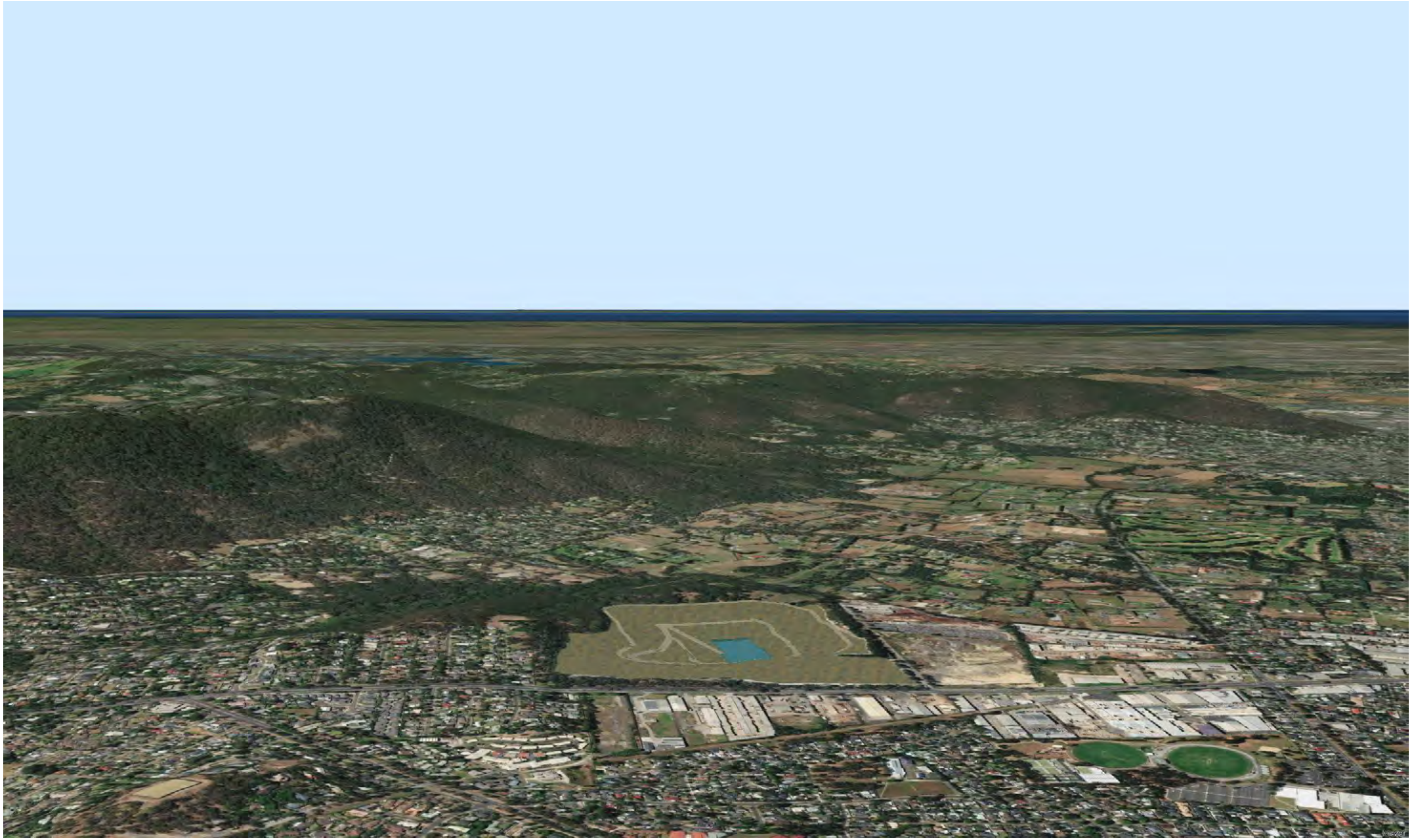


Figure H *External view, looking southeast towards the Dandenong Ranges*

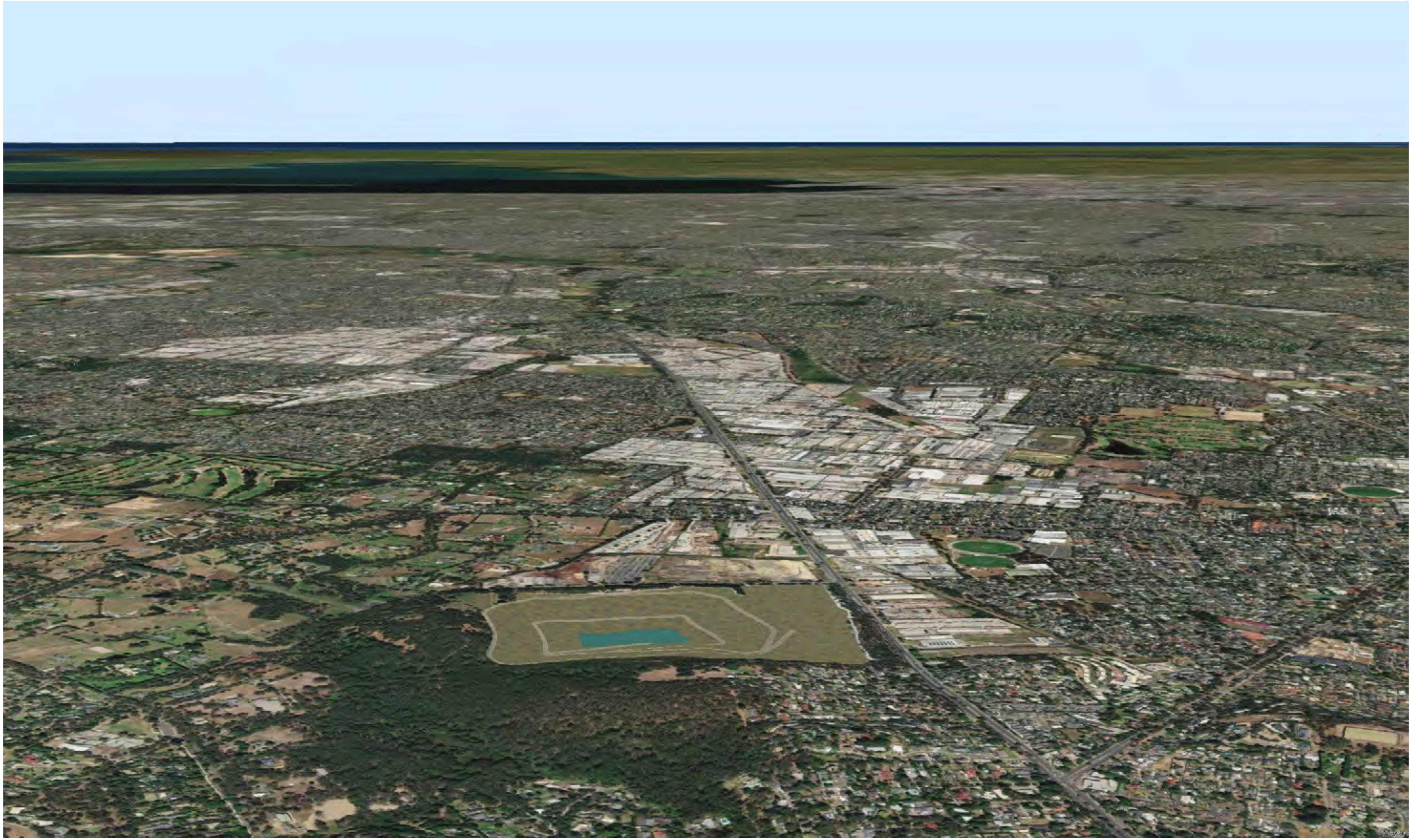


Figure I *External view, looking west towards Melbourne City*

ghd.com

→ The Power of Commitment

Appendix K

Water Risk Register

Appendix K - Water Risk Register

Risk ID	Water Environment	Phase of development	Pathway / Risk Event	Potential receptors or risk entities				Inherent Risk					Residual Risk			Monitoring and on-going management	
				Details of sensitive receptor	Location / proximity	Resultant harm	Supporting evidence	Likelihood	Consequence	Risk Level	Treatment measures / existing controls	Performance standards	Likelihood	Consequence	Risk Level	Aspect to be monitored	Details and ongoing management
SW-1	Surface Water	Operation	Refuelling / heavy plant maintenance activities results in spillage of hazardous materials	Quarry sump	Internal to the quarry	Contaminated water being collected within the quarry sump, and potentially used throughout the site via industrial applications of the sump water.		**Unlikely**	**Moderate**	**Medium**	- Monitoring bore network (although monitoring program not implemented) - Spill kits and emergency response procedures, - Boral quarry environmental procedures to avoid potentially harmful activities occurring in high risk areas.		**Unlikely**	**Minor**	Low		- Boral auditing of implementation of quarry site environmental plan.
SW-2	Surface Water	Operation	Reduction in stormwater flows to Bungalook Creek, due to loss of catchment created by quarry expansion	Streamflow in Bungalook Creek	Existing quarry is within a few hundred meters of Bungalook Ck. Expanded quarry will be within 200m of the creek.	Changes in surface water quality / beneficial uses of the waterway		**Unlikely**	**Moderate**	**Medium**	- Perimeter bunding around quarry so that all stormwater is contained to the quarry footprint, rather than exiting the site		**Rare**	**Minor**	Low		- Risk should be largely eliminated. - Periodical inspection and review of vegetation cover / access tracks / bunding integrity in buffer area are maintained to ensure compliance.
SW-3	Surface Water	Rehabilitation	Inflows into quarry lake are insufficient to maintain permanent water.	Post closure quarry lake.	Internal to the rehabilitated quarry	Changes in groundwater quality / beneficial uses of the closure quarry lake.		**Unlikely**	**Moderate**	**Medium**	- Design water balance and objectives for the post closure quarry lake.	- Melbourne Water works on waterways	**Rare**	**Minor**	Low	Revegetation	- Review of implementation of the Rehabilitation plan
SW-4	Surface Water	Rehabilitation	Sediment laden run-off migrating offsite to pollute neighbouring waterways	Bungalook Creek	Existing quarry is within a few hundred meters of Bungalook Ck. Expanded quarry will be within 200m of the creek.	Increased sediment loads and water quality impacts in waterway, increase potential for siltation and scouring.		**Unlikely**	**Moderate**	**Medium**	- Control of slope and assessment of erosion potential - Revegetation of site - Perimeter landscaping and landforming		**Rare**	**Minor**	Low	Revegetation	- Review of implementation of the Rehabilitation plan
GW-5	Groundwater	Operation	Dewatering required to access lower levels of the quarry	Neighbouring groundwater users	Nearest stock and domestic bores are located approximately 600 m to 1000 m from the quarry	Drawdown results in loss or reduced access to groundwater, i.e. can't pump as much water.	Bores identified on WMIS, however: - nearest registered bore is over 600m from quarry centroid - operational status not confirmed.	**Unlikely**	**Minor**	Low	- Monitoring bore network (although monitoring program not implemented) - Noted that significant change to SWLs has not been identified over last ~19years of available data suggested existing radius of influence is relatively tightly constrained to the quarry.	- Boral licensed to pump up to 120 ML per annum as per their current entitlement. Potential to expand this volume, however, this would need approval from Southern Rural Water.	**Rare**	**Minor**	Low	Volume pumped Groundwater level (drawdown)	- Review of volume pumped and assessment as to whether increase in groundwater entitlement is required. This would trigger SRW licence assessment. - Significant change in groundwater level in monitoring bores located between quarry and nearest private bores would prompt further investigations which could include more frequent monitoring, additional drilling, community consultation / negotiation with the bore owner.
GW-6	Groundwater	Operation	Dewatering required to access lower levels of the quarry	Displacement of contaminated groundwater plumes	Nearest site is on Fussell Road	Interception of contaminated groundwater may result in contamination entering the site and being used for the industrial purposes, and/or entrainment in the waste discharge.	Registered contaminated sites identified on EPA database. May be other sites e.g. along Canterbury that are present but not identified.	**Unlikely**	**Minor**	Low	- Monitoring bore network (although monitoring program not implemented) - Potential for natural attenuation to occur between site and Boral Quarry. - Audit report for Lot 1 indicates plume is stable and not offsite. - Historical quarrying would have already influenced water levels over last >30 years. Contaminated site assessment completed in early 2000s, i.e. optimisation not likely to significantly alter plume migration (but will steep gradients marginally).	-Environmental Reference Standard (2022) '- NEPM (Contaminated Land) and local council planning approvals i.e. should rezoning of land use occur.	**Rare**	**Minor**	Low	Groundwater quality Sump and discharge quality	- No groundwater monitoring along the western boundary. Scope for Boral to update the monitoring network to confirm water level behaviour in the western and northern parts of the site.
GW-7	Groundwater	Operation	Dewatering required to access lower levels of the quarry	Reduction in baseflow to Bungalook Creek (impact to aquatic ecosystems and riparian vegetation). Lowered water levels effect access to groundwater by terrestrial vegetation.	Existing quarry is within a few hundred meters of Bungalook Ck. Expanded quarry will be within 200m of the creek.	Changes to baseflow in the waterway, potential to alter supply to riparian and other potential groundwater dependent ecosystems.	EMMs (2025) indicated there were not any GDEs in the project area with the risk of terrestrial GDE occurrence in the project area deemed to be low to negligible. EMM (2025) indicated that existing vegetation is accessing available moisture within at least the top 3 m of the soil profile, rather than relying on groundwater.	**Unlikely**	**Minor**	Low	- Monitoring bore network (although monitoring program not implemented) - Noted that significant change to SWLs has not been identified over last ~19years of available data. - Quarry would have had an existing impact on baseflows - the optimisation involves only a slight deepening so significant change to baseflow over existing impact not expected. - Flows in Bungalook Creek likely dominated by streamflow, i.e. run-off rather than groundwater contributions. This is confirmed by groundwater level response in nearby Boral monitoring bores. - Return of seepage water to Bungalook Creek (this will mostly aid streamflow and soil moisture rather than baseflow). - No obvious degradation to terrestrial vegetation and riparian habitat near quarry. - Vegetation in higher topographies not likely to be groundwater dependent given the depth to water in these areas.	- EPA discharge licence permits return of groundwater seepage into quarry to Bungalook Creek.	**Unlikely**	**Minor**	Low	Volume pumped Groundwater level (drawdown) Ecosystem health	- Review of volume pumped and assessment as to whether increase in groundwater entitlement is required. This would trigger SRW licence assessment. - Review of groundwater levels in riparian monitoring bores. - Vegetation monitoring plan. If health of vegetation is confirmed as declining despite return of seepage water to Bungalook Ck, design and implement a groundwater recharge system adjacent key areas / high value ecosystems identified by ecologists as requiring protection.
GW-8	Groundwater	Operation	Refuelling / heavy plant maintenance activities results in spillage of hazardous materials	Groundwater within the quarry / ultimately forming seepage into the quarry sump	Internal to the quarry	Contaminated groundwater being collected within the quarry sump, and potentially used throughout the site via industrial applications of the sump water.		**Unlikely**	**Minor**	Low	- Monitoring bore network (although monitoring program not implemented) - Spill kits and emergency response procedures, - Quarry environmental procedures to avoid potentially harmful activities occurring in high risk areas.	-Environmental Reference Standard (2022)	**Unlikely**	**Minor**	Low	Groundwater quality Sump and discharge quality	- Boral auditing of implementation of quarry site environmental plan. - Streamflow gauging station existing at the Melbourne Water retarding basin. Monitoring responsibility rests with Melbourne Water.
GW-9	Groundwater	Operation	Explosives results in excess nitrogen loads to groundwater	Receiving ecosystems such as Bungalook Creek	Existing quarry is within a few hundred meters of Bungalook Ck. Expanded quarry will be within 200m of the creek.	Algal blooms / changes in groundwater quality.	Groundwater quality has been established through groundwater monitoring	**Rare**	**Moderate**	**Medium**	- Monitoring bore network (although monitoring program not implemented) - Groundwater flow in the MDVC will be towards the quarry, hence, potential contaminates would be drawdown towards the quarry sump, making them less likely to interact with Bungalook Creek	-Environmental Reference Standard (2022)	**Rare**	**Minor**	Low	Groundwater quality Discharge quality	
GW-10	Groundwater	Rehabilitation	Dewatering required to maintain access to lower levels of the quarry in order to place backfill.	Neighbouring groundwater users	Nearest stock and domestic bores are located approximately	Drawdown results in loss or reduced access to groundwater, i.e. can't pump as much water.	Bores identified on WMIS, however: - nearest registered bore is over 600m from quarry centroid - operational status not confirmed.	**Possible**	**Moderate**	**Medium**	- Monitoring bore network and monitoring program (implemented during Operation). - Assessment of groundwater recovery rates with numerical groundwater model. - Risk will reduce towards ultimately being eliminated as the need for dewatering is reduced with increased internal backfilling.		**Unlikely**	**Minor**	Low	Groundwater level (recovery)	- Impacts would be identified and mitigated during the operation phase. Risk is therefore eliminated at rehabilitation phase.

Risk ID	Water Environment	Phase of development	Pathway / Risk Event	Potential receptors or risk entities				Inherent Risk					Residual Risk			Monitoring and on-going management	
				Details of sensitive receptor	Location / proximity	Resultant harm	Supporting evidence	Likelihood	Consequence	Risk Level	Treatment measures / existing controls	Performance standards	Likelihood	Consequence	Risk Level	Aspect to be monitored	Details and ongoing management
GW-11	Groundwater	Rehabilitation	Dewatering required to maintain access to lower levels of the quarry in order to place backfill.	Displacement of contaminated groundwater plumes	Nearest site is on Fussell Road	Interception of contaminated groundwater may result in contamination entering the site and being used for the industrial purposes, and/or entrainment in the waste discharge.	Registered contaminated sites identified on EPA database. May be other sites e.g. along Canterbury that are present but not identified.	**Possible**	**Moderate**	**Medium**	- Monitoring bore network and monitoring program (implemented during Operation). - Risk will reduce towards ultimately being eliminated as water levels recover and dewatering ceases, and hydraulic gradients are requillibrated towards those occurring pre quarrying.	-Environmental Reference Standard (2022) '- NEPM (Contaminated Land) and local council planning approvals i.e. should rezoning of land use on impacted site occur.	**Unlikely**	**Minor**	**Low**	Groundwater level (recovery) Groundwater quality	-Rehabilitation will occur in future and water level recovery relatively slow. This provides residence time in aquifer for natural attenuation. Onsite use of groundwater post closure unknown, but not likely to be required if final land use is public open space with quarry lake.
GW-12	Groundwater	Rehabilitation	Dewatering required to maintain access to lower levels of the quarry in order to place backfill.	Reduction in baseflow to Bungalook Creek.	Existing quarry is within a few hundred meters of Bungalook Ck. Expanded quarry will be within 200m of the creek.	Changes to baseflow in the waterway, potential to alter supply to riparian and other potential groundwater dependent ecosystems.		**Possible**	**Major**	**High**	Monitoring bore network and monitoring program (implemented during Operation). - Risk will reduce towards ultimately being eliminated as water levels recover, dewatering no longer required, and hydraulic gradients are requillibrated towards those occurring pre quarrying.		**Unlikely**	**Minor**	**Low**	Groundwater level (recovery)	- '- EMM (2025) indicate no terrestrial GDEs Vegetation monitoring plan - Impacts to Bungalook Crk streamflow identified during the operation phase and mitigations implemented as required. This risk could be eliminated early in the rehabilitation phase (when groundwater extraction stops).
GW-13	Groundwater	Rehabilitation	Quarry pit lake leaks and recharges underlying groundwater.	Future groundwater environment (existing groundwater users, ecosystems receiving groundwater discharge).	Internal to the rehabilitated quarry	Changes in groundwater quality.		**Unlikely**	**Minor**	**Low**	-Quarry lake to receive stormwater runoff. Water quality in lake likely to be better (salinity) than underlying groundwater.	-Environmental Reference Standard (2022)	**Unlikely**	**Minor**	**Low**		- Review of implementation of the Rehabilitation plan - Design of the quarry lake (and capacity to naturally treat run-off) - Landuse objectives for quarry lake, i.e. primary contact recreation, aesthetics

Appendix L

Numerical Groundwater Model Report

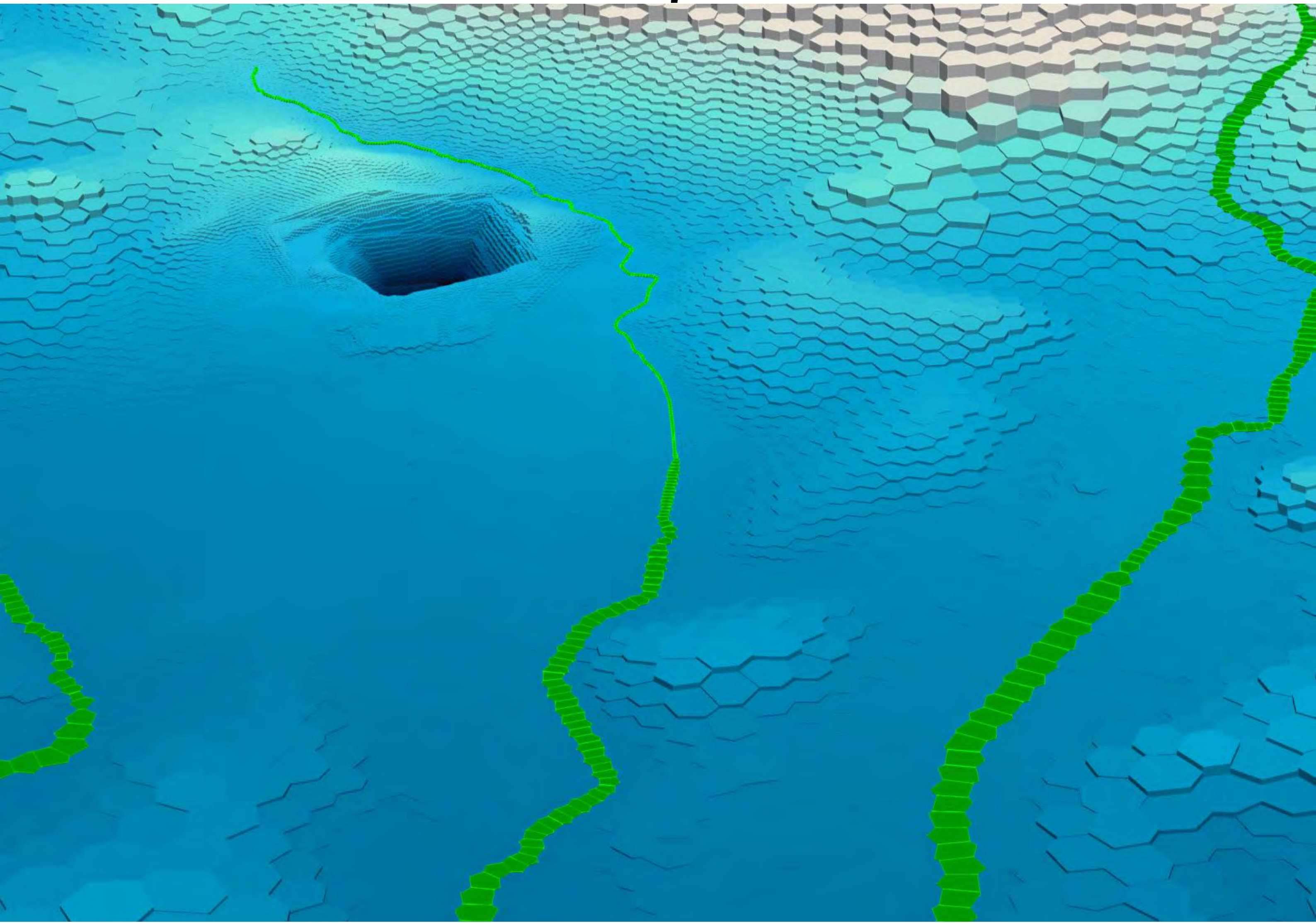
Numerical Groundwater Modelling Report

Boral Montrose Quarry

Boral Resources (Vic) Pty Limited

19 August 2025

→ The Power of Commitment



Project name	Boral Montrose Quarry SWMP and GWMP					
Document title	Numerical Groundwater Modelling Report | Boral Montrose Quarry					
Project number	12570927					
File name	12570927-REP-1_GW_Modelling.docx					

Status Code	Revision	Author	Reviewer		Approved for issue		
			Name	Signature	Name	Signature	Date
S4	1	Rikito Gresswell	Tim R Anderson		Tim R Anderson		8/8/23
[Status code]		Rikito Gresswell	Jeff Morgan		Jeff Morgan		
[Status code]							
[Status code]							
[Status code]							

GHD Pty Ltd | ABN 39 008 488 373

180 Lonsdale Street, Level 9

Melbourne, Victoria 3000, Australia

T +61 3 8687 8000 | **F** +61 3 8732 7046 | **E** melmail@ghd.com | **ghd.com**

© GHD 2025

This document is and shall remain the property of GHD. The document may only be used for the purpose for which it was commissioned and in accordance with the Terms of Engagement for the commission. Unauthorised use of this document in any form whatsoever is prohibited.

The Power of Commitment

Contents

Table index

Figure index

Appendices

1. Introduction

1.1 Purpose of this report

GHD Pty Ltd (GHD) has been engaged by Boral Resources Australia Ltd (Boral) to undertake a surface and groundwater assessment of the proposed expansion of its quarry in Montrose, located approximately 33 km east of Melbourne's central business district. The Montrose Quarry has a long history of operation dating back to 1950s, with the floor of the quarry currently extending to around 17 mAHD at the deepest point (more than 100 m below the surrounding ground level). The quarry represents a local low point in the regional groundwater system, with pooling of water occurring at the base of the quarry where it intersects the water table. The proposed expansion of the quarry has the potential to further modify the local groundwater flow regime and its interaction with the adjacent Bungalook Creek.

Numerical groundwater flow modelling is therefore required to quantify the magnitude, spatial extent and duration of potential groundwater related changes arising from the proposed expansion. This technical report details the findings of numerical groundwater modelling undertaken to inform the surface and groundwater assessment.

1.2 Scope and objective

The objective of numerical groundwater modelling is to quantify potential changes to groundwater due to the proposed expansion of the quarry. Specifically, the modelling is undertaken to quantify the drawdown (lowering) of the water table and associated changes to groundwater fluxes (seepage into the quarry and baseflow to Bungalook Creek).

In order to meet this objective, the numerical groundwater model is required to simulate the essential features of the existing hydrogeological system, as identified in the conceptual hydrogeological model, as well as the changed conditions that would occur once the quarry is rehabilitated. Given the size and depth of the quarry, and the potential for drawdown to extend some distance from the quarry boundary (towards the locations of potentially sensitive groundwater receptors), the modelling is undertaken at a regional scale albeit with enhanced spatial resolution in critical areas where accuracy is considered important.

The findings of numerical groundwater modelling are described in this report with reference to the key stages of the Australian Groundwater Modelling Guidelines (Barnett et al., 2012). These include the model design and construction (Section 2), model calibration (Section 3), model predictions (Section 4) and uncertainty analysis (Section 6). The staged approach allows the findings of the modelling to be presented in a logical order. The uncertainty analysis is also discussed with reference to the uncertainty analysis guideline published by the Independent Expert Scientific Committee (Peeters and Middlemis, 2023).

The existing hydrogeological conditions and conceptualisation of groundwater systems that underpin the development of the numerical model are described in the main surface water and groundwater assessment and are not duplicated herein. Description of key datasets and interpretation of field data are presented where these are considered relevant to support the model design and choice of model parameters.

The groundwater modelling described in this report builds on the prior modelling undertaken by Golder (2006), with several enhancements incorporated to reflect modern modelling practices and additional data collected after the completion of the original assessment.

1.3 Limitations

This report: has been prepared by GHD for Boral Resources (Vic) Pty Limited and may only be used and relied on by Boral Resources (Vic) Pty Limited for the purpose agreed between GHD and Boral Resources (Vic) Pty Limited as set out in section 1.2 of this report.

GHD otherwise disclaims responsibility to any person other than Boral Resources (Vic) Pty Limited arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

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

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

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report (refer section(s) 8 of this report). GHD disclaims liability arising from any of the assumptions being incorrect.

Accessibility of documents

If this report is required to be accessible in any other format, this can be provided by GHD upon request and at an additional cost if necessary.

2. Model design and construction

2.1 Modelling software

For this project, an unstructured grid version of MODFLOW called USG-Transport version 2.01 (Panday, 2023) has been chosen as the most appropriate modelling platform. USG-Transport is based on the MODFLOW-USG code (Panday et al., 2013) developed by the United States Geological Survey and includes several enhancements (such as adaptive time stepping) which are frequently updated by the code's lead developer.

Features of USG-Transport that are particularly suited to this project include:

- Flexible meshing, supporting a range of cell shapes, that allows the model cells to closely follow the geometry of hydrological features (such as Bungalook Creek), enabling more accurate representation of the physical system. The capability to nest a structured sub-grid within an unstructured mesh has been applied in this project to represent the entire area of the quarry with a consistent spatial resolution (using a sub-grid of 10 m by 10 m rectangular cells).
- Efficient local mesh refinement around features of interest within a regional model domain while retaining larger cells elsewhere, enabling an optimal balance between model size (total cell count) and run times without compromising resolution in critical areas. The model layers can also 'pinch out' where hydrostratigraphic units (HSUs) are not present and cells are not required throughout the model domain, reducing the total cell counts and improving numerical stability. This has flow-on benefits to the modern requirements of modelling projects such as run-intensive calibration and uncertainty analysis.
- Robust handling of de-saturation and re-saturation of model cells for tracking the water table across multiple model layers, based on the Upstream Weighting scheme of MODFLOW-NWT (Niswonger et al., 2011). In this case, all model layers are of the Upstream Weighting type.
- Extraction of local water balance, such as in and out of groups of cells, which can be implemented easily using the utility ZONBUDUSG (the ZONEBUDGET program for MODFLOW-USG).
- Interface with the parameter estimation code PEST, including a suite of utilities for facilitating pre- and post-processing of model files.

The unstructured mesh of the USG-Transport model has been generated using AlgoMesh 2 (HydroAlgorithmics, 2020) and model input files have been prepared using a combination of AlgoMesh, Geographic Information Systems (GIS) and a range of in-house and third-party utilities.

2.2 Model domain and mesh

Figure 1 shows the model domain and model mesh. The quarry is located approximately in the middle of the domain, with the down gradient edge of the domain extending around 6 km from the boundary of the quarry (large enough to simulate the depressurisation effect of the quarry without incurring boundary-induced effects). The edge of the model domain follows hydrologically sensible boundaries that have been delineated from the expected flowlines of the regional groundwater system (informed by the topography and other regional datasets such as the water table elevation layer from the Visualising Victoria's Groundwater website). These include no-flow boundaries parallel to regional flowlines and along topographic ridges that form groundwater flow divides and through-flow boundaries in the direction of groundwater flow. The model domain has a large total area of 86.5 km^2.

The model mesh uses Voronoi-shaped (tessellated) cells, which are considered numerically ideal for meeting the requirements of the controlled volume finite difference formulation (a line connecting the centres of two adjacent cells intersects the shared face at or close to a right angle). The exception is at the quarry, where 10 m by 10 m rectangular cells are used to ensure consistent (and high) grid resolution across the entire footprint of the quarry area.

The mesh is locally refined along major water courses, including Bungalook Creek, Dandenong Creek and Tarralla Creek. Bungalook Creek is refined using 10 m wide cells adjacent to the quarry, to accurately define the alignment of the creek, and the cell size is gradually increased further away from the quarry where accuracy is less critical (increasing to cell lengths of 50 m to 100 m). The mesh is also refined over the extent of the Quaternary Alluvium and along geological contacts, with Voronoi cells of around 50 m to 100 m in lengths. Elsewhere, larger Voronoi cells of more than 250 m in lengths are used (outside of the expected area of influence of mining).

Designing an unstructured model mesh requires a sensible balance between the desired accuracy (spatial resolution) and the computational burden (on model run times) incurred as a result. This means the mesh generation process is often iterative, adjusting the level of refinement until sufficient resolution is achieved in critical areas while maintaining a sensible total cell number. Given the scale of the model (and proximity of potentially sensitive receptors to the quarry boundary), the minimum cell length of 10 m across the quarry and along Bungalook Creek is considered appropriate without resulting in excessive number of cells and model run times.

Figure 1 and Figure 2 show the model domain and unstructured grid, including the location of major watercourses simulated in the model, observation bores used to inform the model calibration and stream gauge at Fussell Road Retarding Basin (228369A). There are 20,478 cells in the two dimensional unstructured grid.

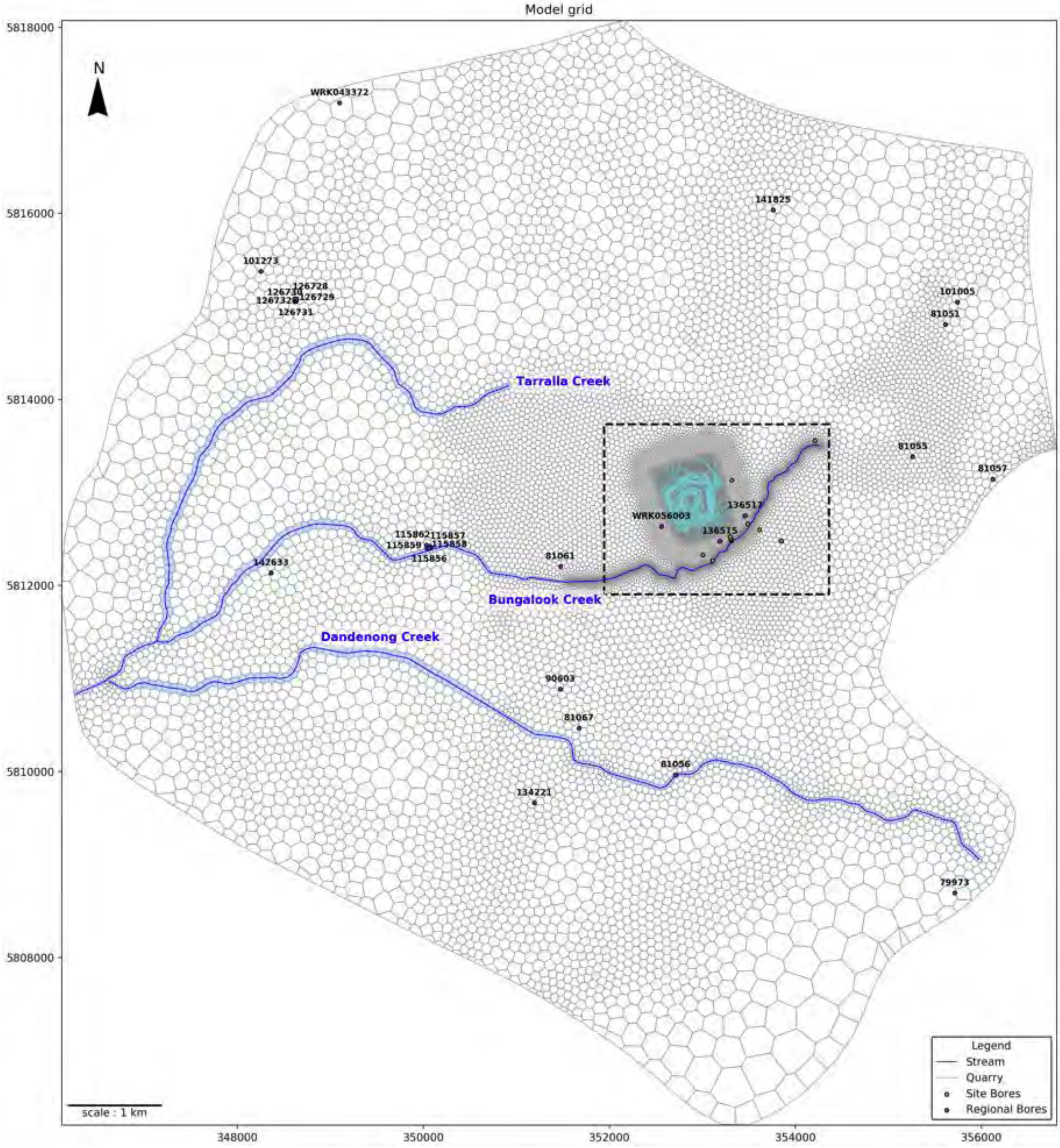


Figure 1 Model domain and unstructured grid

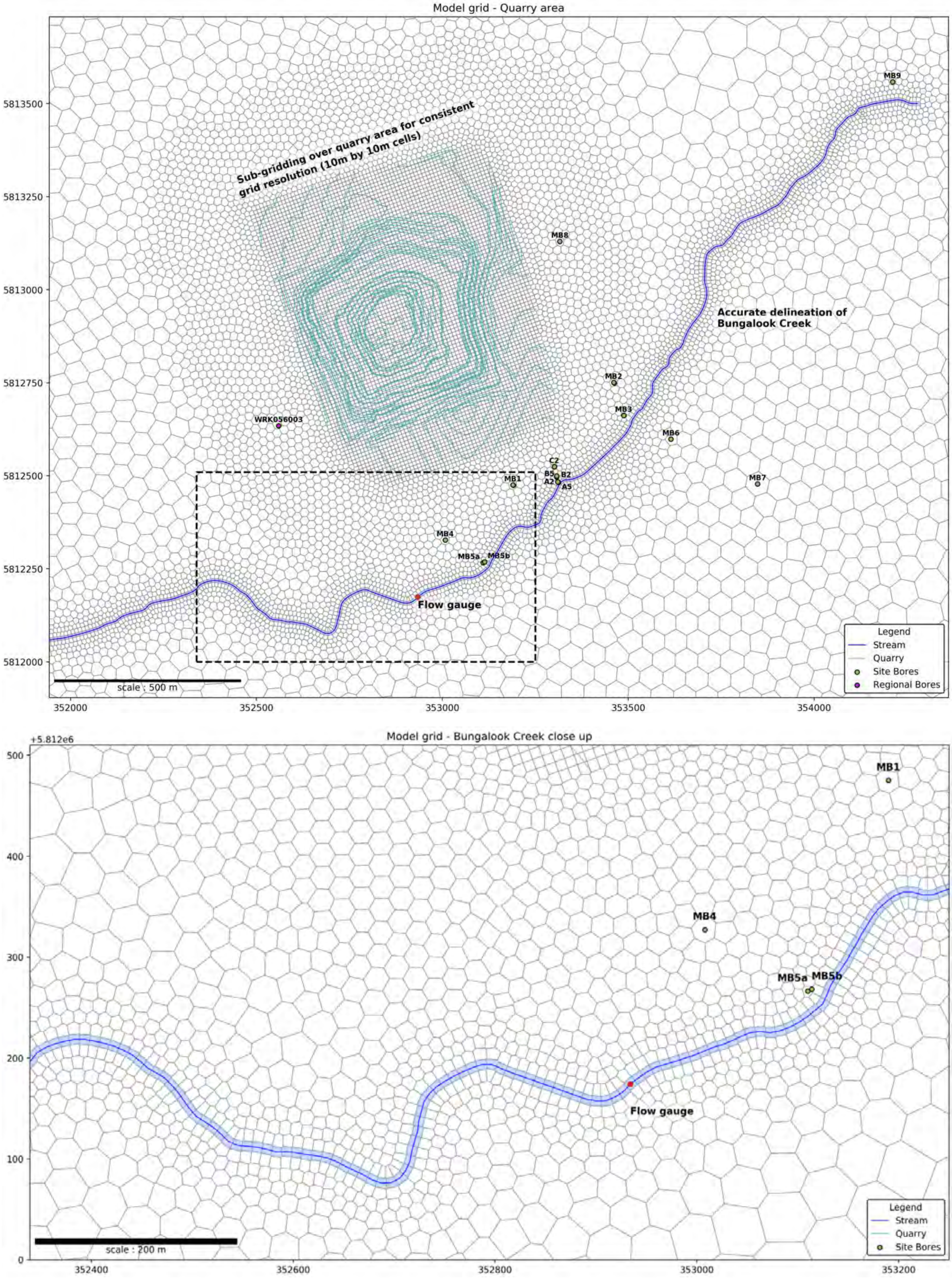


Figure 2 Unstructured grid in quarry area and Bungalook Creek

2.3 Model layers

The geology within the model domain is characterised by a sequence of dipping geological units with well-defined geological contacts. In order to accurately represent the geology, a geological model was developed using a geological modelling software Leapfrog. The geological model incorporates the distribution, dip and thickness of major geological units based on the interpretation of available geological data including borehole logs, geological maps, digital elevation model and data collected during site inspections (Figure 3).

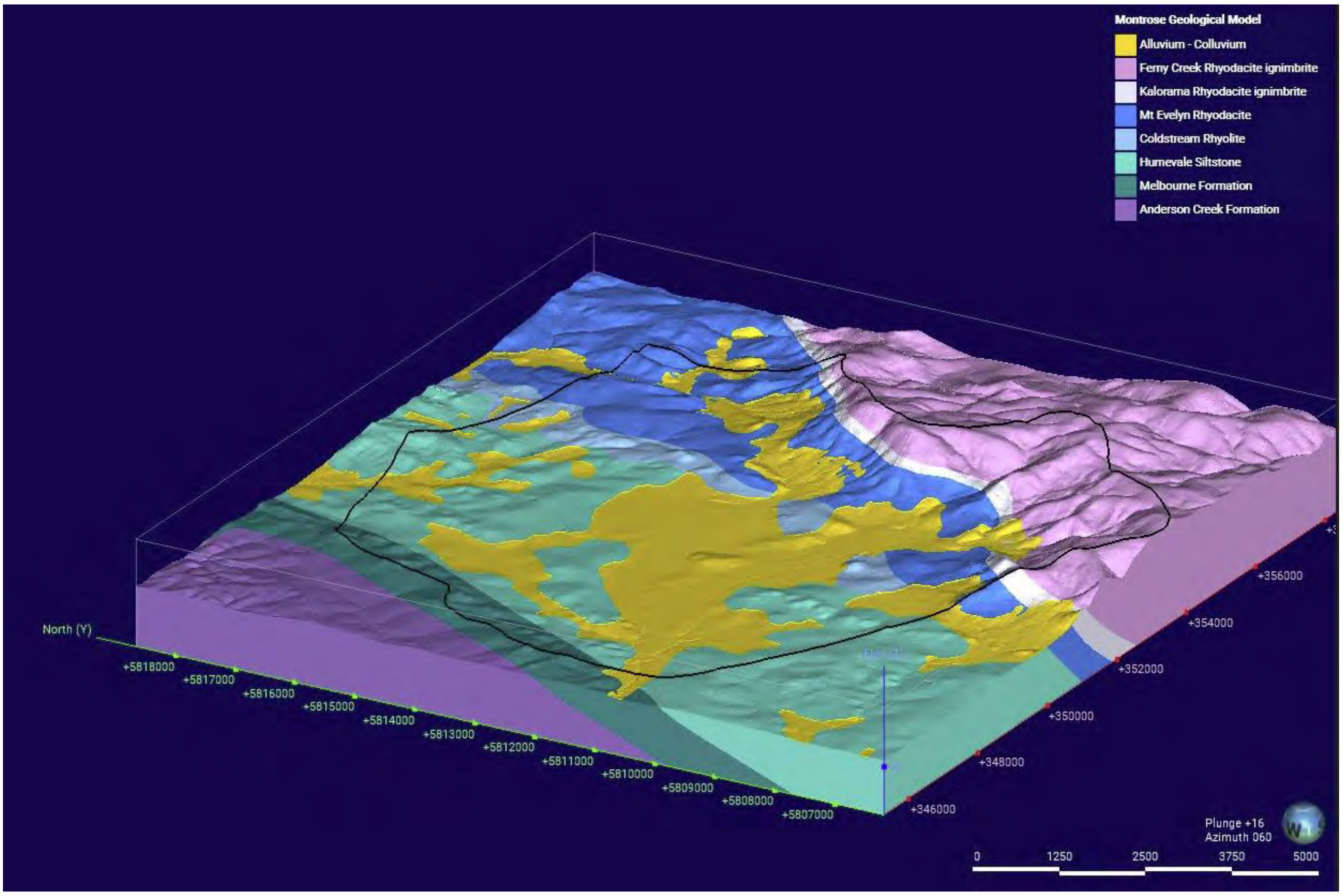


Figure 3 ***Leapfrog geological model***

The surfaces (contacts) from the Leapfrog geological model have been used to define the layers of the groundwater model. Each geological unit within the model domain was initially incorporated as a layer in the groundwater model, with the top and bottom elevation of the layers defined by the top and bottom of the units, including the contacts between adjacent units. This resulted in 7 model layers for 7 geological units contained within the model domain. For the Mt Evelyn Rhyodacite and Coldstream Rhyolite, the layers were further divided into 8 layers each, with the top 7 layers adopting a maximum thickness of 40 m. These units are intersected by the quarry and additional layers are considered warranted to improve numerical accuracy in the vertical direction where the vertical flow component becomes important due to the convergence of groundwater flow towards the point of discharge. A large number of model layers also improves the accuracy of the placement of observation bores, enabling the modelled heads to be compared against the observed heads at elevations close to the actual point of measurement (e.g. position of bore screen). The Humevale Siltstone was also divided into 3 layers of equal ratio. The model layers within each unit are truncated at the edge of the unit where the unit pinches out.

This layer-based approach allows the dipping geological contacts to be accurately incorporated in the groundwater model, whilst maintaining sensible grid resolutions (both horizontally and vertically) and model size (total cell counts). The result is a series of draping model layers along non-vertical geological contacts (and low angle in some places), as shown in the model cross-sections presented in Figure 5. The location of cross-sections and the distribution of geological (hydrostratigraphic) units are shown in Figure 4.

There are 167,011 active cells in total. The extent and top and bottom elevations of each model layer are provided in Appendix A. The base of the model is set at -300 mAHD, which is almost 200 m below the deepest point of the proposed quarry floor and is considered deep enough to minimise the bottom boundary effect on groundwater flow at and below the quarry.

Table 1 Relationship between geological units and model layers

Geological units	Model layers	Cell number
Alluvium	1	10,326
Ferny Creek Rhyodacite	2	722
Kalorama Rhyodacite	3	816
Mt Evelyn Rhyodacite	4, 5, 6, 7, 8, 9, 10, 11	8520, 7716, 7136, 6584, 6079, 5511, 4861, 4685
Coldstream Rhyolite	12, 13, 14, 15, 16, 17, 18, 19	8384, 8623, 8926, 9161, 9372, 9699, 9627, 10976
Humevale Siltstone	20, 21, 22	9550, 9550, 9550
Melbourne Formation	23	637

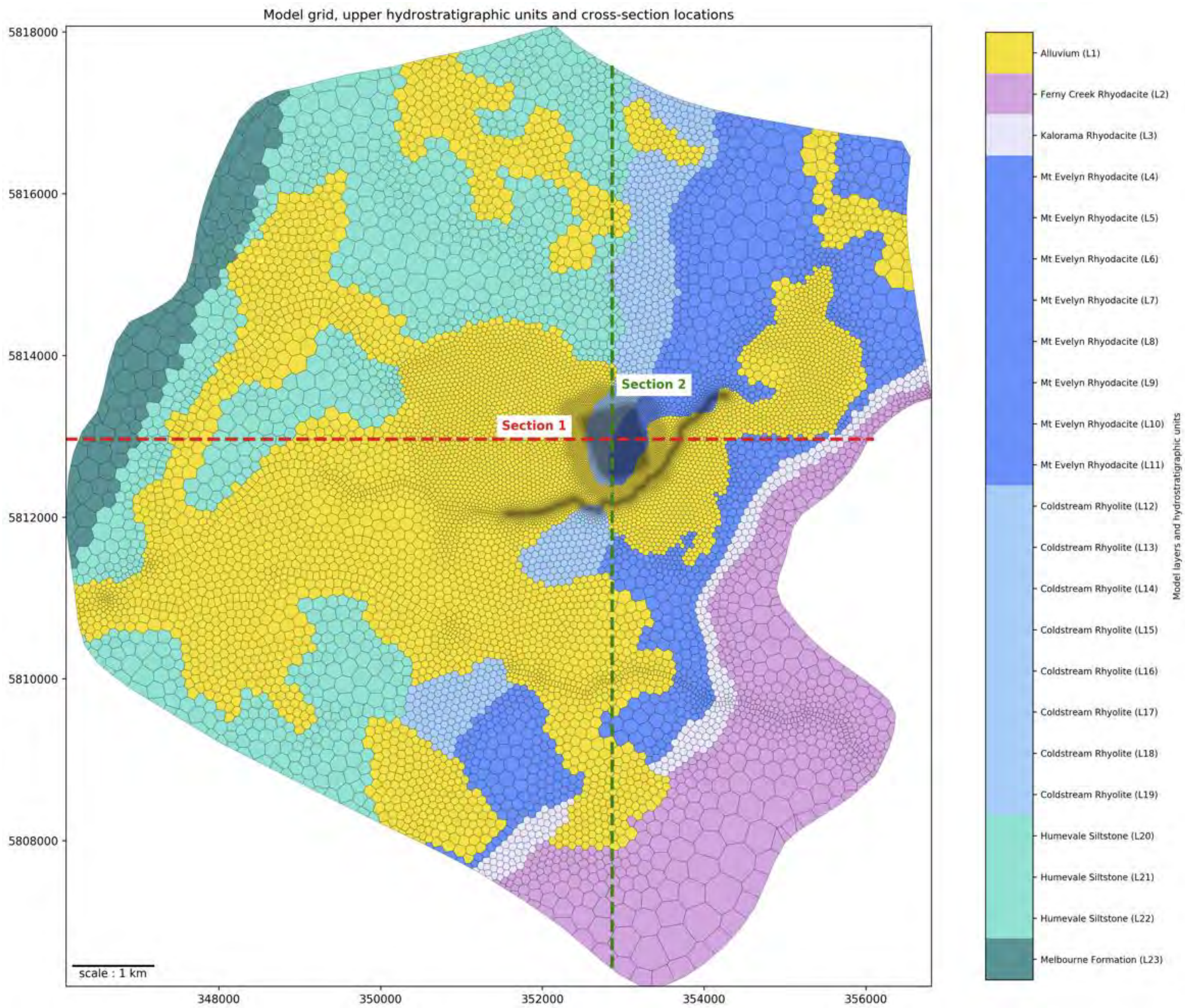


Figure 4 *Model hydrostratigraphic units and cross-section locations*

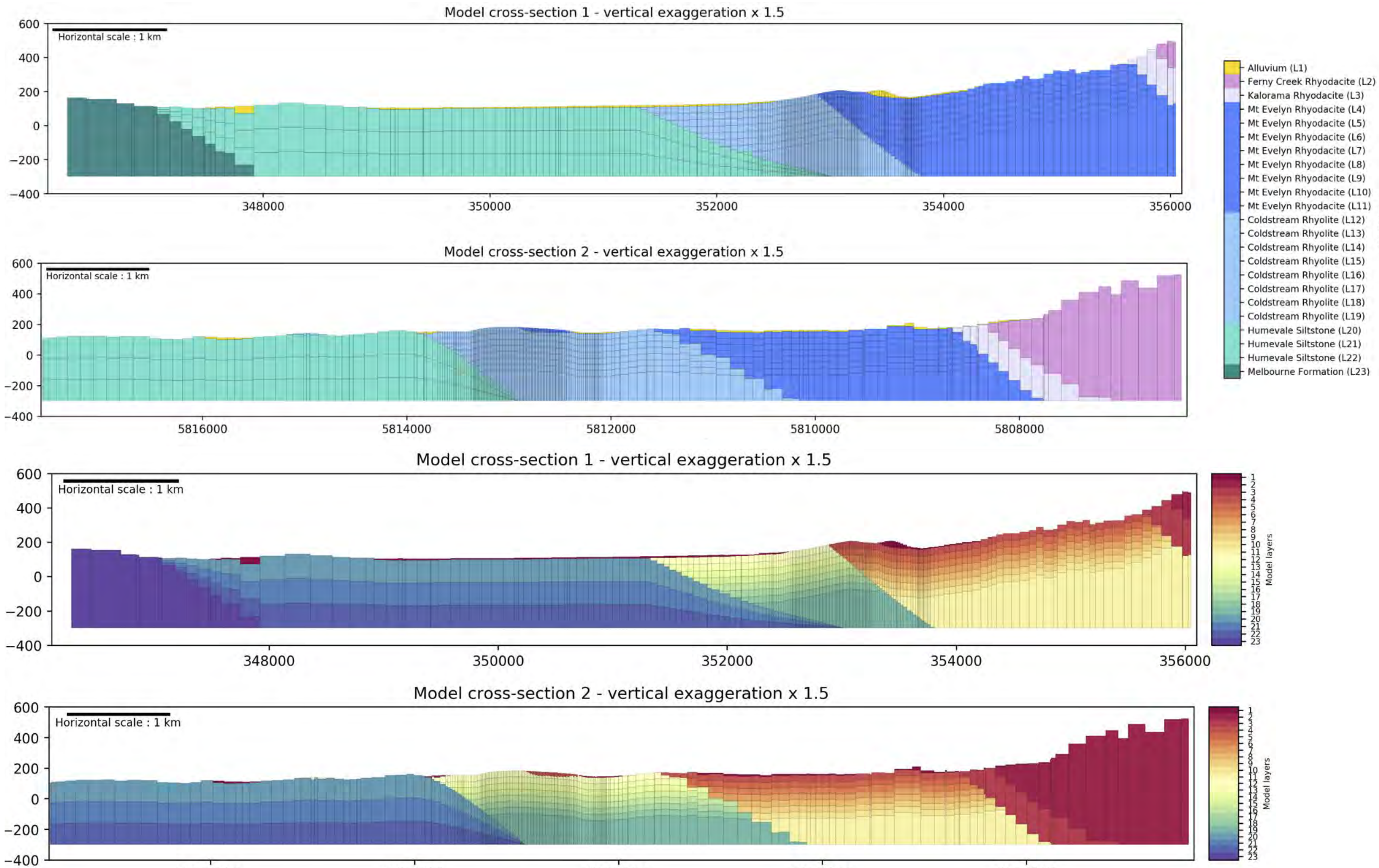


Figure 5 *Model cross-sections*

2.4 Boundary conditions

2.4.1 Recharge and evapotranspiration

Recharge and evapotranspiration are simulated using USG-Transport's Recharge (RCH) and Evapotranspiration (EVT) packages. The time-varying recharge and evapotranspiration rates have been derived using a simple water balance model called LUMPREM (Doherty, 2020) which uses daily climate data and soil zone parameters to derive deep drainage, runoff and evapotranspiration. The outputs from LUMPREM are sensitive to the assumed soil zone parameters such as soil moisture store, soil hydraulic conductivity, crop factor and recharge delay. These parameters have been adjusted during the automated calibration process (refer to Section 3). The main benefit of using LUMPREM is its capability to generate hydrologically sensible recharge and evapotranspiration rates using daily climate data, which is well suited to incorporating the effects of climate change (for example, using climate change factors applied to daily climate data, as described in Section 5).

The daily rainfall and pan evaporation data from a Bureau of Meteorology (BoM) station, 86234, are used as climate inputs to the LUMPREM model. This station has been selected due to the availability of continuous climate records, with less data gaps compared to other nearby BoM stations such as 86076.

In recognition of the spatial variability in rainfall across the model domain, the LUMPREM generated recharge at the location of station 86234 is scaled by a multiplier grid before recharge is distributed to the USG-Transport grid (see Figure 6). The multiplier grid has been derived using BoM's long term average rainfall map and calculating the spatial difference relative to the long-term average rainfall calculated at station 86234 (over the same period).

The spatially scaled recharge is further adjusted to account for different land uses, based on broad classifications into undeveloped, residential, and industrial land, as per the previous modelling completed by Golder (2006). The extent of each land use area has been delineated from aerial imagery and is shown in Figure 6).

The time-varying evapotranspiration rates from the LUMPREM model are applied as spatially constant values across the model domain. Evapotranspiration becomes active only in areas where the modelled water table is within the specified extinction depth, calculated from evapotranspiration surface (set equal to model top). The evapotranspiration rate is assumed to decrease linearly with depth and becomes nil at the extinction depth.

2.4.2 Stream boundary condition

USG-Transport's Stream Flow Routing (SFR) package is used to simulate the major water courses (Bungalook Creek, Dandenong Creek and Tarralla Creek) and their interaction with the groundwater system (Figure 1). The main advantage of the SFR boundaries, compared to alternative head-dependent flux boundaries like the River (RIV) package, is that the volume of water available for interaction with the modelled groundwater system is limited to that which has accumulated from upstream within the defined stream channel network (from baseflow, and/or any runoff and artificial discharges, less any diversions). In dry times, there may be no or little water flowing down the stream network, thus avoiding unrealistic leakage of water into the model from these head-dependent boundaries.

In this study, the SFR boundaries are applied in a relatively simple manner, with a time-constant stage equal to the most accurate elevation data (using the surveyed topographical contours along Bungalook Creek, adjacent to the quarry). This configuration is analogous to the way RIV cells function except that streamflows are routed down the defined channel network to preserve realistic water balance. This simplified (time-constant stage) approach is numerically more stable than the alternative approach using Manning's equation, without compromising the ability of the model to simulate realistic flow volumes. The duration curve of the Fussell Road stream gauge indicates a stage of less than 0.2 m (above gauge zero) for 90% of the time, implying small temporal variability along Bungalook Creek that can be approximated using a time-constant stage. The alignment of Bungalook creek and other major water courses is derived from Vicmap except where more accurate site specific survey data is available adjacent to the quarry (using the watercourse polyline delineated in Boral's survey data).

The stage and stream bed elevations are assigned with enforced topographic fall down the stream network. The channel width is assumed to increase from 0.5 m at the upstream end, to 2 m at the downstream end, based on field observations and broad inspection of aerial imagery. The stream bed thickness is set to 0.5 m and the stream length within each model cell is calculated rigorously based on the mapped stream geometries. Hydraulic conductivity of the bed material (and hence the stream bed conductance) is adjusted during model calibration using a single model-wide zone.

The SFR boundaries are used in this study primarily for the purpose of simulating the baseflow (groundwater-fed) component of streamflow. Under this assumption, the modelled flows only approximate total streamflow during dry periods when there are little to no contributions from run-off and interflow. This assumption is considered conservative for the purpose of groundwater impact assessment, as changes to baseflow would be most critical during dry periods when surface water flow contributions are limited. The potential influence of much larger volumes of surface water available to interact with the groundwater system is also examined in a simplified manner, using the flow gauge data as inflow to the upstream segment of the SFR boundaries.

2.4.3 Drain boundary condition

USG-Transport's Drain (DRN) package is used to simulate the progression of mining and associated dewatering of aquifers. For historical progression, the DRN elevations are sourced from historical mine surfaces at selected time periods (where this information is available), as shown in Figure 7. Between these time periods, the DRN elevations are assumed to change linearly (resulting in progressive dewatering as well as backfilling in some places). The DRN conductance is set to a high number of 200 m^2/d to allow unconstrained flow i.e. DRN outflow represents the rate of seepage into the quarry, controlled by the material properties of the surrounding aquifers.

Section 4.1 provides further descriptions of the DRN elevations used to simulate future progressions.

2.4.4 General-head boundary condition

USG-Transport's General-Head Boundary (GHB) package is used to simulate throughflow of groundwater across small sections of the model boundary, where the available regional data suggests a component of flow perpendicular to the model boundary. This occurs along a small section of model's northern boundary intersected by the Alluvium (associated with a minor creek called Brushy Creek) and along the southwest boundary of the model where Dandenong Creek exits the model. The GHB elevations have been estimated from groundwater levels recorded in nearby registered bores and regional water table elevation map (downloaded from the Visualising Victoria's Groundwater web portal). The conductance term has been calculated for each cell based on the cross-section area and a hydraulic conductivity of 0.04 m/d (based on the calibrated hydraulic conductivity of Humevale Siltstone from previous modelling).

Flow simulated across these boundaries have no effect on the groundwater behaviour simulated at the quarry due to considerable distances from the quarry. Nonetheless, the GHB cells have been incorporated in the model to ensure consistency with the expected regional flow behaviour along the boundary of the model. Figure 8 shows the location of the GHB cells and regional datasets used for the boundary assignment.

2.5 Parameterisation

Parameterisation involves making choices about how the spatial distribution of aquifer properties will be represented in the model (Barnett et al., 2012). Models with the smallest number of parameters possible are described as parsimonious, whereas models with a large number of spatially varying parameters are described as highly parameterised. In modelling studies, a balance is sought between parsimony and complexity (highly parameterised spatial variability) that is consistent with the objective of modelling, the physical system of interest and supporting data.

In this study, the model has been parameterised on an HSU basis, however, hydraulic conductivities have been varied spatially within the Mt Evelyn Rhyodacite (layers 4 to 11) where all of the site observation bores are located (providing the basis for inferring spatial differences in hydraulic conductivity). Such flexibility in parameterisation can also be important for exploring model uncertainty based on the observed hydraulic head differences, which may be difficult to do in a meaningful way if the model were reduced to the smallest number of parameters to attain parsimony. The vertical hydraulic conductivity (kz) is estimated from the horizontal hydraulic conductivity (kh) using a multiplier (kh/kz)

Specific yield and specific storage are assigned a constant value to each HSU, applying the principal of parsimony where appropriate and introducing complexity (spatial variability) only as necessary to simulate the physical system of interest in a manner consistent with the data available.

Model parameterisation is discussed in further detail in Section 3, as part of model calibration.

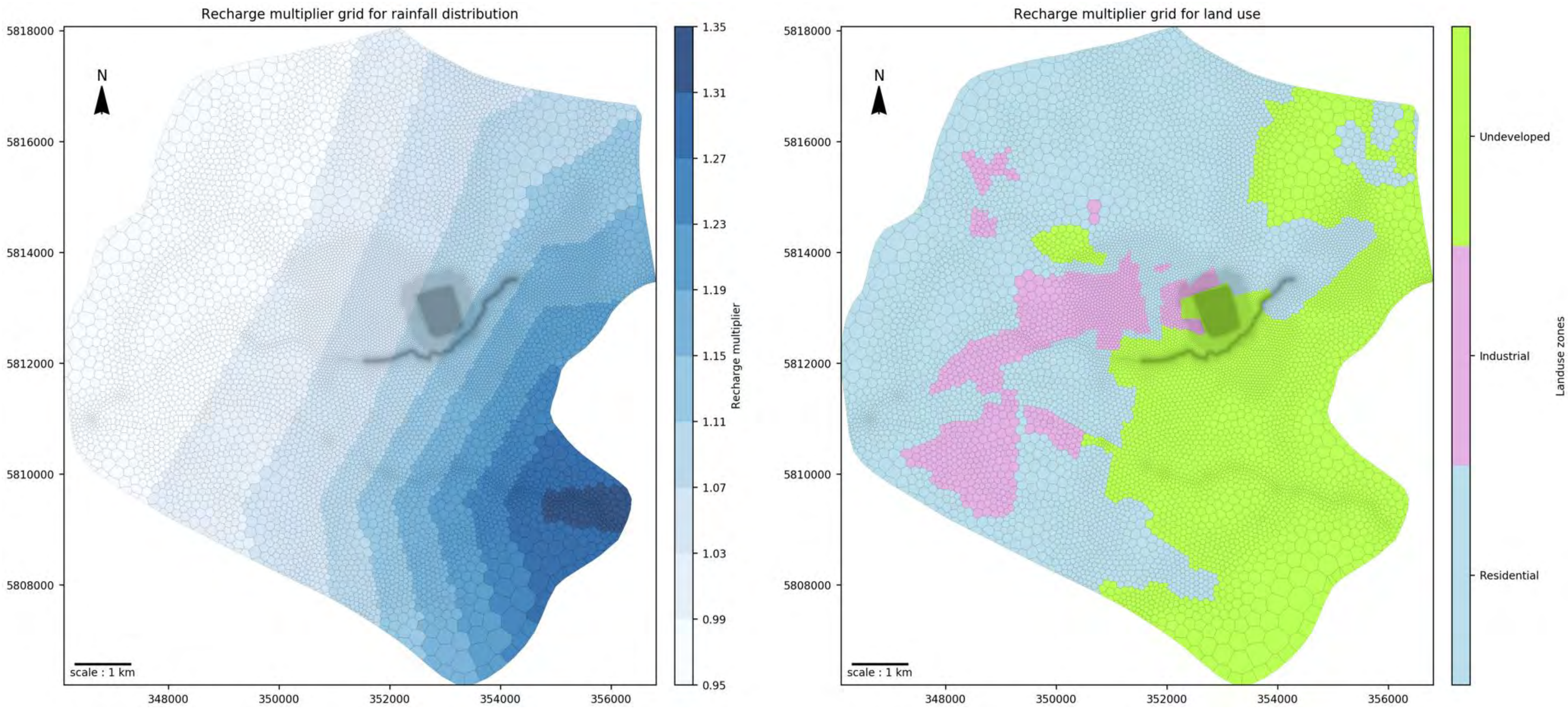


Figure 6 *Recharge multipliers*

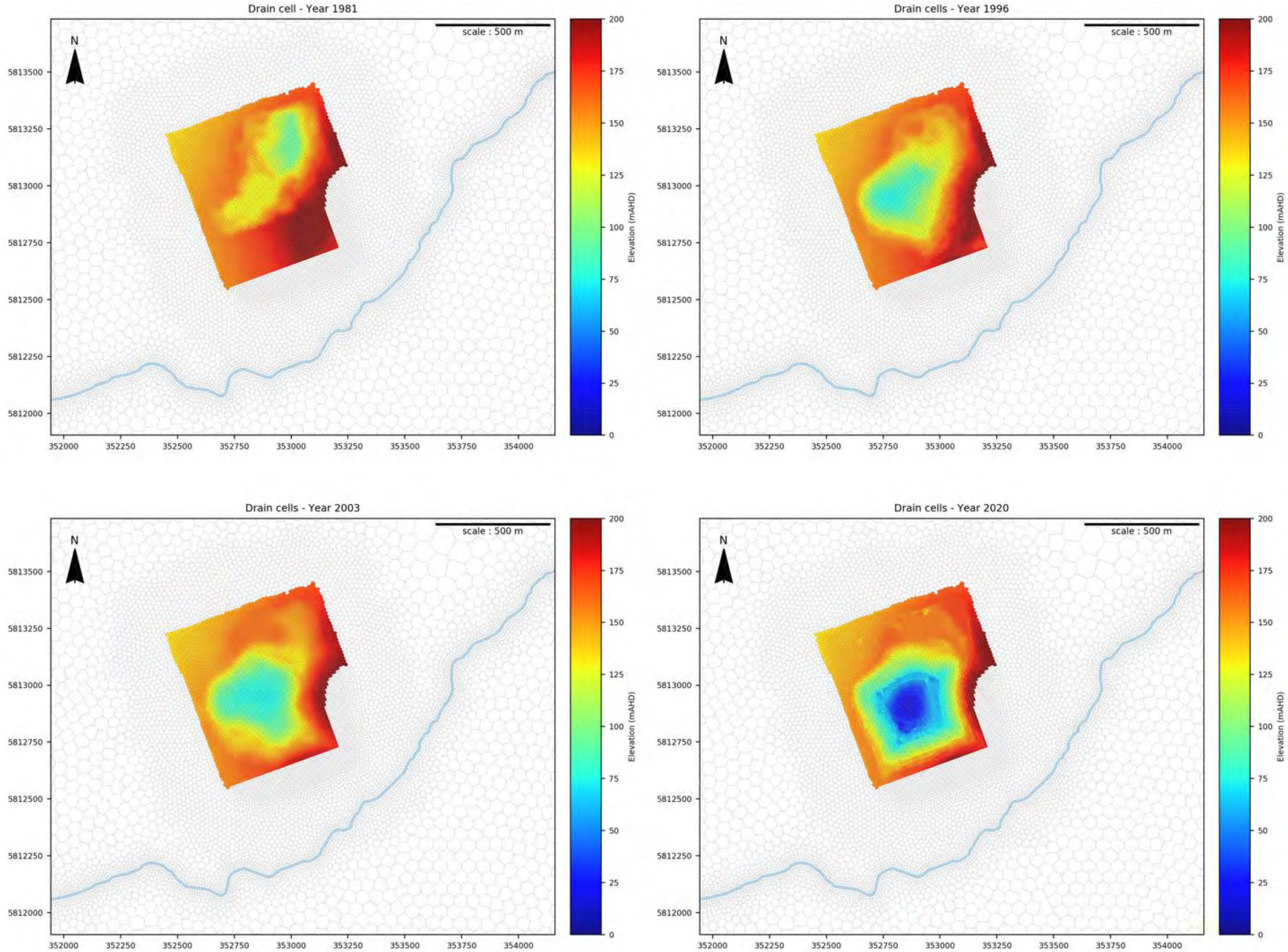


Figure 7 *Historical drain elevations*

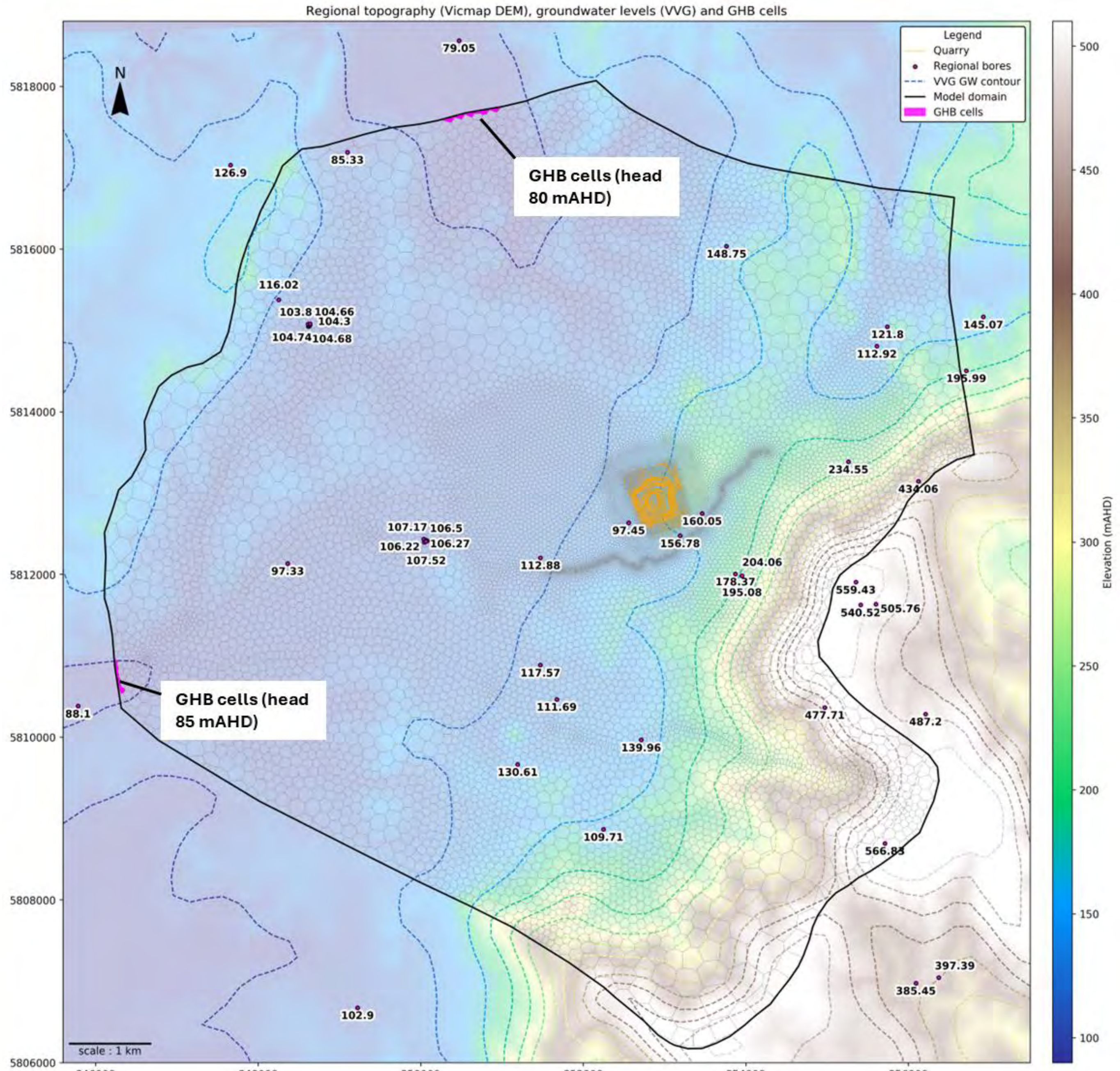


Figure 8 Regional topography, groundwater levels and GHB cells

3. Model calibration

3.1 Calibration approach

3.1.1 Calibration period

Model calibration is a process by which model parameter values are altered within realistic bounds until the model outputs fit historical measurements, such that the model can be accepted as a reasonable representation of the physical system of interest (Barnett et al., 2012).

Given the long history of mining, the model calibration has been undertaken transiently with the calibration period commencing in January 1975 and ending in February 2023. This differs from the steady state calibration approach previously adopted by Golder (2006), where a condition of dynamic equilibrium was enforced to mimic an approximate average condition at around 2003 and 2004. There are several advantages to undertaking long term transient calibration, even in instances where historical information is limited (such as continuous long term measurements). These include the following:

- Benchmark the performance of the model against long-term climate and progressive dewatering of the quarry, particularly the declining groundwater levels observed in selected bores at the onset of the Millennium Drought and groundwater levels recorded more recently in December 2022 and February 2023.
- Incorporate groundwater levels recorded in registered regional bores as secondary calibration targets at the correct point in time, to ensure the model behaviour over the broader region is reasonable e.g. the distribution of hydraulic heads is consistent with the applied fluxes (recharge rates) and material properties.
- Simulate changes in groundwater seepage rate over time, including calibration against the seepage rate estimated in 2003 and higher seepage rates estimated more recently due to the deepening of the quarry since 2003.
- Overcome some of the limitations of model non-uniqueness associated with steady state assumptions, including the use of both hydraulic heads (and their derivatives, such as trends) and flow observation targets.
- Provide a sound basis for projecting long term effects of future extraction and rehabilitation, including the influence of climate change.

Although the quarry is understood to have been operational since the 1950s, the available historical information on the quarry elevation suggests that direct interaction with the underlying groundwater system is likely to have been limited in the early stages of mining. In recognition of this, and to minimise excessive model run time, a starting year of 1975 has been chosen. This also corresponds with the post-1975 climate reference period used in Victoria Government's climate change guidelines (DELWP, 2020), which is considered a sufficiently long period to capture the natural range of variations in climate.

To expedite the model runs and to facilitate the run-intensive automated calibration procedure, a stress period length of 5 years is used up to the end of year 1999. From the start of year 2000, the stress period length is reduced to quarterly (approximately 3 months) to simulate the seasonal variation in recharge and evapotranspiration. The exception is the shorter final stress period, which extends from January 2023 to end of February 2023. This stress period has been incorporated to enable calibration against groundwater level measurements collected in February 2023. There are 98 stress periods in total over an approximately 48-year calibration period.

3.1.2 Calibration targets

Hydraulic head targets

The primary hydraulic head targets are the measurements of groundwater level taken from 15 monitoring bores constructed by Boral (referred to as the "site bores" in this report and shown in Figure 2). The measurements are available from the selected bores in 1996, 1998, 2002, 2003, 2004, 2022 and 2023. Although there are gaps in the monitoring record, the change in groundwater levels measured over time, particularly the declining groundwater levels from the late 1990s to 2004 during the Millennium Drought, provides some indications of seasonal variability. For this reason, both the groundwater levels (head), as well as the change in groundwater levels over time (head difference) have been incorporated as calibration targets. There are 119 hydraulic head targets from the 15 site bores and 104 head difference targets (calculated as the difference between the initial measurement and all subsequent measurements).

Table 2 summarises the site bores used in calibration and the number of head observation targets associated with each bore. MB8 is a deep bore which recorded a very slow rate of recovery (stabilisation) following the construction of the bore. Only the stabilised readings have been included for this bore, noting that the groundwater levels at this bore was previously considered potentially anomalous by Golder (2006).

Table 2 Site bore head targets

Bore	Easting (MGA55)	Northing (MGA55)	Pipe (mAHD)	Ground (mAHD)	Depth (mbgl)	Bottom (mAHD)	Model layer	Head obs
MB1	353189.9454	5812475.147	169.08	169.07	65.5	103.57	5	15
MB2	353460.9457	5812750.143	171.69	171.29	70.5	100.79	4	16
MB3	353487.9459	5812662.143	158.51	158.09	8.3	149.79	1	16
MB4	353007.945	5812327.147	161.63	161.78	100	61.78	6	1
MB5a	353109.9453	5812266.146	151.86	151.94	60	91.94	5	11
MB5b	353113.9454	5812268.146	152.16	152.24	5	147.24	4	6
MB6	353614.9462	5812598.141	167.62	167.69	67.5	100.19	4	13
MB7	353847.9469	5812478.139	190.66	190.73	50	140.73	4	11
MB8	353315.945	5813129.146	212.7	212.88	130	82.88	6	5
MB9	354210.9466	5813558.125	181.34	181.39	49	132.39	4	10
A2	353312.4257	5812482.195	153.5	152.75	3.1	149.65	1	3
A5	353310.6357	5812483.585	153.51	152.81	8	144.81	1	3
B2	353307.7856	5812496.445	154.19	153.44	3	150.44	1	3
B5	353307.7756	5812499.215	154.3	153.58	8	145.58	4	3
C2	353301.0156	5812524.025	155.76	155.01	12	143.01	4	3

In addition to the site bores, groundwater level measurements available from bores registered in the Victorian Government database are incorporated as secondary hydraulic head targets. Most of these are opportunistic single water level measurements that are approximate and are used only for the purpose of ensuring sensible regional groundwater behaviour. These are referred to as the "regional bores" (as shown in Figure 1). There are 28 regional bores with 36 water level measurements within the model domain.

Flow targets

According to Golder (2006), Boral estimated a groundwater seepage rate of around 3.5 L/s into the quarry based on the rate of rise of water level observed in the sump in May 2003. During a field inspection carried out around the same time, Golder (2006) estimated a slightly lower seepage rate in the range of 1 L/s to 2 L/s from several seepage points observed in the quarry. In order to derive groundwater seepage rates under a more recent condition (with a deeper quarry floor), the water level in the quarry was monitored from Dec 2022 to February 2023. Based on the ponded surface area calculated from the aerial survey completed in February 2023, approximate seepage rates have been estimated from the magnitude and duration of recovery following several pumping cycles.

Figure 9 shows the estimated seepage rates based on this method. The seepage rate estimated for each recovery accounts for contributions from rainfall and evaporation over the ponded area, calculated using the daily rainfall and evaporation from the nearest BoM station 86076. These seepage rates generally agree with the seepage rates derived from an alternative method based on the estimated pumping volume and the percentage recovery (fraction of drawdown recovered following pumping). The seepage rates are estimated to range from around 3.4 L/s to 9 L/s. Given the deepening of the quarry since 2003, a typical seepage rate would be expected to be higher than the 1 L/s to 3.5 L/s range estimated in 2003 and the 3.4 L/s to 9 L/s range estimated is therefore considered plausible.

For the purpose of model calibration, a seepage rate of 6 L/s (the middle of the estimate range) has been used as a flow observation target assigned at the end of model calibration.

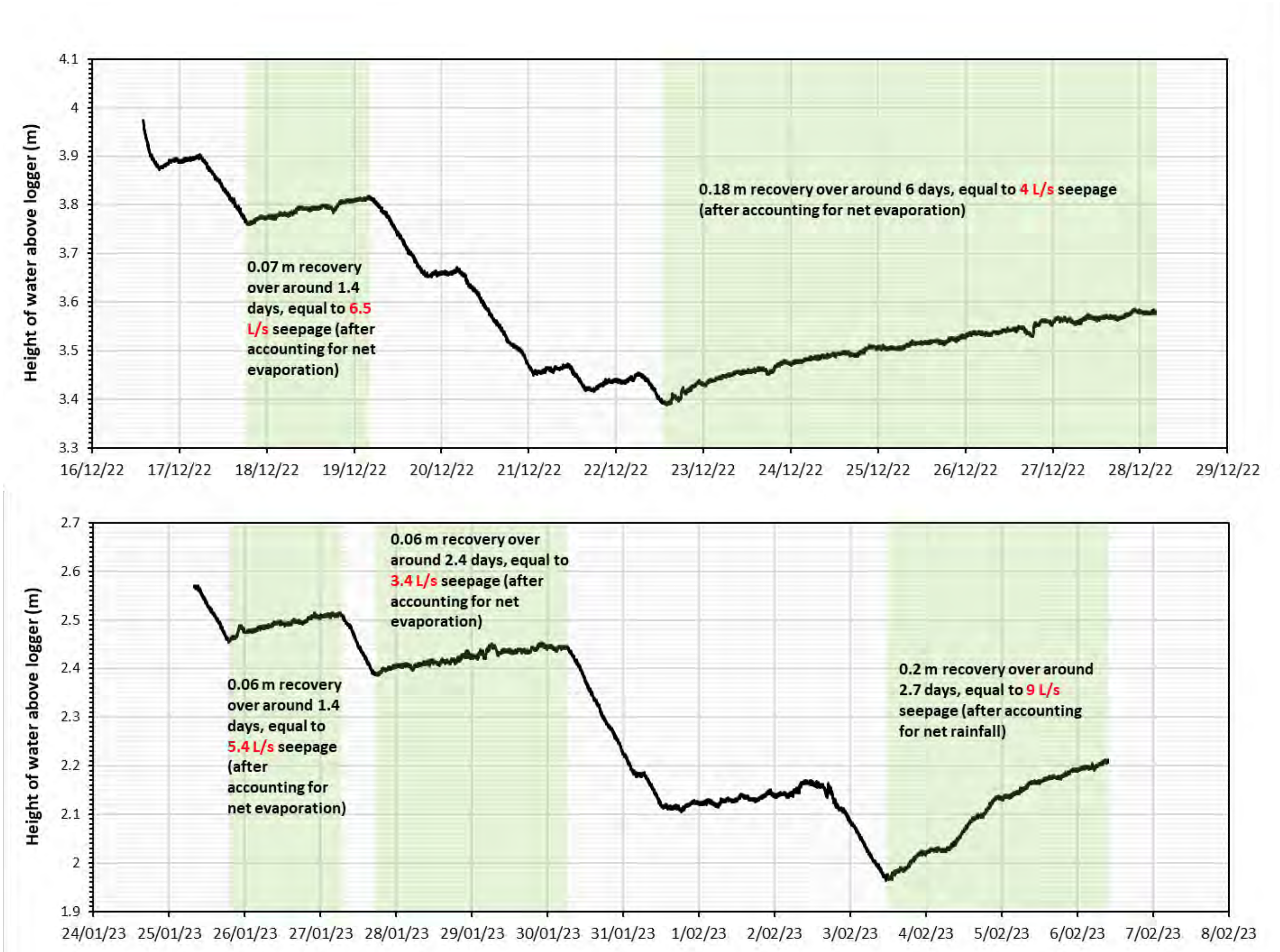


Figure 9 *Estimated groundwater seepage rates*

The Bungalook Creek flow record from gauge 228369A at the Fussell Road retarding basin indicates typical daily flow rates ranging from around 15 L/s to 60 L/s, with flow rates in excess of 1,000 L/s recorded in very wet periods. During dry periods, the flow rate typically falls below the gauge threshold of around 3 L/s to 5 L/s, indicating generally limited groundwater baseflow contribution. This is supported by the field observations during dry periods, both in the past (limited to no flow in January 1998 and November 2002) and recently (December 2022 and February 2023).

According to Golder (2006), a typical baseflow between 1980 and 1996 (a wet period prior to the Millennium Drought) was estimated to be in the range of 4 L/s to 5 L/s, although there is low confidence in this estimate due to the low baseflow contributions at, or below, the threshold of accuracy of the flow gauge. For the purpose of model calibration, a baseflow target of 4.5 L/s has been incorporated for an average flow between 1980 and 1996.

3.1.3 Calibration parameters

The aquifer parameters adjusted during calibration include horizontal and vertical hydraulic conductivities, specific yield and specific storage. For recharge and evapotranspiration, the parameters of the LUMPREM model are adjusted along with the scaling factors to account for different land uses and evapotranspiration extinction depth. For stream reaches, the stream bed hydraulic conductivity is adjusted.

Table 3 summarises the initial, minimum and maximum parameter values specified during calibration. Aquifer parameters are adjusted on an HSU basis except for the Mt Evelyn Rhyodacite, where 10 adjustable pilot points are used to introduce spatial variability in horizontal hydraulic conductivity across the monitoring bore network. There are also 24 pilot points distributed regionally that are “tied” to one of the regional adjustable pilot points (kxp9). This is to prevent spurious interpolation of hydraulic conductivity values over the broader region, where there is no data to infer (or justify) spatial variability.

Figure 10 shows the location of adjustable pilot points around the quarry area (note kxp9, and associated tied pilot points, are located outside of this area of interest). The range of aquifer parameter values are based on the combination of field testing data (slug tests in the Mt Evelyn Rhyodacite), prior modelling work by Golder (2006), and literature derived values for representative materials. For example, a higher hydraulic conductivity limit of 0.5 m/d (the maximum value from slug testing) has been assigned to three adjustable pilot points (kxp2, kxp8 and kxp10) based on the presence of the shear zone (near kxp10) and a high hydraulic conductivity zone along Bungalook Creek inferred from previous modelling by Golder (2006).

The vertical hydraulic conductivity is derived from the horizontal hydraulic conductivity using a single anisotropy factor for each unit. Specific storage and specific yield are also assigned using a constant value for each unit.

Prior to calibration, the LUMPREM model parameters were adjusted until the average recharge value was approximately equal to the steady state recharge value derived from the previous modelling by Golder (2006). The initial LUMPREM parameter values presented in Table 3 are based on this pre-calibration adjustment.

Recharge derived from the LUMPREM model is scaled by a multiplier grid to reduce recharge over the residential and industrial areas (compared to the undeveloped areas). The multiplier for the industrial area (“rch_mult2”) is calculated as a fraction of the multiplier for the residential area (“rch_mult1”). This ensures that recharge multiplier over the industrial areas is either equal to or less than that of the residential areas (but not greater). Recharge is set to zero over the SFR cells, where the flow is maintained by baseflow only. Evapotranspiration is also reduced to zero over the SFR cells by setting a very high evapotranspiration surface (to prevent excessive discharge directly over the water course).

Table 3 Model parameters

Parameter type	Parameter ID	HSU/Feature	Initial	Minimum	Maximum	Comment
Horizontal hydraulic conductivity (Kx)	al_kx1	Alluvium	0.01 m/d	0.001 m/d	0.5 m/d	Fine sand and clayey near creek, higher value possible
	fc_kx1	Ferny Creek Rhyodacite	0.002 m/d	0.0002 m/d	0.02 m/d	Zone-based (one value per HSU)
	km_kx1	Kalorama Rhyodacite	0.002 m/d	0.0002 m/d	0.02 m/d	Zone-based (one value per HSU)
	kxp1 – kxp10	Mt Evelyn Rhyodacite	0.02 m/d	0.0001 m/d	0.3 m/d	10 x pilot points, up to 0.5 m/d for three pilot points
	cs_kx1	Coldstream Rhyolite	0.025 m/d	0.0002 m/d	0.2 m/d	Zone-based (one value per HSU)
	hv_kx1	Humevale Siltstone	0.04 m/d	0.0002 m/d	0.2 m/d	Zone-based (one value per HSU)
	mb_kx1	Melbourne Formation	0.04 m/d	0.0002 m/d	0.2 m/d	Zone-based (one value per HSU)
Kz factor	al_kzf1	Alluvium	0.1	0.001	1	Zone-based (one value per HSU)
	fc_ kzf1	Ferny Creek Rhyodacite	0.1	0.001	1	Zone-based (one value per HSU)
	km_ kzf1	Kalorama Rhyodacite	0.1	0.001	1	Zone-based (one value per HSU)
	kzfp1	Mt Evelyn Rhyodacite	0.1	0.001	1	Zone-based (one value per HSU)
	cs_ kzf1	Coldstream Rhyolite	0.1	0.001	1	Zone-based (one value per HSU)
	hv_ kzf1	Humevale Siltstone	0.1	0.001	1	Zone-based (one value per HSU)
	mb_ kzf1	Melbourne Formation	0.1	0.001	1	Zone-based (one value per HSU)
Specific storage	al_ss1	Alluvium	5×10^{-6} m^{-1}	1×10^{-6} m^{-1}	1×10^{-5} m^{-1}	Zone-based (one value per HSU)
	fc_ ss1	Ferny Creek Rhyodacite	5×10^{-6} m^{-1}	1×10^{-6} m^{-1}	1×10^{-5} m^{-1}	Zone-based (one value per HSU)
	km_ ss1	Kalorama Rhyodacite	5×10^{-6} m^{-1}	1×10^{-6} m^{-1}	1×10^{-5} m^{-1}	Zone-based (one value per HSU)
	mt_ ss1	Mt Evelyn Rhyodacite	5×10^{-6} m^{-1}	1×10^{-6} m^{-1}	1×10^{-5} m^{-1}	Zone-based (one value per HSU)
	cs_ ss1	Coldstream Rhyolite	5×10^{-6} m^{-1}	1×10^{-6} m^{-1}	1×10^{-5} m^{-1}	Zone-based (one value per HSU)
	hv_ ss1	Humevale Siltstone	5×10^{-6} m^{-1}	1×10^{-6} m^{-1}	1×10^{-5} m^{-1}	Zone-based (one value per HSU)
	mb_ ss1	Melbourne Formation	5×10^{-6} m^{-1}	1×10^{-6} m^{-1}	1×10^{-5} m^{-1}	Zone-based (one value per HSU)

Parameter type	Parameter ID	HSU/Feature	Initial	Minimum	Maximum	Comment
Specific yield	al_sy1	Alluvium	0.1	0.05	0.3	Zone-based (one value per HSU)
	fc_ sy1	Ferny Creek Rhyodacite	0.05	0.01	0.1	Zone-based (one value per HSU)
	km_ sy1	Kalorama Rhyodacite	0.05	0.01	0.1	Zone-based (one value per HSU)
	mt_ sy1	Mt Evelyn Rhyodacite	0.05	0.01	0.1	Zone-based (one value per HSU)
	cs_ sy1	Coldstream Rhyolite	0.05	0.01	0.1	Zone-based (one value per HSU)
	hv_ sy1	Humevale Siltstone	0.05	0.01	0.1	Zone-based (one value per HSU)
	mb_ sy1	Melbourne Formation	0.05	0.01	0.1	Zone-based (one value per HSU)
Stream bed conductivity	sfrcond	Streams	0.1 m/d	0.002 m/d	2 m/d	Model-wide single value
Soil store	maxvol	LUMPREM	1	0.2	2	Maximum soil store
Soil hydraulic conductivity	ks	LUMPREM	0.001 m/d	0.0001 m/d	0.01 m/d	Controls the rate of drainage from soil zone
Soil store drainage	soilm	LUMPREM	0.5	0.5	2	Controls the shape of drainage rate versus stored water relationship
Crop factor	cropf	LUMPREM	0.8	0.2	0.8	Crop factor
Gamma	gamma	LUMPREM	2	0.1	10	Defines relationship between EVT and soil store
Recharge multipliers	rch_mult1	Residential land use	0.01	0.001	1	Multiplier used to reduce recharge over residential land
	rch_mult2	Industrial land use	0.01	0.001	1	Factor applied to “rch_mult1” above, to derive a multiplier used to reduce recharge over industrial land
Extinction depth	exdp	Evapotranspiration	2.5 m	0.5 m	8 m	Model-wide single value

Notes:
Alluvium near Bungalook Creek is generally silty and clayey, with field testing indicating generally low hydraulic conductivity. However, higher hydraulic conductivity is plausible where the Alluvium is more developed and this could be important for transmitting baseflow. A value of up to 0.5 m/d is therefore allowed.

Horizontal hydraulic conductivity of Mt Evelyn pilot points has been allowed to vary by up to 0.5 m/d (maximum value from field testing) at 3 out of 10 pilot points, where calibration, prior modelling and geological information (presence of shear zone) suggests possible presence of locally elevated value.

Specific yield is based on the plausible range of values from the literature for the lithologies encountered on site (Johnson, 1966). For fractured rock aquifers (all units except the Alluvium), specific yield can be very low where the drainable porosity is controlled by tight fractures.

Specific storage is based on the plausible range of values for unconsolidated sediments from a publication by Rau et al., (2018).

A wide range of value is allowed for stream bed hydraulic conductivity to partly compensate for uncertainty in the bed thickness.

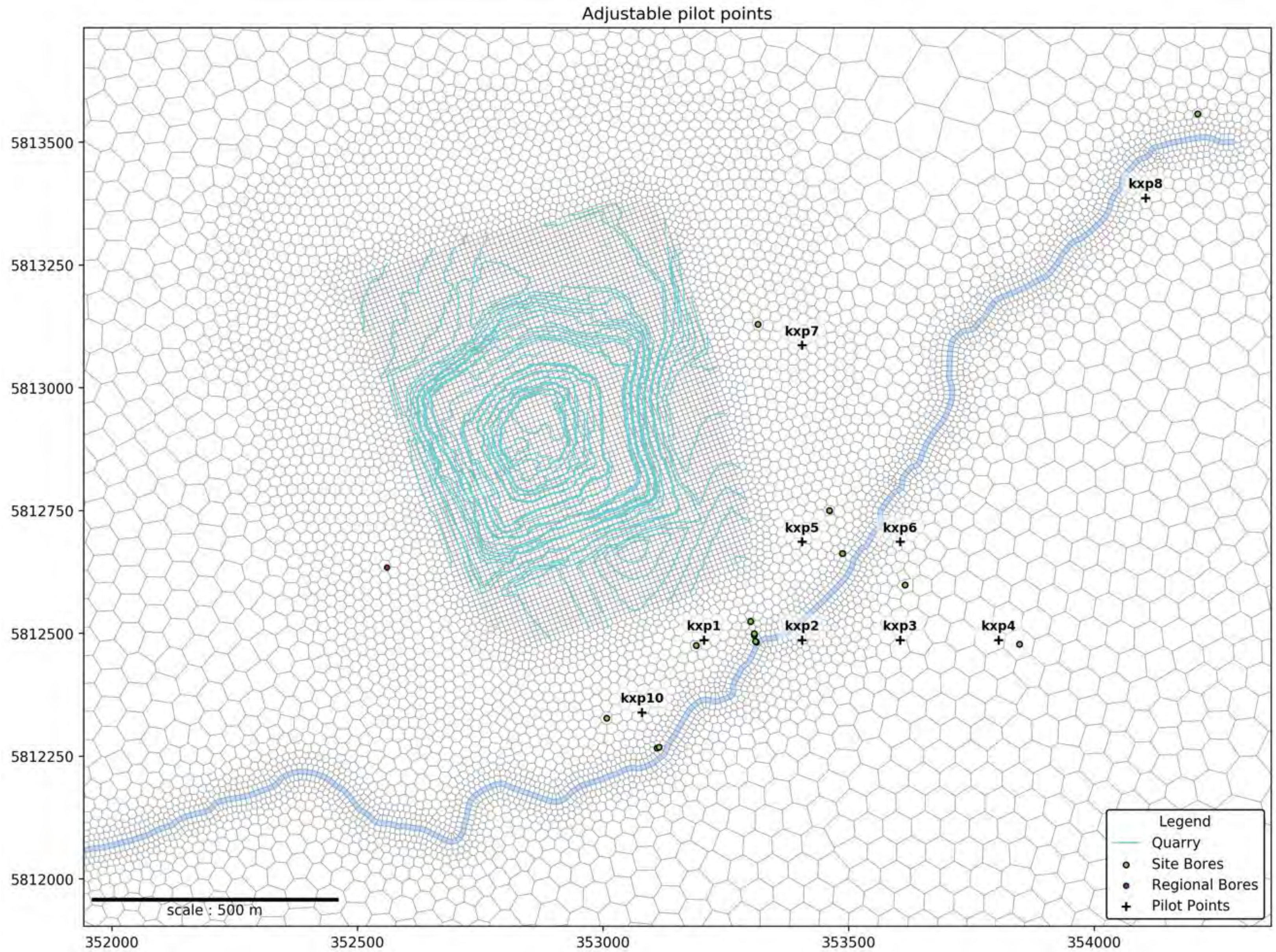


Figure 10 ***Adjustable pilot points***

Note: Pilot point kxp9 not shown on image as it is located further from the quarry

3.1.4 Calibration workflow

Calibration has been undertaken rigorously using PEST_HP (Doherty, 2017) in a highly parallelised computing environment. The automated calibration used a number of third-party utilities to facilitate pre- and post-processing of model data, including:

- PEST utility PLPROC that undertakes spatial interpolation of parameters from pilot points to the model mesh, in this case to generate spatially varying arrays of horizontal and vertical hydraulic conductivity for the Mt Evelyn Rhyodacite.
- PEST utility PAR2PAR that converts spatially constant (homogeneous) horizontal hydraulic conductivity into vertical hydraulic conductivity, using the vertical hydraulic conductivity factors adjusted by PEST_HP. PAR2PAR is also used to write the horizontal and vertical hydraulic conductivity values to the Layer-Property Flow (LPF) file, as well as the specific yield and specific storage for all units (assumed to be constant for each unit/layer).
- PEST utility USGMOD2OBS that extracts computed hydraulic heads at the time and location of observations and SMPDIFF that converts the computed hydraulic heads into temporal hydraulic head differences (trends) at the location of observations.
- USGS utility ZONBUDUSG that extracts flow budget from the computed cell-by-cell binary file. In this case, the outflow from the DRN file is used to compare against the estimated groundwater seepage rate in the quarry at the end of calibration.

In addition to the PEST utilities listed above, project-specific scripts have been prepared in Python and Fortran to write model input files based on parameters adjusted by PEST and to post-process model outputs. These include scripts that:

- Write the RCH and EVT files from the LUMPREM model output file. The RCH rates are adjusted to account for spatial differences in rainfall and land use using multiplier grids, before RCH is interpolated to the USG-Transport unstructured grid. The scripts write both the transient and steady state files, with the latter calculated using the long term average values from the 48-year transient calibration period. The steady state RCH and EVT files are used to generate initial heads for the transient calibration simulation. The RCH and EVT files are updated in this manner every time the LUMPREM model parameters are updated and rerun by PEST_HP.
- Read the streamflow time series computed by the GAGE package at stream gauge 228369A and calculate average flow from 1980 to 1996. This average simulated flow is compared against the estimated average baseflow.

The automated calibration has been undertaken primarily in the regularisation mode, using the parameter initial values (as well as a pilot point covariance matrix) as prior information to minimise parameter variability unless deemed necessary by PEST_HP. For spatially correlated (pilot point) parameters, covariances are defined using distance-based factors developed using PEST tools MKPPSTAT and PPCOV_SVA (Doherty, 2018).

Figure 11 is a graphical representation of the automated calibration workflow.

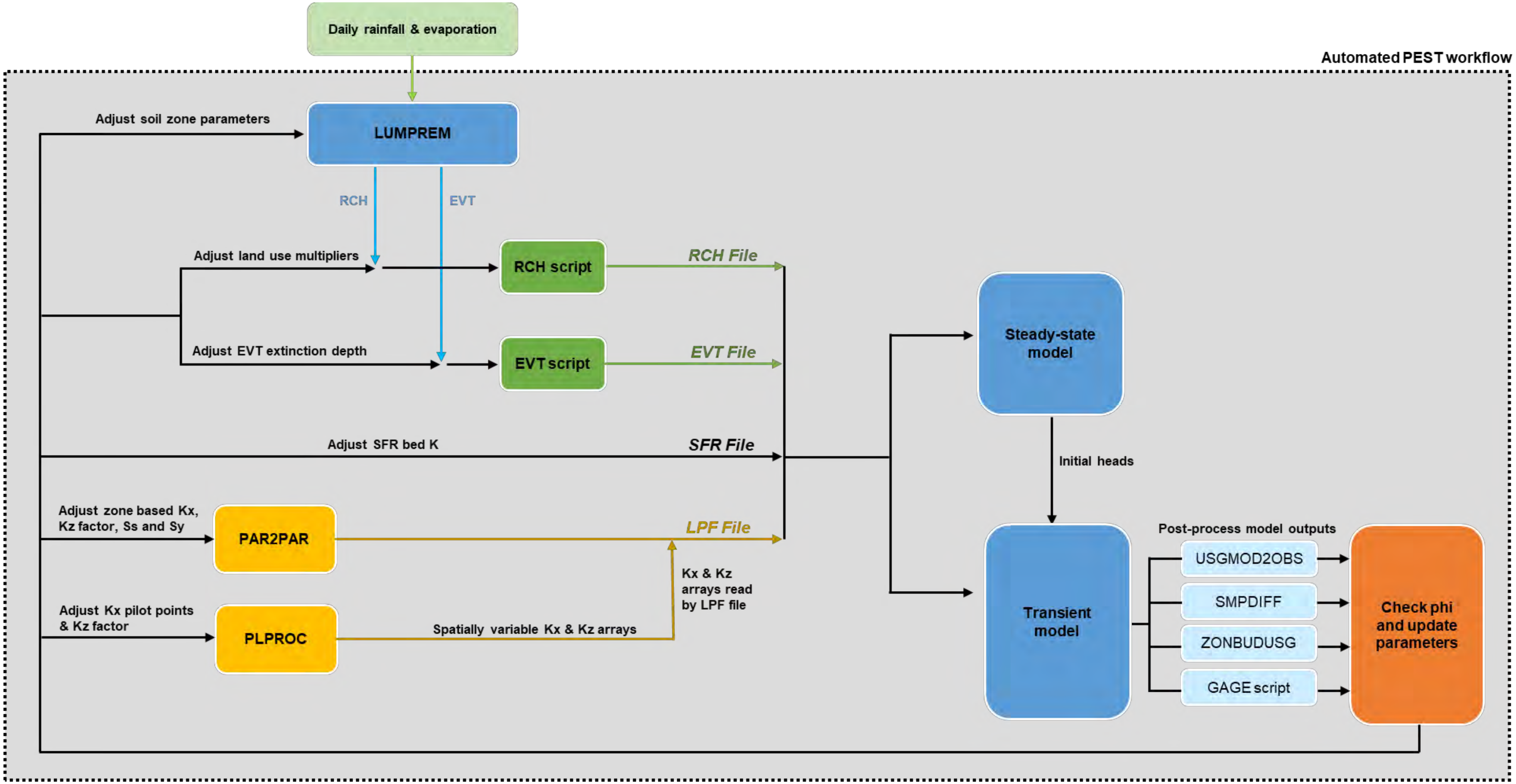


Figure 11 Automated calibration workflow

3.2 Calibration results

The automated calibration procedure has been highly iterative, necessitating progressive adjustments to observations weights where the model calibration was identified to be deficient and adjusting parameter bounds to introduce greater flexibility in some parameters where this was deemed necessarily or warranted based on the successive outcomes of the calibration. Although the model calibration has been primarily undertaken in the regularisation mode, some fine-tuning of the parameters has been undertaken in the estimation mode, fixing insensitive parameters and adjusting key parameters, and closely examining their effect on a subset of observations.

During automated calibration, many different parameter realisations are generated. Some are better calibrated to observed heads while others are more closely calibrated to estimated seepage rates and/or baseflow. Qualitative indicators, such as the magnitude of seasonal variations and recharge distribution, are also considered in assessing the reasonableness of model performance.

For the purpose of model calibration, a set of model parameters that best satisfy both the heads and flow observations targets has been selected and used as the basis for projecting future impacts associated with the proposed expansion (as detailed in Section 3.2.3). The effect of model non-uniqueness arising from parameter uncertainty is further detailed in Section 6, as part of uncertainty analysis.

3.2.1 Calibration statistics

Figure 12 shows a scatter plot of the observed and computed heads, which provide useful indications of the overall quality of model calibration. The Scaled Root Mean Squared (SRMS) error is around 0.94 % for the site bores and regional bores combined, which is well below the 5 % SRMS error generally considered a good statistical fit for regional scale modelling. For the site bores only, the SRMS error is 4.29 % and Mean Sum of Residual (MSR) error is around 1.3 m.

The cumulative mass balance error is less than 0.01 % and the mass balance error for all time steps is also less than 0.01 %, well below the maximum 1 % error recommended by the Australian Groundwater Modelling Guidelines (Barnett et al., 2012).

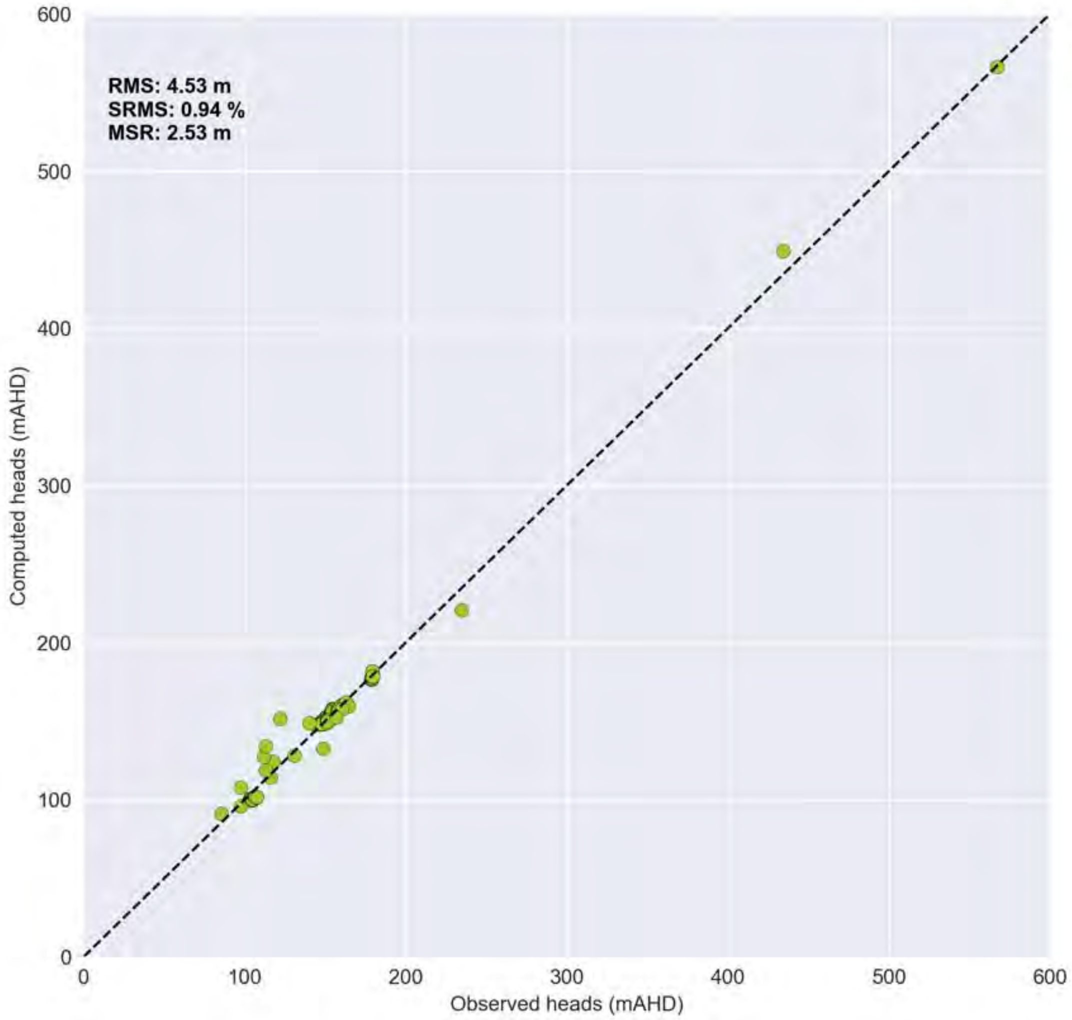


Figure 12 *Calibration scatter plot of heads*

3.2.2 Calibration performance

Hydraulic heads

Figure 13 and Figure 14 present the hydrographs of modelled and observed heads for the site bores. The model simulates the subtle declining trend observed between late 1990s and 2004 at bores MB1, MB2 and MB3. This declining trend continues into 2010, over the Millennium Drought, where a similar climatically induced variation has been observed across many parts of Victoria. The model simulates an increase in groundwater level in response to periods of above average rainfall, including the wet period of 2011/2012 (one of the wettest periods on record) and more recently since 2020, as verified by the recent measurements of groundwater levels.

The nearest registered bore with long term monitoring data is 79930 (State Observation Bore Network), which is located between Mount Dandenong and Silvan Reservoir. Although this bore is located outside of the model domain and potentially in a different hydrogeological setting, its long term trend broadly aligns with the trend simulated at one of the site bores (MB5b). This is shown in Figure 15, which compares the observed and simulated change in groundwater levels since 1980 at these two bores. It should be noted that the model simulates much wider variations at other bores, which is expected due to the differences in the local hydrogeological regime. The purpose of Figure 15 is to simply demonstrate that the groundwater level trends simulated by the model are plausible and broadly consistent with the trends typically expected from the long term climate record in this region of Victoria.

Figure 16 presents the simulated distribution of hydraulic heads and contours of the water table at the end of calibration. Figure 17 focuses on the area around the quarry, showing the locally depressed water table.

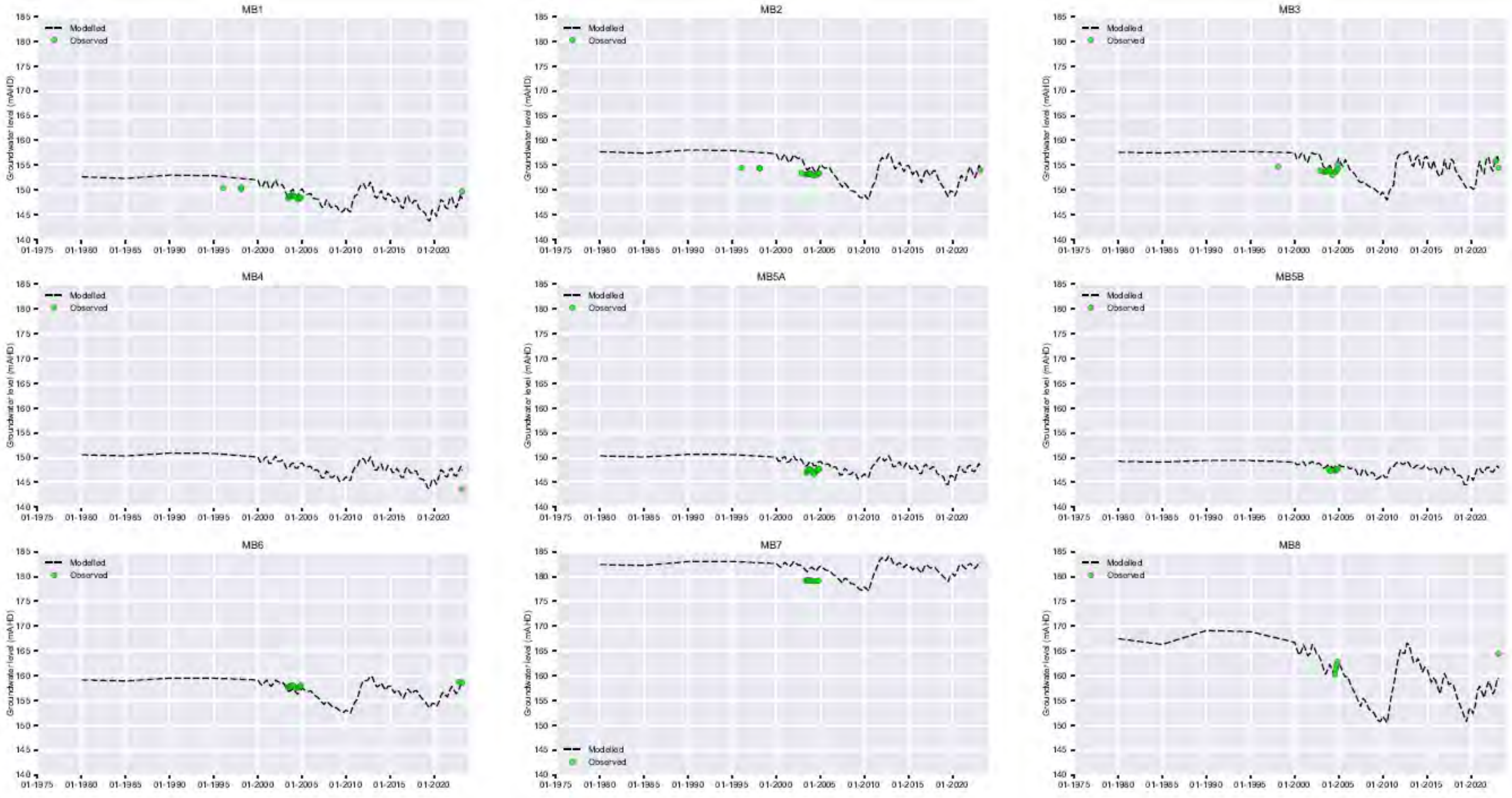


Figure 13 ***Calibrated hydrographs – bore MB1 to MB8***

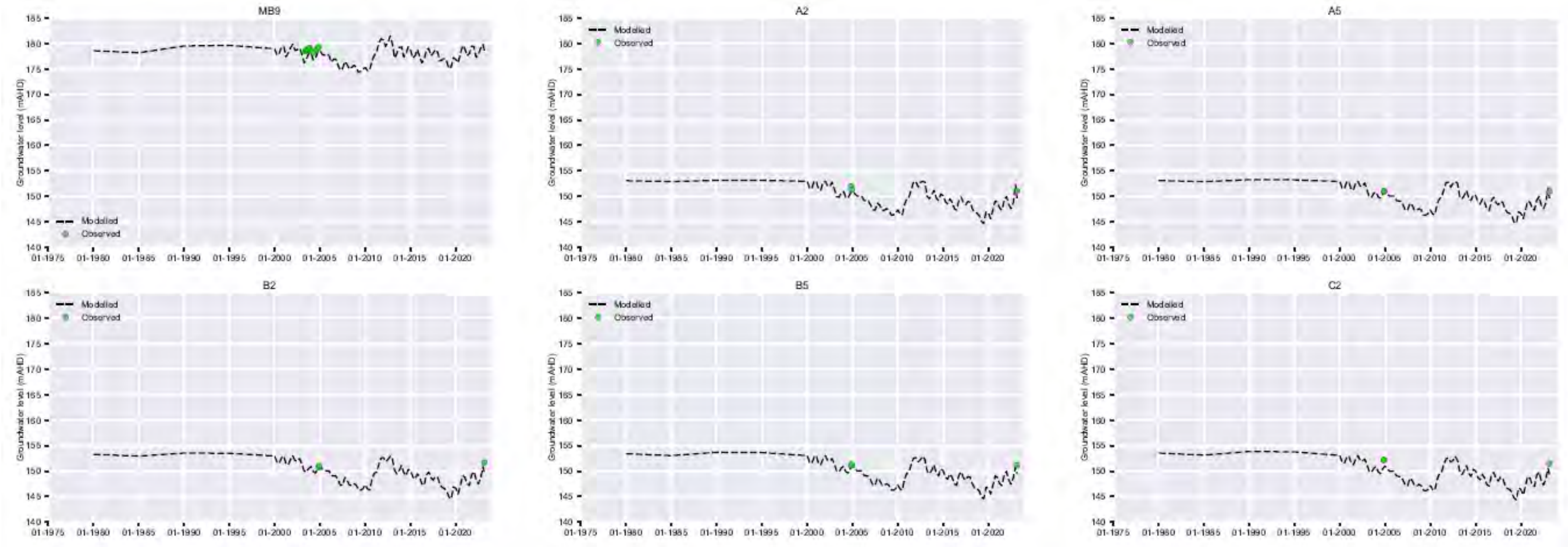


Figure 14 *Calibrated hydrographs – bore MB9 to C2*

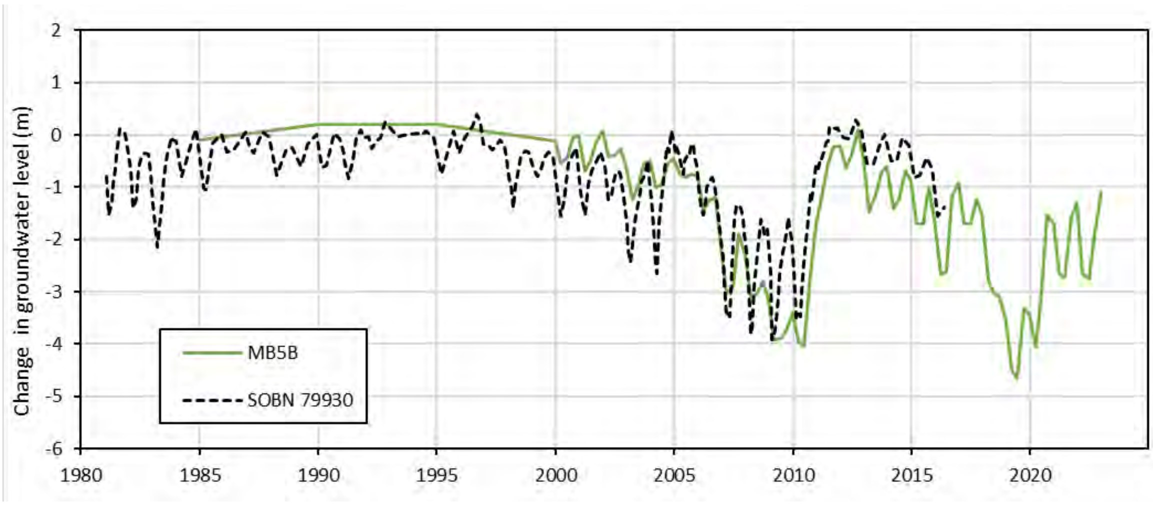


Figure 15 *Change in groundwater level since 1980 - comparison against SOBN bore 79930*

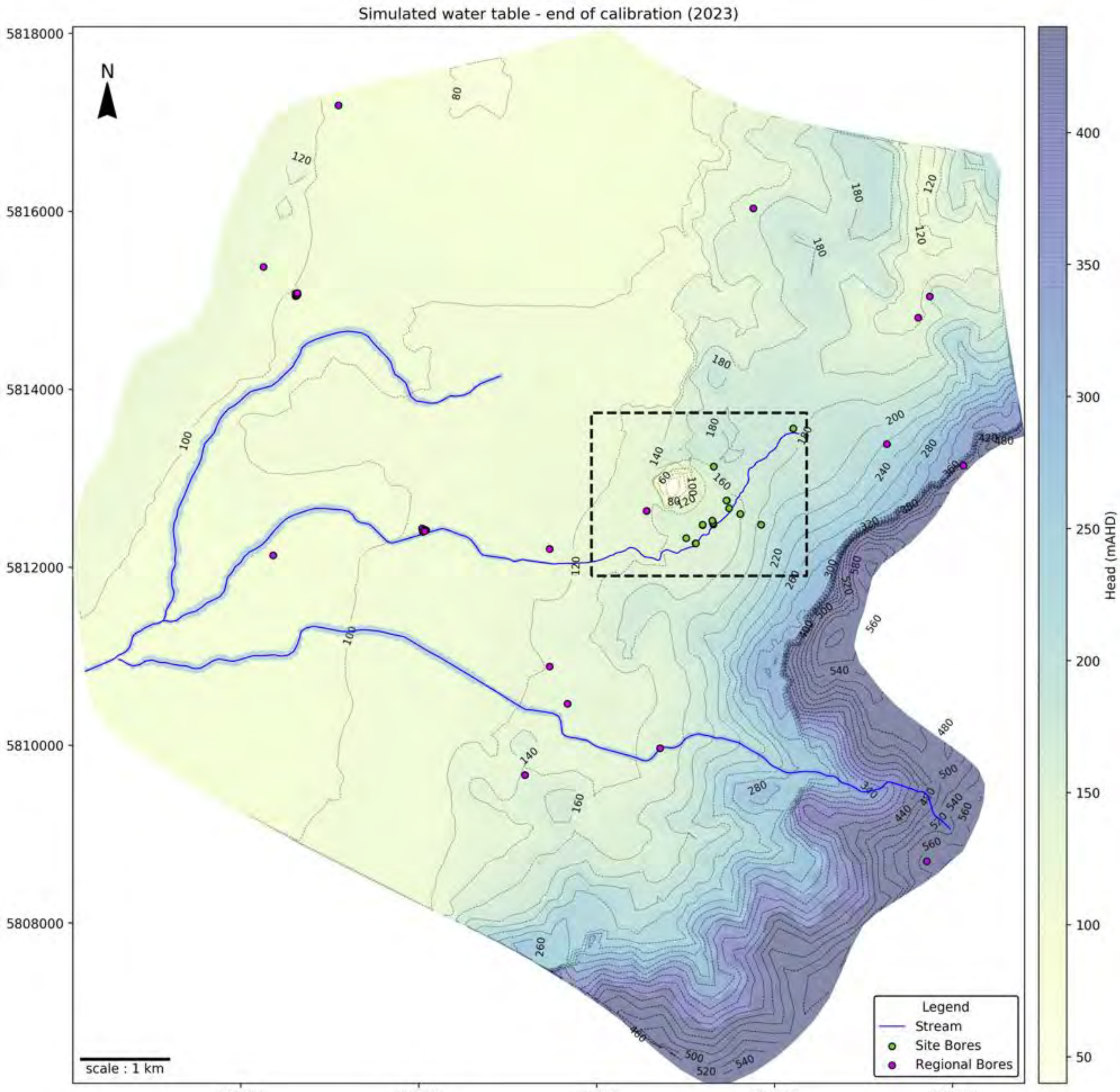


Figure 16 *Simulated water table at the end of calibration – regional view*

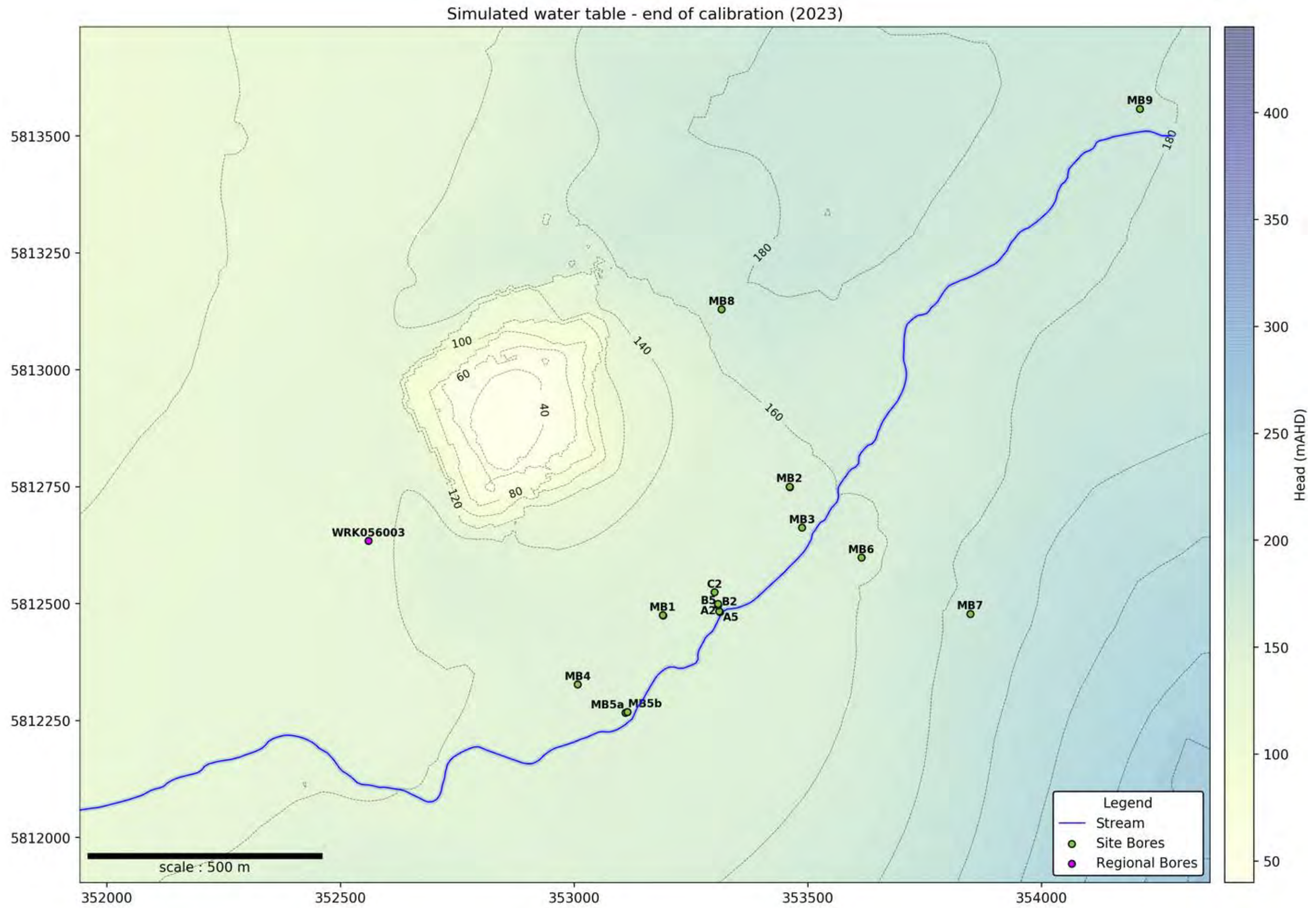


Figure 17 Simulated water table at the end of calibration – quarry area

Flows

A hydrograph of simulated groundwater seepage rate is shown in Figure 18, which is calculated from the DRN outflow (minus any contributions from direct recharge over the active DRN cells). The simulated seepage rate in 2003 is around 2.7 L/s, which is between the 1 L/s to 3.5 L/s range estimated by Golder (2006) and around 6.4 L/s at the end of calibration, very close to the estimated average of 6 L/s (noting that the simulated rate fluctuates between 5.5 and 6.4 L/s, depending on seasonal variations in recharge).

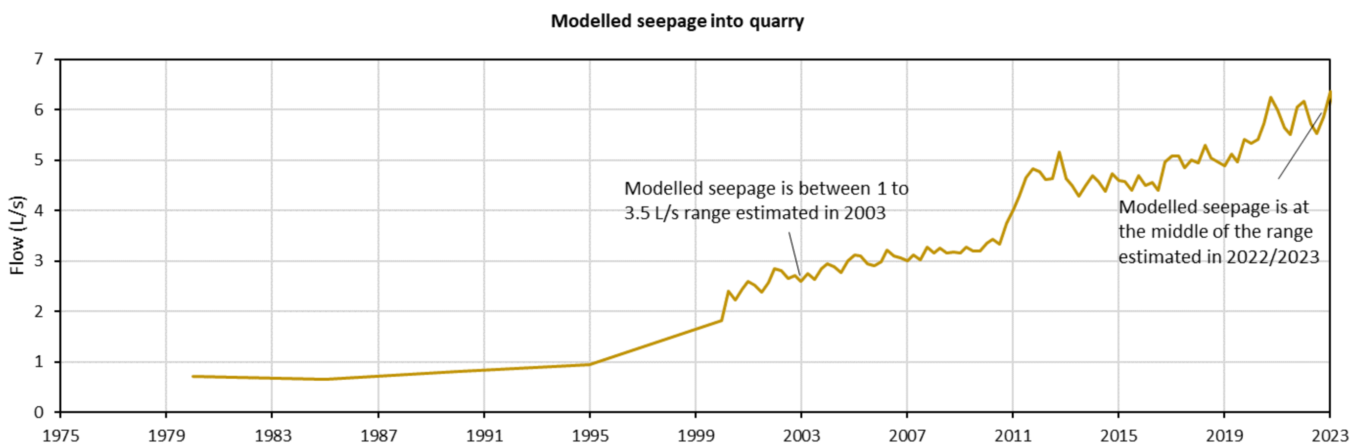


Figure 18 Modelled groundwater seepage into quarry

A hydrograph of baseflow computed at gauge 228369A at the Fussell Road retarding basin is presented in Figure 19. The average computed baseflow between 1980 and 1996 is approximately in the middle of the 4 L/s to 5 L/s range estimated. For year 2000, the model uses quarterly stress periods and the effect of seasonal variations in climate can be seen in the baseflow variations. Limited baseflow is simulated towards the end of the calibration period, consistent with limited flows observed in the field.

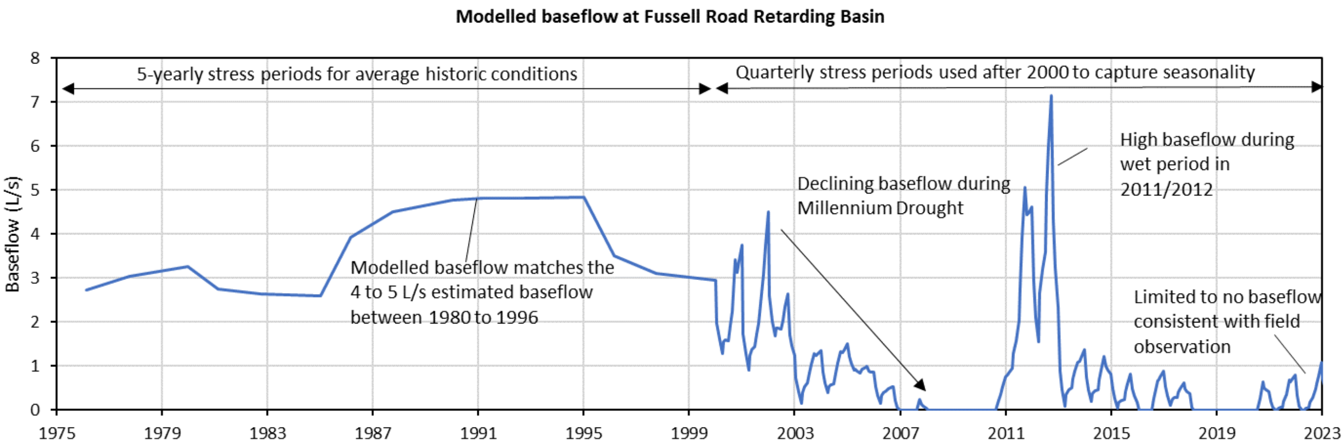


Figure 19 ***Modelled baseflow***

3.2.3 Calibrated parameters

The calibrated model parameters are presented graphically in Figure 20 and Figure 21, along with their initial (pre-calibration) estimates and upper and lower parameter bounds. The spatial distribution of calibrated horizontal hydraulic conductivity of the Mt Evelyn Rhyodacite is shown in Figure 22 (note the same spatial distribution is mapped to model layers 4 to 9, which are dipping gently to the east, as shown in the figure). A region of high horizontal hydraulic conductivity has been delineated along Bungalook Creek, to the south of the quarry. This is consistent with a high hydraulic conductivity zone assigned in the previous model by Golder (2006). Conceptually, a zone of enhanced hydraulic conductivity in this region is likely to be associated with the presence of the northwest-southeast trending shear zone, which is dipping to the northeast and partly exposed in the southern corner of the quarry. It is also possible that the hydraulic conductivity is locally enhanced by the creek (via weathering) or the presence of the creek itself indicates a zone of weakness in the underlying geology.

Calibrated recharge across the area of interest (at and around the quarry) typically ranges from 3 % to 9 % of rainfall. Golder (2006) estimated a steady-state recharge rate of 45 mm/yr, which is similar to the calibrated average recharge rate of 47 mm/yr from 2002 to 2004 (a period of time when the steady state assumption adopted in the previous modelling would have been valid). The calibrated recharge rates are lower than the recharge rates used in Victorian Government’s ecoMarkets Port Phillip model (GHD, 2010). For example, long term average recharge from 1991 to 2005 is around 114 mm/yr in the Port Phillip model in the area of the quarry, compared to the calibrated recharge rate of 68 mm/yr over this period. The difference is likely to be the result of the more targeted calibration effort to site specific data, noting that the lower recharge rates are considered more consistent with the underlying geology (a fractured rock aquifer system with low to moderate hydraulic conductivity).

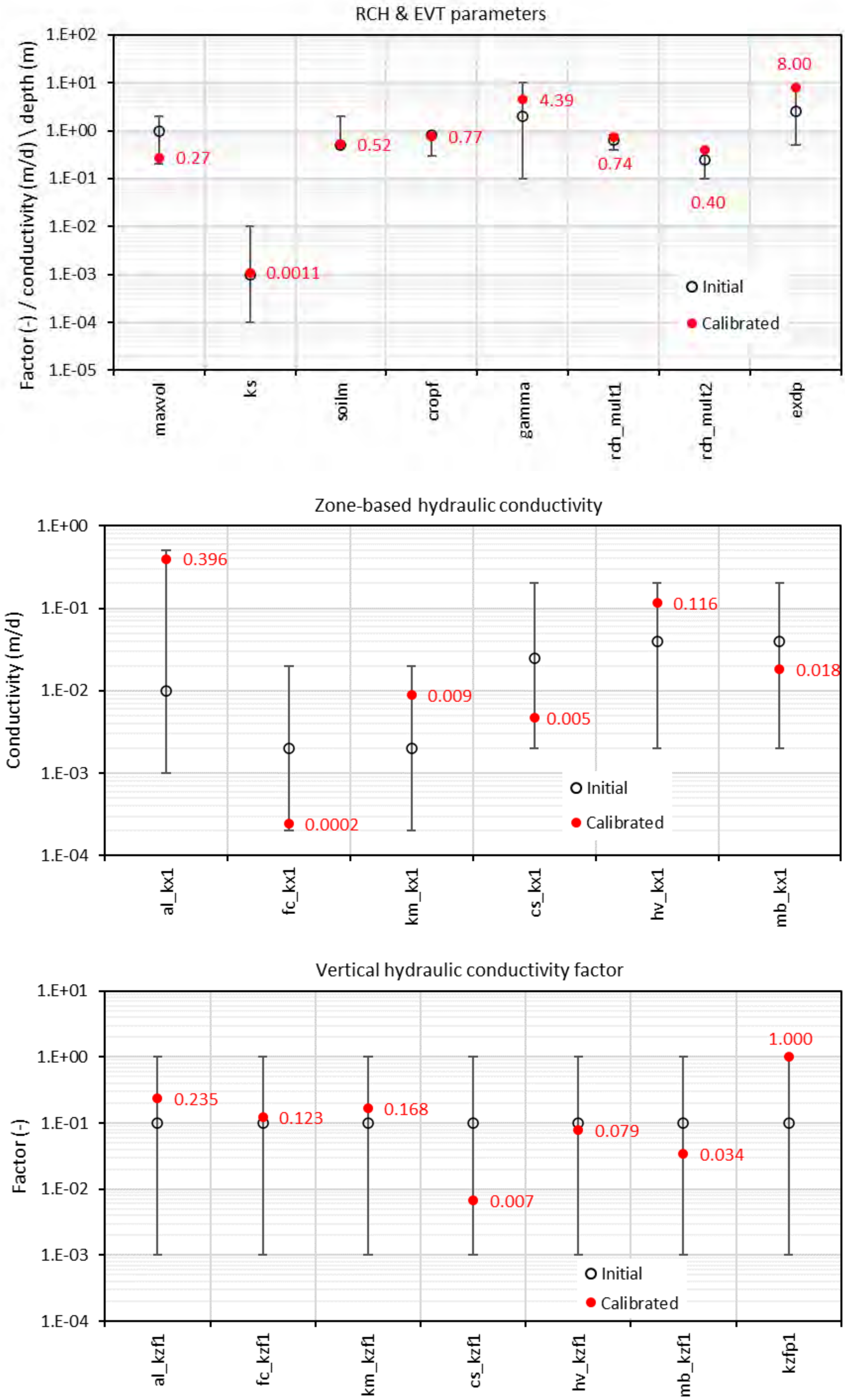


Figure 20 Calibrated parameters – part 1

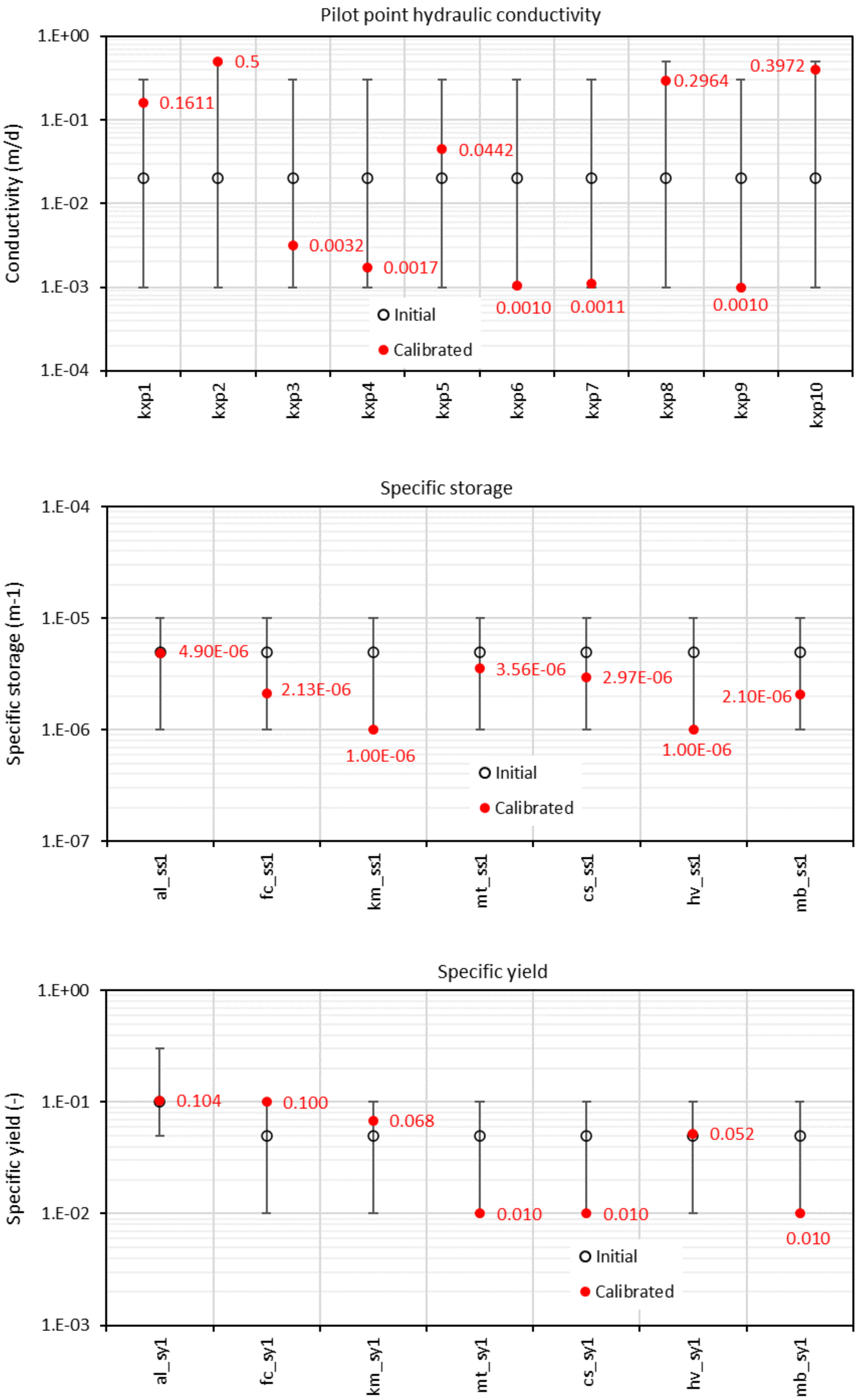


Figure 21 Calibrated parameters – part 2

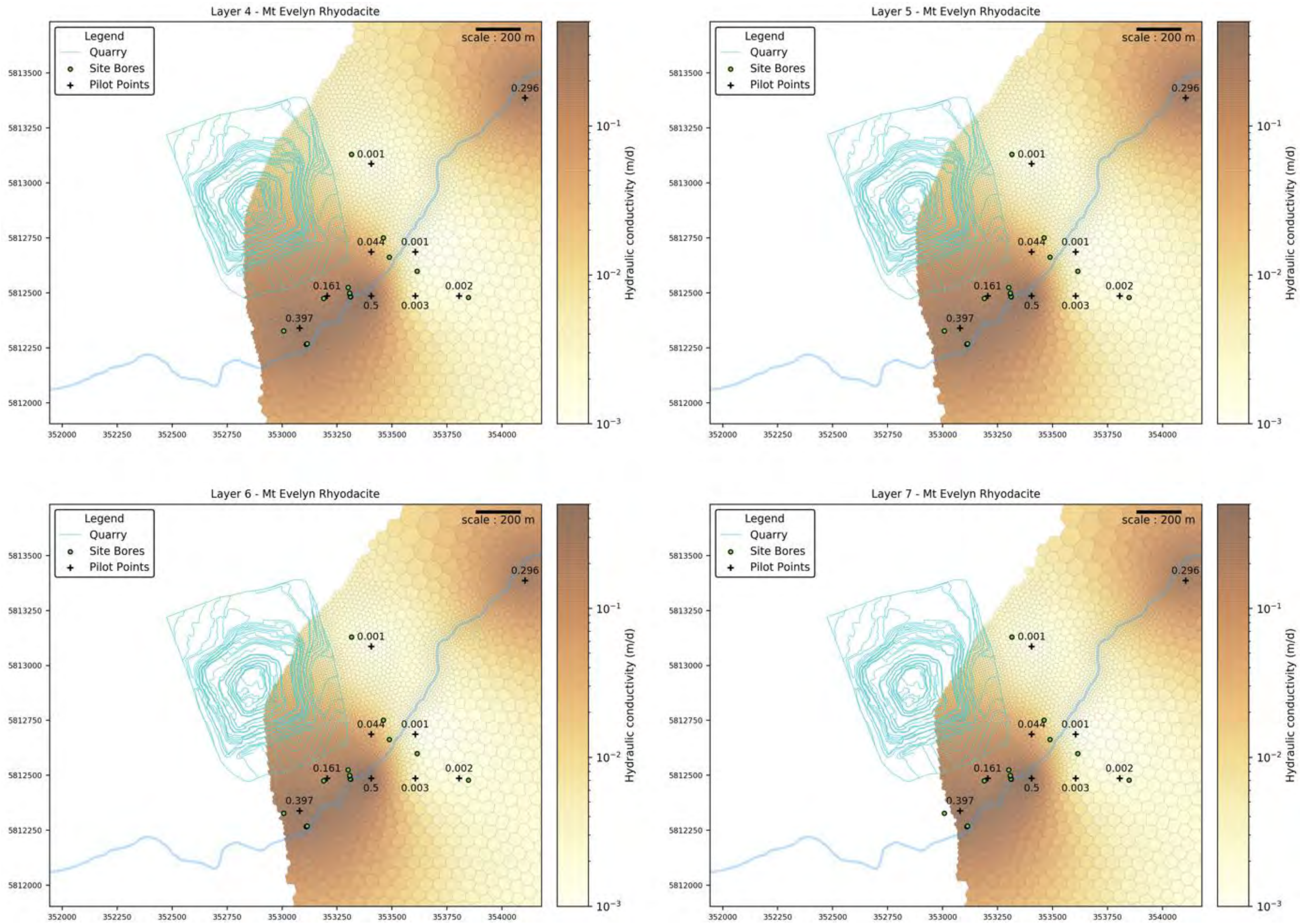


Figure 22 *Calibrated horizontal hydraulic conductivity – Mt Evelyn Rhyodacite*

Figure 23 presents the average annualised modelled recharge over the calibration period and recharge per stress period. The first 5 stress periods are 5 years in length, reducing to quarterly stress periods from stress period 6. The low annualised recharge rate in 2023 is due to the calibration period ending in February 2023. The calibrated annualised groundwater evapotranspiration rate ranges from 385 mm/yr to 706 mm/yr, with a long term average of 512 mm/yr.

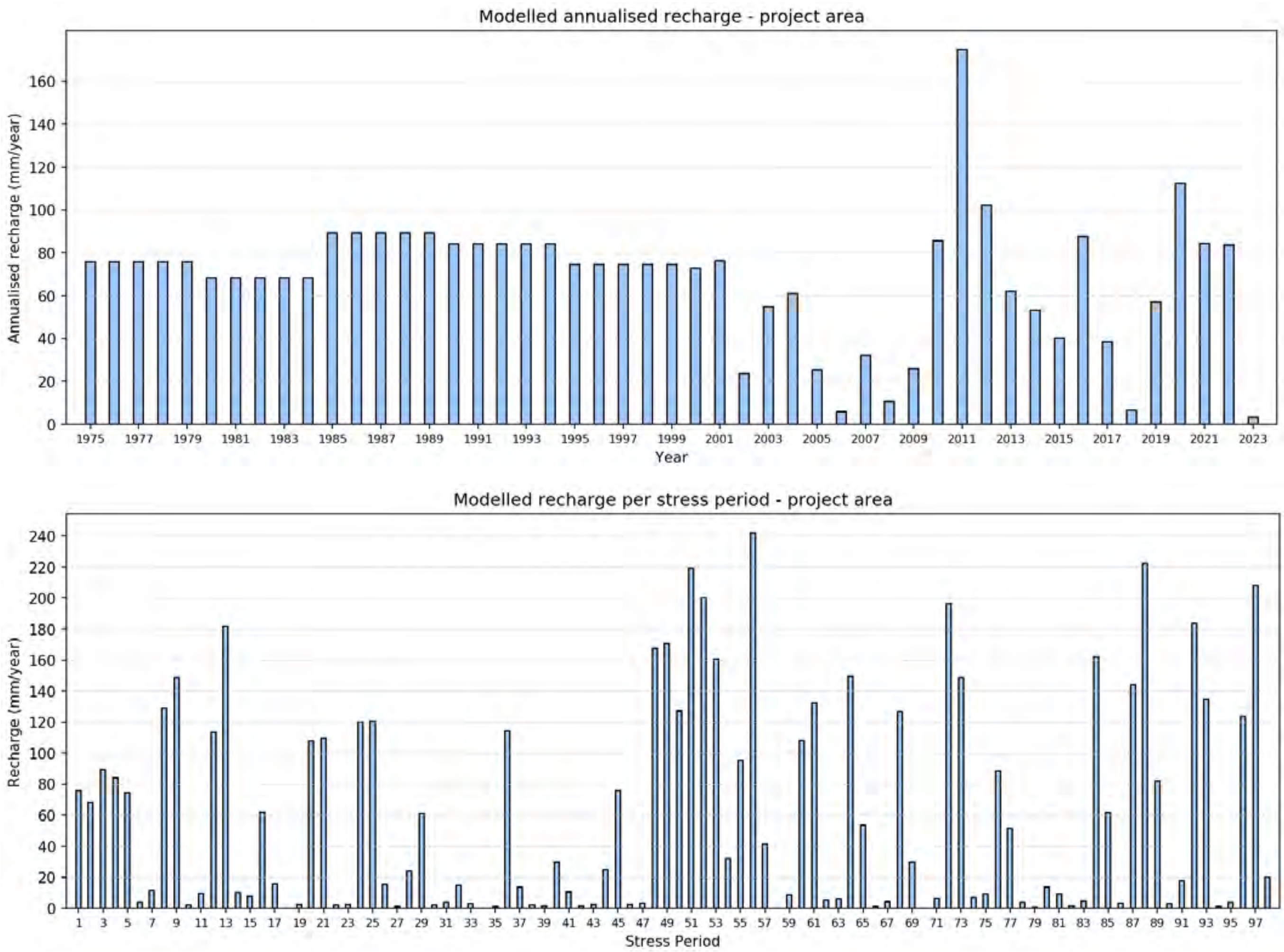


Figure 23 *Calibrated recharge*

3.3 Effect of historical extraction and streamflow

The model calibration has been undertaken with the quarry in place, which means the effect of historical extraction is not easy to discern in the model outputs. In order to quantify this effect, a base case model run has been undertaken to simulate a background condition without the presence of the quarry (by excluding the quarry/DRN cells from the calibrated model while retaining all other features). The difference between the calibrated model and the base case model provides indications of the historical effects of quarry dewatering.

Figure 24 compares the modelled baseflow at gauge 228369A with, and without the quarry. The model simulates a reduction in baseflow over time due to the lowering of the water table at the quarry, resulting in lower hydraulic gradients and reduced groundwater flow towards Bungalook Creek. This means there is less baseflow available in the downstream section of Bungalook Creek to supply recharge to the water table (stream leakage, where the model simulates a losing condition). The result is a localised lowering of the water table simulated downstream of the Fussell Road Retarding Basin, which is not caused directly by the drawdown from the quarry but indirectly by the reduced baseflow accumulated from upstream (within the modelled area of influence of the quarry).

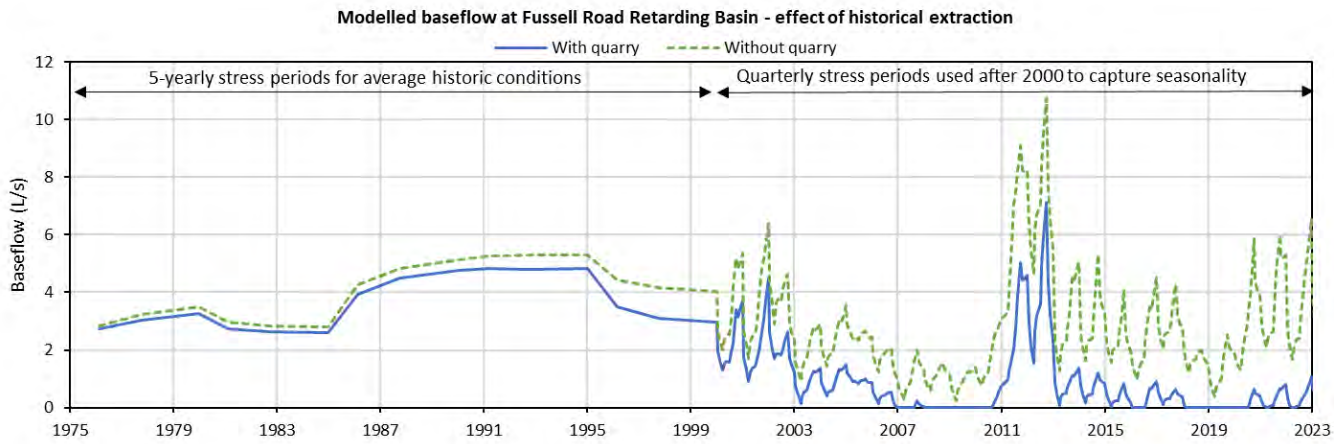


Figure 24 Modelled baseflow with and without quarry

This leads to an important point of consideration regarding the highly conservative modelling approach that assumes only groundwater baseflow, and the extent to which much larger volumes of surface water (total stream) flow influences the groundwater system by suppling recharge to the water table. For example, the gauge data indicates typical daily streamflow rates ranging from around 15 L/s to 60 L/s (and frequently exceeding 100 L/s), which is much greater than the magnitude of baseflow simulated by the model (indicating much larger volumes of water available to interact with the groundwater system).

To examine the potential influence of this surface water contribution, the historical gauged flow data has been used to direct flow into the upstream segment of Bungalook Creek (as an inflow component to the SFR segment, using average flow rate per stress period). This approach is an approximation, as it does not separate contributions from baseflow that may have accumulated from upstream of the gauge or compensate for stream loss due to leakage. Nonetheless, it provides a useful point of reference for understanding the potential influence of much larger volumes of surface water flow than baseflow, enabling the SFR cells to feed recharge to the water table when and where the flow data indicates more than sufficient volumes available to do so.

Figure 25 and Figure 26 show the modelled drawdown (lowering) of the water table due to historic extraction, without and with the surface water flow contribution respectively. The water table drawdown is similar at and around the quarry, with two important differences. Firstly, the lowering of the water table in the downstream section of Bungalook Creek is minimised when more realistic volumes of streamflow are allowed to interact with the groundwater system. Secondly, the magnitude of water table drawdown along Bungalook Creek, to the south of the quarry, is smaller.

The distribution of drawdown contours in both scenarios is also influenced by the geology and the spatial variability in the calibrated material properties. For example, the depressurisation effect simulated within the Mt Evelyn Rhyodacite is more extensive along zones of higher hydraulic conductivity (to the south) and the shape of the drawdown contours is modified along the contact between the Coldstream Rhyolite and Mt Evelyn Rhyodacite. Localised zones of water table drawdown are also simulated to the west-northwest of the quarry, where the water table is located below the bottom of the Alluvium (in the underlying layers where the depressurisation effect is more pronounced). Figure 27 shows the relationship between the simulated drawdown and geology. The contact between the Coldstream Rhyolite and Mt Evelyn Rhyodacite dips to the east-southeast, with the shape of the water table drawdown contours in the quarry influenced by the position of the contact exposed along the floor of the quarry. This is demonstrated in Figure 28, which shows the modelled geology exposed in the quarry.

It should be noted that the magnitude and extent of simulated drawdown from historical extraction is not significant enough to cause major changes to the dynamics of surface water – groundwater interactions along Bungalook Creek. This is supported by the modelled hydrographs at the site bores and calibration statistics, which remain similar with and without the routing of total streamflow (as shown in Figure 29 and Figure 30). The main difference can be seen in the hydrographs of shallow bores close to Bungalook Creek, where the declining trend during dry periods (such as the Millennium Drought) is subdued by induced stream leakage (albeit the magnitude of inter-annual seasonal fluctuations can be greater with leakage of surface water). Similarly, there is very little difference to the simulated groundwater seepage rate into the quarry (Figure 31).

The modelled surface water – groundwater interaction along Bungalook Creek varies spatially and temporally depending on the seasonal differences in recharge, evapotranspiration and stream flow. During dry periods there is limited runoff and little to no baseflow due to a lower water table, leading to no downstream flow at the Fussell Road gauge. During wet periods, high runoffs cause a rapid increase in stream flow, leading to induced leakage to the groundwater system. As the flow in the stream recedes, the higher water table from prior leakage and recharge results in an increase in baseflow. While the modelling assumes an average (time-constant) stage, the fluctuations of the water table and induced leakage (enhanced by surface water flow routing) allows the seasonal dynamics of the surface water – groundwater interaction to be replicated in a sensible manner. This is demonstrated in Figure 32, which compares the stream leakage simulated by the model in a very dry period (end of the Millennium Drought) and a wet period when surface water flow is incorporated. Positive leakage implies stream loss (losing condition) and negative leakage implies baseflow (gaining condition). The leakage rates are expressed per unit length of each stream reach, to provide a consistent measure of flow rate. The figure shows the loss of stream leakage during the dry period, indicating no flow reaching the Fussell Road gauge (consistent with the observed flow data). During the wet period, areas of baseflow are simulated due to the higher water table. For an average condition, the modelled surface water-groundwater interactions would be some average of the two extreme conditions presented.

Figure 33 also compares the simulated depth to water table for the two extreme climate conditions, calculated by subtracting the modelled water table from the model top elevation (modified at the quarry using the modelled floor elevation at the time of dry and wet periods). Due to the variability in topography and the presence of the quarry, the depth to water table surface is not smooth. The purpose of the figure is to simply highlight the influence of prevailing climate conditions on the water table depth, with a broader area of shallow water table simulated along Bungalook Creek under a wetter condition (consistent with more baseflow/gaining sections).

The effect of surface water routing becomes more critical under the proposed expansion scenario due to the potential for much larger drawdown to extend to Bungalook Creek. This effect is discussed further in Section 4.

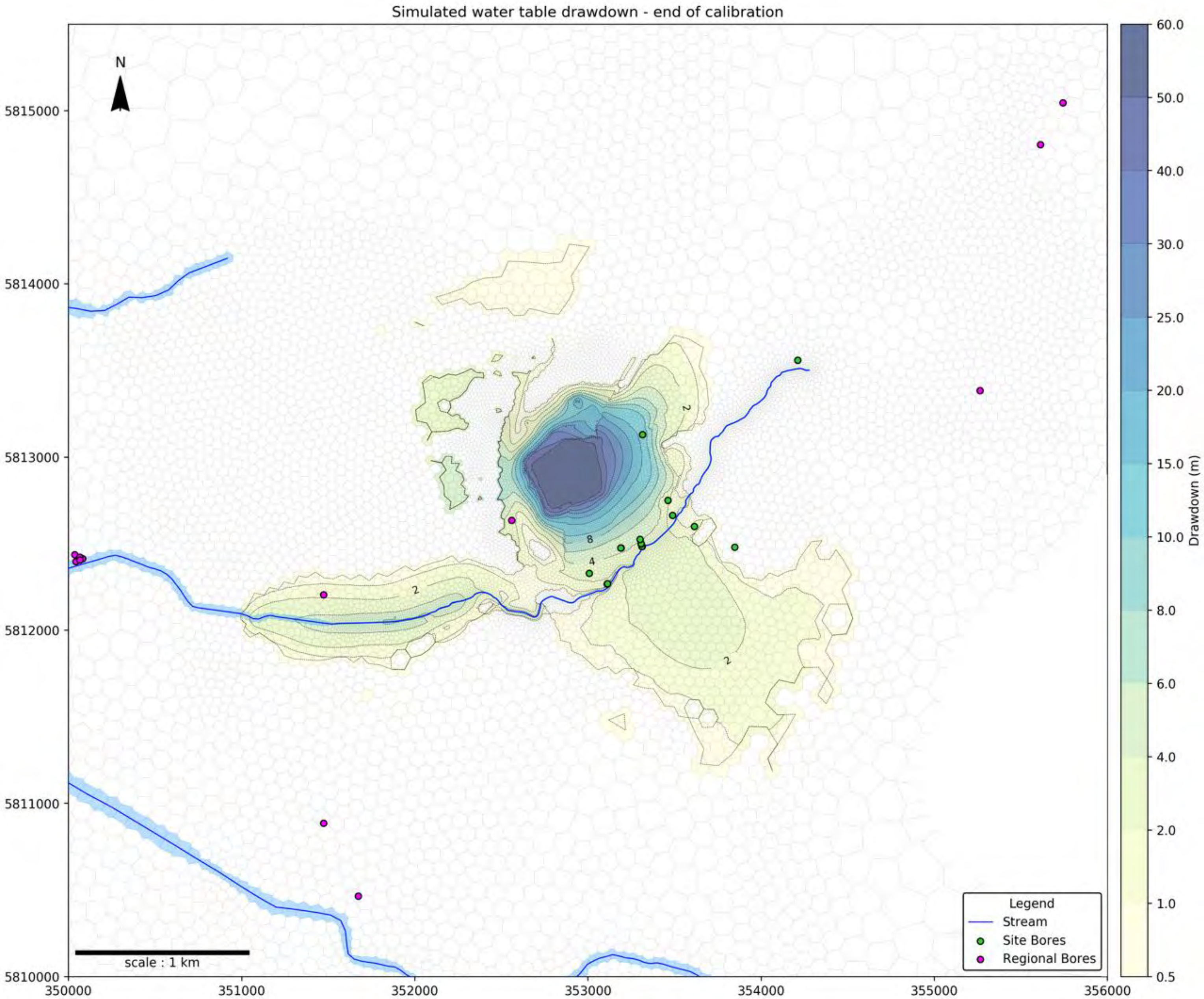


Figure 25 Modelled drawdown at the end of calibration – baseflow only

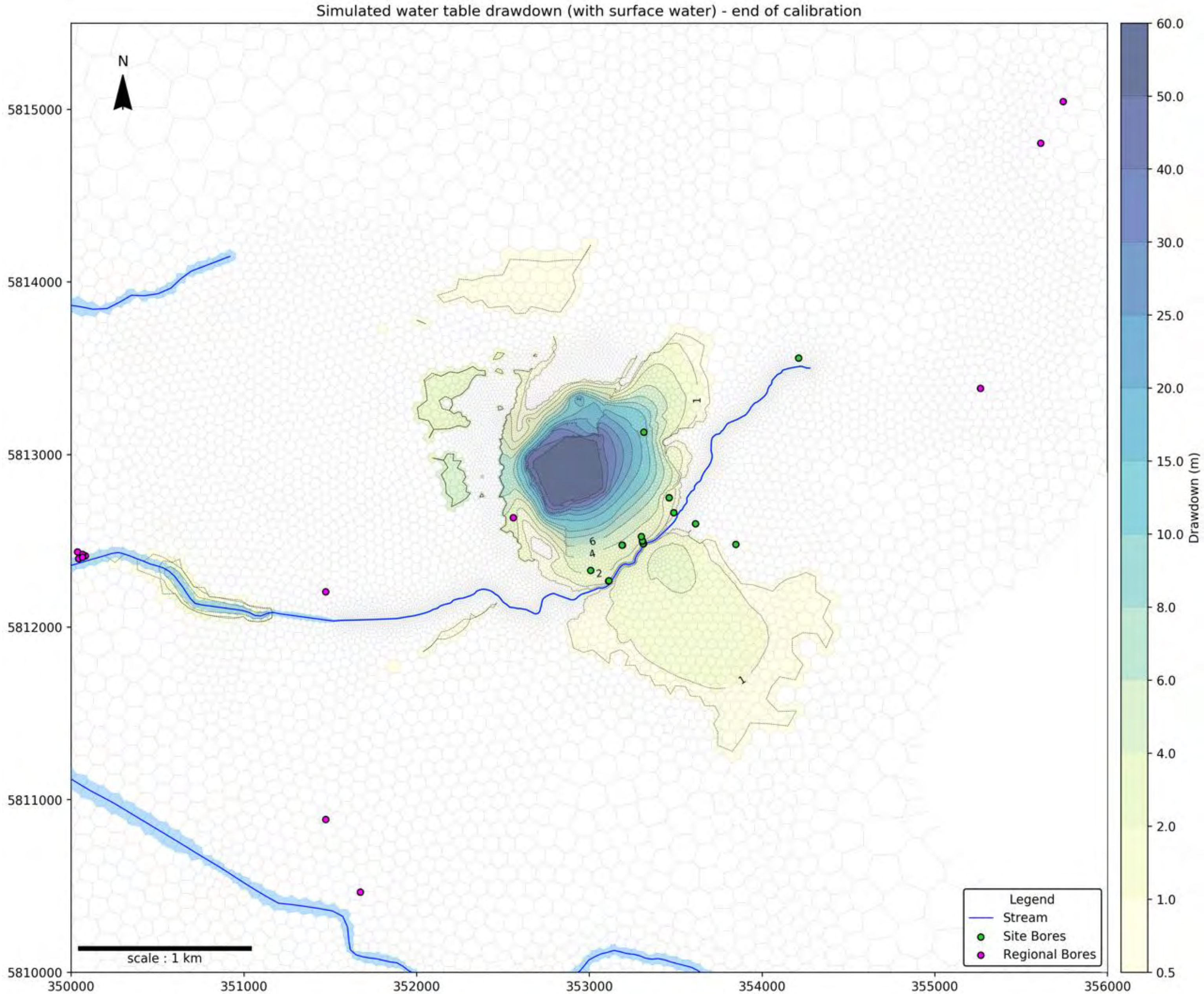


Figure 26 Modelled drawdown at the end of calibration – with surface water flow

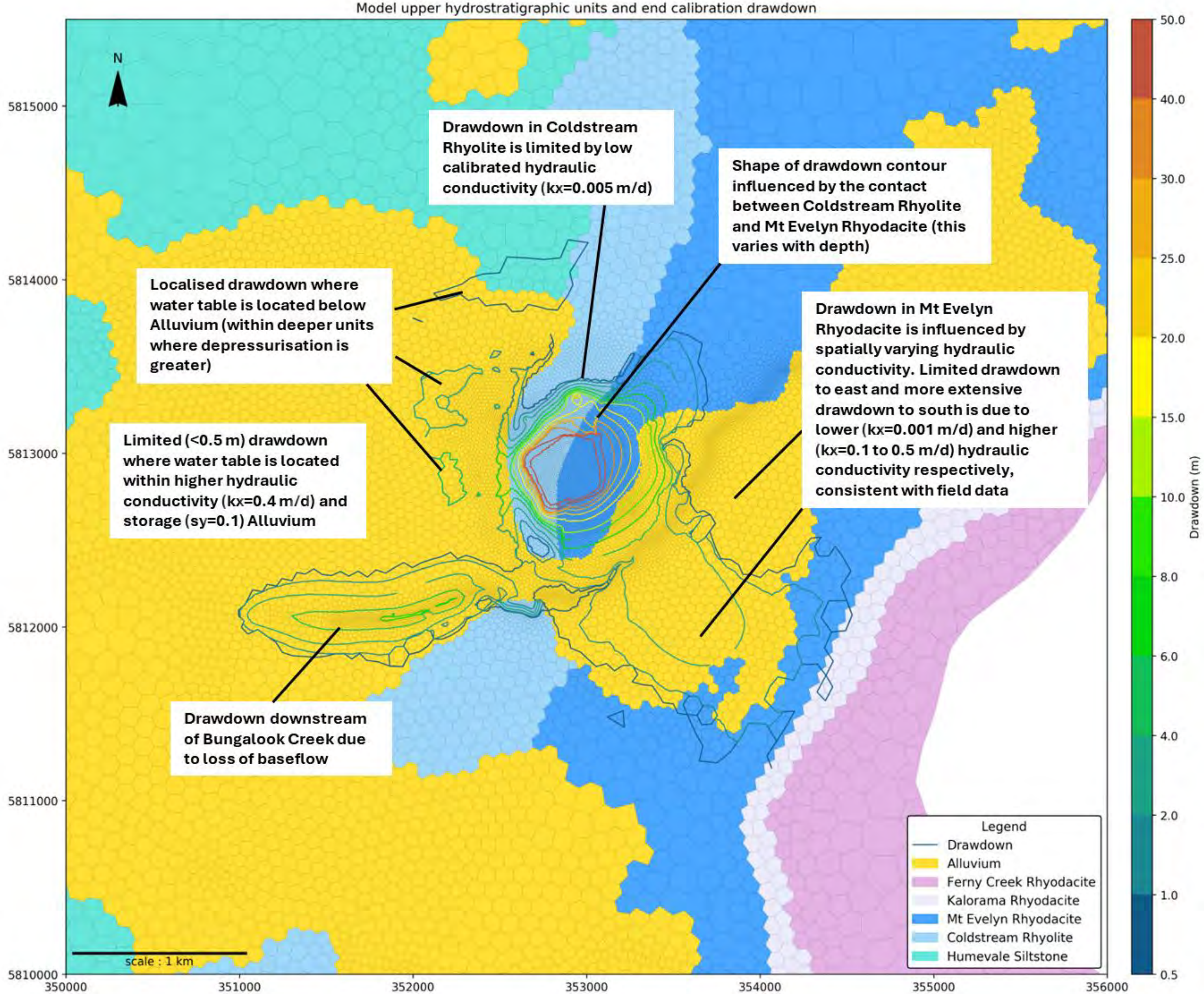


Figure 27 ***Relationship between modelled geology and water table drawdown***

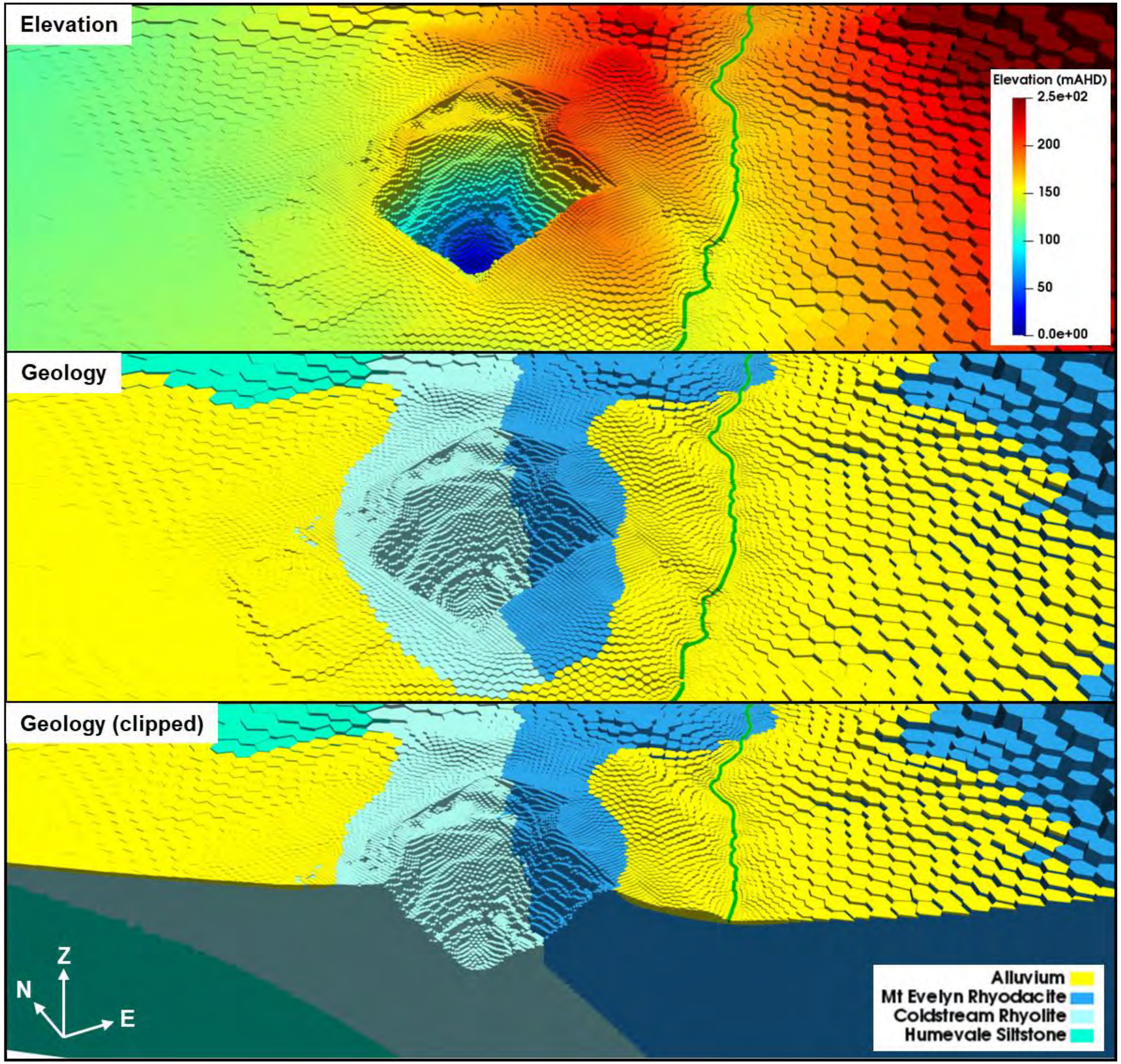


Figure 28 Quarry and modelled geology – with vertical exaggeration

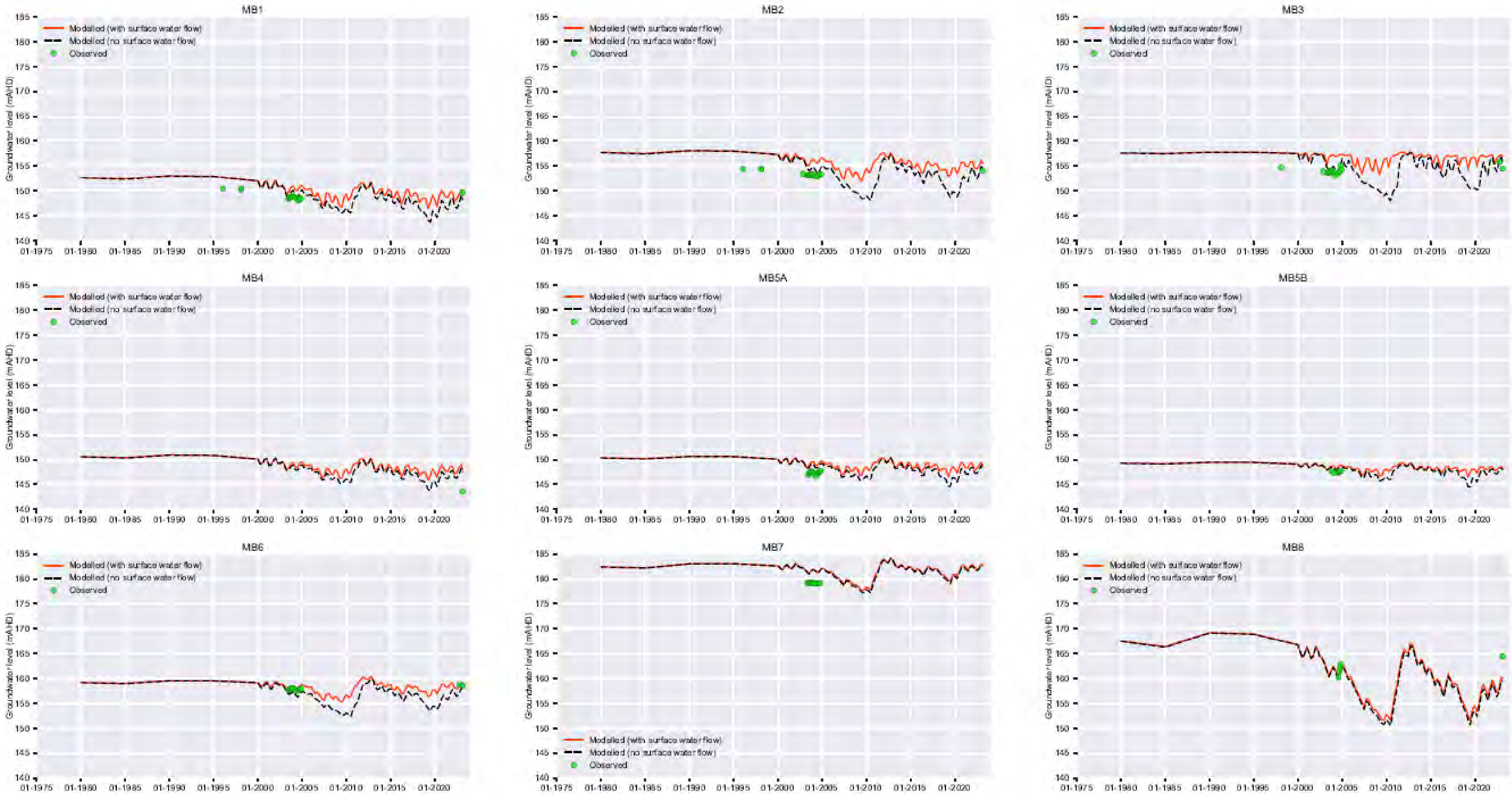


Figure 29 ***Calibrated hydrographs – with and without surface water flow - bore MB1 to MB8***

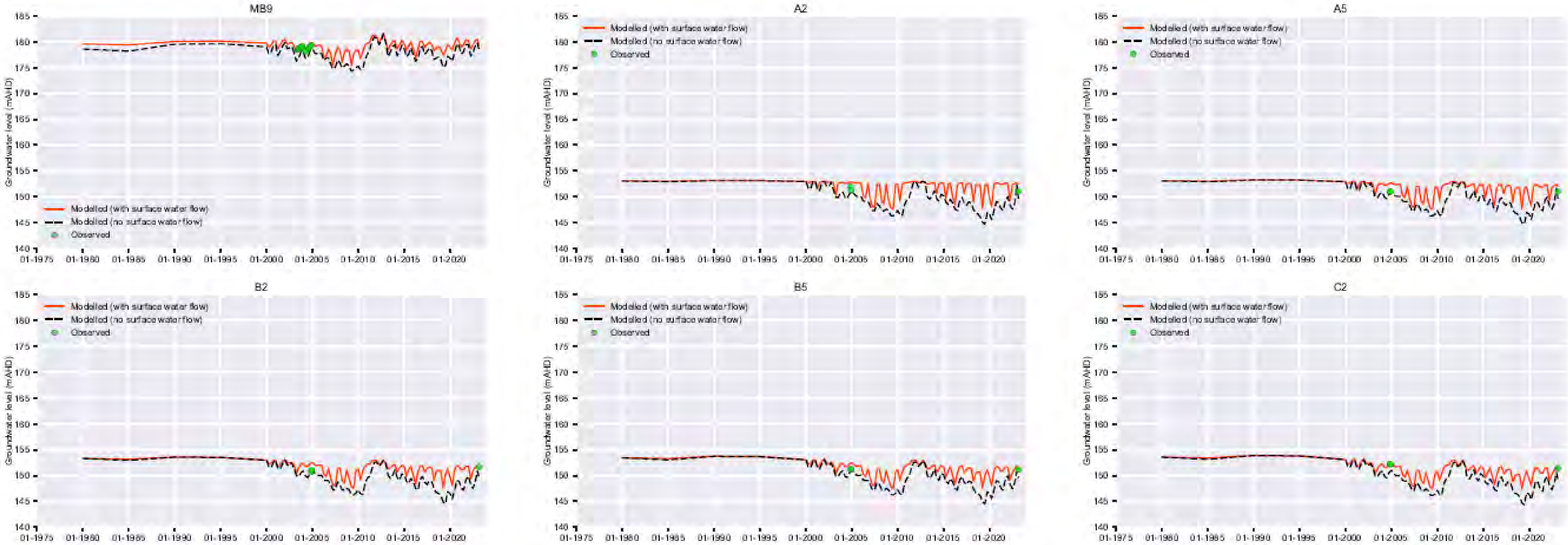


Figure 30 *Calibrated hydrographs – with and without surface water flow - bore MB9 to C2*

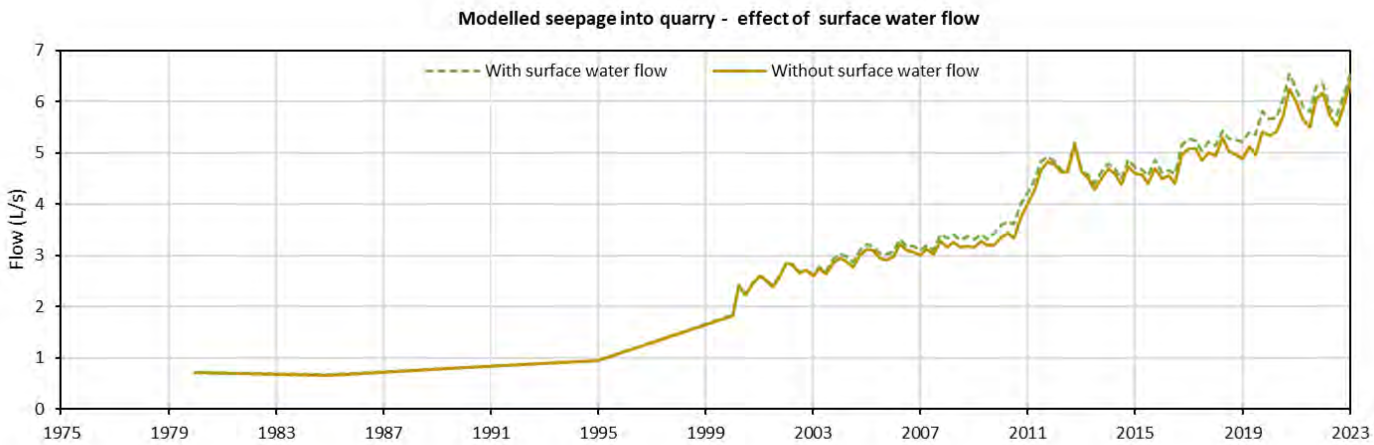


Figure 31 *Modelled groundwater seepage into quarry - with and without surface water flow*

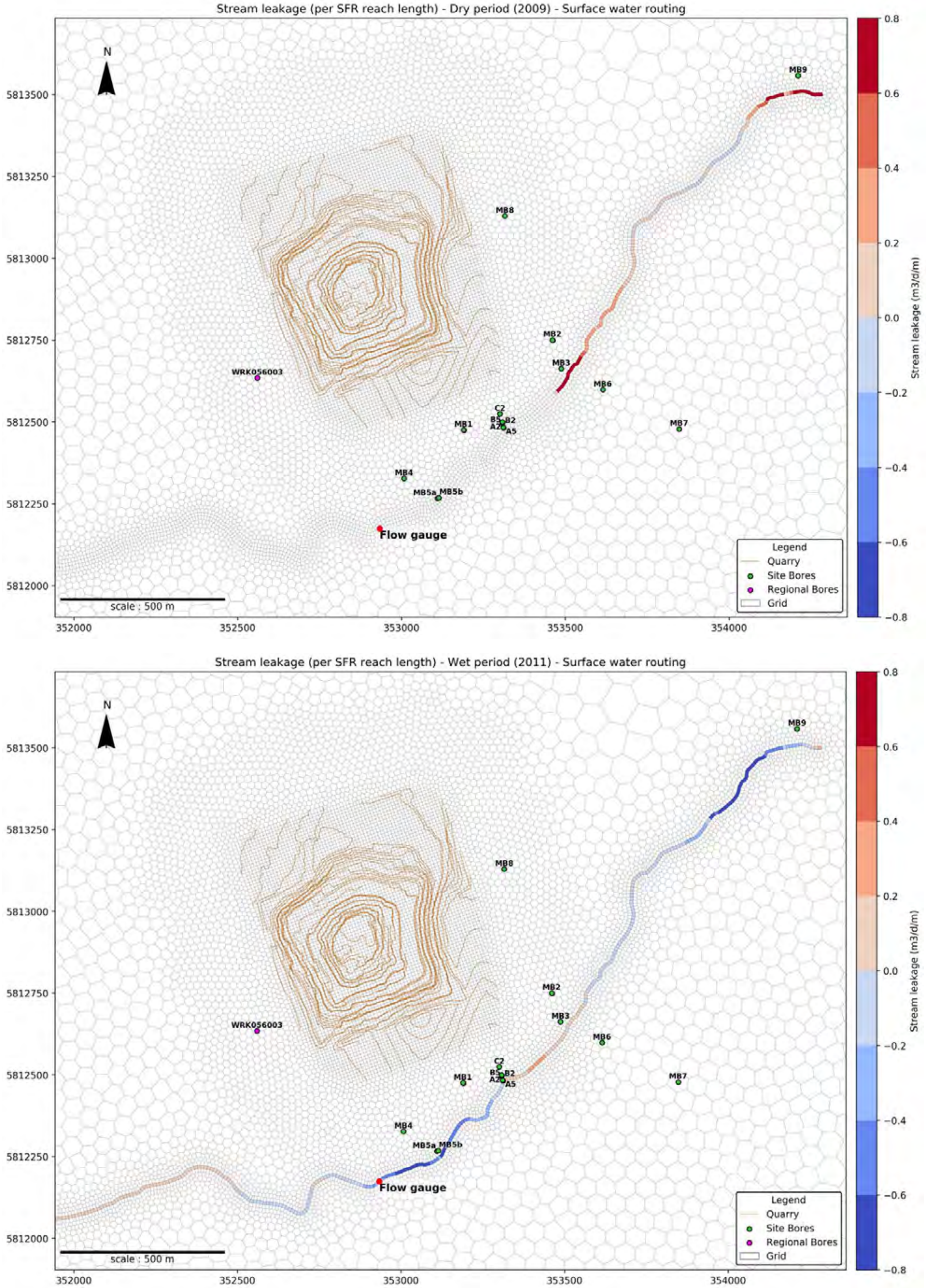
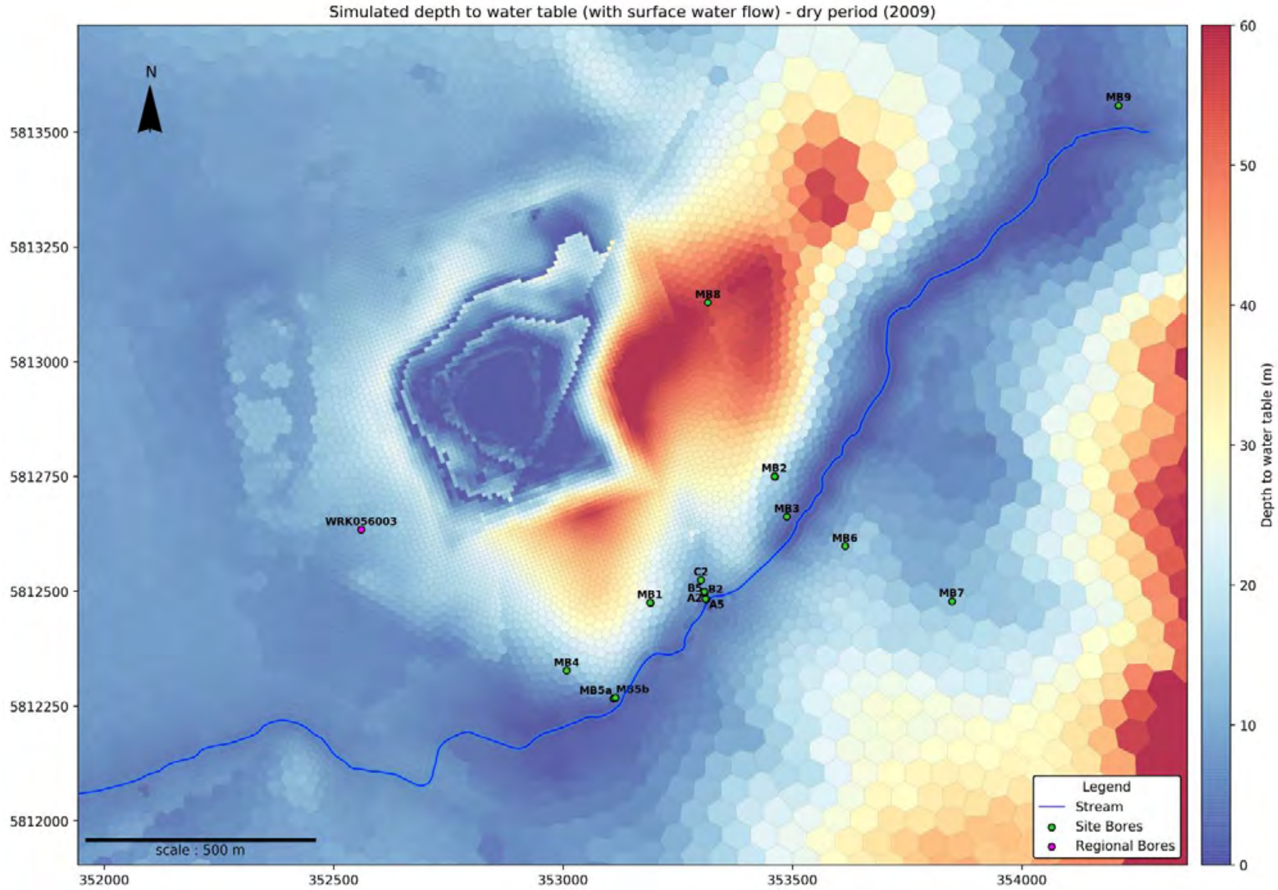


Figure 32 Modelled surface water-groundwater interactions – dry and wet periods



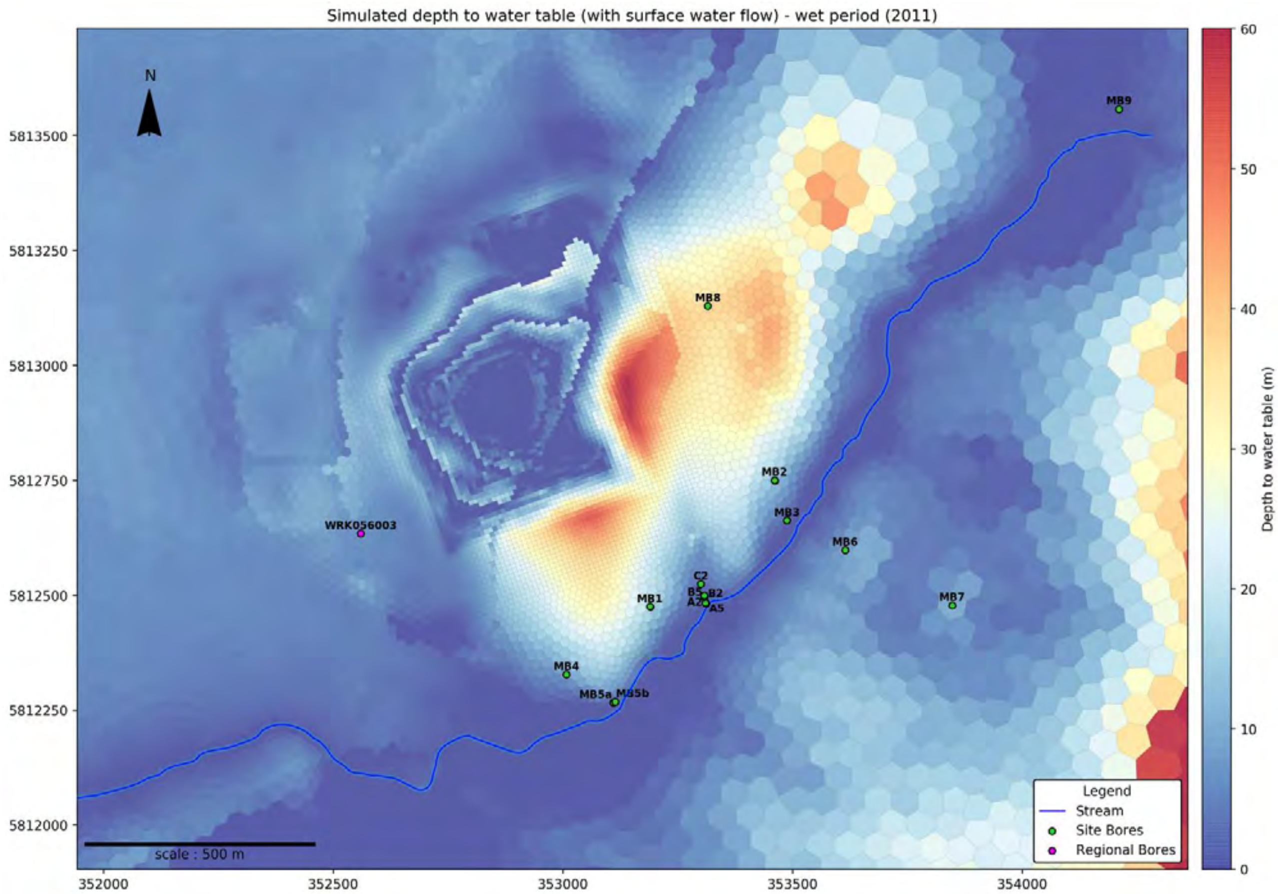


Figure 33 Simulated depth to water table – dry and wet periods

4. Model prediction

4.1 Predictive modelling setup

The purpose of predictive modelling is to simulate the hydrogeological effects of the proposed expansion of the quarry and subsequent rehabilitation, and to quantify potential changes to groundwater levels and fluxes (water balance) arising from these effects.

The proposed expansion would involve widening of the quarry footprint and deepening of the quarry base over a period of around 40 years. This will be followed by backfilling of the quarry, which would occur in 5 stages (each typically lasting around 10 years). The total predictive modelling period is 94 years, which is simulated using 94 yearly stress periods.

Time-varying recharge and evapotranspiration are generated using LUMPREM, based on historical daily rainfall and evaporation data used in model calibration and repeated as necessary i.e. from 1975 to end of 2022, and repeated until the end of year 94. As outlined in Section 3.1.1, the calibration period corresponds to the post-1975 reference period used in the climate change guidelines (DELWP, 2020) and is considered a sensible choice for assessing project impacts under a wide range of natural climate variability as well as projecting the effects of climate change into the future (see Section 5.1). The synthetic daily rainfall for the predictive modelling period is shown in Figure 34.

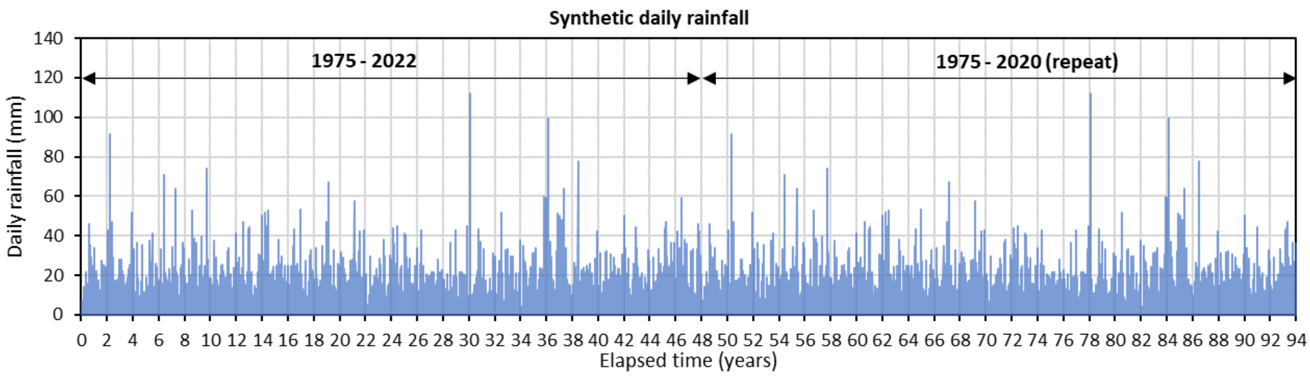


Figure 34 Synthetic daily rainfall for predictive modelling

The future extraction and subsequent backfilling are simulated using the DRN package, as per the historic extraction. The extent and elevation of DRN cells are derived from the currently available mine plans and are assumed to vary linearly between the key stages. These are shown in Figure 35 and Figure 36 and a 3d view of the modelled quarry is presented in Figure 37, comparing the existing and expanded quarry voids.

The change in material properties due to backfilling is simulated using USG-Transport's Time-Variant Materials (TVM) package. The material properties are changed at the end of expansion (end of year 40), when the model cells within the quarry void are fully dewatered and before re-saturation commences in response to backfilling. The material to be used for backfilling is currently not known although it is likely to be generally low hydraulic conductivity material comprising of a mixture of fine sand, silt and clay. For the purpose of predictive modelling, specific yield of 0.1 and horizontal and vertical hydraulic conductivity of 0.1 m/d and 0.01 m/d have been assumed for the backfill respectively. Specific storage is retained as per the in-situ material, as the recovery of the water table (unconfined condition) would be insensitive to this parameter.

In order to clearly separate out the effects of quarry expansion from background hydrogeological stresses, a suitable base case scenario is required. Due to the presence of the existing quarry, there would be antecedent effects on the hydrogeological system as it tends towards dynamic equilibrium if the existing quarry were to remain in place without expansion. For the purpose of predictive modelling, a base case scenario has assumed ongoing presence of the existing quarry (the current condition remaining in perpetuity) while an expansion scenario assumed expansion and deepening of the quarry. The effect of the expansion is quantified as the difference between the two scenarios, as shown in Figure 38, with the maximum impact (drawdown) occurring at the end of expansion in year 40.

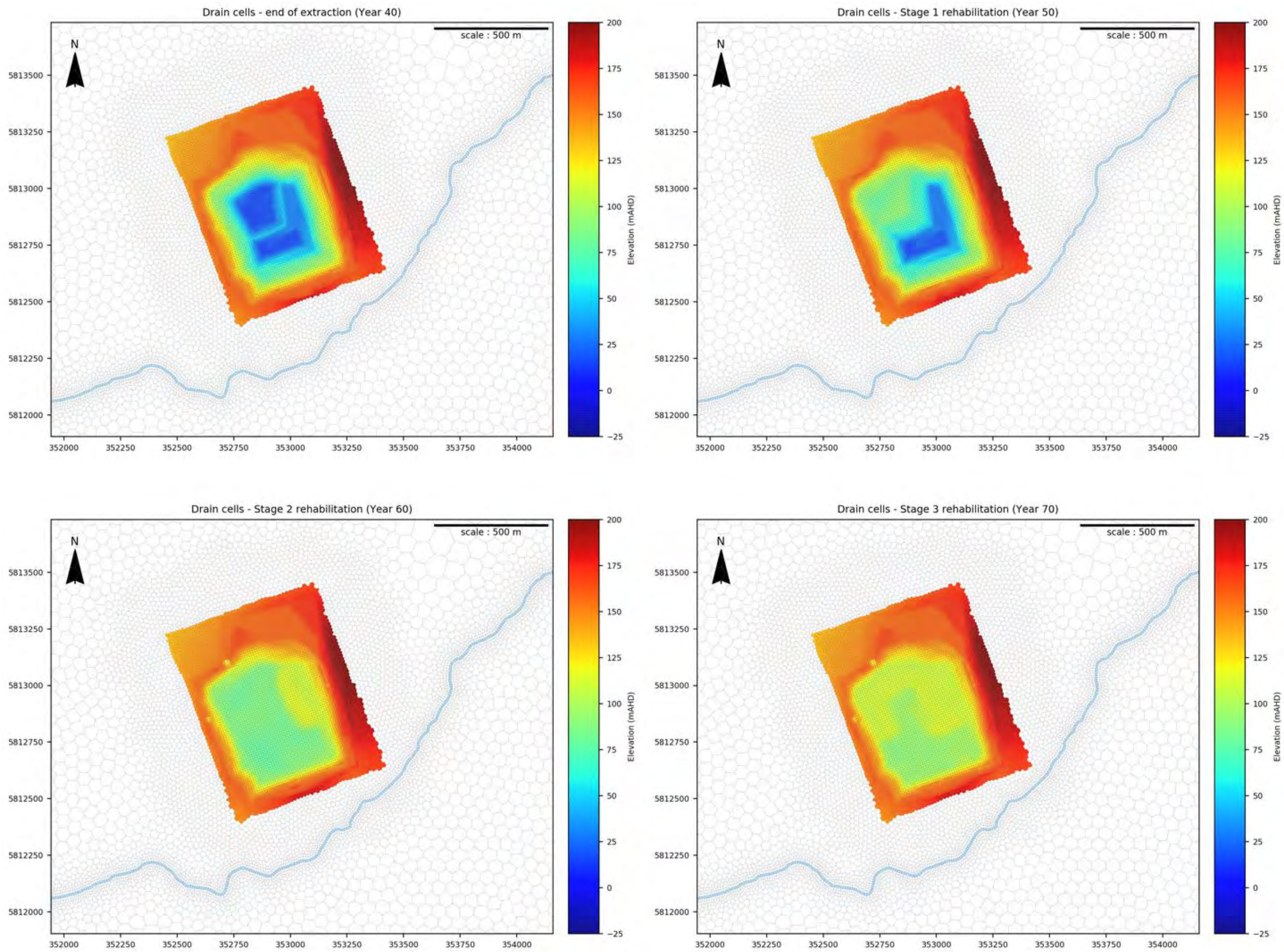


Figure 35 *Drain elevation – year 40, 50, 60 and 70*

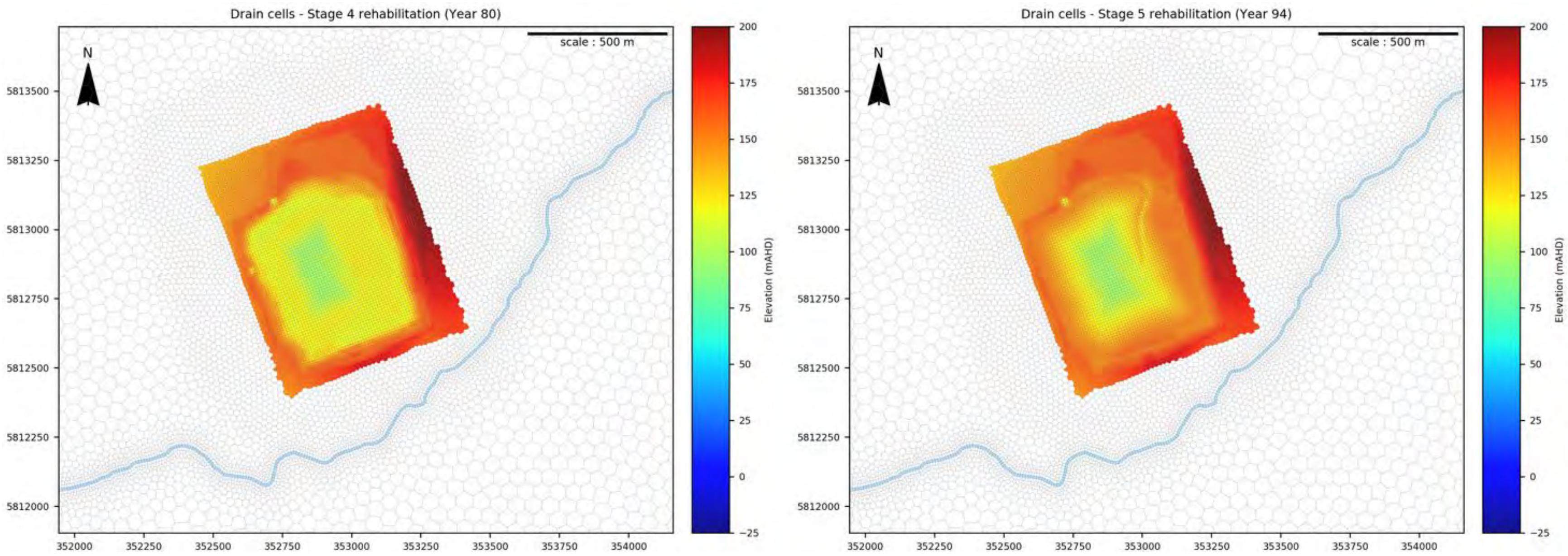


Figure 36 Drain elevation – year 80 and 94

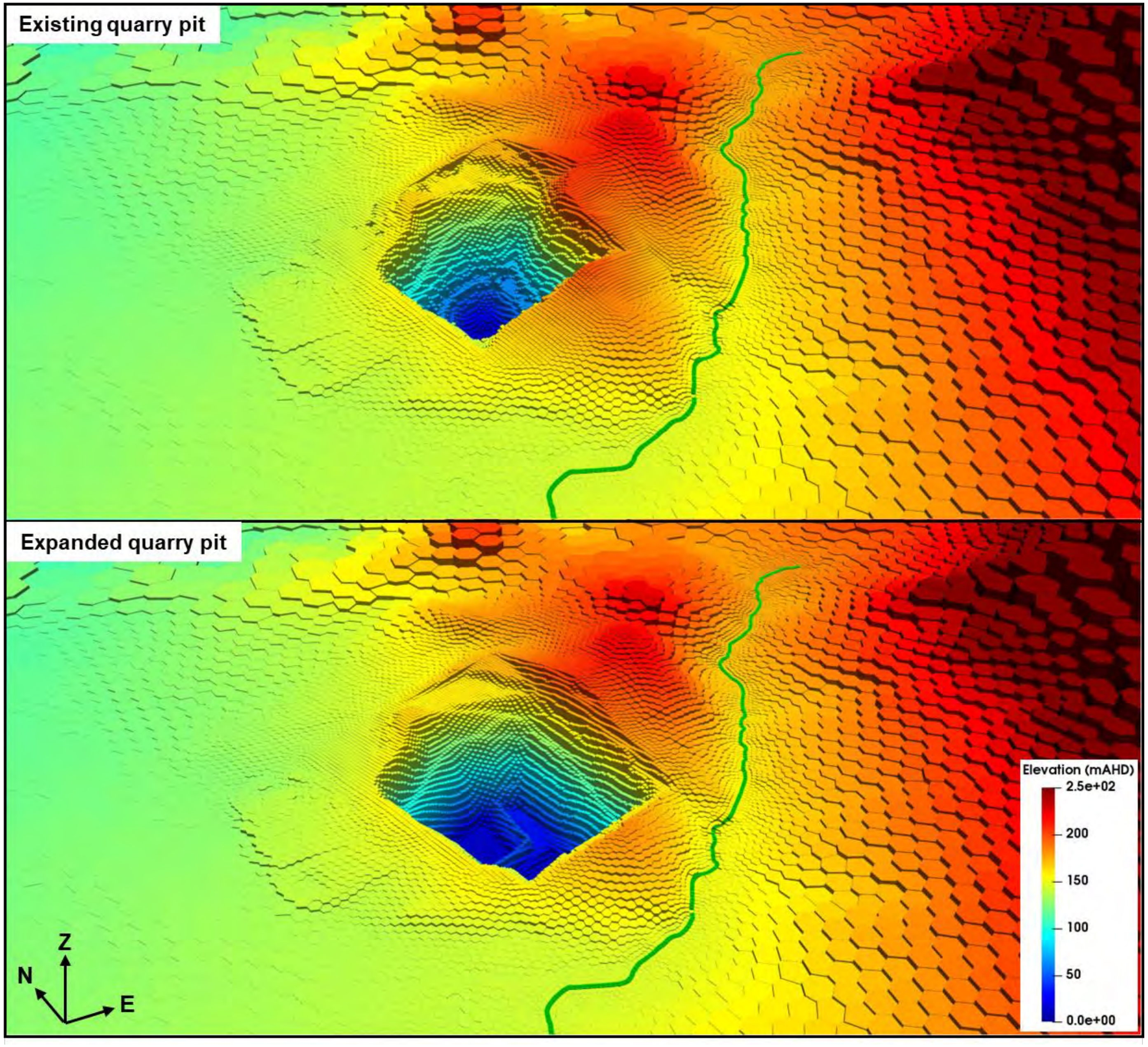


Figure 37 Quarry elevation – 3d view of existing and expanded quarry

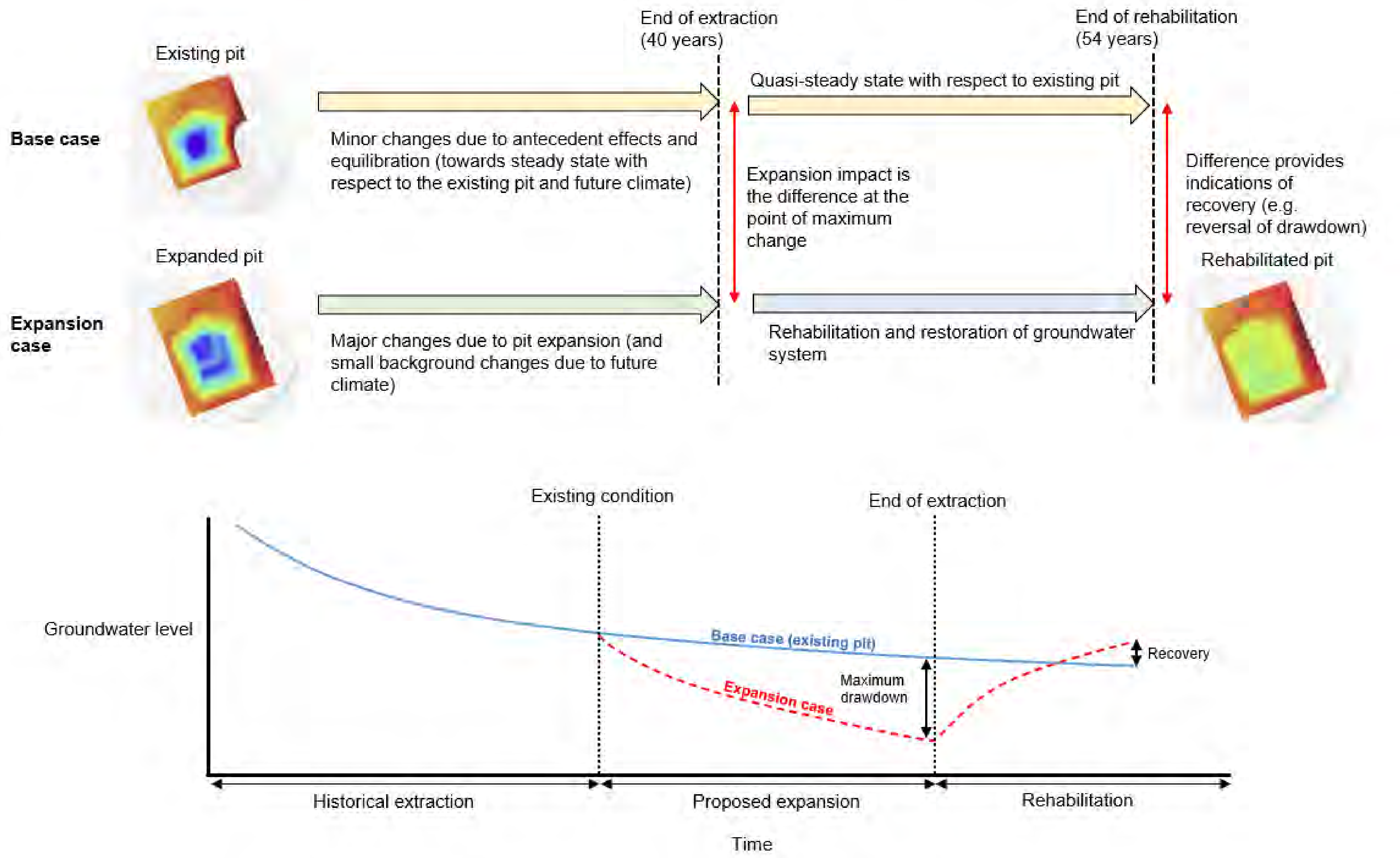


Figure 38 Predictive modelling set up – base case and expansion case

Due to the expansion of the quarry towards Bungalook Creek, there is the potential for the water table drawdown to increase near the creek, resulting in greater induced stream leakage. Although the modelling has been undertaken with a focus on the groundwater (baseflow) component of streamflow, neglecting the contributions from much larger volumes of surface water may not lead to a realistic understanding of the loss of streamflow and the effect of stream leakage on the water table near Bungalook Creek. In order to address this, predictive modelling results are presented with respect to the following two scenarios:

1. **Scenario 1 - baseflow only**, as per the previous modelling undertaken by Golder (2006).

   In this set up, the flow in the creek is maintained by baseflow which occurs when/where the water table is above the elevation of the stream stage along the modelled stream network.

   When drawdowns occur as a result of quarrying and the water table is reduced such that it falls below the stream stage, baseflow into the stream will cease. This is considered highly conservative with respect to drawdown predictions, which would be applicable only under an extreme condition with an extended period of little to no surface water flow contribution.

   Based on the stream gauging information the incidences of no flow are limited throughout the available record.

2. **Scenario 2 – with surface water flow**.

   This is considered to provide more realistic indications of water table drawdown near Bungalook Creek and loss of flow downstream due to induced leakage. With this approach, streamflow is routed down the stream network. When drawdowns from the quarry extend such that the groundwater level falls below the stream stage, there will be no groundwater contribution to flow in the waterway i.e. as per Scenario 1. Streamflow may continue to occur, however, as it could be derived from that generated from runoff within the broader catchment.

   If there is flow in the waterway but the groundwater level has been drawn down below the stream stage, this will create a hydraulic gradient causing a portion of this streamflow to leak downwards and recharge the groundwater system. This, in turn, influences the groundwater behaviour elsewhere i.e. if some streamflow is lost through leakage, it results in less streamflow further downstream being available to leak and recharge groundwater in these downstream areas (where the influence of drawdown may have extended to).

   The numerical model has been set up to simulate such behaviour. In lieu of undertaking a detailed catchment runoff model, the historical streamflow data has been used (repeated, as per the climate data) to calculate annualised average flow per stress period, which is assigned to the upstream segment of the SFR boundary as inflow. As discussed, in Section 3.3, this approach is approximate and intended to demonstrate the potential influence of stream leakage under more realistic flow conditions. In this scenario, both the base case and expansion case model runs are repeated with the surface water flow applied to the SFR boundary.

4.2 Predicted changes to groundwater level

4.2.1 Scenario 1 – baseflow only

Figure 39 presents the contours of predicted water table drawdown at the end of extraction (year 40), calculated as the difference in the computed water table between the base case and expansion case. As the base case already accounts for the effect of the existing quarry, the drawdown contours shown in the figure represent the “additional” drawdown that would occur directly as a result of the expansion to the south i.e. limited additional drawdown is simulated to the north as the water table has already been depressed by the existing quarry.

The largest drawdown is predicted at the quarry, with the cone of depression extending across Bungalook Creek. The predicted drawdown is greater to the south, due to the expansion of the quarry in this direction and also partly due to the higher hydraulic conductivity assigned in this region (near the shear zone and Bungalook Creek). The water table is simulated to become locally disconnected from Bungalook Creek, where 25 m to 30 m of drawdown is predicted.

Figure 40 presents the contours of predicted drawdown during the first 40 years of rehabilitation. The magnitude and extent of drawdown is shown to decrease over time as the quarry is backfilled and rehabilitated. An area of drawdown is predicted along the downstream section of Bungalook Creek in Year 70. This corresponds to a wet period (in the synthetic climate) and drawdown is caused by the loss of baseflow downstream of the Fussell Road retarding basin.

The influence of climate variability and associated changes to baseflow on the water table along Bungalook Creek can be seen in a drawdown hydrograph presented in Figure 41. This is a composite time series representing the maximum drawdown calculated at the end of each stress period anywhere along Bungalook Creek (adjacent to the southern boundary of the quarry, between gauge 228369A and bore MB3). Drawdown is predicted to increase at a greater rate from around year 22, corresponding to the start of a dry period (equivalent to the start of the Millennium Drought) and the expansion of drawdown cone as the quarry is deepened. Drawdown in excess of 30 m is predicted for several years after the end of extraction in year 40, before recovery occurs in response to backfilling and rehabilitation. The maximum drawdown at the end of rehabilitation is around 2 m, near gauge 228369A, although this is localised and drawdown is generally less than 1 m along most of Bungalook Creek.

A hydrograph at the point of maximum drawdown along Fussell Road is shown in Figure 42. This represents the western boundary of the quarry adjacent to industrial sites, where drawdown has the potential to modify the groundwater flow directions and transport of solutes associated with these sites. The maximum drawdown simulated at this location is around 4 m.

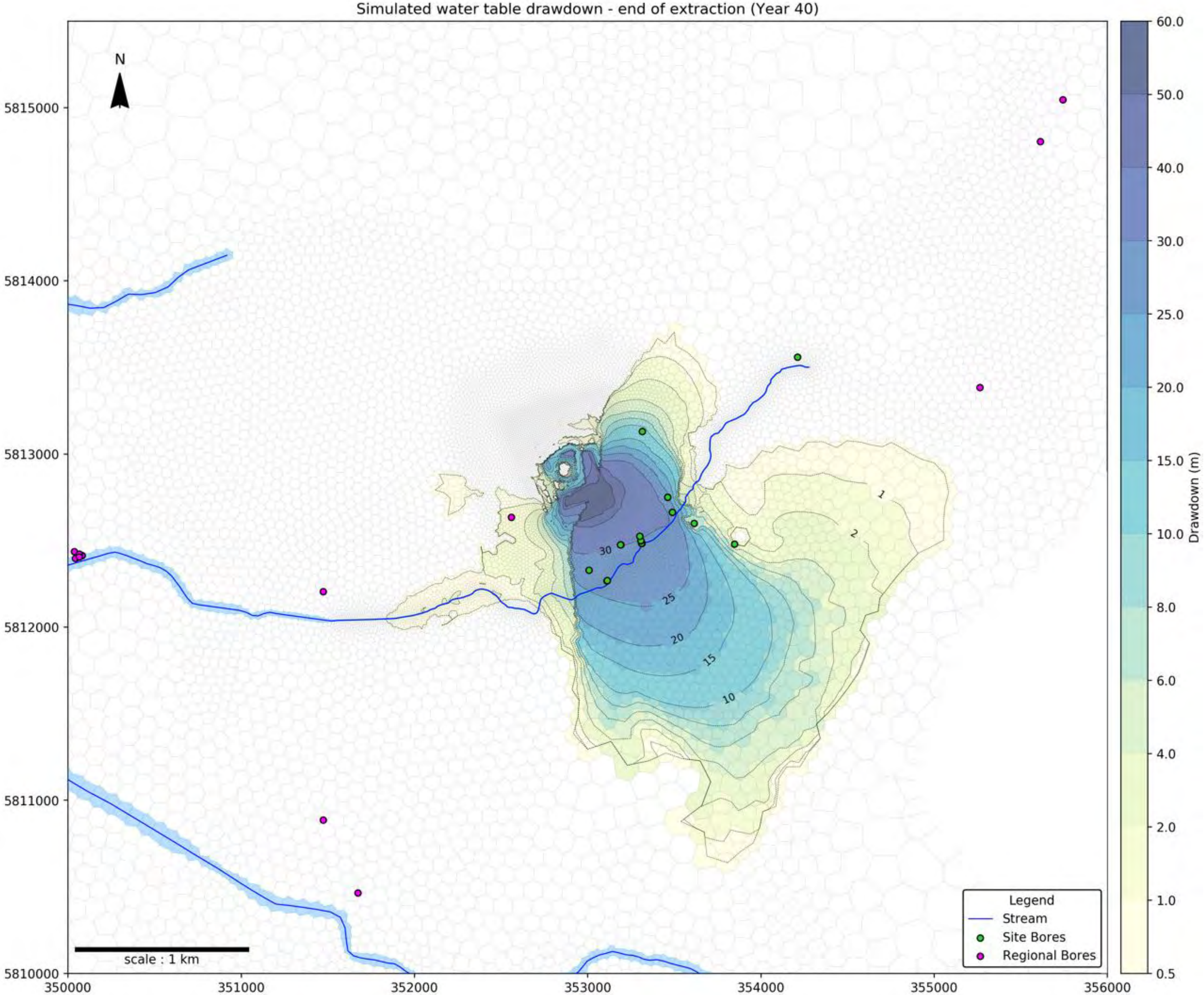


Figure 39 ***Simulated water table drawdown at end of extraction (baseflow only)***

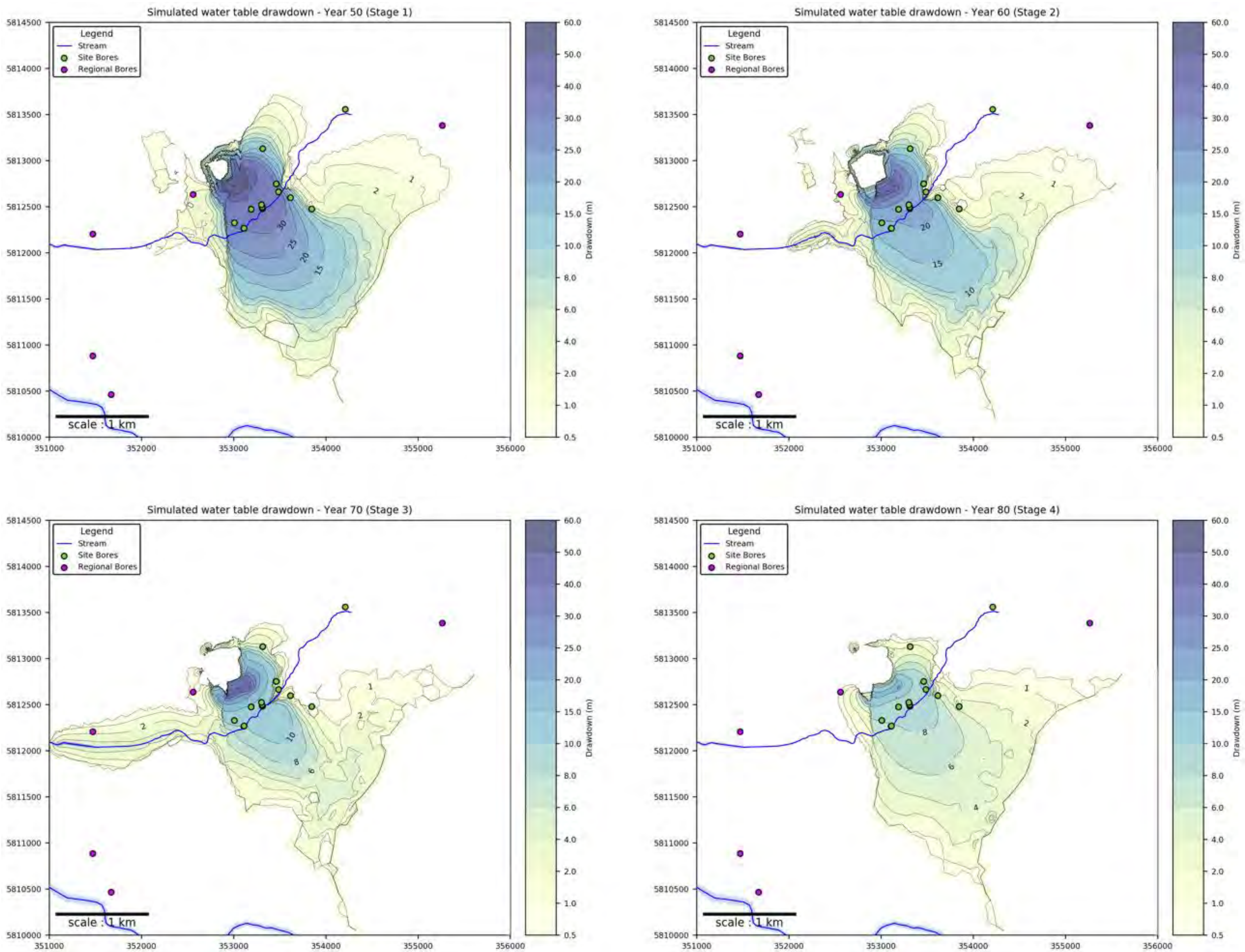


Figure 40 ***Simulated water table drawdown during rehabilitation (baseflow only)***

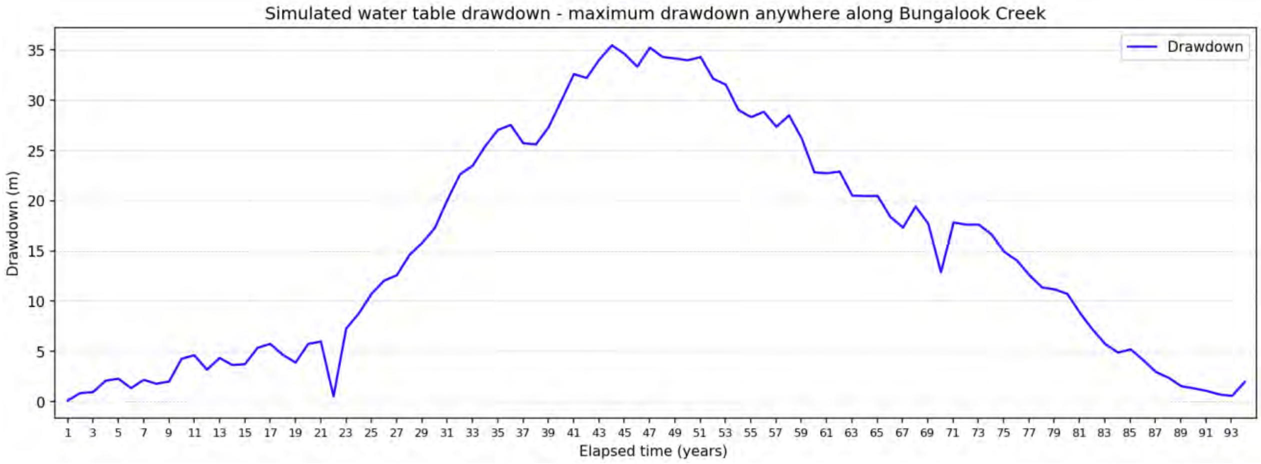


Figure 41 ***Bungalook Creek maximum drawdown hydrograph (baseflow only)***

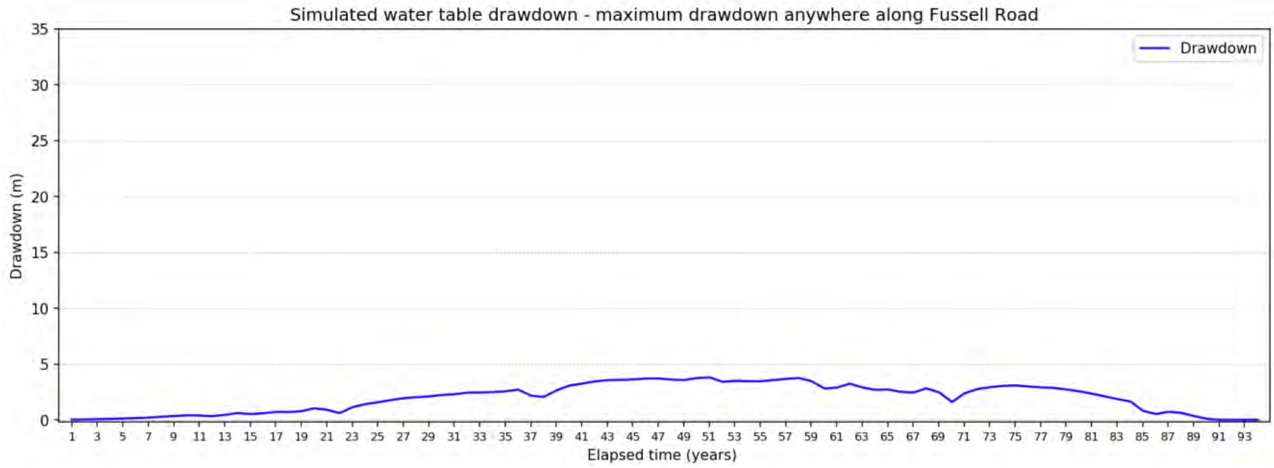


Figure 42 ***Fussell Road maximum drawdown hydrograph (baseflow only)***

4.2.2 Scenario 2 – surface water flow

Figure 43 presents the contours of predicted water table drawdown at the end of extraction (year 40), with surface water flow incorporated. The magnitude of drawdown predicted along Bungalook Creek is around 10 m or less, which is less than half of the maximum drawdown predicted when only baseflow is assumed. This is the result of induced leakage from Bungalook Creek when the water table is lowered below the stream level and there is sufficient streamflow to supply recharge to the water table. The induced leakage leads to less streamflow reaching the downstream section of Bungalook Creek, resulting in localised drawdown along the creek.

The contours of predicted drawdown during the first 40 years of rehabilitation are shown in Figure 44. The magnitude and extent of drawdown is shown to decrease over time as the quarry is backfilled and rehabilitated. The model indicates a faster rate of recovery when the additional stream leakage from surface water is incorporated.

Figure 45 shows the simulated hydrograph of maximum drawdown along Bungalook Creek. The maximum drawdown of around 23 m is predicted at year 35, corresponding to a dry period when total streamflow is limited. The water table is subsequently replenished by higher streamflow, with drawdown along Bungalook Creek generally limited to 3 to 10 m, depending on the prevalent climate and streamflow. The water table along Bungalook Creek is fully recovered by the end of the rehabilitation.

A hydrograph of maximum drawdown along Fussell Road (western boundary of the quarry) is shown in Figure 46. The maximum drawdown simulated at this location is around 4 m, similar to Scenario 1 (drawdown at this location is not sensitive to the influence of streamflow).

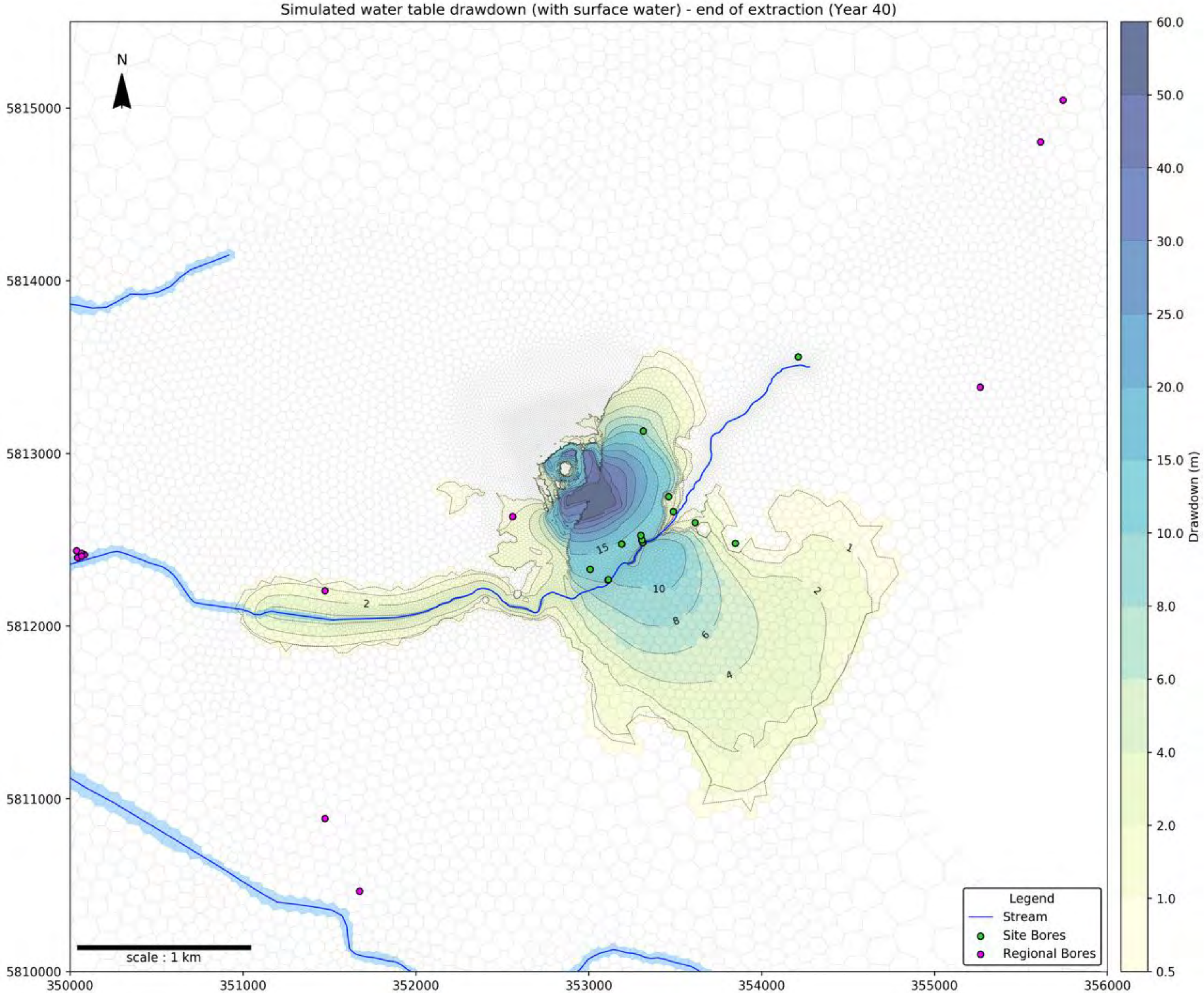


Figure 43 ***Simulated water table drawdown at end of extraction (with surface water flow)***

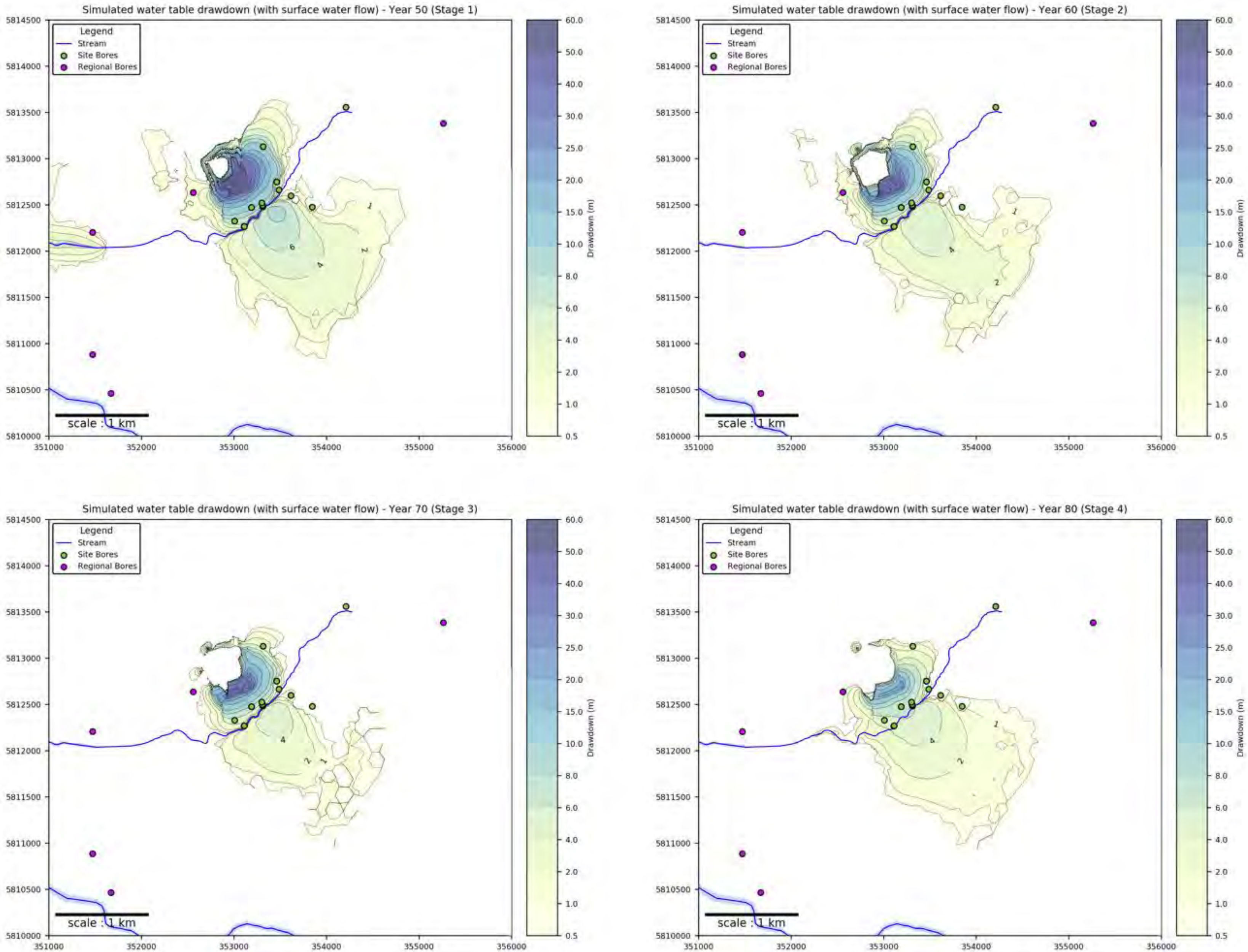


Figure 44 ***Simulated water table drawdown during rehabilitation (with surface water flow)***

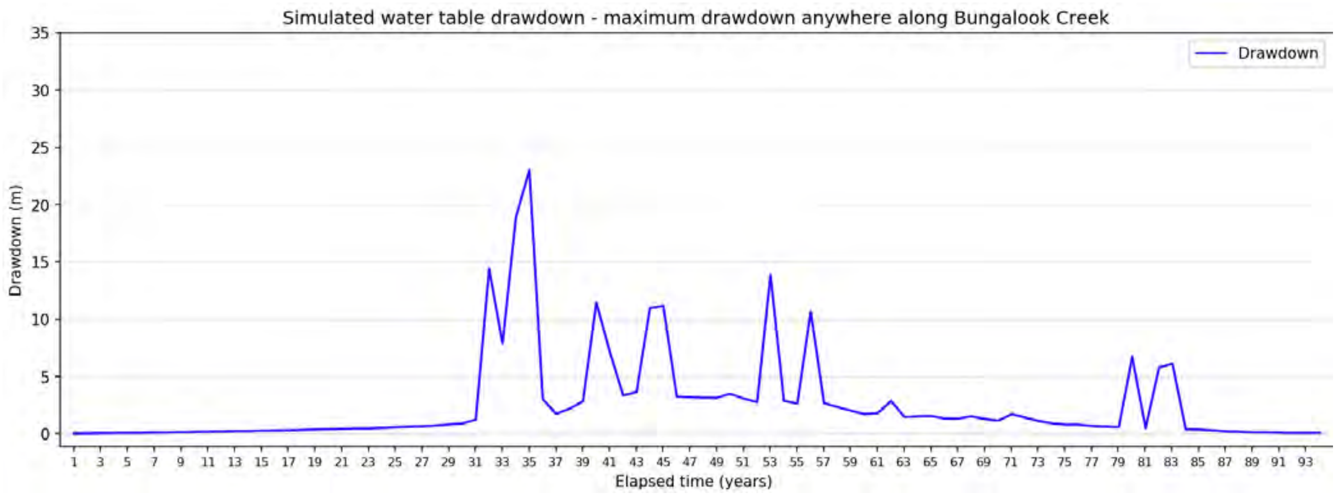


Figure 45 Bungalook Creek maximum drawdown hydrograph (with surface water flow)

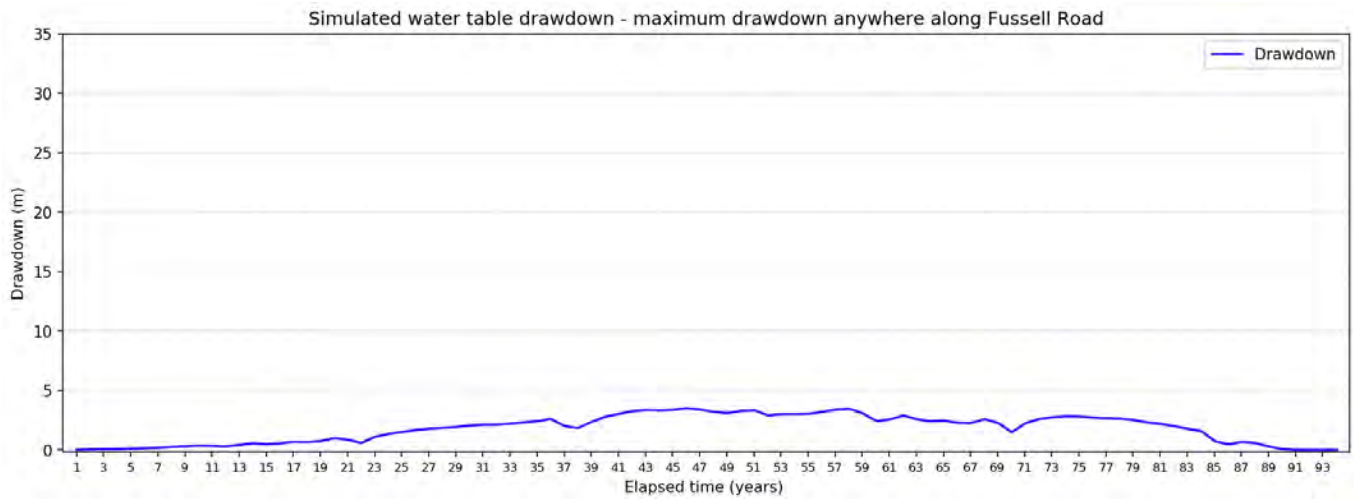


Figure 46 Fussell Road maximum drawdown hydrograph (with surface water flow)

4.3 Predicted changes to groundwater fluxes

4.3.1 Predicted changes to baseflow and impacts of stream leakage

Figure 47 compares the time series of predicted baseflow at gauge 228369A for the base case and expansion case, assuming no surface water contribution (Scenario 1). The lowering of the water table due to the expansion results in less accumulation of baseflow from upstream of the gauge. Additionally, the little baseflow accumulated is lost as leakage due to drawdown, resulting in little to no baseflow reaching the location of the gauge.

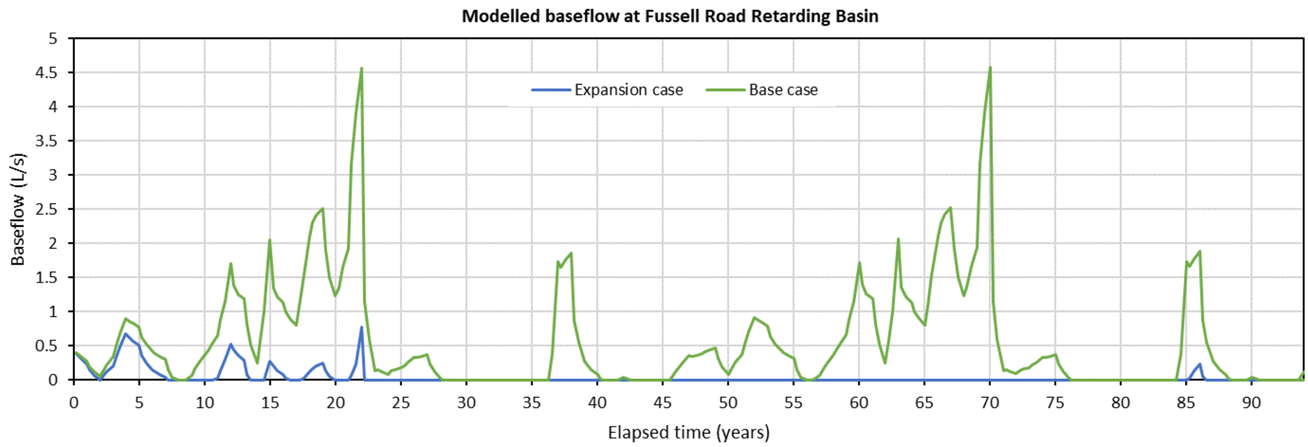


Figure 47 ***Modelled baseflow – Scenario 1***

Figure 48 compares the time series of predicted total streamflow at gauge 228369A for the base case and expansion case, when surface water flow is routed (Scenario 2). Also shown in the figure is the percentage of streamflow reduced by the quarry expansion. The modelling indicates that during dry periods, when the total streamflow is less than 10 L/s, all of the streamflow is lost as leakage due to the expansion of the quarry and associated drawdown of the water table. During these low flow periods, the loss of streamflow in the upstream section of Bungalook Creek results in localised drawdown along the downstream section of Bungalook Creek, as shown in Figure 43 (in year 40).

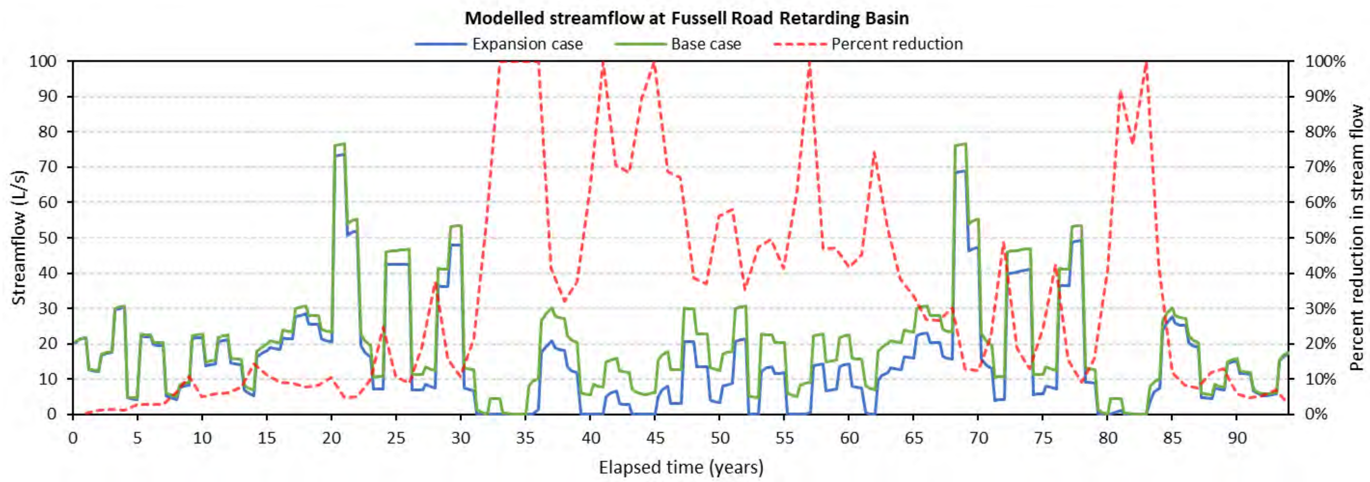


Figure 48 ***Modelled streamflow – Scenario 2***

4.3.2 Predicted changes to groundwater seepage

Figure 49 presents the predicted groundwater seepage rate into the quarry, with and without surface water flow. Also shown in the figure is the modelled recharge rate in the area of the quarry. The seepage rate is predicted to increase over time, as the quarry undergoes expansion and deepening. The seepage rate is also sensitive to the assumed climate condition, which influences both recharge and streamflow that feeds water into the groundwater system.

The model predicts higher seepage rates from around year 22 when total streamflow is incorporated (Scenario 2). This is due to much large volumes of stream leakage supplied to the water table, which ultimately discharges into the quarry. This effect is most pronounced under a drier climatic condition, assumed to occur from around year 22 (equivalent to the climatic condition of the Millennium Drought within the synthetic data). The maximum seepage rate of 12 L/s is predicted with baseflow only (Scenario 1) and a higher maximum seepage rate of 18 L/s is predicted with surface water flow (Scenario 2).

The modelled seepage rate decreases as the quarry is backfilled and rehabilitated. The rate of reduction in seepage is a function of the rate of backfilling and assumed climatic condition. For example, the rate of reduction in seepage is partly minimised by the wetter than average condition assumed between year 45 and 70, before accelerating from year 70 in response to a drier than average condition. The modelled rate of seepage at the end of rehabilitation is around 5 L/s to 6 L/s, which is towards the lower end of the estimated range of seepage rate under the existing condition.

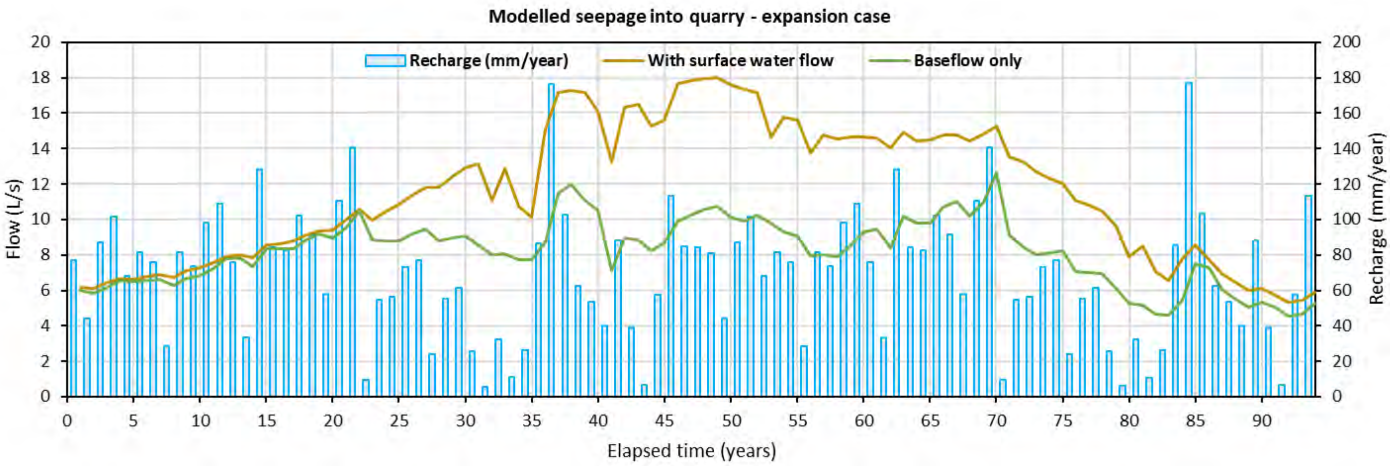


Figure 49 Modelled groundwater seepage into quarry - expansion case

5. Climate change effects

5.1 Modelling approach

Changes to climate have the potential to affect the groundwater system, primarily by altering the dynamics of recharge and evapotranspiration. Predicting potential changes induced to these processes by future climate variations is challenging due to their dependence on multiple climate variables and complex interactions between vegetation, soil and climate (McCallum et al., 2010).

Some studies suggest that a warmer climate (higher temperature) may not necessarily imply reduced recharge if the same amount of rainfall were available because vegetation would have a lower leaf area index, leading to less rainfall interception (Crosbie et al., 2010). Conversely, an increase in rainfall or rainfall intensity may not necessarily imply higher recharge if the seasonality of rainfall is altered in such a way that larger episodic rainfall events occur in generally dry months (summer) when the soil is not sufficiently wetted to facilitate infiltration of rainwater.

The potential impact of climate change on groundwater is assessed in this project with reference to the Victorian Government's Guidelines for Assessing the Impact of Climate Change on Water Availability in Victoria (DELWP, 2020). The guidelines provide projections of percentage changes in key climate parameters such as average annual rainfall, potential evapotranspiration and runoff under three climate change conditions (low, medium and high impact). The percentage changes (or scaling factors) for each of the three climate change conditions are provided for years 2040 and 2065, under two emission scenarios referred to as high Representative Concentration Pathway (RCP) 8.5 and low RCP 4.5. The RCP8.5 percentage changes are considered more conservative and have been adopted in this project.

The percentage changes can be used to linearly scale climate parameters up to year 2040 and then up to 2065. Where model simulation periods extend beyond 2065, the guidelines indicate the scaling factors can be linearly extend up to year 2075. Beyond 2075, the scaling factors are assumed to be time constant as further linear extrapolation results in climate conditions that are considered extreme (particularly when RCP8.5 emission scenario is assumed and the climate data already includes extended dry periods such as the Millennium Drought). Figure 50 shows the projected percentage changes in rainfall, potential evapotranspiration (PET) and runoff applied to this project.

As discussed in Section 4.1, the synthetic future climate used in predictive modelling is based on the historical data from 1975 to end of 2022 (and repeated once), which also corresponds to the post-1975 reference period used in the guidelines. To incorporate the climate change effects, the daily rainfall and evaporation data are scaled by the percentage changes shown in Figure 50 and supplied to the LUMPREM model to generate time-varying recharge and groundwater evapotranspiration files used in the USG-Transport model. Figure 51 shows the annualised recharge for the three climate change conditions and how these compare to the base climate (with no climate change, as applied to the predictive modelling described in Section 4.1).

The effects of climate change are quantified by repeating the predictive modelling (base case and expansion case) for each of the three climate change conditions. In this case, only the scenario with surface water flow (Scenario 2) is considered. This is because reductions in baseflow under climate change conditions render the quantification of project impacts more challenging e.g. little to no baseflow under the dry climate change condition makes it hard to quantify the impact of the project on surface water-groundwater interactions. Incorporating surface water flow is considered more realistic and useful in understanding the extent to which the frequency and magnitude of stream leakage may be modified by the climate-induced changes to recharge and streamflow (runoff), and how this could impact the water table along Bungalook Creek and the groundwater system further downstream. For each climate change condition, the surface water flow assigned to the SFR boundary has been scaled by the runoff percentage changes provided in the climate change guidelines (see Figure 52).

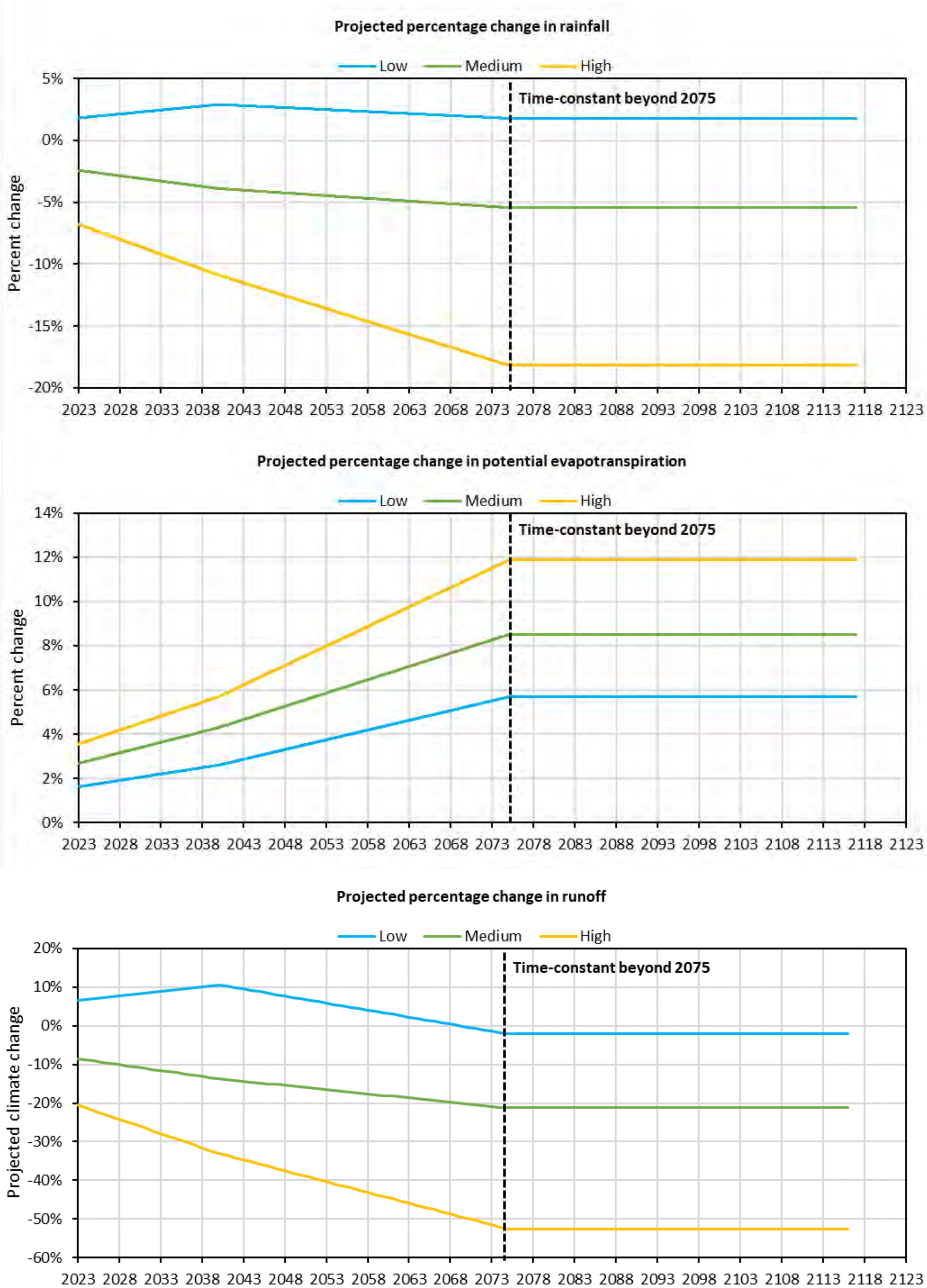


Figure 50 ***Rainfall and potential evapotranspiration percentage changes for climate change***

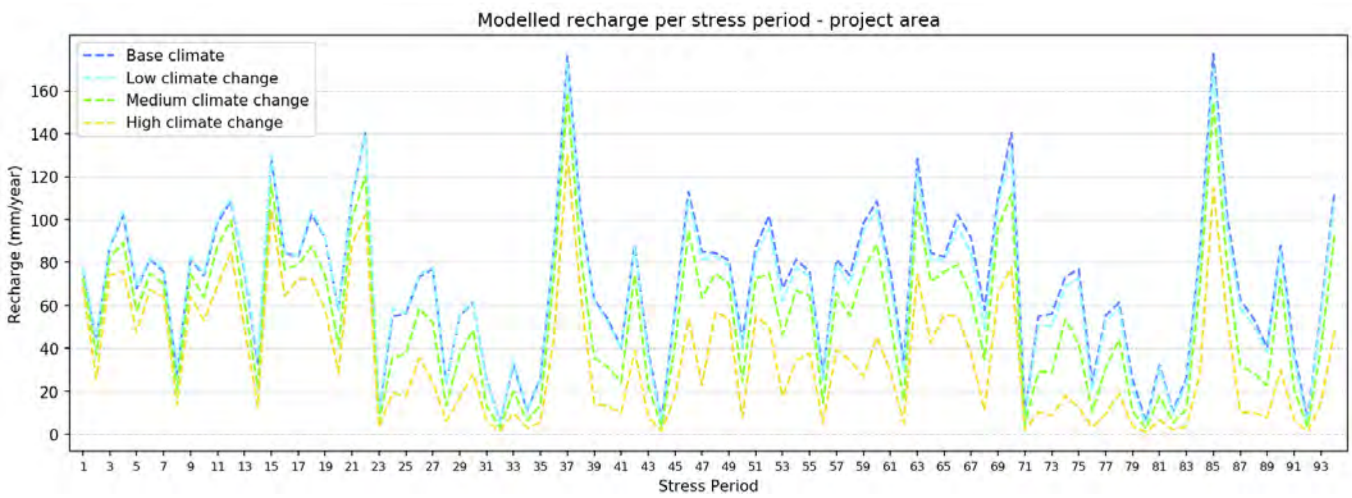


Figure 51 Modelled recharge with climate change

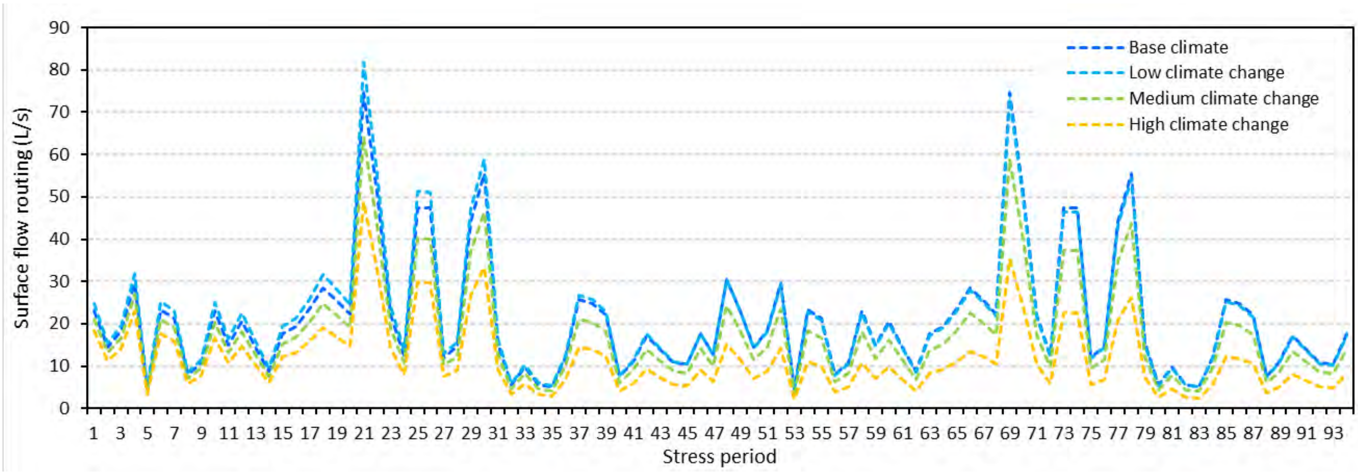


Figure 52 Modelled stream inflow with climate change

5.2 Predicted changes to groundwater level

Figure 53 compares the contours of predicted water table drawdown of the base climate against those of the three climate change conditions at the end of extraction. These are calculated by subtracting the model outputs of the expansion case from the outputs of the base case for each climate condition. Because the climate change effects are applied to both the base case and expansion case, the drawdown contours represent the magnitude and spatial extent of the impact of the quarry expansion under the condition of climate change i.e. climate change would occur irrespective of the project and the drawdown contours represent how the incremental effect of the expansion may vary relative to the base case when climate change effects are incorporated.

The contours of the base climate and low climate change condition are very similar due to the relatively small changes to recharge, evapotranspiration and streamflow. For the medium and high climate change conditions, greater drawdown is simulated along Bungalook Creek and beyond. The contours also show a larger area of downstream drawdown for the base climate and low climate change condition compared to the medium climate condition. This is because larger volumes of streamflow are maintained for the base case under the base climate and low climate change condition, resulting in greater drawdown when this flow is lost under the expansion case. In comparison, the base case streamflow is already reduced under the medium climate change such that the loss of this flow in the expansion case does not lead to material increase in drawdown. For the dry climate change condition, a much greater overall reduction in streamflow and recharge means the drawdown impact of the quarry becomes more pronounced, resulting in a broader area of impact downstream.

Figure 54 presents the water table contours at the end of Stage 4 rehabilitation, to demonstrate the differences in the rate of recovery of water table.

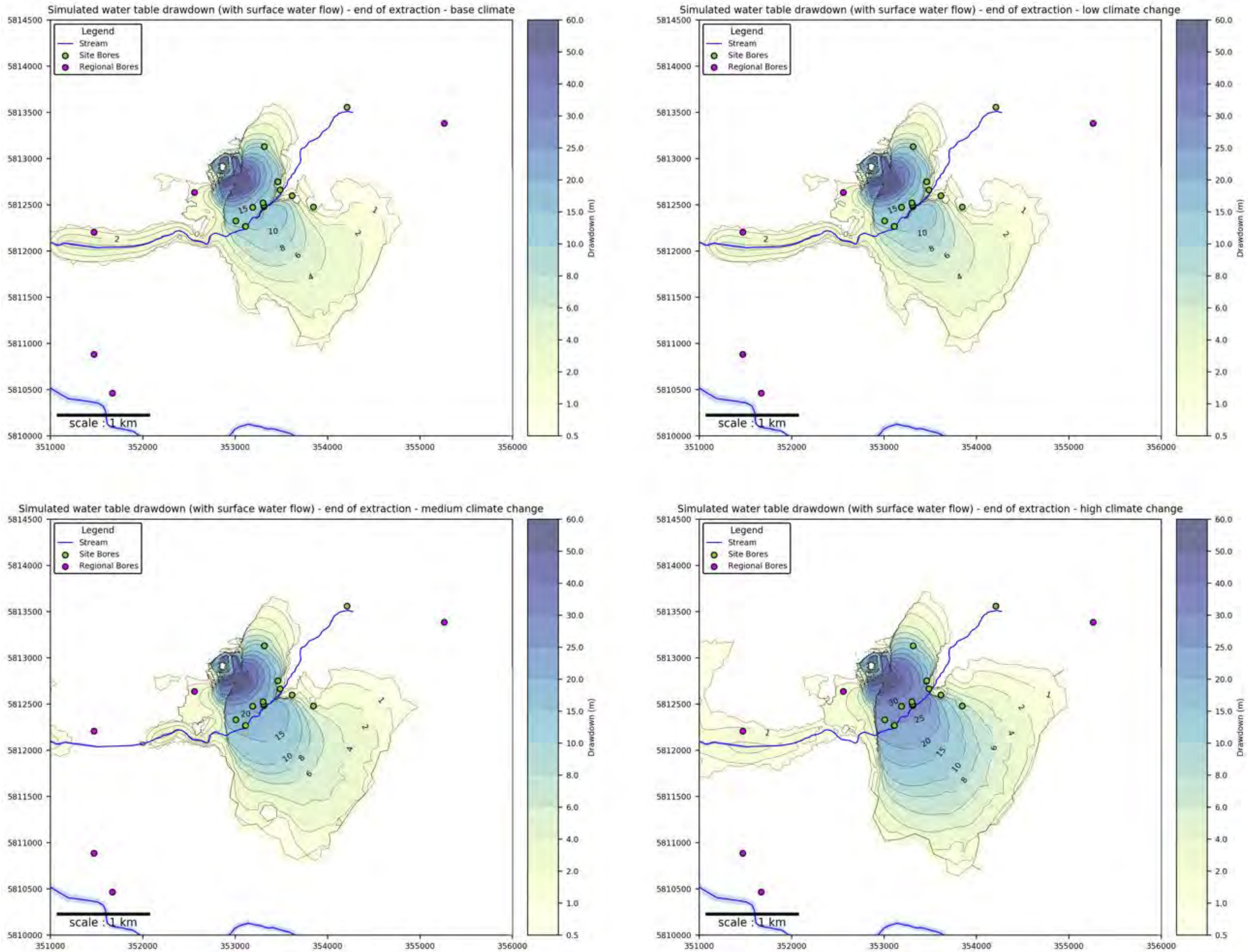


Figure 53 *Simulated water table drawdown at end of extraction (with surface water flow) – climate change*

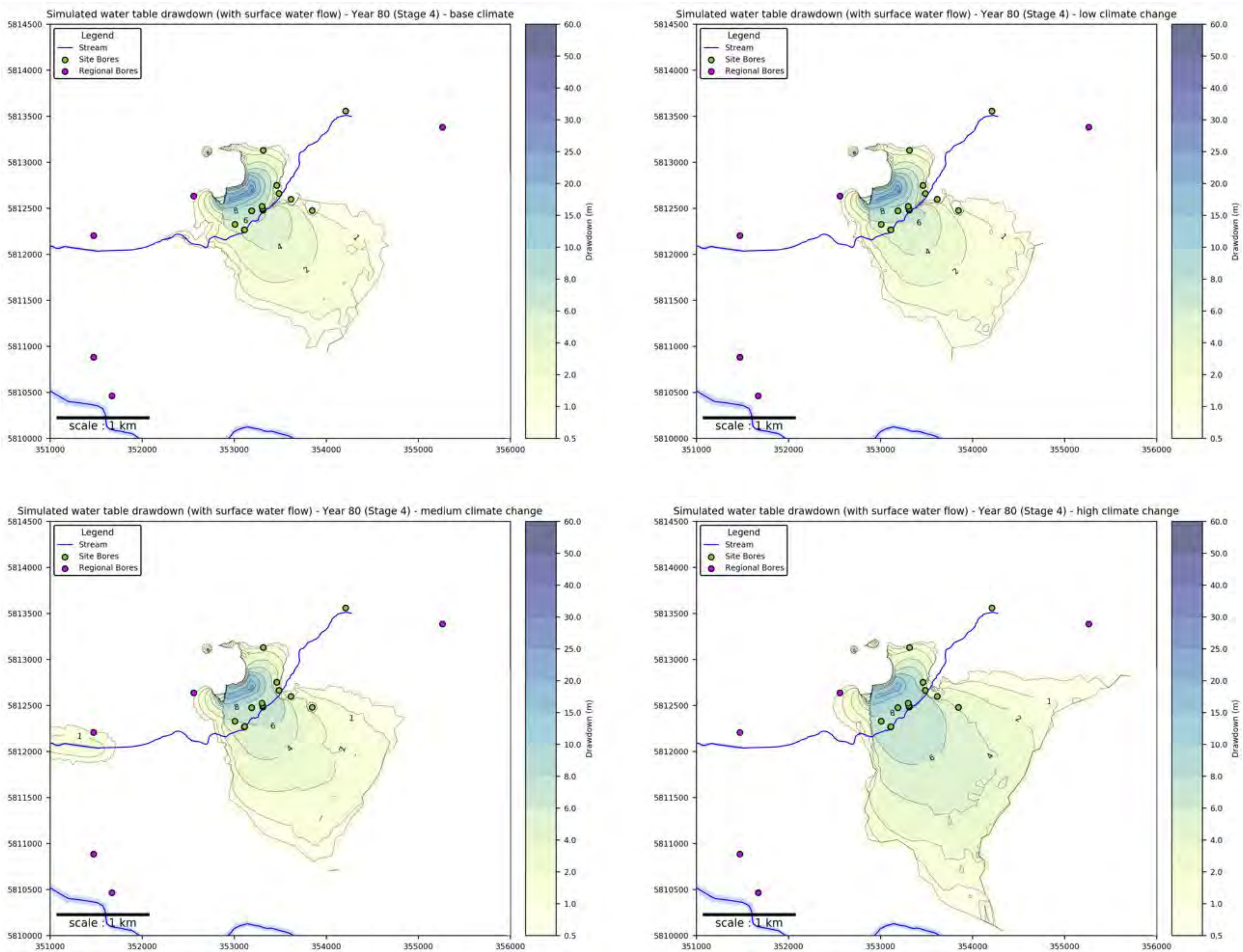


Figure 54 ***Simulated water table drawdown during rehabilitation (with surface water flow) – climate change***

Figure 55 compares the simulated hydrograph of maximum drawdown along Bungalook Creek under different climate change conditions. The maximum drawdown of up to around 37 m is predicted under the high climate change condition, compared to around 23 m for the base climate. The timing of maximum drawdown also occurs later for the high climate change condition, corresponding to an extended period of reduced streamflow (see Section 5.3.1). With the exception of the high climate change condition, the water table is predicted to fully recover along Bungalook Creek at the end of Stage 5 rehabilitation.

The maximum drawdown predicted along Fussell Road is less variable and is less than 5 m for all climate change conditions.

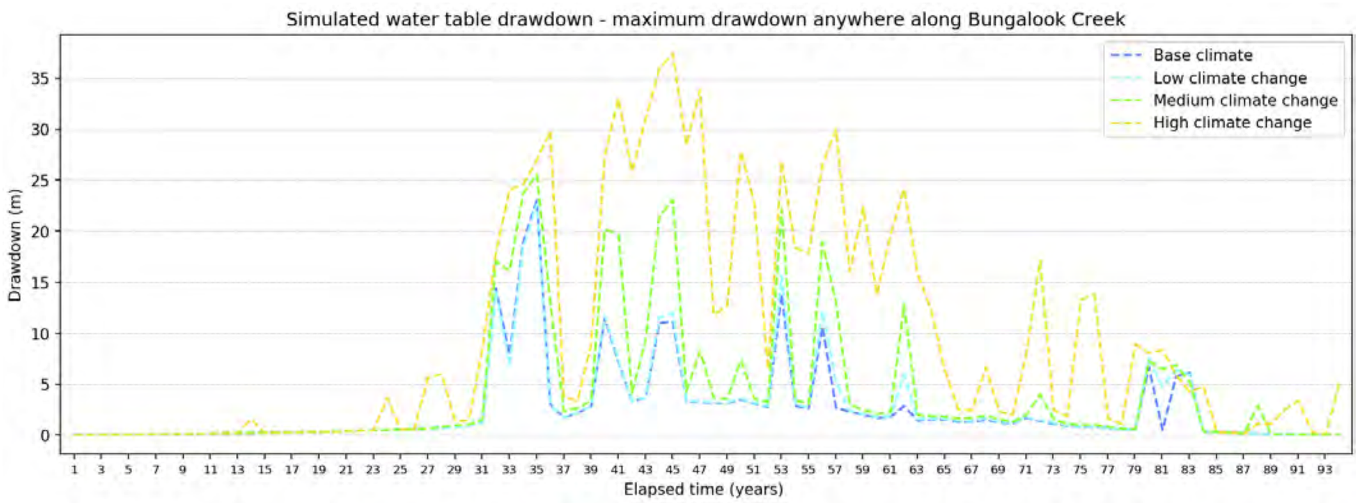


Figure 55 **Bungalook Creek maximum drawdown hydrograph (with surface water flow) – climate change**

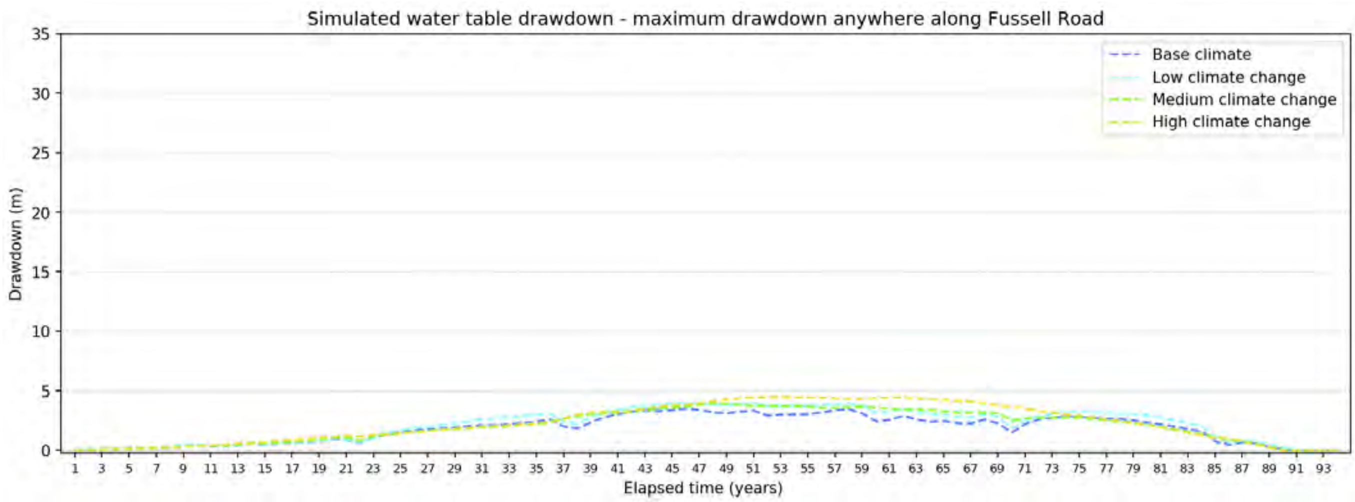


Figure 56 **Fussell Road maximum drawdown hydrograph (with surface water flow) – climate change**

The magnitude of climate change effects on groundwater levels can be assessed by calculating the difference between the modelled water table for low and high climate change conditions. Figure 57 presents the water table difference plot between the two extreme climate change conditions for the base case (top image) and expansion case (bottom image) calculated in year 40 (at the end of expansion). For the base case, the effect of climate change results in typically less than 5 m difference near the quarry when the existing void is maintained. Regions of very high difference is calculated to the east and southeast of the quarry, where the calibrated hydraulic conductivity of the Mt Evelyn Rhyodacite is low (a regional pilot point value of 0.001 m/d) and the modelled groundwater levels are more sensitive to the differences in the applied recharge rates across different climate change conditions[1]. For the expansion case (right image), the difference is greater in the area of predicted

[1] While different land uses are accounted for in the recharge calculation, the effect of underlying geology on deep drainage is not incorporated. Regions of higher hydraulic conductivity may facilitate greater deep drainage than regions of lower hydraulic conductivity. Further (longer term) monitoring data would be necessary to determine if spatial adjustments in recharge are warranted based on the modelled hydraulic conductivity distribution.

drawdown south of the quarry due to the effect of climate change on induced stream leakage when the water table is lowered adjacent to Bungalook Creek (as discussed further in Section 5.3). When the drawdown effect is quantified by subtracting the water table of the expansion case from the base case (as presented in Figure 53 and Figure 54), the climate change effect in regional areas outside of the zone of influence of quarry are cancelled out.

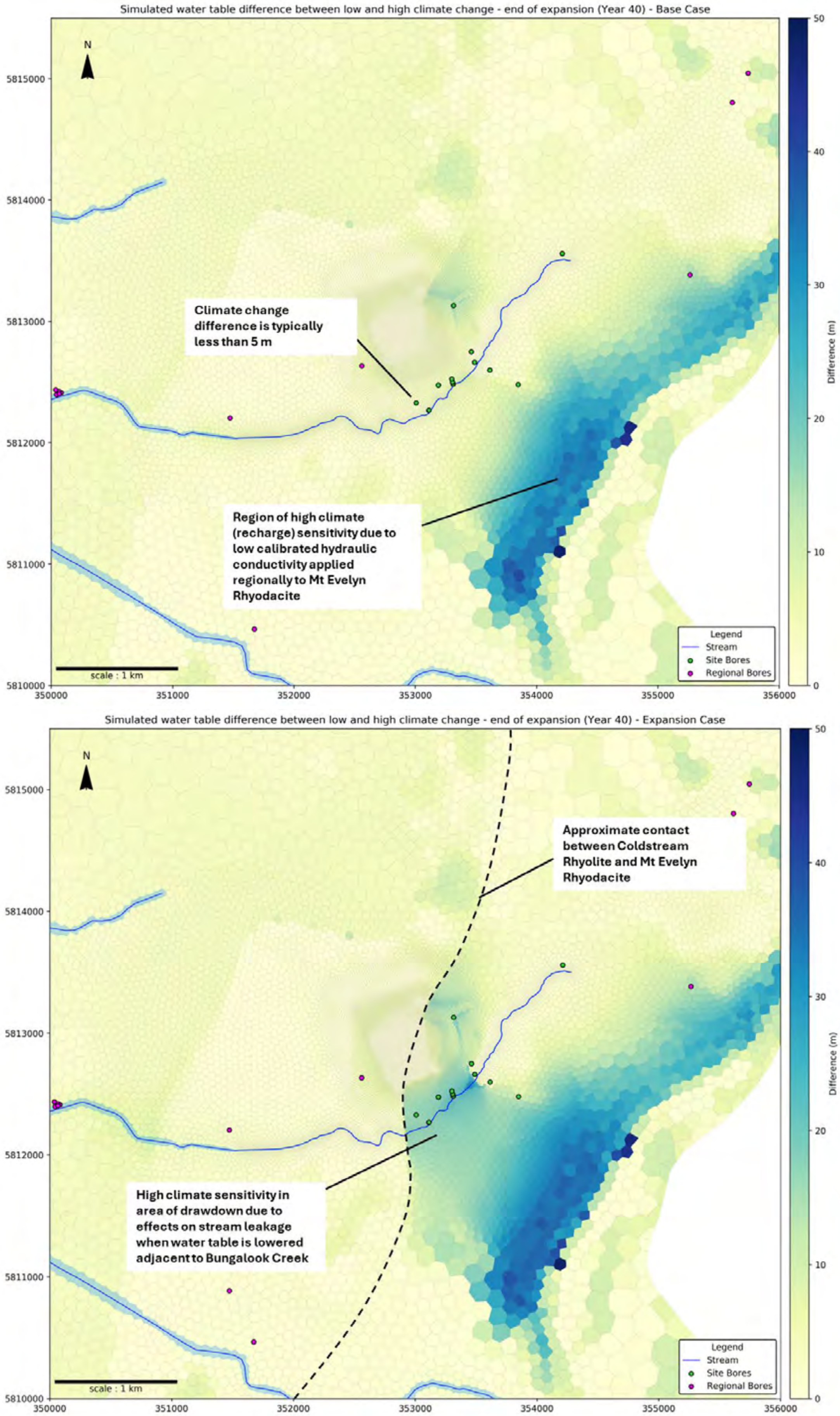


Figure 57 *Simulated water table difference between low and high climate change – Base Case and Expansion Case*

5.3 Predicted changes to groundwater fluxes

5.3.1 Predicted impacts of stream leakage

The impact of quarry expansion on total streamflow is demonstrated by comparing the modelled streamflow at gauge 228369A for the base case and expansion case under the three climate change conditions. Under the high impact climate change condition, there is a long period (from year 30 to around 68) where the streamflow in the base case is simulated to be less than 10 L/s. In the expansion case, most of this streamflow is lost as stream leakage, resulting in little to no flow reaching downstream of the flow gauge.

As discussed in Section 5.2, the model simulates limited to no streamflow in year 40 (end of extraction) for both the base case and expansion case under the medium and high climate change condition. In comparison, streamflow is slightly higher for the base case under the low climate change condition, resulting in a larger magnitude of stream loss when leakage is induced in the expansion case. This is expressed as a larger area of drawdown in the downstream section of Bungalook Creek for the low climate change condition compared to the medium and, to a lesser extent, the dry climate change condition (as seen in Figure 53).

The climate change assessment indicates the potential for a downstream impact to arise due to the reduction in streamflow from the effects of climate change alone (even under the base case, with the existing quarry). The expansion of the quarry has the potential to exacerbate this effect, resulting in more frequent and longer periods of little to no downstream flow due to induced leakage (as seen in Figure 59, which compares the streamflow difference between the base case and expansion case for each climate change scenario) .

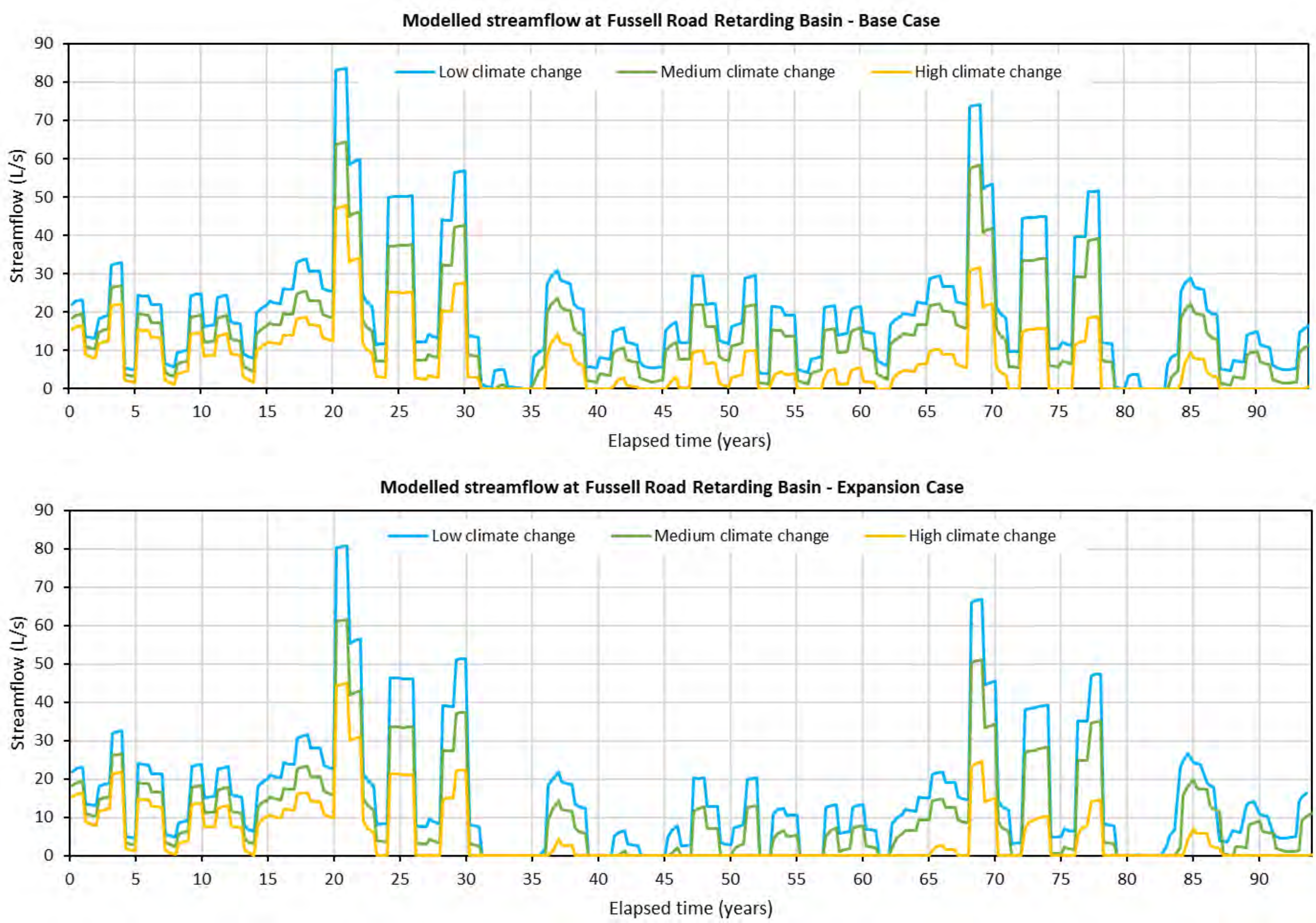


Figure 58 *Modelled streamflow – climate change*

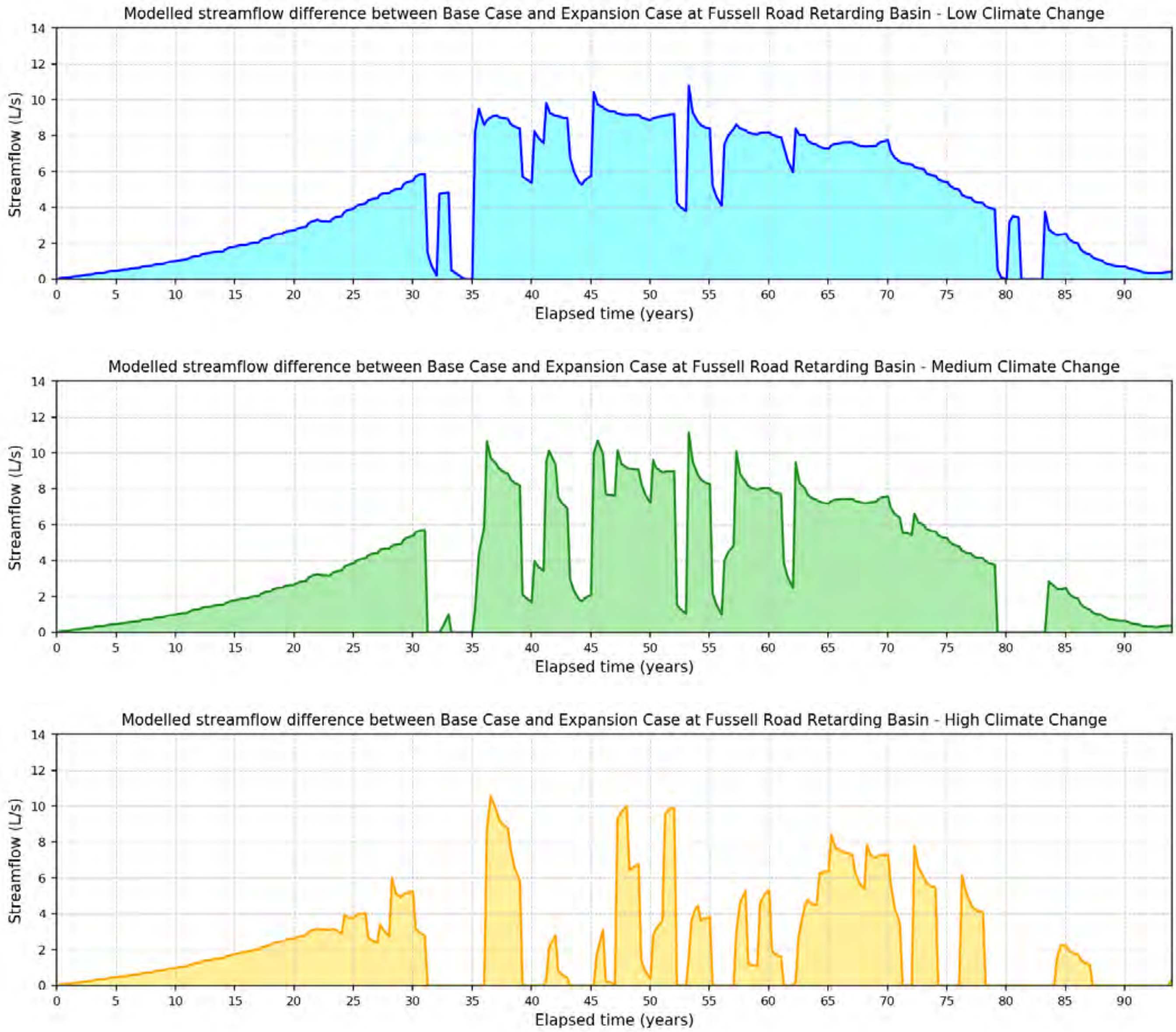


Figure 59 Modelled streamflow difference between Base Case and Expansion Case – climate change

5.3.2 Predicted changes to groundwater seepage

Figure 60 compares the modelled seepage rate into the quarry for the three climate change conditions. The seepage rates are similar for the low and medium climate change conditions whereas the seasonal variations are most pronounced under the high climate change condition. Although the magnitude and spatial extent of drawdown is predicted to be greater under the high climate change condition, the reduced recharge and stream leakage means there is less throughflow of groundwater towards the quarry. In other words, an overall lowering of the regional water table due to the effects of climate change is likely to result in less seepage of groundwater into the quarry.

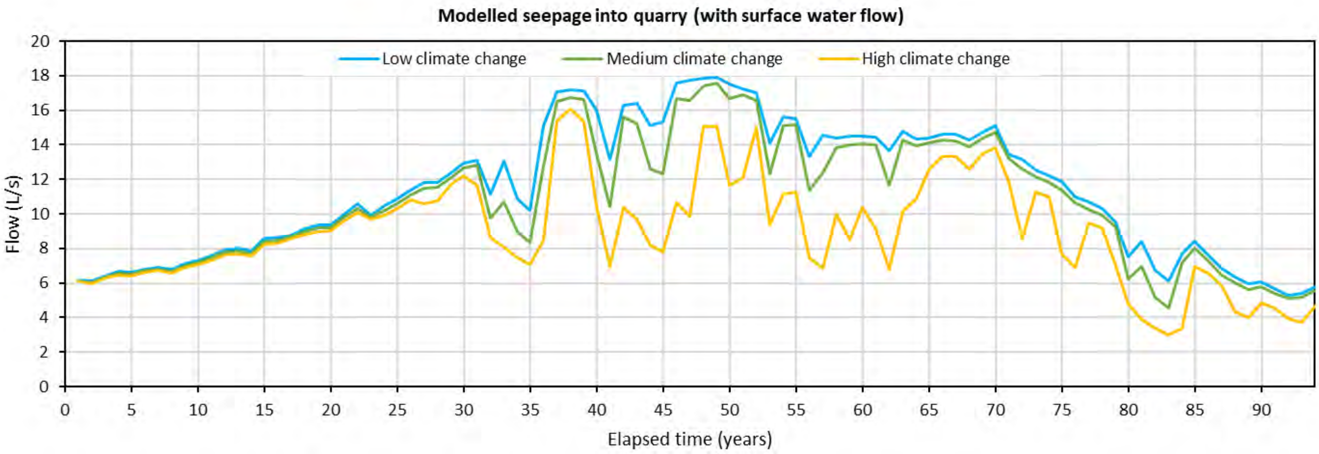


Figure 60 *Modelled seepage into quarry – climate change*

6. Uncertainty analysis

6.1 Sources of model uncertainty

Hydrogeological systems are complex natural systems whose properties cannot be measured at all spatial and temporal scales. Hydrogeological processes that have occurred in the past can only be inferred from a finite number of measurements. Simplifications are therefore necessary in groundwater modelling and uncertainty is inherent in all model predictions.

In groundwater modelling, uncertainty in model parameters can lead to the problem of model non-uniqueness or identifiability (Barnett et al., 2012). This is when the behaviour of the groundwater system being modelled depends on a particular combination of parameters rather than a single parameter in isolation. Because model parameters are uncertain, with a plausible range of values, different combinations of parameter values could result in more than one plausible realisation of the same model.

The predictive uncertainty analysis described in this section is designed to primarily quantify the effect of this parameter uncertainty on model predictions, by identifying the range of alternative parameter combinations whose predictions can be regarded as equally plausible based on the existing calibration dataset. However, the uncertainty analysis has also been extended to include a form of structural uncertainty analysis, in which the potential influence of a geological structure (shear zone) is examined by incorporating this feature into the model as a zone of different material properties.

6.2 Parameter uncertainty analysis

6.2.1 Approach

Uncertainty in key model predictions has been explored using a numerically efficient form of calibration-constrained Monte-Carlo analysis based on PEST and its Null Space Monte Carlo methodology (Doherty, 2016). Monte Carlo analysis involves running many realisations of the model with a range of parameter values and using the outputs from these models to estimate the uncertainty range of the outputs produced by the model. The term ‘calibration-constrained’ means only those model realisations that are sufficiently well calibrated are deemed plausible and used for the Monte Carlo runs. The Null Space Monte Carlo methodology is a form of non-linear uncertainty analysis, which is the most comprehensive form of uncertainty analysis commonly applied in groundwater modelling (one of the ensemble methods for uncertainty analysis, as discussed in Peeters and Middlemis, 2023).

The uncertainty analysis has been undertaken using the following PEST utilities:

– PREDUNC7 to generate posterior parameter uncertainty and covariance matrix files from the Jacobian sensitivity matrix of the final calibrated model and parameter variances specified in the prior parameter uncertainty file. The parameter variances have been defined as one quarter of each parameter’s allowable range (plausible lower and upper bounds, as per the calibration), thereby implying a 95% confidence interval.
– RANDPAR to generate random parameter combinations based on the posterior parameter covariance matrix obtained from above. This results in parameter combinations that are centred on the minimum error variance (best calibrated) parameter set. A total of 150 parameter combinations (realisations) have been generated for the 46 adjustable parameters.

The RANDPAR generated parameter combinations can sometimes result in poorly calibrated models. In such case, PNULPAR can be used to undertake a null-space projection of the RANDPAR generated parameters, which adjusts the parameters so that each parameter set is more likely to satisfy the calibration requirements (albeit often resulting in narrower parameter ranges). In this case, the wider parameter bounds captured by the RANDPAR parameters (compared to their PNULPAR equivalents) were considered more conservative and appropriate for the purpose of impact assessment.

For the material properties of the backfill (TVM parameters), the plausible upper and lower bounds have been set based on the literature derived values for the expected fill material. The horizontal hydraulic conductivity (KH) has been allowed to vary by two orders of magnitude, from 0.005 m/d to 0.5 m/d, and the vertical hydraulic conductivity (KZ) is adjusted using an anisotropy factor (KH/KZ) that varies from 0.01 to 1. Specific yield is varied from 0.05 to 0.3. These parameters have been incorporated into the RANDPAR generated parameter sets (as randomly generated parameters centred on their preferred values).

6.2.2 Stochastic history matching results

The calibration model has been run using all 150 RANDPAR generated parameters to benchmark their performance against the historical observation dataset. Of the 150 model runs, 4 had failed to achieve convergence. In addition, the following criteria have been applied to filter out model runs where the calibration performance is deemed insufficient:

- SRMS error of greater than 1.2 % and RMS error of greater than 6 m for all head observations (compared to the SRMS error of 0.94 % and RMS error of 4.53 m for the calibrated model)
- SRMS error of greater than 6.5 % and RMS error of greater than 2.3 m for the site bores head observations (compared to the SRMS error of 4.29 % and RMS error of 1.53 m for the calibrated model)
- Average baseflow (1980 and 1996) of greater than 6 L/s (compared to the 4 to 5 L/s estimated range)
- Groundwater seepage (DRN outflow) greater than 9 L/s (the upper bound of the estimated seepage rates).

The application of the above criteria resulted in a total of 131 parameter realisations where the model calibration performance is considered acceptable. Figure 61 graphically presents the calibration performance of all 131 realisations against the criteria selected above. Also included in the figure is the minimum, average and maximum annualised model-wide recharge over the calibration period for all 131 realisations, demonstrating the wide range of recharge rates assessed as part of the uncertainty analysis.

Figure 62 graphically presents the range of parameter values adopted for the uncertainty analysis, after accounting for the calibration constraints. The parameter bounds adopted from the 131 realisations remain wider than those generated by PNULPAR while retaining satisfactory calibration performance. The reasonableness of the size of the ensemble (the number of parameter realisations) adopted can be further assessed using convergence plots, showing how the model outputs vary as more parameter realisations are added to the ensemble (Peeters and Middlemis, 2023). Figure 63 shows the convergence plots for some of the key model calibration performance indicators such as the MSR error for head calibration targets and flux targets such as baseflow and drain outflow. For most of these outputs, the variability across the 90th percentile confidence interval (between the 5th and 95th percentiles) stabilises after around 100 realisations. While there are limitations with these plots (as demonstrated by Peeters and Middlemis, 2023), the stabilisation of variability statistics generally suggests that adding more realisations to the ensemble is unlikely to be warranted (at the expense of greater computation efforts) or lead to additional insights into the sources of model uncertainty (based on the information currently available).

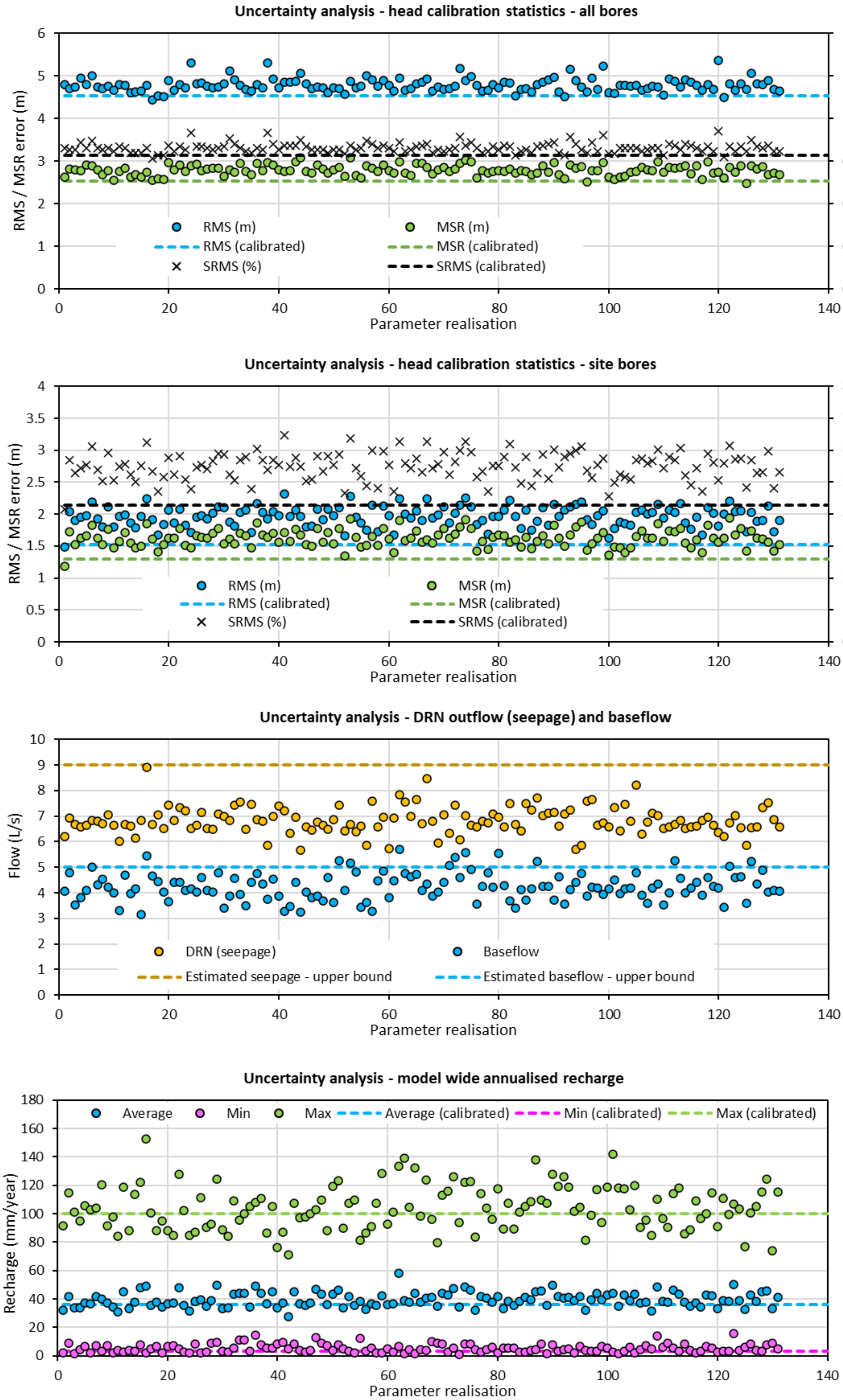


Figure 61 *Stochastic history matching results – 131 realisations*

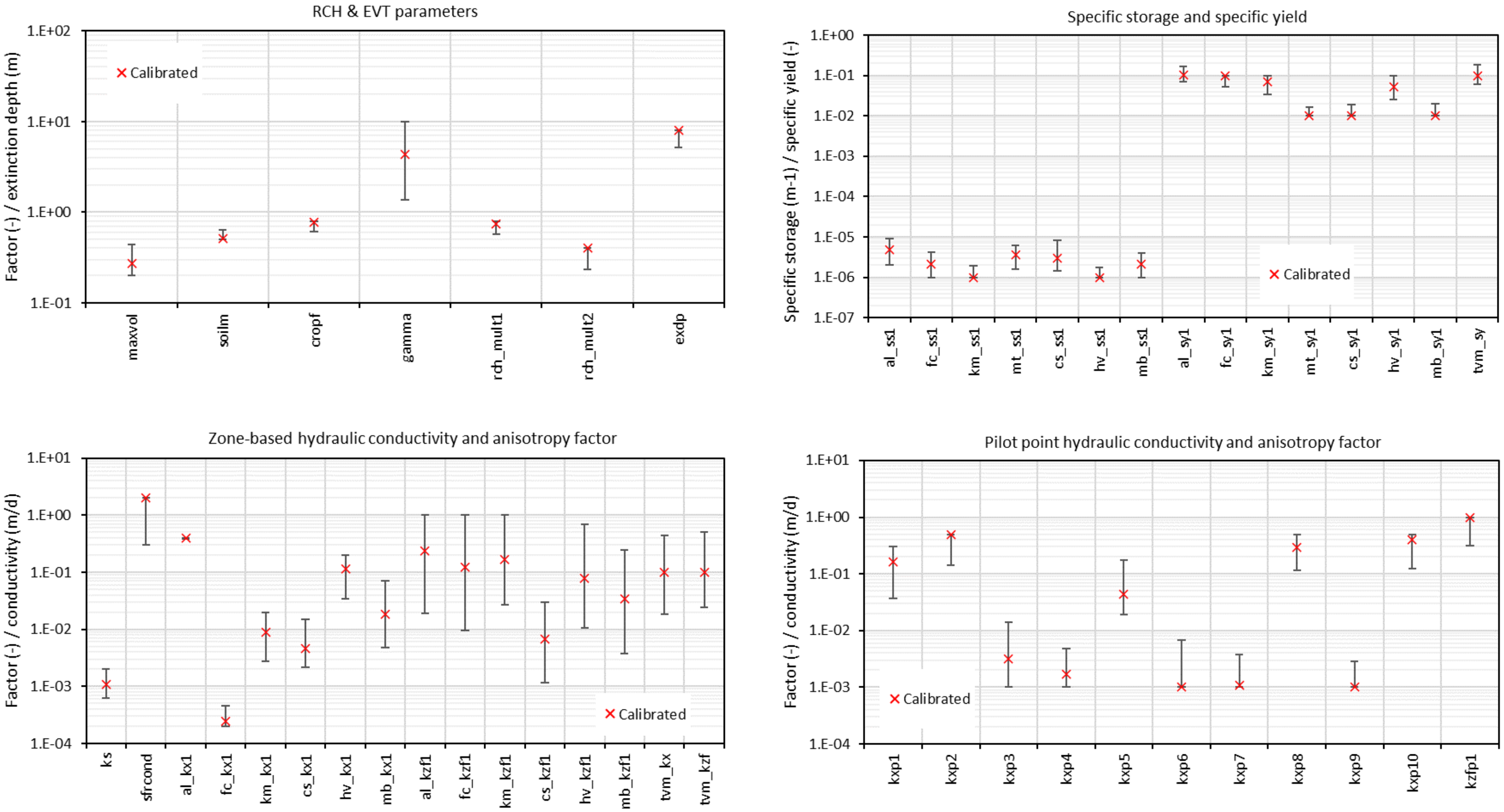


Figure 62 *Uncertainty parameter ranges*

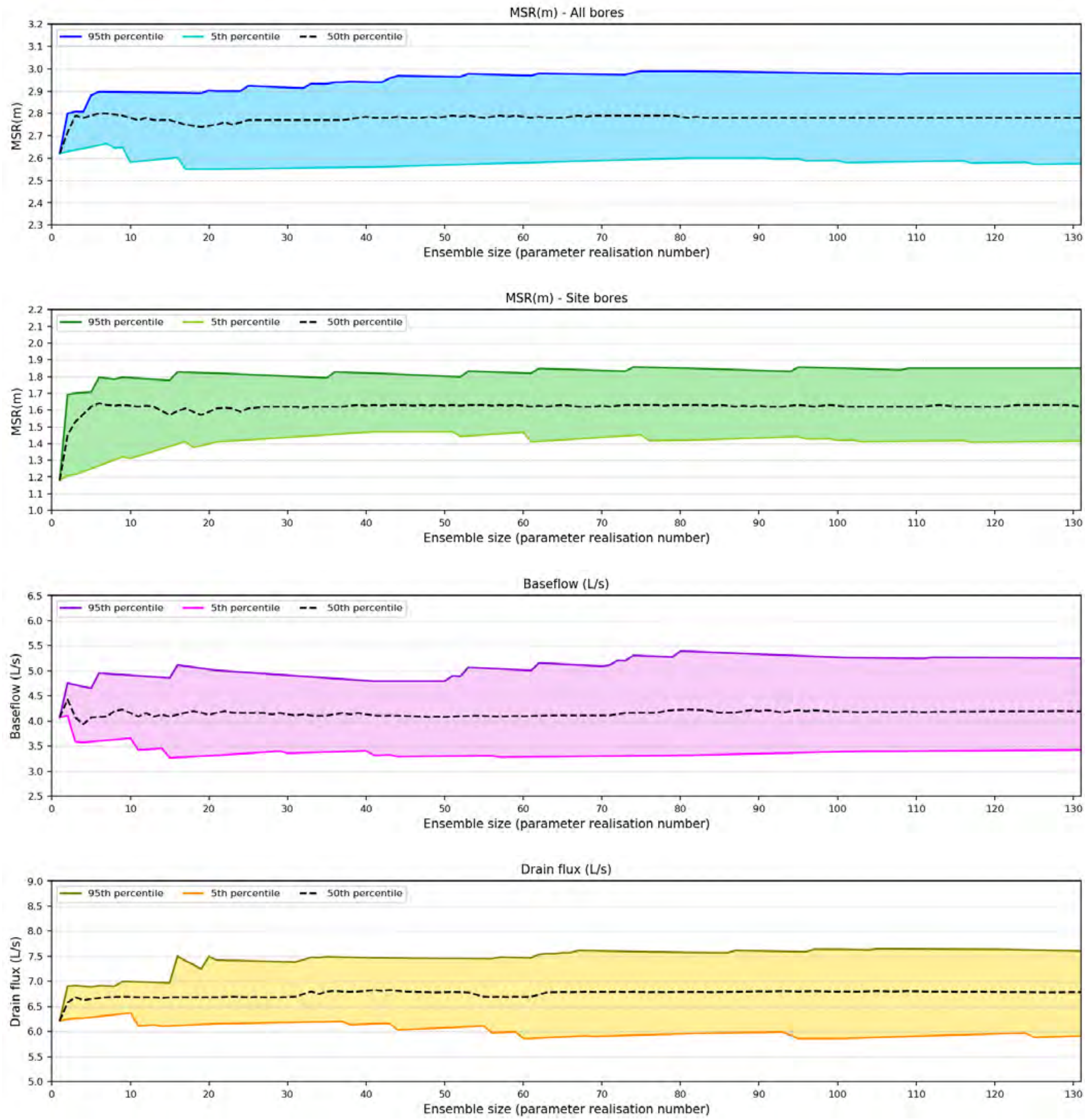


Figure 63 ***Convergence plots for key model calibration performance indicators***

6.2.3 Stochastic predictive modelling results

The predictive uncertainty analysis involves running the predictive model, as described in Section 4.1, for all of the 131 plausible parameter realisations. As per the predictive model, the base climate condition is assumed (no climate change scaling is applied to the rainfall, evaporation and stream flow inputs) so the contribution of parameter uncertainty on model outputs can be clearly understood. Only the predictive Scenario 2, with surface water flow, has been subjected to predictive uncertainty analysis, for the same reasons explained in Section 5.1.

6.2.3.1 Uncertainty associated with predicted groundwater level changes

Uncertainty in the simulated magnitude and extent of drawdown is demonstrated using contours of water table differences (drawdown) between the expansion case and base case, as described in Section 4.2. The water table drawdown at each location within the model grid is aggregated from all 131 parameter realisations to produce statistical composite maps. This means each map is not from any one of the 131 model runs; rather, they are a composite statistical representation of predicted drawdown across 131 model results. The 5th and 95th percentile composite drawdown maps are used to demonstrate the plausible range of impacts across 90% confidence interval.

Figure 64 and Figure 65 present the 5th and 95th percentile composite drawdown maps at the end of extraction, representing the lower and upper bound estimate of drawdown respectively e.g. 95^{th} percentile means 95% of the 131 model realisations produce drawdown that is less than that shown in Figure 65 (hence the Project is unlikely to result in drawdown greater than that shown in the figure). The difference between the 95th and 5th percentile contours can be calculated to demonstrate how the uncertainty in the predicted drawdown varies spatially, as shown in Figure 66. For example, the largest uncertainty occurs at and to the south of the quarry (centred on Bungalook Creek), where the largest changes in groundwater levels are expected (as the quarry expands into an area that has not been previously stressed from historical extraction).

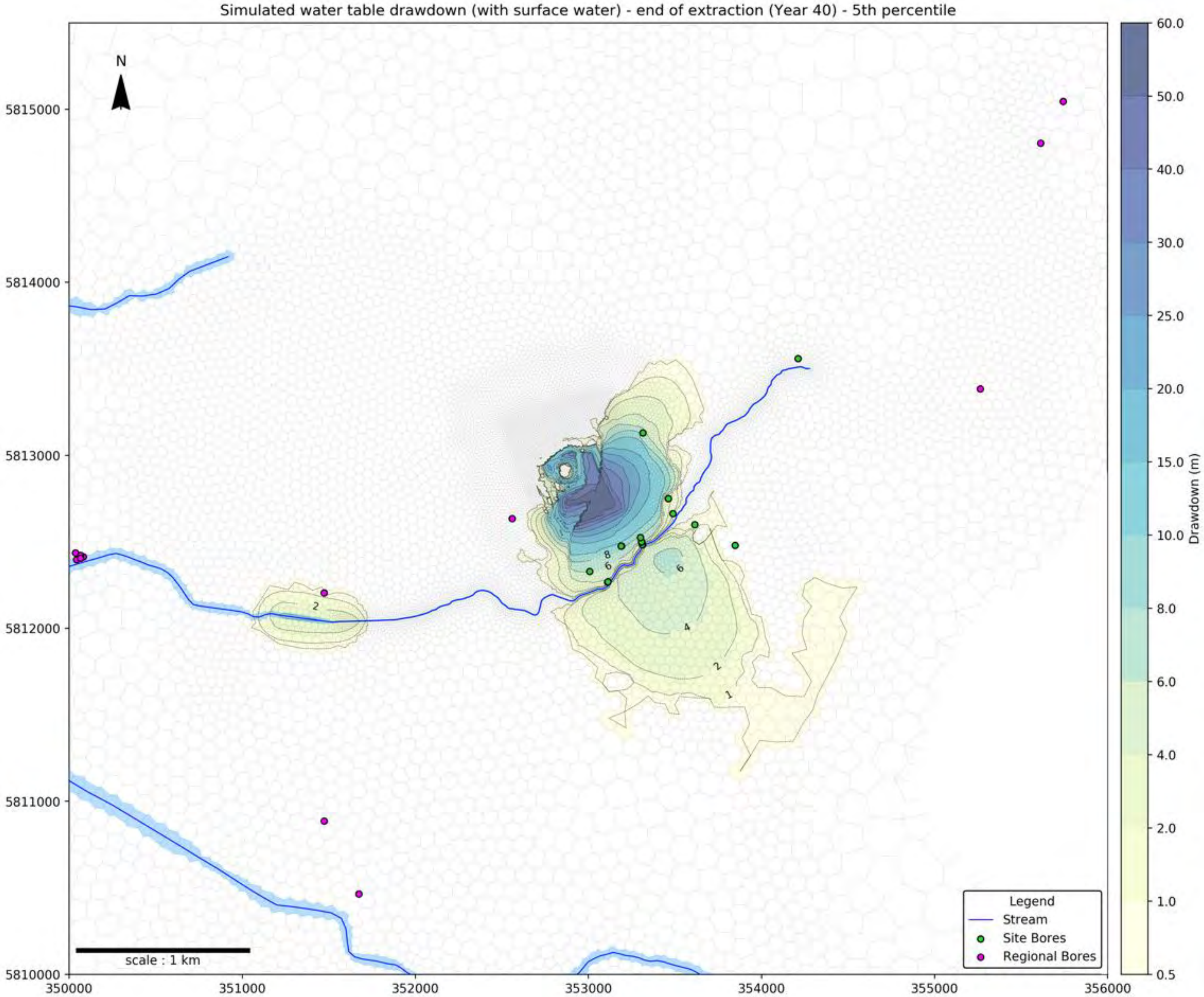


Figure 64 ***Simulated water table drawdown at end of extraction (with surface water flow) – 5th percentile (lower bound)***

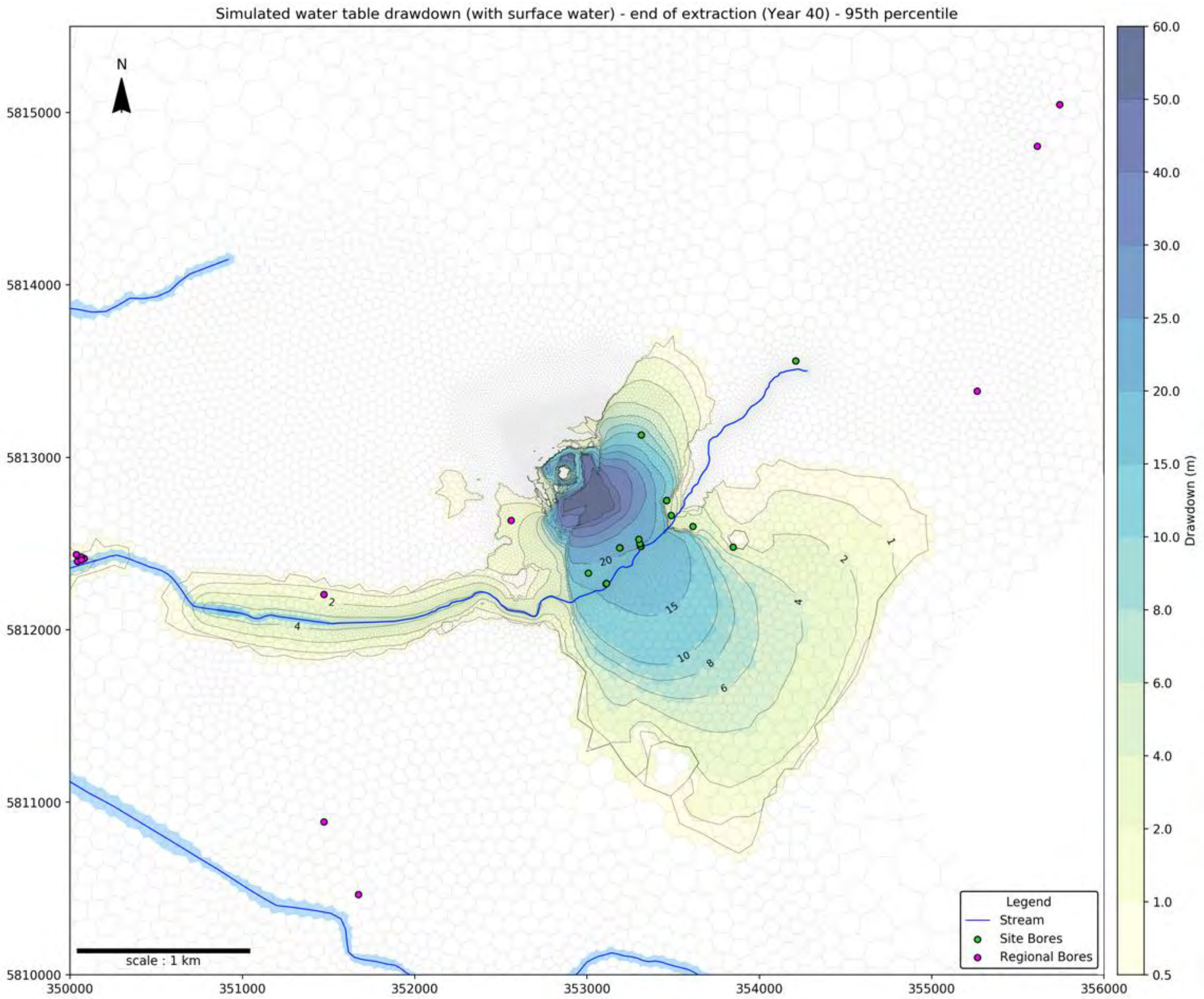


Figure 65 ***Simulated water table drawdown at end of extraction (with surface water flow) – 95th percentile (upper bound)***

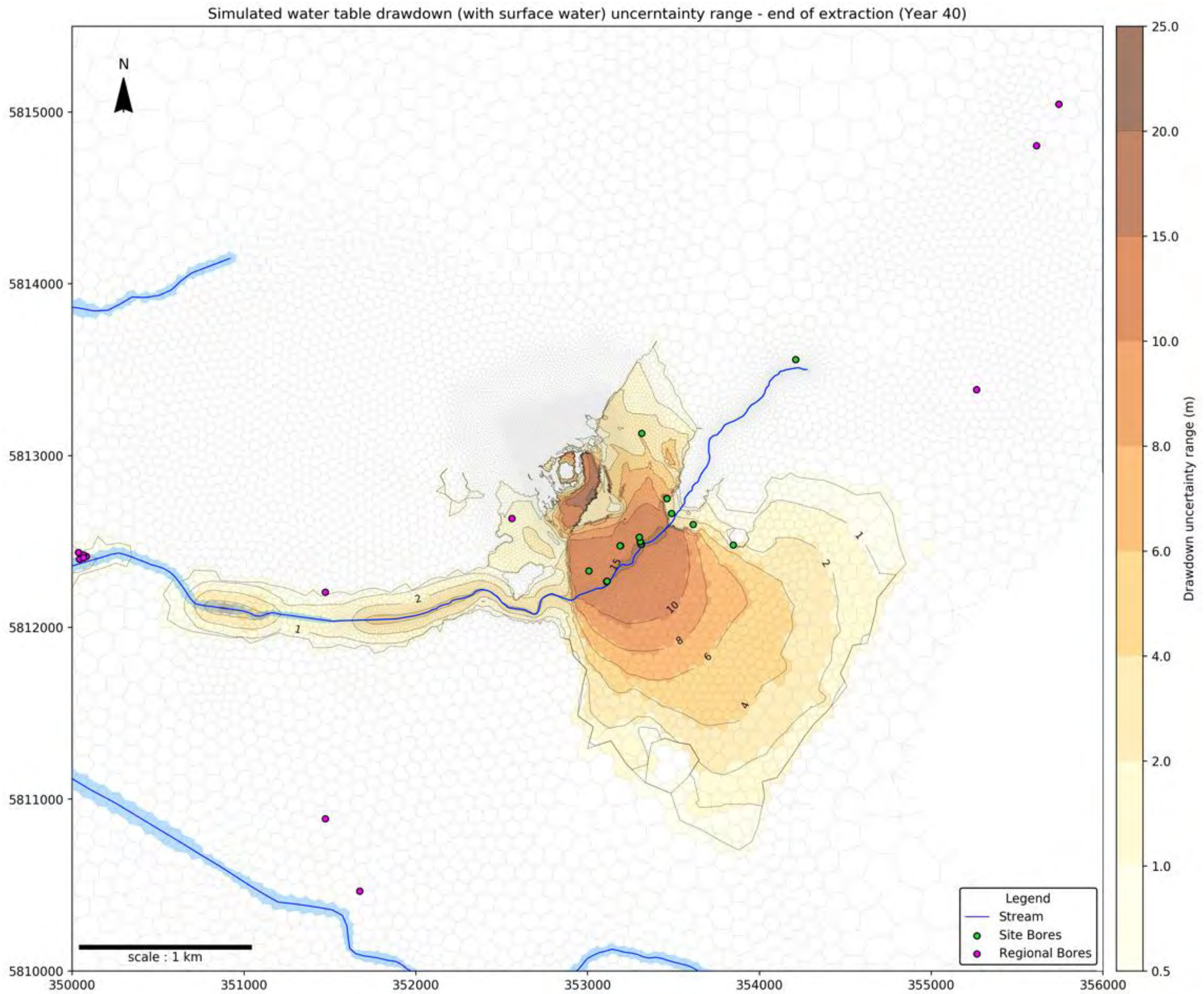


Figure 66 ***Simulated water table drawdown uncertainty range at end of extraction (with surface water flow)***

Figure 67 and Figure 68 present the 5th and 95th percentile composite drawdown maps during rehabilitation (at the end of Stages 1 to 4), respectively.

The effect of model uncertainty on predicted water table drawdown along Bungalook Creek is further demonstrated in Figure 69. This shows the time series of maximum drawdown calculated anywhere along Bungalook Creek (adjacent to the quarry) for all 131 parameter realisations, including their 5th and 95th percentiles. The figure indicates the potential for large drawdowns to occur during dry periods when the stream flow is limited. The maximum drawdown is predicted at around year 35, which ranges from 15 m for the 5th percentile to 27 m for the 95th percentile (an uncertainty range of 12 m). During normal flow periods, the maximum predicted drawdown for most realisations is less than 15 m, with many indicating less than 5 m. The time series of maximum drawdown along Fussell Road is also shown in Figure 70, where the uncertainty range is much narrower (typically less than 4 m) and the maximum water table drawdown is predicted to be less than 5 m.

The post-excavation recovery of the water table within the quarry footprint is sensitive to the elevation of the rehabilitated surface (which varies over time), material properties of the fill and the rate of groundwater seepage that re-saturates the fill material. To demonstrate the effect of model uncertainty on the recovery, hydrographs of the water table elevations within the footprint (floor) of the quarry are presented in Figure 71. These are generated by calculating the highest, average and lowest water table elevations anywhere within the quarry footprint for every simulation output time and plotting these for all 131 parameter realisations. During excavation, the water table elevation is constrained by the quarry elevation as the floor cuts into the water table. The largest differences occur during the post-excavation recovery period, due to the uncertainty in the fill material properties and groundwater seepage rates. The hydrographs indicate that there is around 10 m of uncertainty associated with the recovery of the water table, on average.

The hydrograph of the lowest water table shows a drop in year 41, when the filling commences. This is an artefact of the modelling, where the TVM package modifies the material properties of the entire cell volume resulting, in some cases, increases in storage (specific yield) and hydraulic conductivity that causes the water table to locally drop (where the drain elevation remained above the cell bottom, as explained in Figure 72). In this case, the lowest water table elevation should be assumed to be constrained by the quarry floor elevation at around 15 mAHD until the lowest floor elevation begins rising from around year 50.

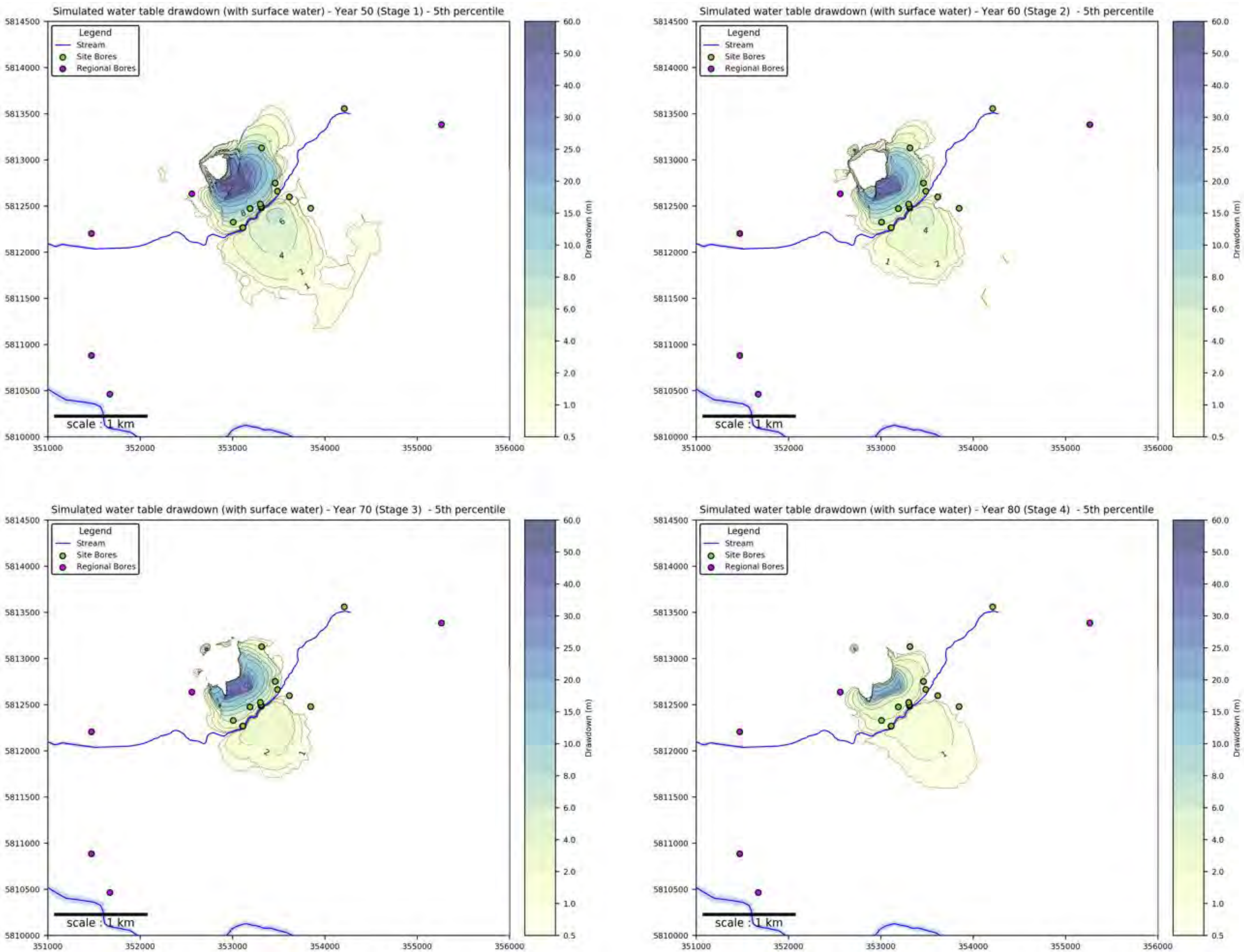


Figure 67 *Simulated water table drawdown during rehabilitation (with surface water flow) - 5th percentile (lower bound)*

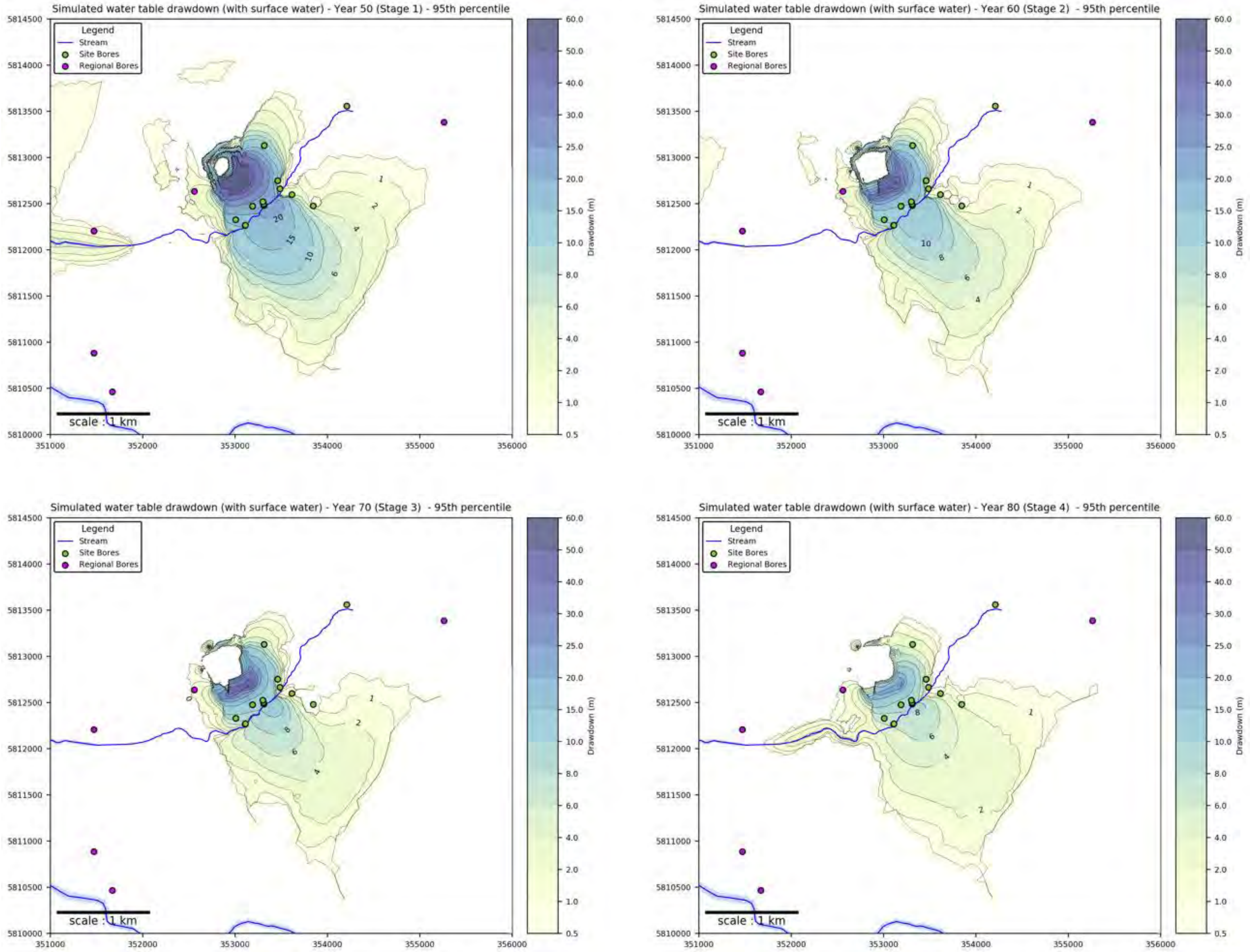


Figure 68 ***Simulated water table drawdown during rehabilitation (with surface water flow) - 95th percentile (upper bound)***

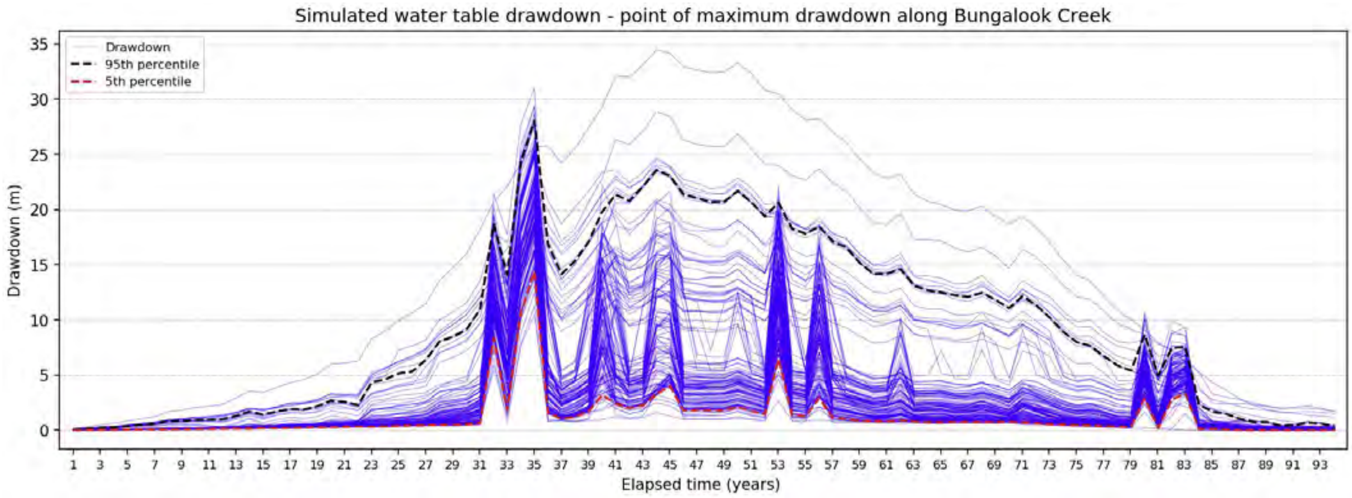


Figure 69 ***Bungalook Creek maximum drawdown hydrograph (with surface water flow) – uncertainty analysis***

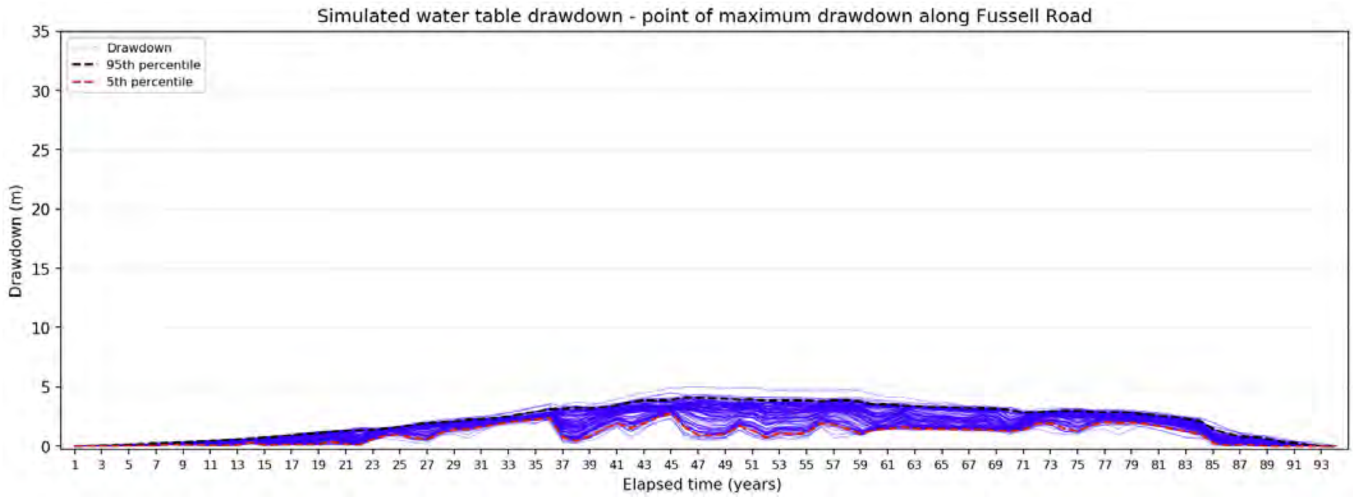


Figure 70 ***Fussell Road maximum drawdown hydrograph (with surface water flow) – uncertainty analysis***

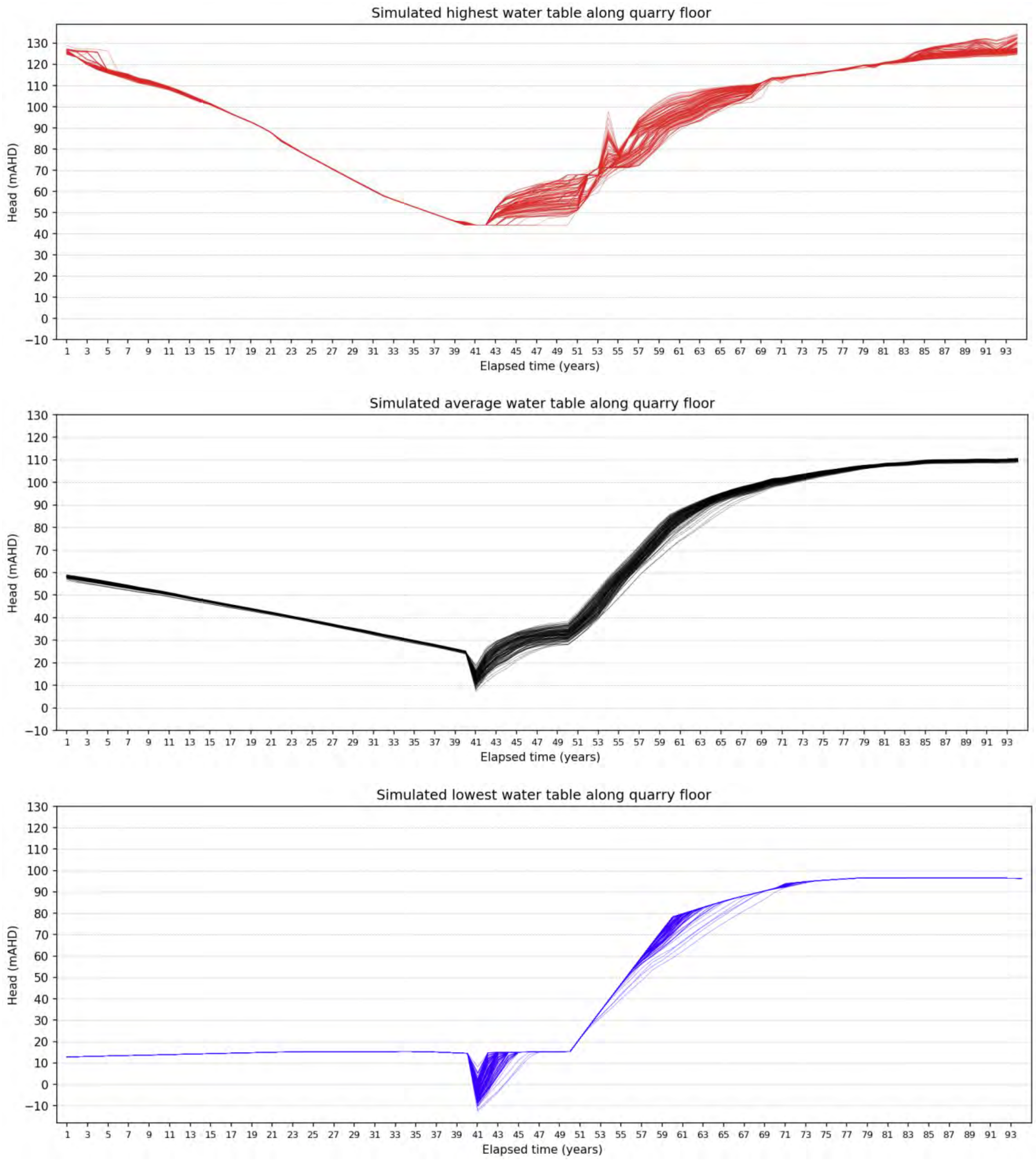


Figure 71 Hydrographs of highest, average and lowest water table in quarry – uncertainty analysis

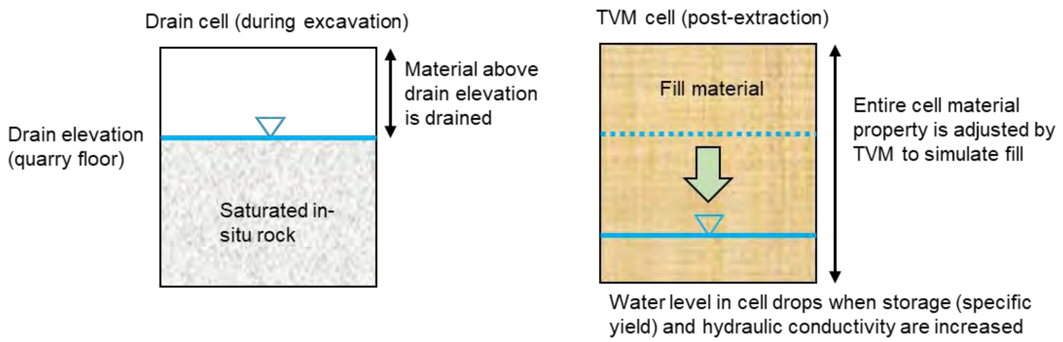


Figure 72 Water table drop at start of filling due to material property changes

Hydrographs of drawdown and associated uncertainty at registered bores within the predicted area of influence are shown in Figure 73 and Figure 74. These registered bores are potentially accessing groundwater for irrigation and/or stock and domestic use. The positive drawdown shown in the hydrographs represent the lowering of the groundwater levels and vice versa. The rising groundwater level (negative drawdown) trends are recorded in bores located within the area where the groundwater level is recovering during rehabilitation (relative to the base case). In general, the hydrographs indicate the maximum drawdown is likely to be less than 10 m at most registered bores, with the potential for the post-extraction groundwater levels to be higher than the current level at some registered bores.

Table 4 summarises the use, depth, location and proximity of these registered bores to the boundary of the quarry.

Table 4 Registered bores within predicted area of influence

Bore ID	Registered use	Depth (m)	Easting (MGA55)	Northing (MGA55)	Approximate distance from quarry (m)
139907	Dewatering	90	352673.2	5813184.1	80
WRK056003	Industrial	108	352560	5812634	570
81043	Stock & domestic	51.8	353953.2	5811984.1	950
81044	Stock & domestic	73	353953.2	5811984.1	950
81045	Stock & domestic	64	353873.2	5812004.1	880
81061	Stock & domestic	121	351473.2	5812204.1	1,340
81067	Stock & domestic	112	351673.2	5810464.1	2,330
WRK032565	Industrial	100	351611	5811577	1,500
134221	Stock & domestic	91.3	351193.2	5809664.1	3,250
WRK983590	Not specified	24	351660	5812926	940
WRK967196	Stock & domestic	45	350277.2	5812832.1	2,330
WRK968757	Stock & domestic	19	350680	5814860	2,620
81055	Stock & domestic	64.57	355263.2	5813384.1	2,000

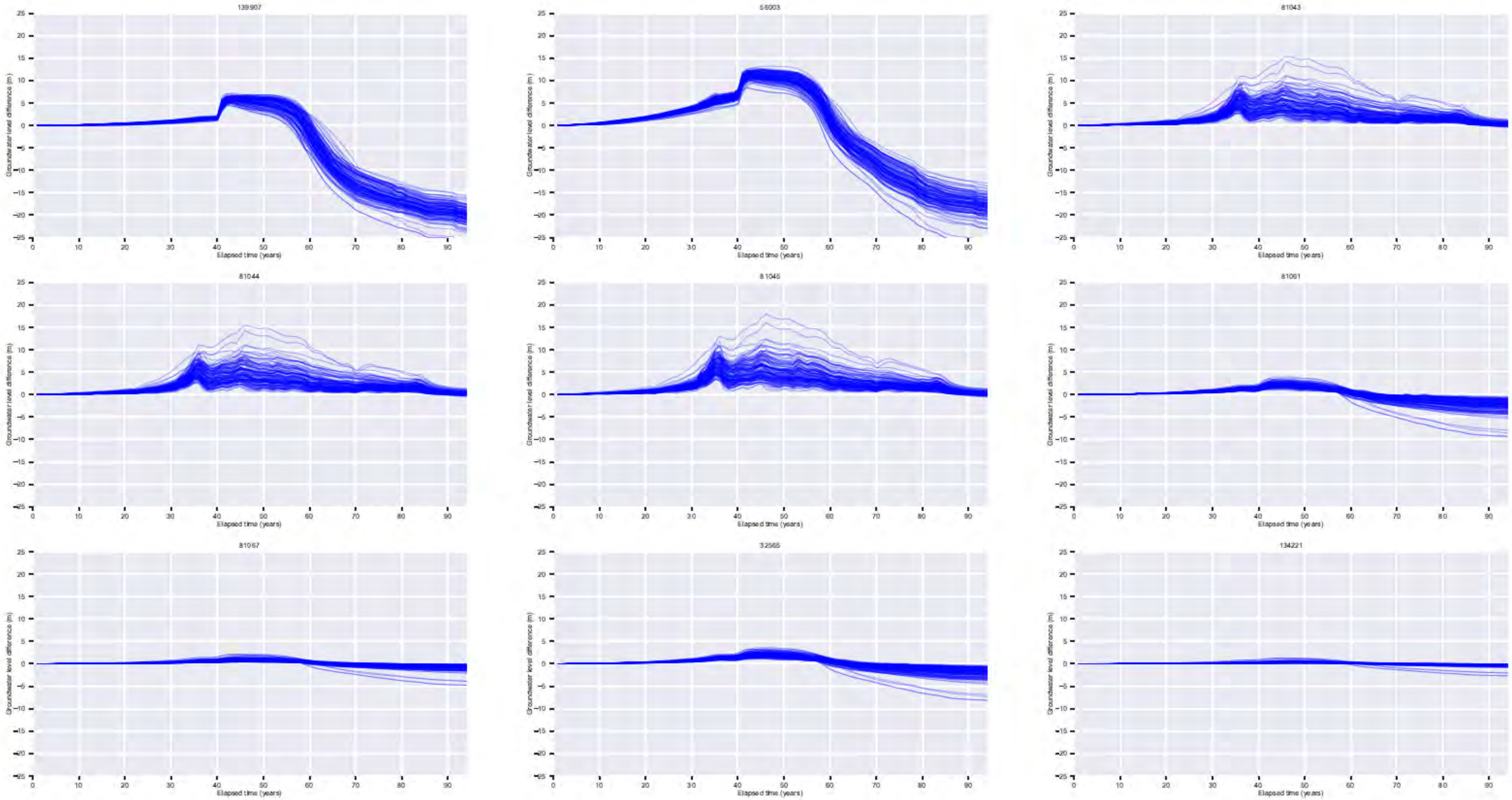


Figure 73 **Predicted hydrographs of groundwater level changes – registered bores (part 1)**

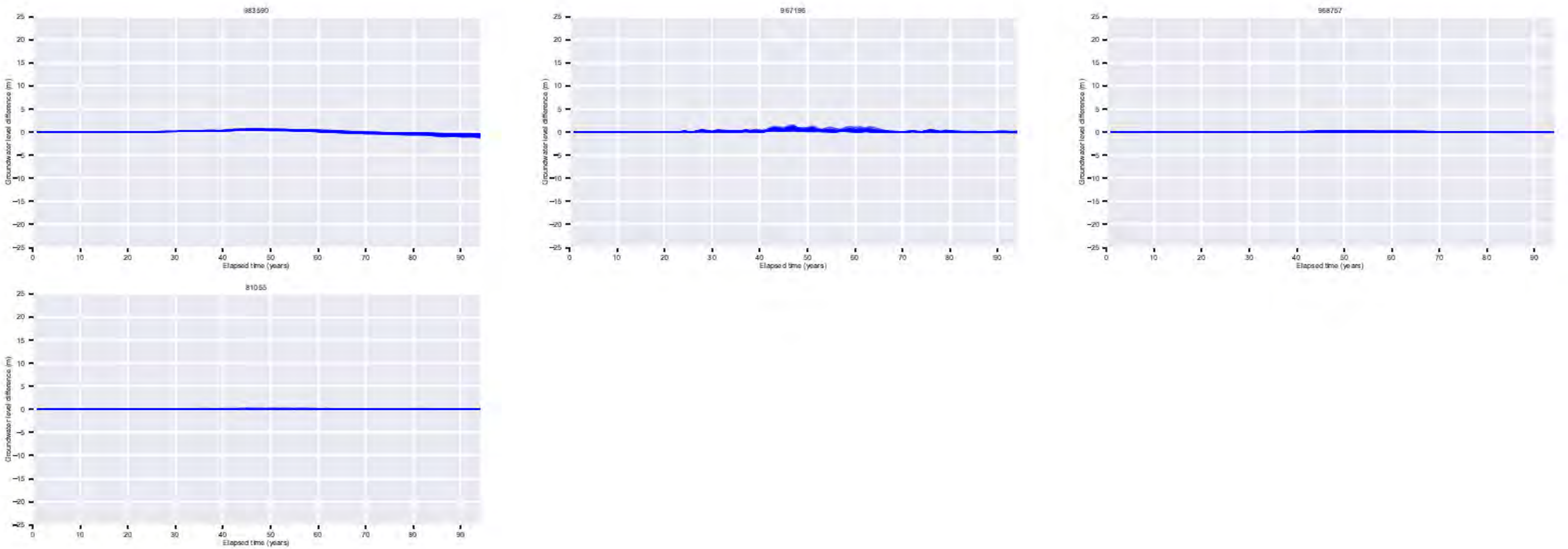


Figure 74 ***Predicted hydrographs of groundwater level changes – registered bores (part 2)***

6.2.3.2 Uncertainty associated with predicted groundwater flow changes

Uncertainty in the modelled streamflow is demonstrated in Figure 75, which shows the modelled streamflow at gauge 228369A for all 131 realisations. During periods of normal flow, the uncertainty in streamflow arising from the uncertainty in model parameters is around 5 L/s. During periods of low flow and high drawdown (from year 35 to 58), the uncertainty range is wider (up to around 10 L/s) and this influences the frequency and duration of periods with limited to no streamflow. When compared with the outputs from the climate change assessment (Section 5.3.1), the uncertainty in streamflow due to model parameter uncertainty is less than that arising from the uncertainty in future climate (with the latter indicating potential flow differences of 20 L/s or more).

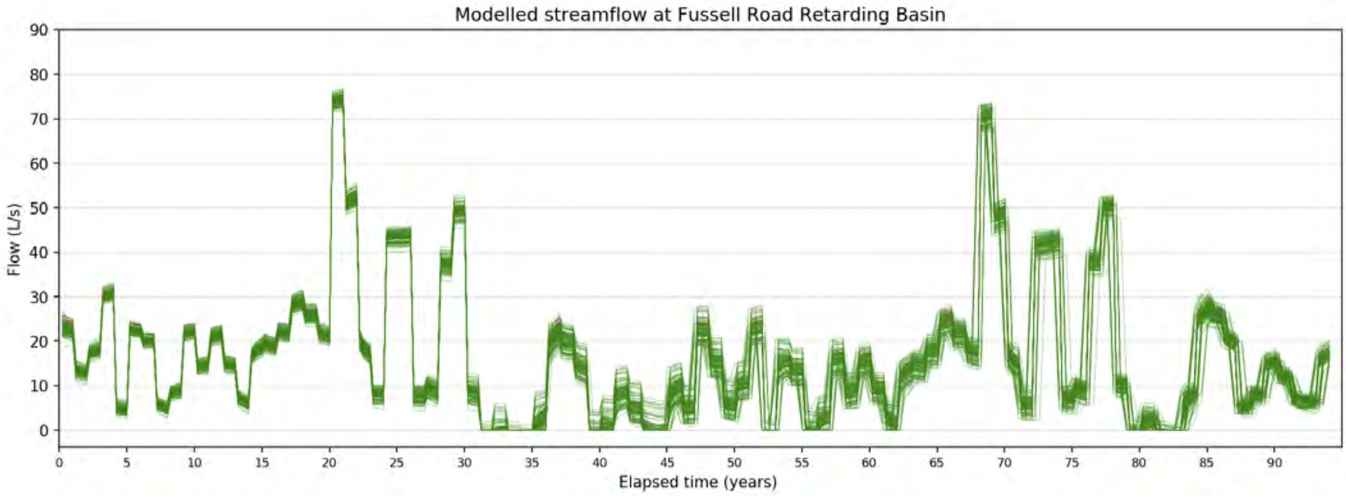


Figure 75 Modelled streamflow – uncertainty analysis

Uncertainty in the predicted groundwater seepage rate is shown in Figure 76, which includes the modelled groundwater seepage for all 131 realisations and their 5th and 95th percentile values. The level of uncertainty in the estimated seepage rate ranges from around 2.5 L/s to 5 L/s, with the upper end associated with the end of extraction and 20 to 30 years into rehabilitation i.e. the estimated seepage rate is most uncertain at the end of extraction and the first few decades into rehabilitation. The uncertainty range reduces towards the end of rehabilitation, as the groundwater levels recover and the rate of seepage decreases.

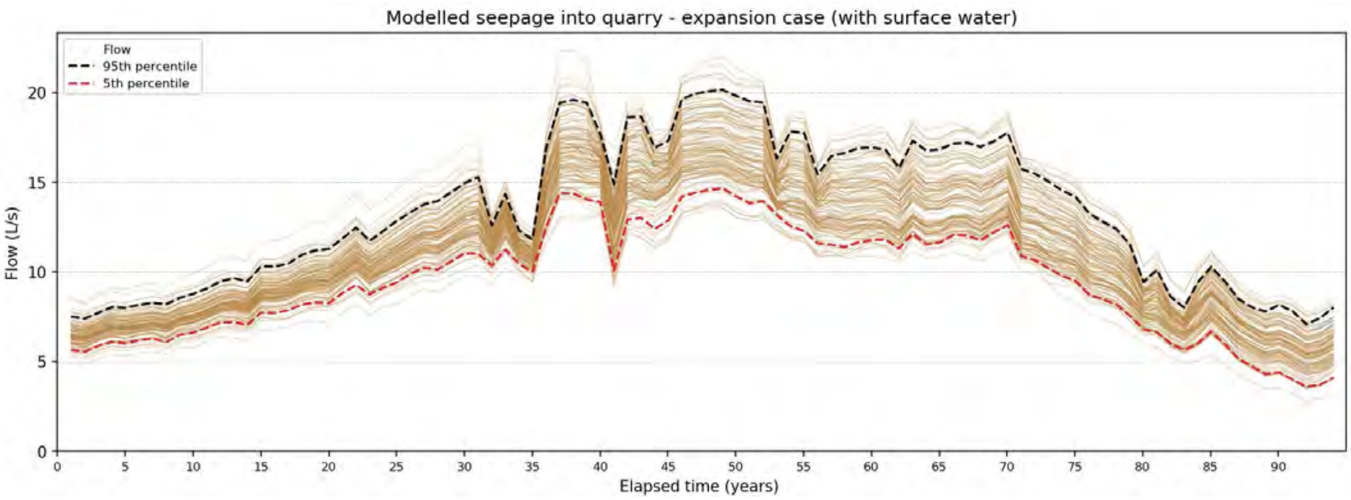


Figure 76 Modelled seepage into quarry – uncertainty analysis

6.3 Structural uncertainty analysis

6.3.1 Approach

The available geological data indicates the presence of a shear zone in the southwest corner of the existing quarry. The shear zone is interpreted to be trending northwest to southeast and dipping to the northeast. Although the lateral extent of this shear zone is not known, its fractured nature (where exposed in the quarry) suggests the potential for the hydraulic conductivity to be locally enhanced along this feature (which may explain the higher hydraulic conductivity derived in the area between the quarry and Bungalook Creek during model calibration, as discussed in Section 3.2.3). This means the shear zone has the potential to act as a preferential pathway, along where the depressurisation effect from the quarry could propagate.

The structural uncertainty analysis described in this section is designed to examine the potential influence of a major geological structure such as the shear zone and how this may affect the model calibration and predicted extent of drawdown. The presence of the shear zone is simulated explicitly in the model as a separate hydraulic conductivity zone. This explicit representation differs from the method adopted in the calibrated model, in which the spatial variability in the hydraulic conductivity is derived via interpolation of values assigned to strategically positioned pilot points (informed by calibration to observed data). For the purpose of this analysis, the lateral extent of the shear zone is assumed to extend across the Mt Evelyn Rhyodacite and Coldstream Rhyolite (the two HSUs intersected by the quarry). The angle of the shear zone is simulated by adjusting the extent of the shear zone in each model layer based on its interpreted dip and where the zone is expected intersect each layer (with the zone effectively steeping down thought the model layers). This is presented schematically in Figure 77.

6.3.2 Results

The model calibration has been repeated with the shear zone incorporated. In order to account for the influence of the shear zone while retaining an acceptable level of model calibration, the adopted values for some of the parameters have been modified from those presented in Section 3.2.3. For the shear zone, the model recalibration resulted in a horizontal hydraulic conductivity value of 0.074 m/d. This is close to the average hydraulic conductivity value adopted in the previous modelling by Golder (2006) and is higher than the adopted value for the Coldstream Rhyolite (resulting in a zone of enhanced hydraulic conductivity within this unit). For the Mt Evelyn Rhyodacite, the pilot points immediately adjacent to the shear zone have been assigned slightly higher values of 0.11 m/d and 0.17 m/d while lower values are assigned to the pilot points further to the east (suggesting generally higher hydraulic conductivity near the shear zone). The overall quality of calibration achieved is similar to that outlined in Section 3.2. For example, the SRMS error with respect to the hydraulic head observations is 1.02 % for the site bores and regional bores combined, compared to the 0.94 % error achieved for the calibrated model described in Section 3.2.

Following recalibration with the shear zone, the predictive modelling has been repeated as per Section 4.1 (Scenario 2 only, assuming total stream flow).

The magnitude and extent of drawdown predicted at the end of extraction is shown in Figure 78. The influence of the shear zone can be clearly seen in the figure, with the predicted drawdown contours extending in the northwest to southeast orientation along this feature, to the south of the quarry. There are also some differences in the drawdown contours compared to those presented in Figure 43 which are due to the differences in the adopted parameter values e.g. a lower maximum drawdown on the eastern side of Bungalook Creek and a slightly wider drawdown extent to the northeast of the quarry.

The structural uncertainty analysis suggests the potential for the shear zone to act as a pathway for the depressurisation effect, which could influence the drawdown extent (depending on its continuity). However, the overall impact of drawdown towards Bungalook Creek is not materially altered by this explicit representation of the shear zone, as the model calibration based on pilot points also resulted in higher hydraulic conductivity in this area. In both cases, drawdown is predicted to extend towards the creek and beyond, which is predicted to result in a loss of stream flow and the lowering of the water table in the downstream area of the creek due to reduced flow.

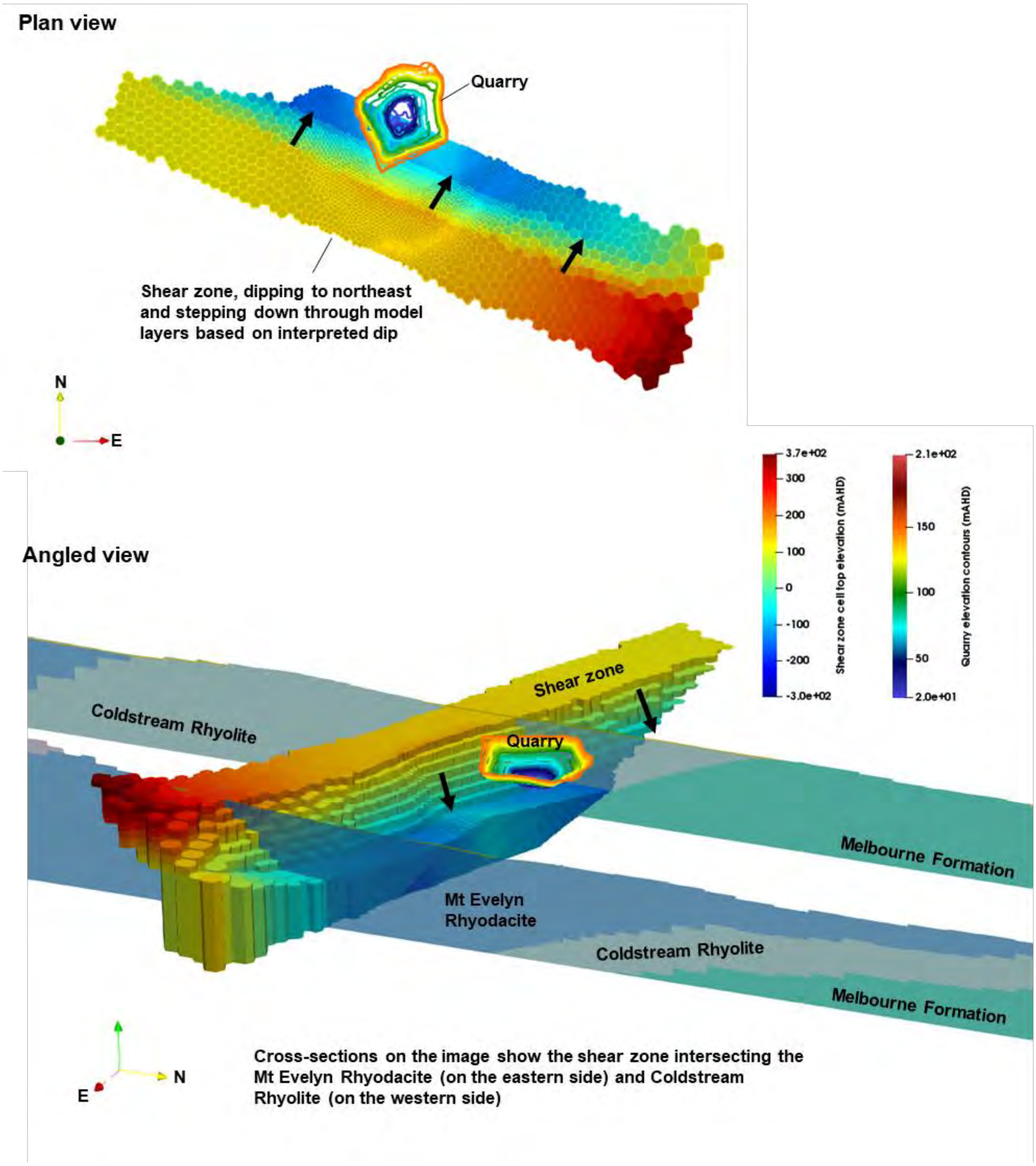


Figure 77 ***Model representation of shear zone representation***

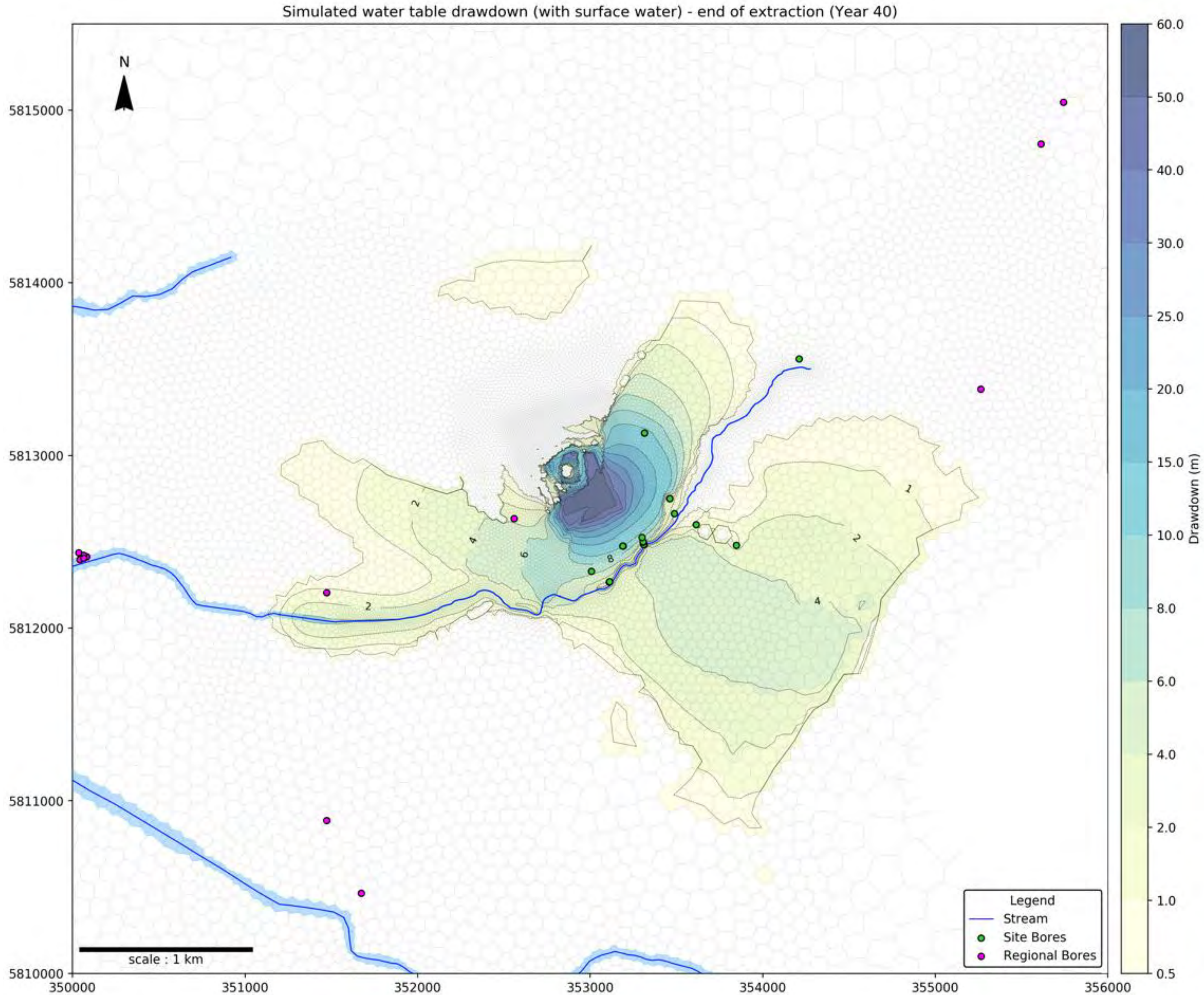


Figure 78 ***Simulated water table drawdown at end of extraction (with surface water flow) – influence of shear zone***

7. Mitigation scenario modelling

7.1 Preliminary mitigation options

This section details the findings of preliminary modelling undertaken to explore potential mitigation measures to minimise drawdown of the water table and associated impacts on streamflow along Bungalook Creek. Two preliminary mitigation options have been considered. These are:

– Option 1 - groundwater capture and direct discharge to the stream
– Option 2 – groundwater capture and re-injection

Option 1 examines the effect of capturing the volume of groundwater seeping into the quarry and discharging this to Bungalook Creek to maintain stream flow and encourage leakage to offset the water table drawdown predicted along and adjacent to Bungalook Creek. This is simulated in the model by assigning the groundwater seepage rate computed by the DRN cells (corrected for recharge, as per Figure 49) to the upstream segment of the SFR boundary of Bungalook Creek (in addition to the gauged flow, representing the flow generated from within the catchment).

Option 2 examines the effect of capturing the volume of groundwater seeping into the quarry and injecting a portion of this water into the water table aquifer adjacent to Bungalook Creek to offset drawdown, maintain baseflow and minimise stream leakage. This option allows the water table aquifer to be directly recharged, which is more targeted than Option 1 where a large portion of streamflow may be lost downstream. However, the rate of injection is likely to be limited by the generally low hydraulic conductivity of the aquifer, requiring either a large number of injection bores or a laterally extensive recharge trench. For the purpose of modelling, the following two injection scenarios are assumed and shown in Figure 79:

– Constant injection scenario – this assumes that injection can be achieved by a row of 18 injection bores, spaced roughly 50 m apart, with each bore capable of injecting at 0.3 L/s (a rate considered plausible based on the hydrogeological conditions of the site). This equates to a constant total injection rate of around 5.4 L/s. The bores are assigned to model layers within the upper 50 m.
– Scaled injection scenario – the predictive modelling results indicate the potential for the groundwater seepage rate to increase to up to 18 L/s to 20 L/s, depending on the prevailing climate condition and hydrogeological properties (around 3 to 4 times the 5.4 L/s injection rate assumed under the constant injection scenario). This means there is the potential for more flow to be captured and redirected into the aquifer over time, assuming sufficient injection capacity to sustain higher injection rates. This scenario considers the injection rates scaled up and down over time to enable large percentages (80 to 90 %) of groundwater captured in the quarry to be redirected to the aquifer.

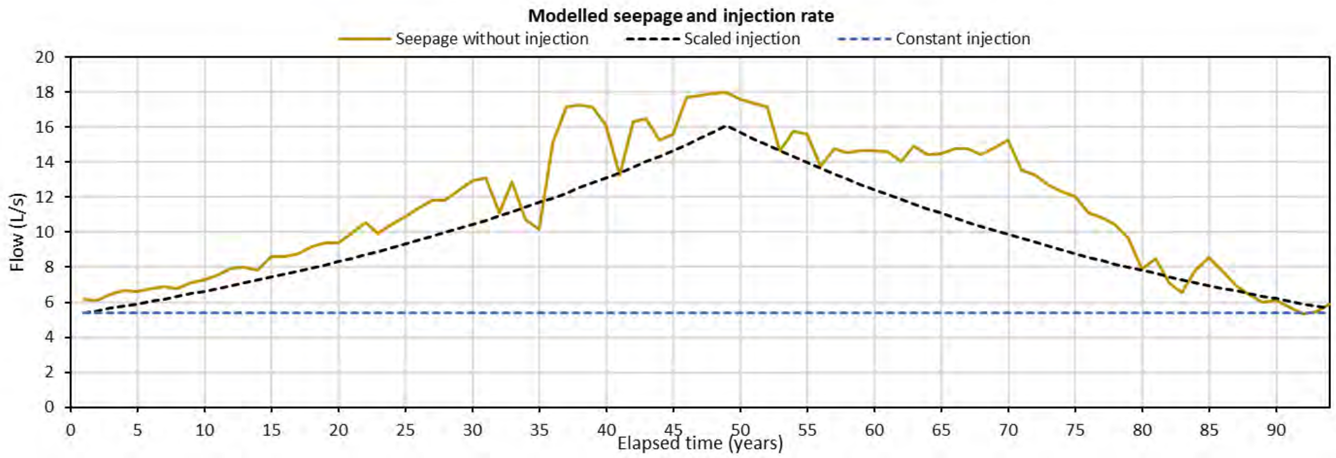


Figure 79 Option 2 constant and scaled injection rates

7.2 Results

7.2.1 Option 1 – direct discharge to stream

The contours of predicted water table drawdown at the end of extraction are presented in Figure 81 for the Option 1 scenario (direct discharge of quarry water). The extent and magnitude of drawdown are significantly reduced compared to the contours presented in Figure 43, including the absence of drawdown in the downstream area of Bungalook Creek due to the routing of additional flow. The modelling suggests that the increased stream leakage from the higher flow may not be sufficient to prevent drawdown along the creek and in adjacent areas. The hydrograph of the maximum water table drawdown simulated along Bungalook Creek, shown in Figure 80, indicates the additional flow could limit the maximum drawdown to no greater than 5 m but does not reduce it to zero.

The model assumptions for the Option 1 scenario are potentially conservative, as the stream boundary condition is not configured to simulate wider stream extents and higher stream levels that may arise from the higher flow, which has the potential to supply greater recharge to the water table (assuming other parameters, such as the stream bed conductance, are accurate), i.e. as the waterway floods, it may break its banks and flood a wider area. More detailed modelling, supported by additional data on surface water-groundwater interactions, would be necessary to confirm the effectiveness of this mitigation option.

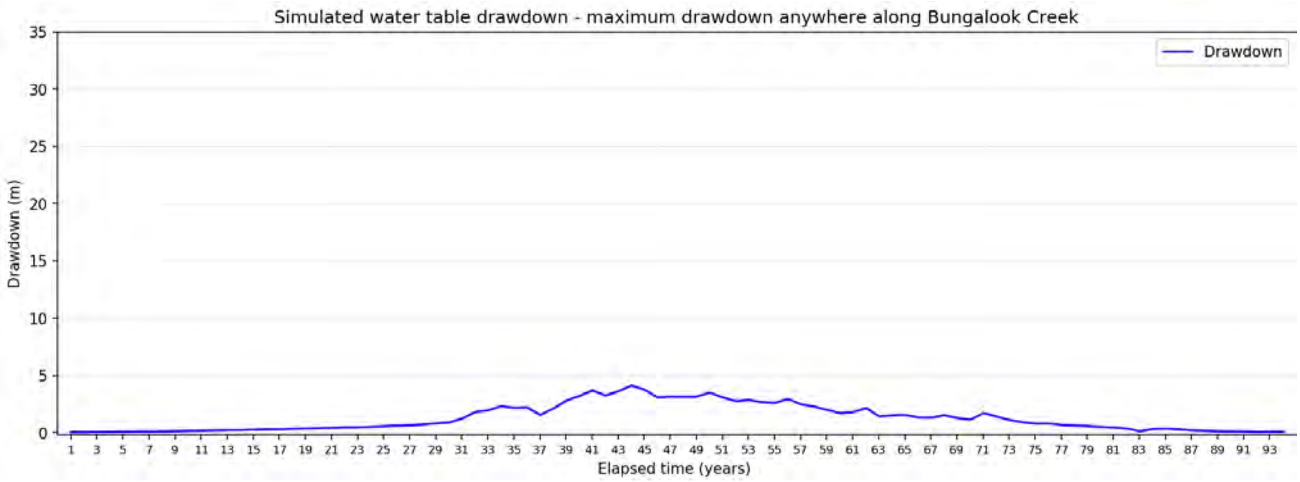


Figure 80 ***Bungalook Creek maximum drawdown hydrograph (with surface water flow and discharge of quarry water)***

7.2.2 Option 2 – injection bores

The contours of water table drawdown predicted at the end of extraction for the two injection scenarios are presented in Figure 82 and Figure 83. Also included in the figures are the locations of 18 injection bores assumed for the scenarios.

The modelling indicates that constant injection at 0.3 L/s per bore (5.4 L/s in total) is unlikely to limit drawdown of the water table, given the injection rate accounts for less than third of the peak groundwater seepage rate (replenishing only a small part of the aquifer storage affected by dewatering). With scaled injection rates, 80 % to 90 % of groundwater seepage is redirected into the aquifer and under this scenario the drawdown extent is constrained with no drawdown predicted at the sites of the injection bores. Drawdown is predicted to extend to the southern side of Bungalook Creek due to depressurisation from a deeper level, as shown in the northwest to southeast model cross-section across the quarry and Bungalook Creek (Figure 84). Nevertheless, the magnitude and extent of drawdown are much smaller than those from other mitigation scenarios. No drawdown is predicted along Bungalook Creek, as leakage from the stream is sufficient to top up the water table.

The scaled injection scenario assumes that each bore is capable of injecting up to 0.9 L/s. In reality, the aquifer properties may not support such high injection rates; however, under such condition, the volume of groundwater reporting to the quarry and the magnitude and extent of drawdown arising from it would also be expected to be less (requiring less water to be injected to offset smaller drawdown). Regardless of the hydrogeological properties, an effective mitigation measure will likely require a system capable of capturing and redirecting the majority of groundwater seeping into the quarry which could replenish the aquifer storage and reduce drawdown extents.

Returning the quarry water back into the aquifer via induced stream leakage (Option 1) or injection bores (Option 2) has the potential to result in some recirculation of that water. Figure 85 compares the modelled groundwater seepage rates for scenarios with and without the mitigations.

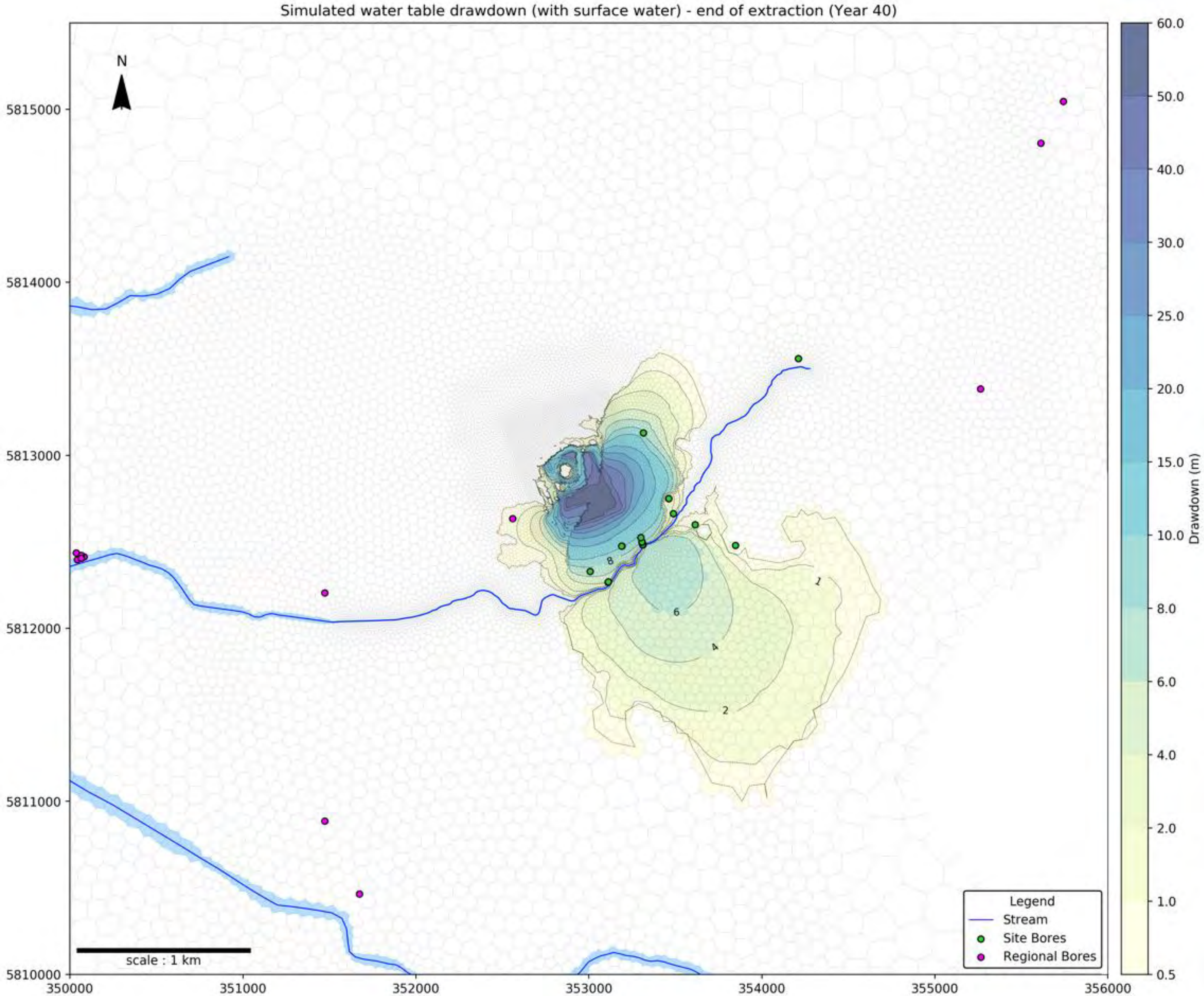


Figure 81 ***Simulated water table drawdown at end of extraction (with surface water flow and discharge of quarry water)***

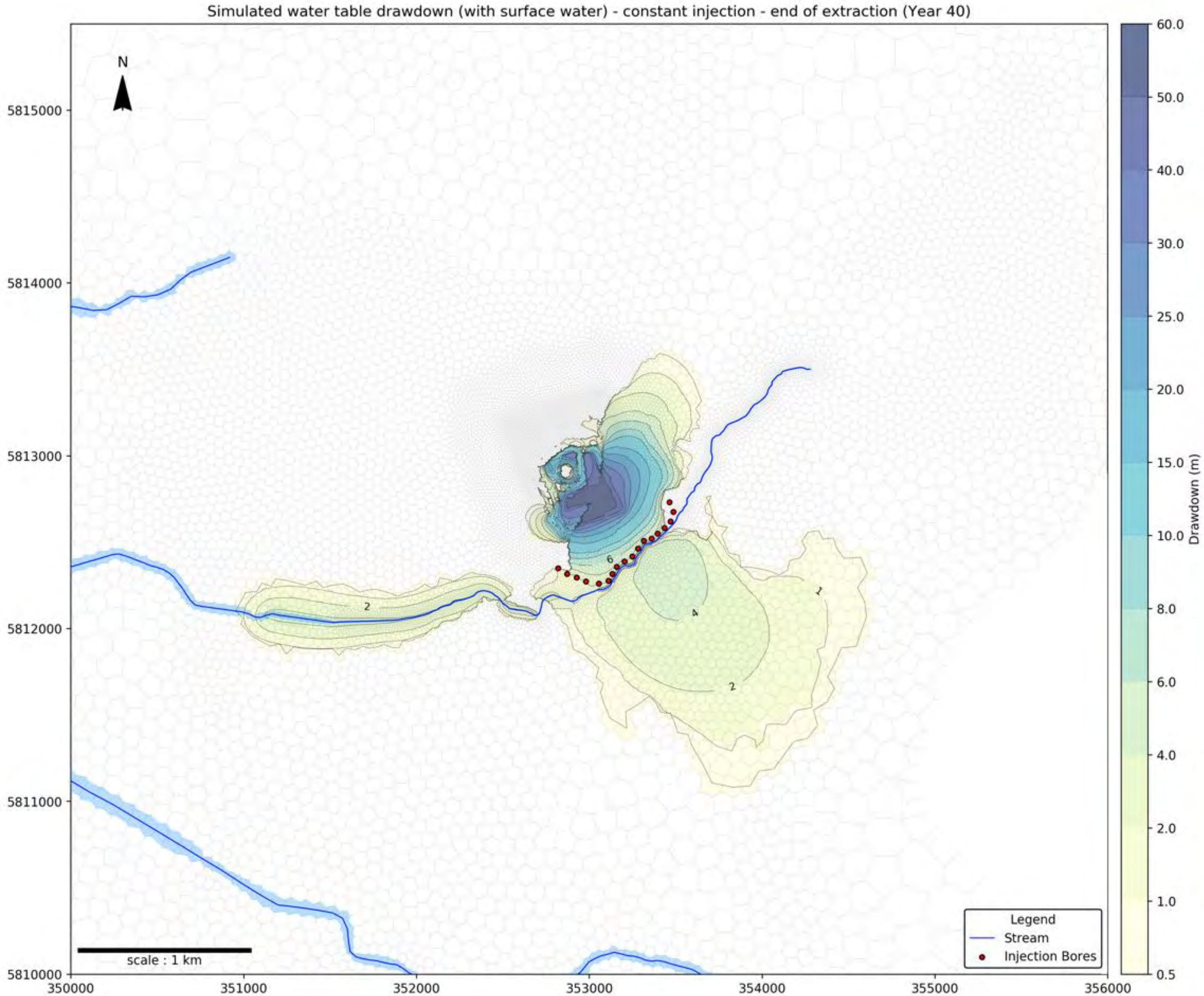


Figure 82 ***Simulated water table drawdown at end of extraction (with surface water flow and constant injection rate)***

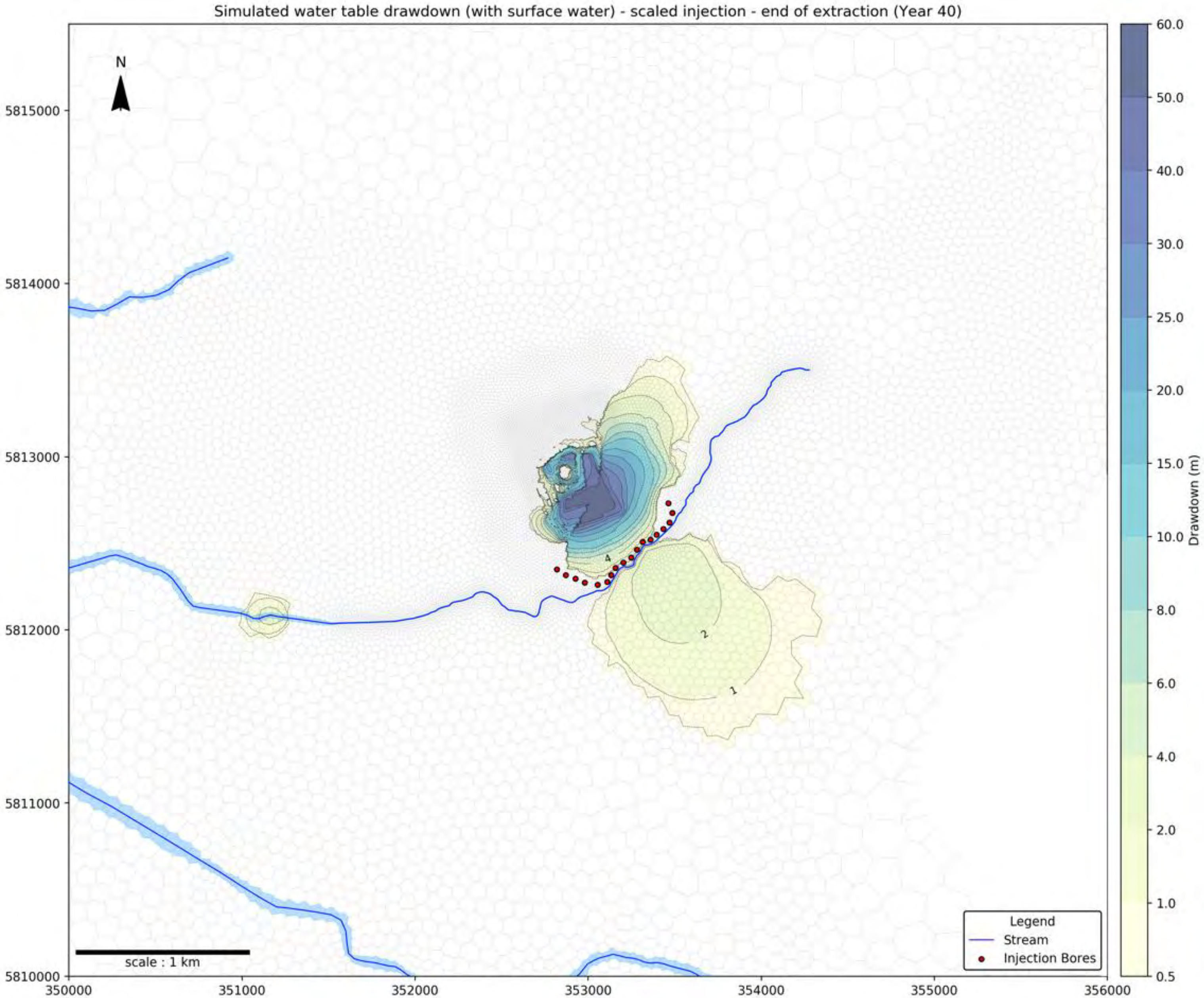


Figure 83 ***Simulated water table drawdown at end of extraction (with surface water flow and scaled injection rates)***

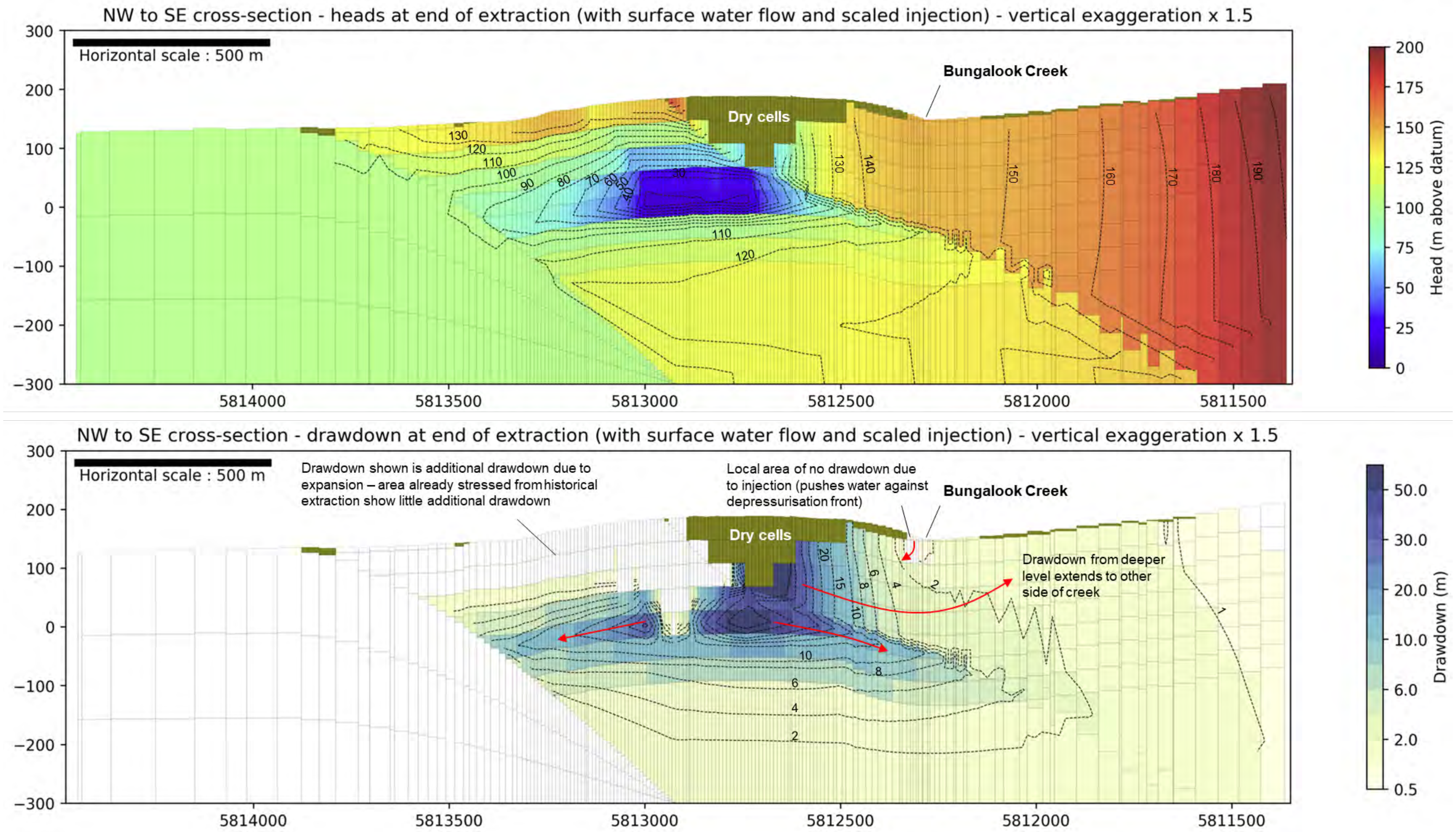


Figure 84 *Northwest to southeast model cross-section – heads and drawdown at end of extraction with scaled injection*

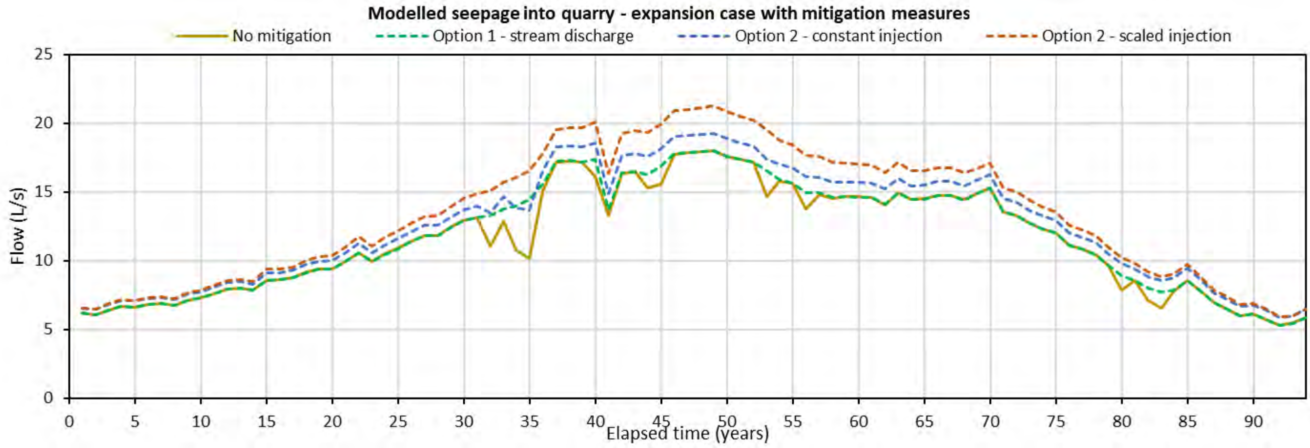


Figure 85 Modelled seepage into quarry –effect of mitigation measures

8. Model confidence and limitations

8.1 Model confidence

When a groundwater model is used to inform the outcome of a particular future scenario, the level of confidence in model's outputs depends fundamentally on the data used to calibrate the model and their relevance to the hydrological processes of future scenarios. It follows that a model that is required to predict responses to hydrological stresses that are similar to those of the past and for a period of time similar to the period of historical observations would have high confidence in its predictions, provided that the model has been adequately calibrated and the results of the model are mathematically sound. This forms the basis of the confidence level classification in the Australian Groundwater Modelling Guidelines (Barnett et al., 2012).

The Montrose quarry has a long history of extraction (commencing in the 1950s), with the period of historical extraction comparable to the period of future extraction and rehabilitation. The depth of historical extraction is also similar to that proposed for the future extraction, imposing a similar magnitude of hydrogeological stress on the groundwater system albeit over a larger extent (extending into an area previously subjected to less stress). In theory, this would suggest that the model could be designed to achieve high confidence; however, there are gaps in the available hydrogeological data, both spatially and temporally, that limits the ability of the model to generate predictions with a level of confidence that would be considered equal to the highest (Class 3) confidence level classification of the Australian Groundwater Modelling Guidelines. For example, there are gaps in the long term monitoring record that create uncertainty in the long term seasonal behaviour and how this may have been modified near the quarry under the influence of historical extraction. Similarly, the majority of monitoring bores are located in the Mt Evelyn Rhyodacite aquifer, near the critical areas of sensitive receptors, and this creates a gap in the understanding of the hydrogeological effects in other areas (such as the Coldstream Rhyolite and beyond).

In recognition of this limitation, the model calibration has been designed to simulate the long term behaviour of the hydrogeological system, benchmarking this against the water levels available from regional bores, and ensuring that the simulated water levels match with those measured in the site monitoring bores at different points in time (e.g. in 1996, 1998, 2002, 2003, 2004, 2022 and 2023). Furthermore, the available flux data, such as the estimated seepage rates into the quarry and baseflow along Bungalook Creek, have been included as calibration targets to further constrain the model parameters. Based on the quality of the calibration achieved and overall performance of the model, a confidence level classification of Class 2 (moderate confidence) is considered appropriate for the project.

Where there are gaps in the hydrogeological knowledge, a rigorous calibration-constrained uncertainty analysis has been undertaken to explore their influence on the predictions of interest. This approach is consistent with the recommendations of the recently revised IESC uncertainty guidelines (Peeters and Middlemis, 2023), which suggest that the confidence level classification of the Australian Groundwater Modelling Guidelines is no longer a useful measure of whether or not the model is fit for purpose, and more efficient and effective uncertainty analysis should be undertaken to address recognised data gaps and limitations of the model.

8.2 Model limitations

Numerical groundwater models are a mathematical representation of complex real world systems. The physical domain of interest, comprising layers of rocks and sediments, is discretised into a number of cells and parameters that control the movement of groundwater through these layers are prescribed to each cell. The governing groundwater flow equations are solved by the code to compute hydraulic head and fluxes in and out of each cell.

This mathematical representation of a natural physical system, using a finite number of cells, is a necessary simplification that is inherent in all numerical modelling, the degree of which is influenced by factors including the availability of data, scale of the model, intended model use and computational demand of modelling techniques. The groundwater model described in this report is of regional scale, consistent with the scale of the project, with a level of detail commensurate with the intended model use and available data.

It is not designed to simulate groundwater flow processes at all spatial scales (for example, the influence of individual fractures) which is neither necessary to inform the potential impacts of the project nor possible with the data currently available.

This report describes several tasks undertaken to address recognised limitations of modelling. These include:

– Using unstructured gridding to enable accurate representations of the project-induced effects (progression of extraction and backfilling, and interaction with Bungalook Creek) within a regional model domain.
– Using available hydrological data to calibrate the model and guide the selection of parameters, including regional bore data and groundwater fluxes such as seepage and baseflow.
– Uncertainty analysis, which included detailed non-linear analysis of parameter uncertainty and deterministic analysis of uncertainty associated with a geological structure (shear zone).

9. Conclusions

The following conclusions are drawn from the findings of the detailed numerical groundwater modelling undertaken for the proposed expansion of the quarry at Montrose:

- The modelling suggests the potential presence of a zone of enhanced hydraulic conductivity in an area to the south of the quarry and along Bungalook Creek, which may explain the lower hydraulic gradient interpreted locally in this area. This may be associated with the northwest – southeast trending shear zone that has been identified in the southwest corner of the exposed quarry face. Due to the proximity of the proposed expansion towards Bungalook Creek and the potentially higher hydraulic conductivity in this area, there is the potential for the drawdown cone to extend towards the creek.
- Flow along Bungalook Creek is likely to be supplying recharge to the water table via stream leakage, particularly during periods of high flow. The modelling suggests that historical extraction at the quarry is likely to have resulted in some drawdown towards Bungalook Creek, albeit temporary and limited to periods of low flow when there is insufficient leakage to top up the water table.
- During proposed expansion, a further lowering of the water table from dewatering has the potential to locally disconnect the water table from the bottom of the creek and induce more leakage. The modelling suggests that when the total stream flow is less than 10 L/s, there is the potential for all of the stream flow to be lost via leakage. This would result in little to no flow routing to the downstream area, which could lower the water table along the creek downstream of the quarry.
- The water table drawdown along Bungalook Creek is highly sensitive to the prevailing climatic condition. The largest drawdown is expected during dry periods, when there is insufficient stream flow to supply recharge to the water table. The uncertainty analysis suggests that the largest drawdown could be in the order of 15 m to 27 m along Bungalook Creek if a dry period occurs near the end of the proposed 40-year expansion. For the most period, the maximum water table drawdown along Bungalook Creek is estimated to be 5 m to 15 m.
- The climate change assessment suggests that changes in stream flow and recharge due to climate change has the potential to result in large differences in the water table drawdown along Bungalook Creek, with the maximum water table drawdown ranging from around 27 m for the low (wet) climate change condition to around 37 m for the high (dry) climate change condition (and occurring more frequently under this dry condition). This means the uncertainty in future climate has a similar (if not, bigger) contribution to the uncertainty in modelled water table drawdown compared to that arising from the uncertainty in model parameters.
- Returning the volume of groundwater captured at the quarry to Bungalook Creek could maintain the stream flow and locally offset drawdown via leakage. However, a large portion of this flow may be lost downstream as the rate of leakage would be expected to be lower than the rate in which the flow is routed downstream. Direct recharge of this water via a series of injection bores is likely to be more effective in returning groundwater back into the aquifer (from where it is originally derived) and maintain the water table along the creek.
- The direct recharge could be achieved via a row of injection bores. The modelling suggests that the water table drawdown adjacent to Bungalook Creek could be significantly reduced as long as the injection rate can be scaled over time to enable a large percentage of groundwater reporting to the quarry to be captured and redirected into the aquifer. Based on the aquifer properties modelled, this would require around 18 injection bores with each capable of injecting at 0.3 L/s to up to 0.9 L/s. In reality, the aquifer properties may not support such high injection rates and therefore greater bore numbers may be required. However, under such condition, the volume of groundwater reporting to the quarry and the magnitude and extent of drawdown arising from it would also be expected to be less. In other words, as the rate of groundwater seepage and injection are both dependent on the aquifer properties, the re-injection of quarry water would be expected to be effective in preventing drawdown at the sites of injection as long as most of that seepage water can be captured and returned to the aquifer.

10. References

Barnett, B, Townley, LR, Post, V, Evans, RE, Hunt, RJ, Peeters, L., Richardson, S, Werner, AD, Knapton, A, and Boronkay, A. 2012, "Australian groundwater modelling guidelines", National Water Commission, Waterlines Report Series No. 82 June 2012 ISBN: 978-1-921853-91-3 (online).

Crosbie, RS, McCallum, JL, Walker, GR, Chiew, FHS, 2010, "Modelling climate-change impacts on groundwater recharge in the Murray-Darling Basin, Australia", Hydrogeology Journal (2010) 18: 1639–1656.

DELWP, 2020, "Guidelines for Assessing the Impact of Climate Change on Water Availability in Victoria. Final, November 2020", Department of Environment, Land, Water and Planning, Victoria.

Doherty, J. 2016, "PEST Model-Independent Parameter Estimation. User Manual Part II: PEST Utility Support Software. Version 6", Watermark Numerical Computing, Brisbane, Australia

Doherty, J. 2017, "PEST_HP. PEST for Highly Parallelized Computing Environments", Watermark Numerical Computing, 2017.

Doherty, J, 2020, "A Simple Lumped Parameter Model for Unsaturated Zone Processes", Watermark Numerical Computing, 2020.

Golder, 2006. Report on Montrose Quarry Groundwater Effects Assessment for Proposed Quarry Extension, March 2006.

HydroAlgorithmics, 2020, "AlgoMesh 2 User Guide, August 2020"

McCallum, JL, Crosbie, RS, Walker, GR & Dawes, WR 2010, "Impacts of climate change on groundwater in Australia: a sensitivity analysis of recharge", Hydrogeology Journal (2010) 18:1625–1638.

Peeters, LJM and Middlemis, H. 2023, "Information Guidelines Explanatory Note: Uncertainty analysis for groundwater modelling", A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of Climate Change, Energy, the Environment and Water, Commonwealth of Australia, 2023.

Niswonger, RG, Panday, S & Ibaraki, M., 2011, "MODFLOW–NWT. A Newton formulation for MODFLOW–2005", U.S. Geological Survey Techniques and Methods, book 6, chap. A37, 44 p.

Panday, S, Langevin, CD, Niswonger, RG, Ibaraki, M and Hughes, J., 2013, "MODFLOW–USG Version 1: An Unstructured Grid Version of MODFLOW for Simulating Groundwater Flow and Tightly Coupled Processes Using a Control Volume Finite-Difference Formulation", chapter 45 of Section A, Groundwater Book 6, Modelling Techniques. Techniques and Methods 6–A45

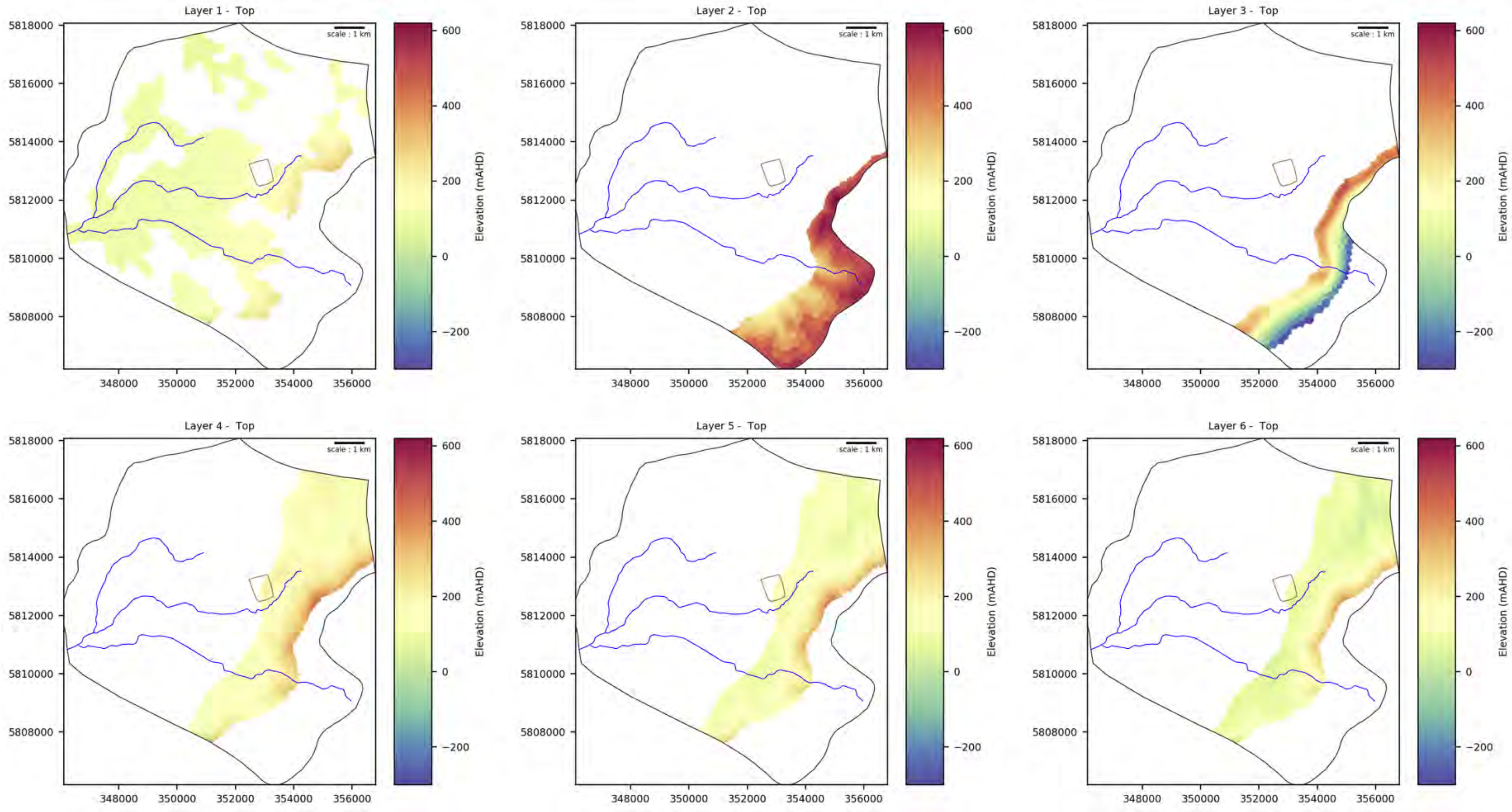
Panday, S, 2023, "USG-Transport Version 2.1.0: The Block-Centered Transport Process for MODFLOW-USG", GSI Environmental, January, 2023.

Rau, GC, Acworth, TI, Halloran, LJS, Timms, WA & Cuthbert, MO, 2018, "Quantifying Compressible Groundwater Storage by Combining Cross-hole Seismic Surveys and Head Response to Atmospheric Tides", Journal of Geophysical Research: Earth Surface 123(8),1910-1930.

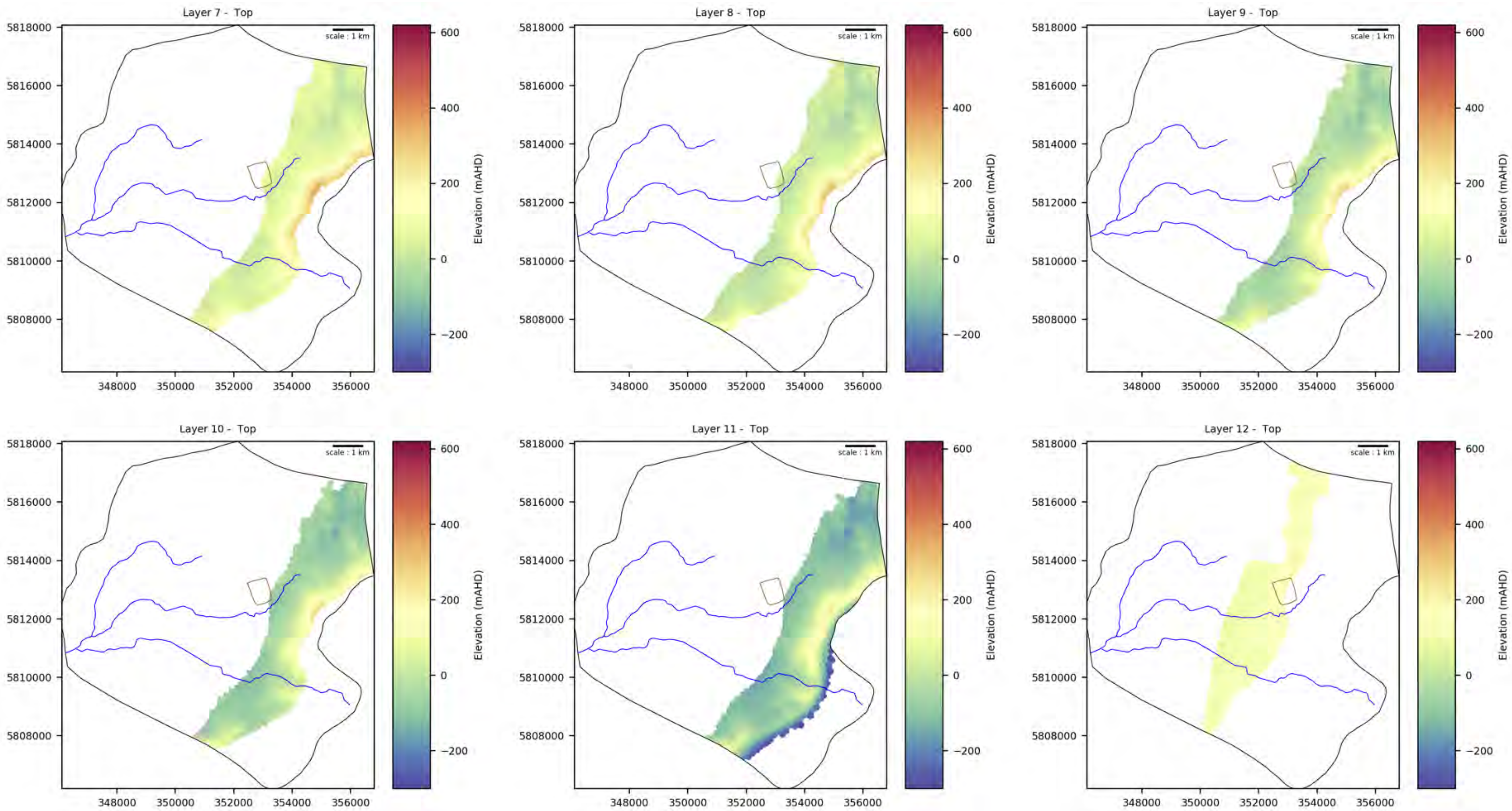
Appendices

Appendix A

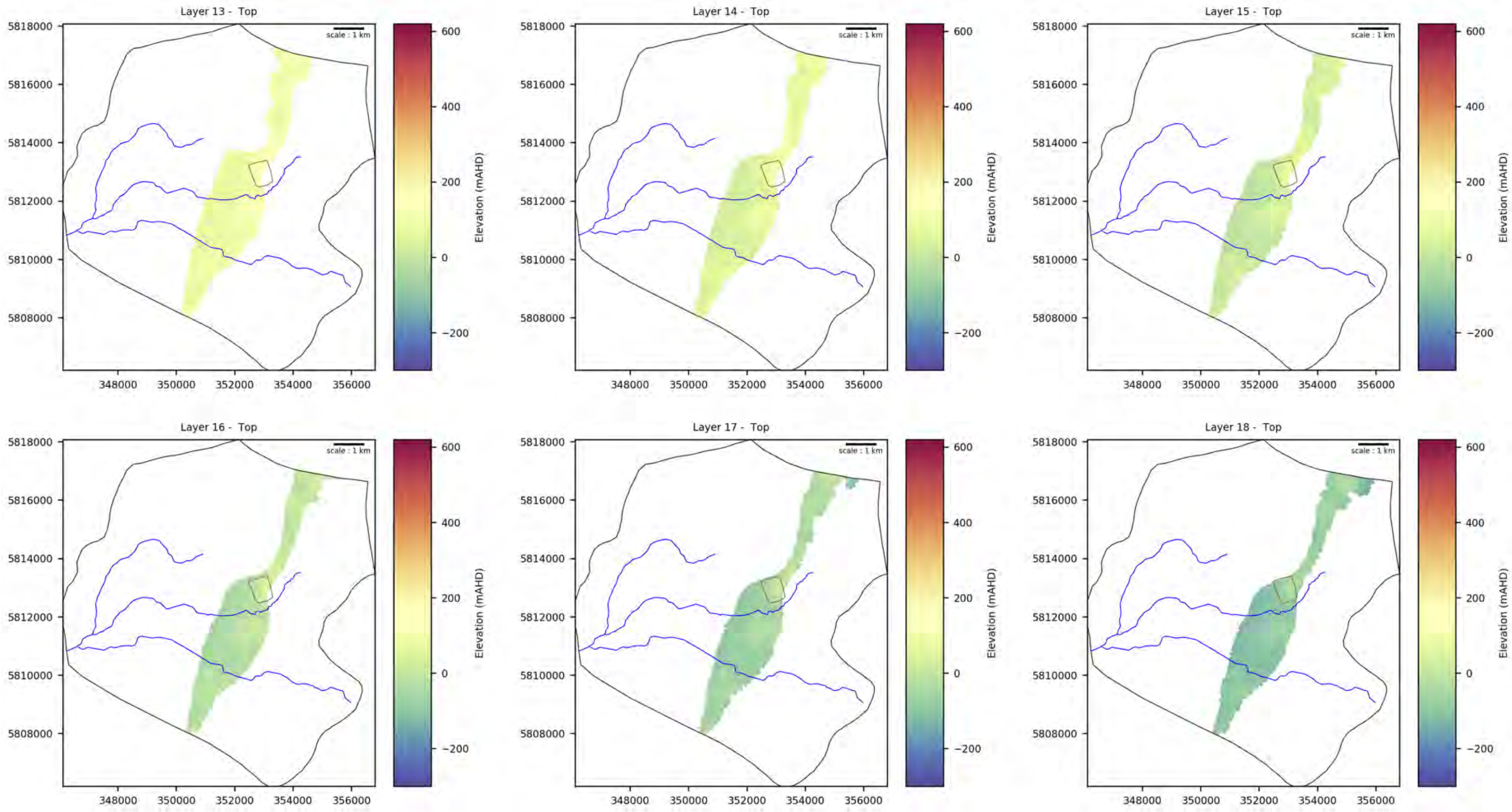
Model layer elevation



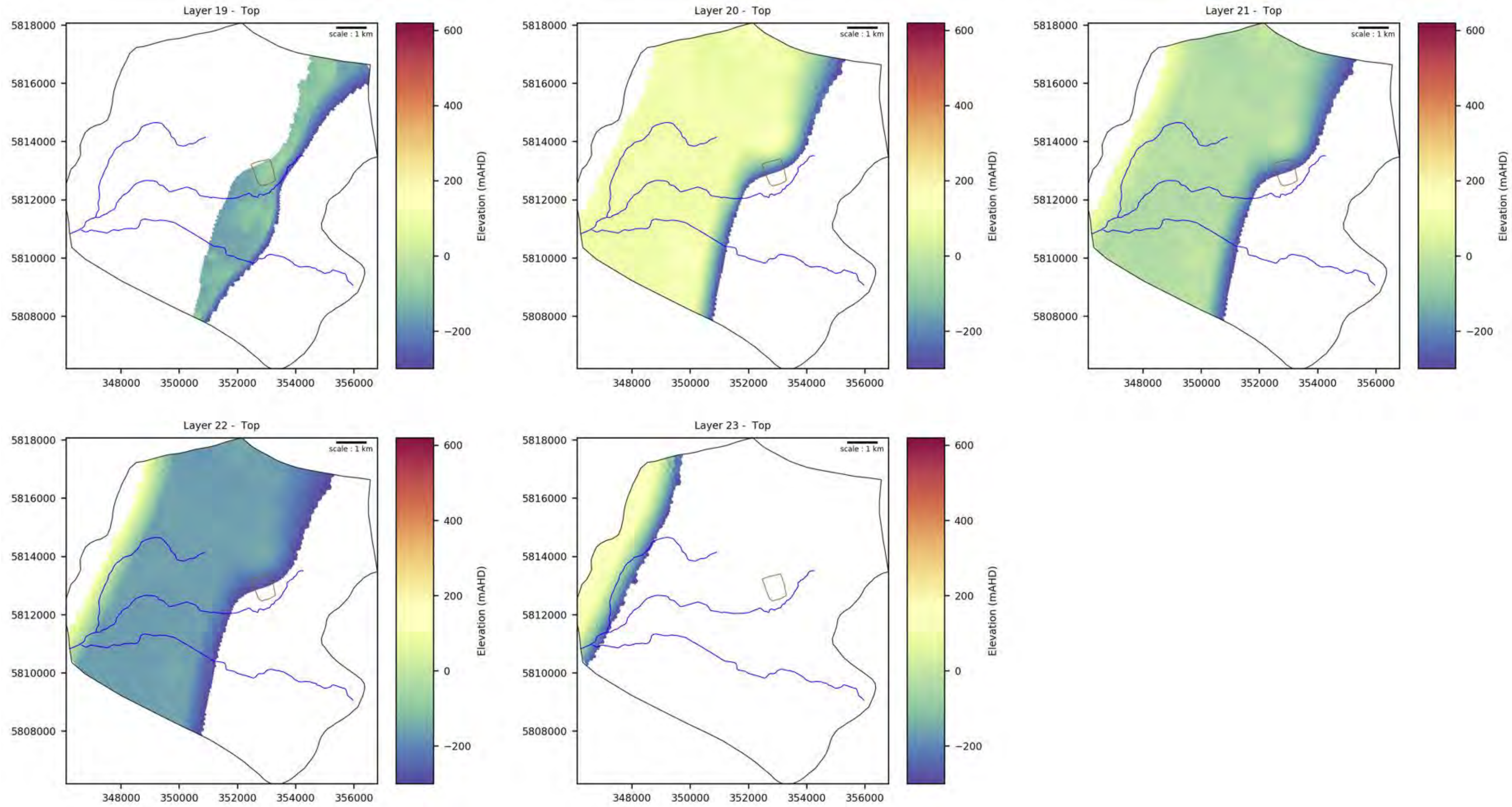
Model top – layer 1 to 6



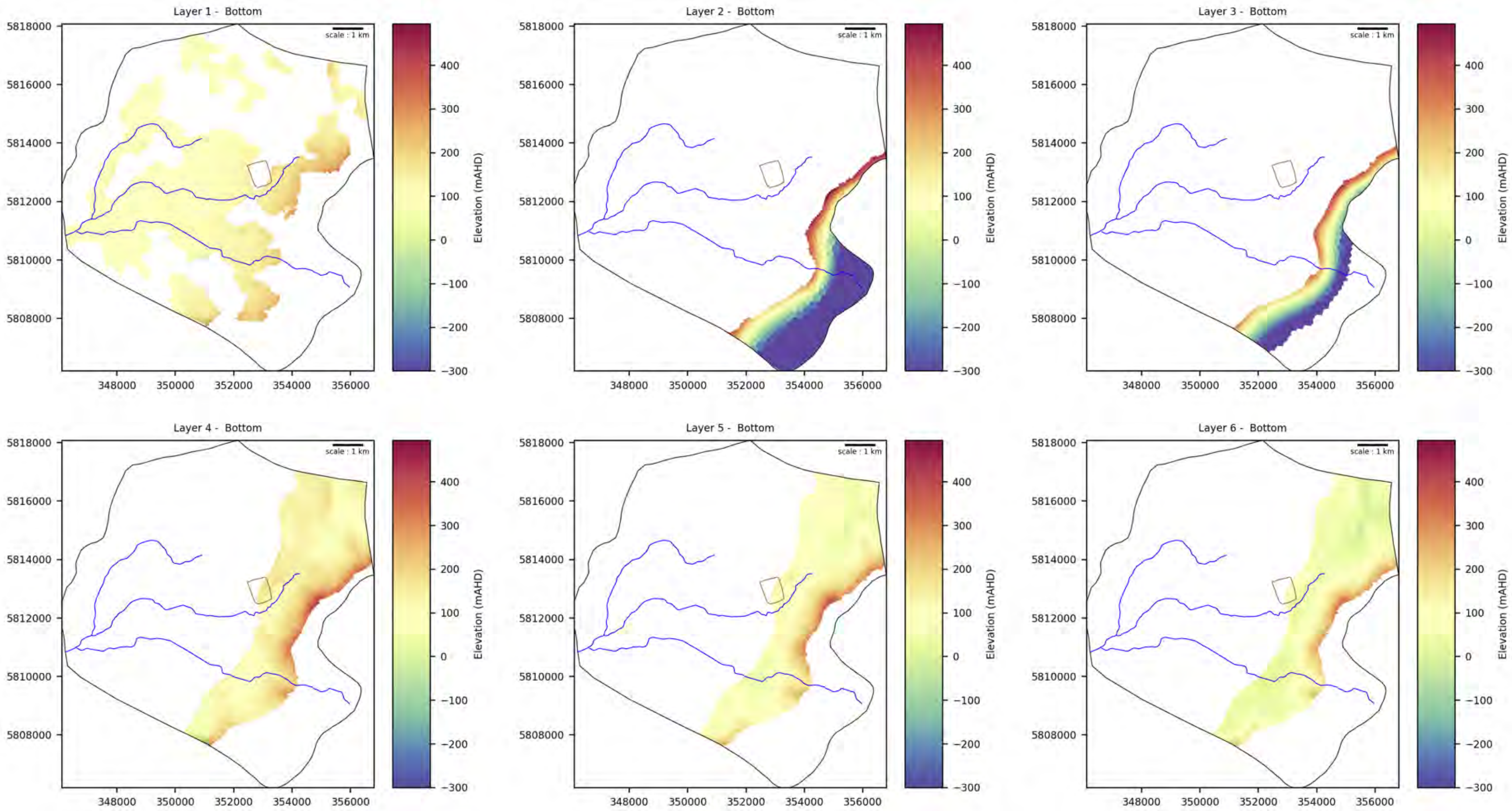
Model top – layer 7 to 12



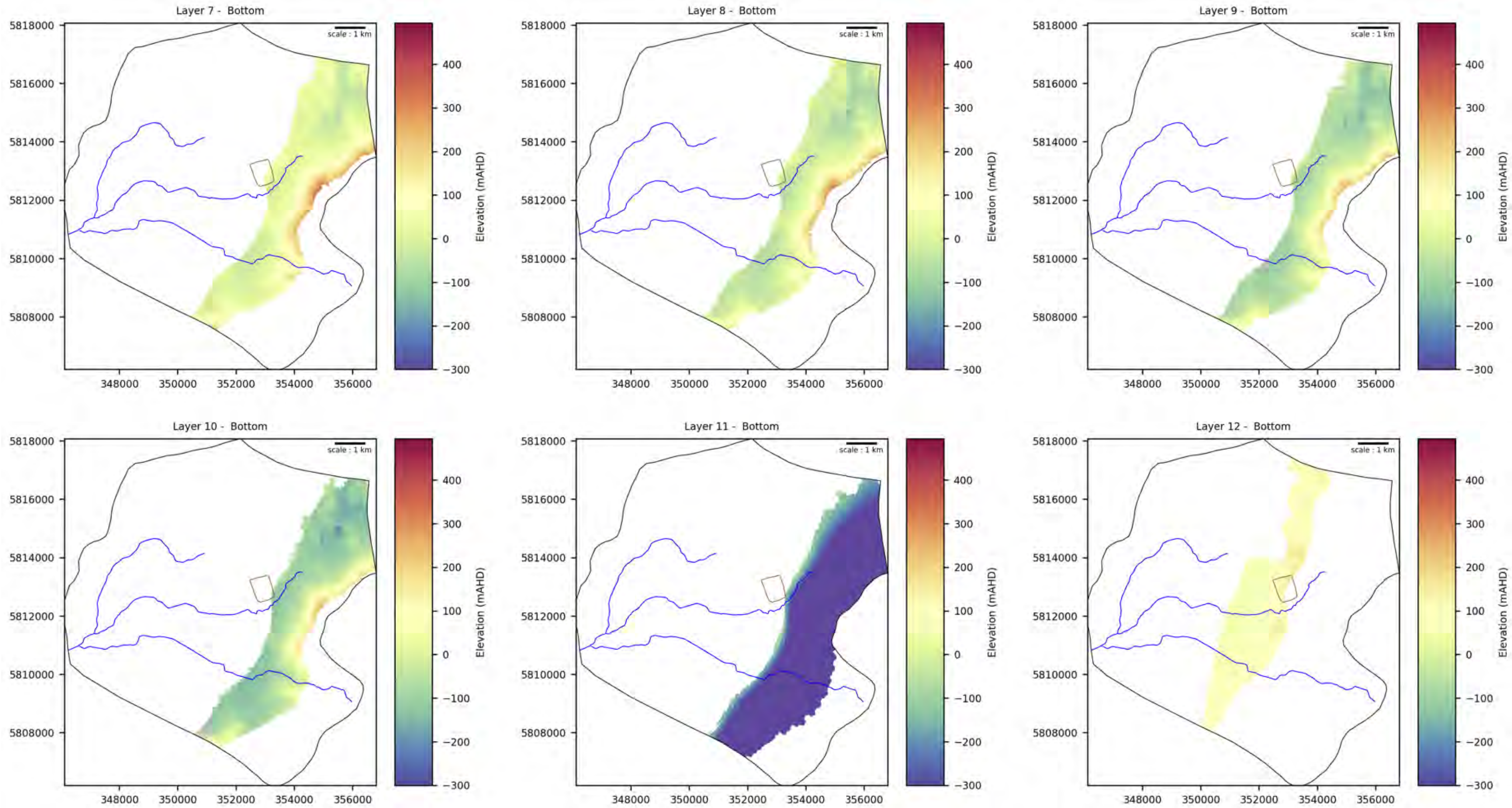
Model top – layer 13 to 18



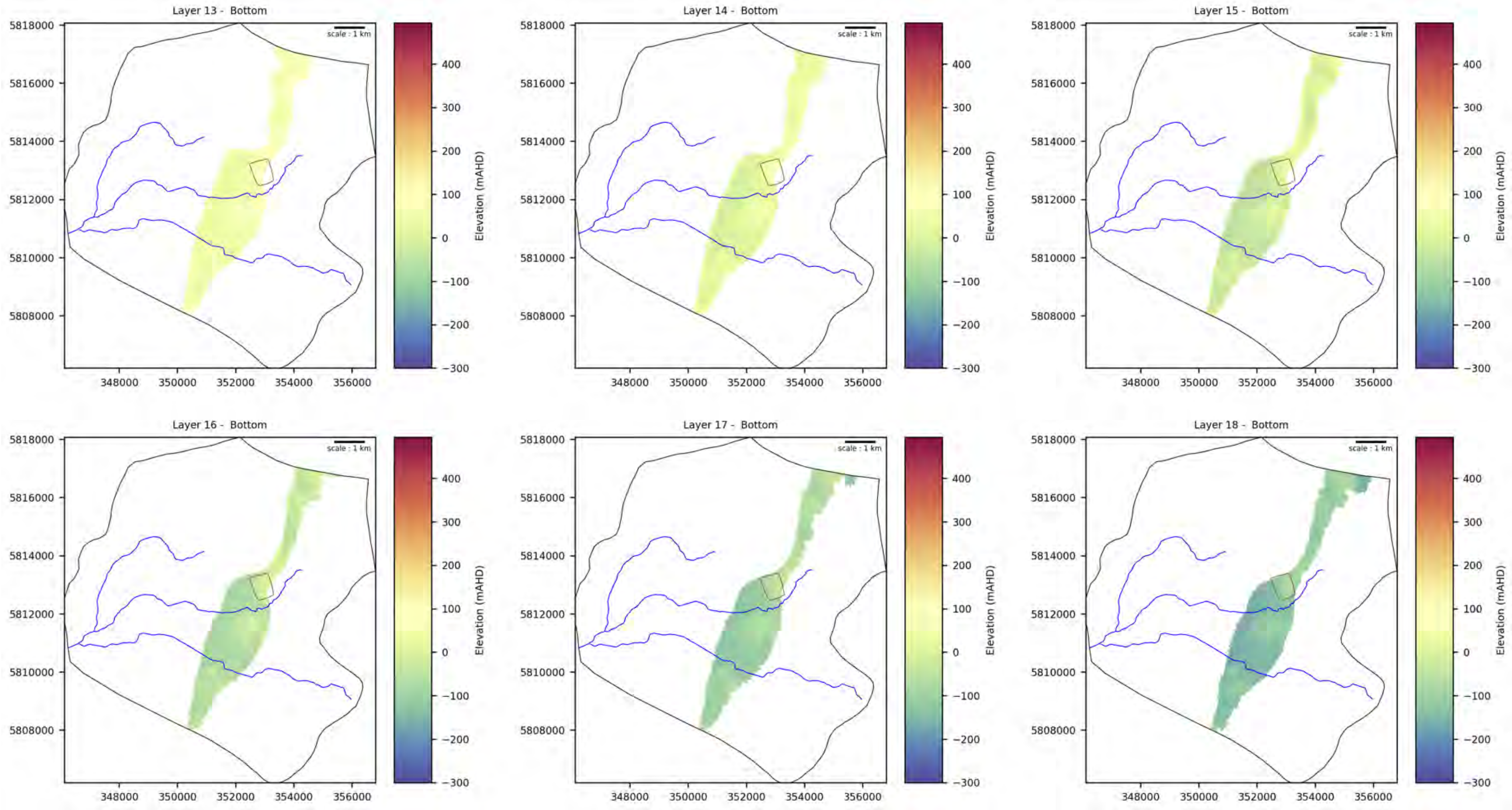
Model top – layer 19 to 23



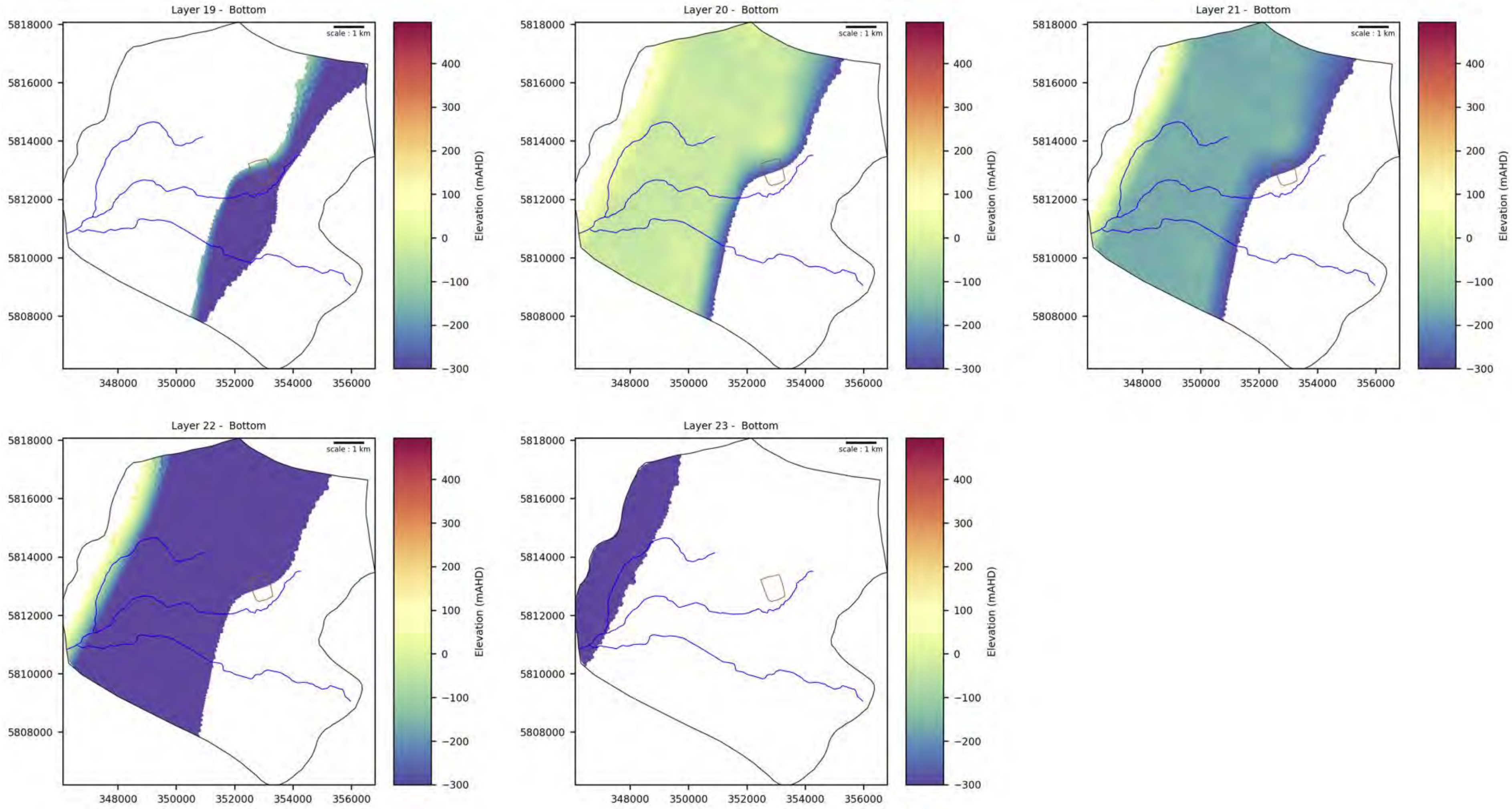
Model bottom – layer 1 to 6



Model bottom – layer 7 to 12



Model bottom – layer 13 to 18

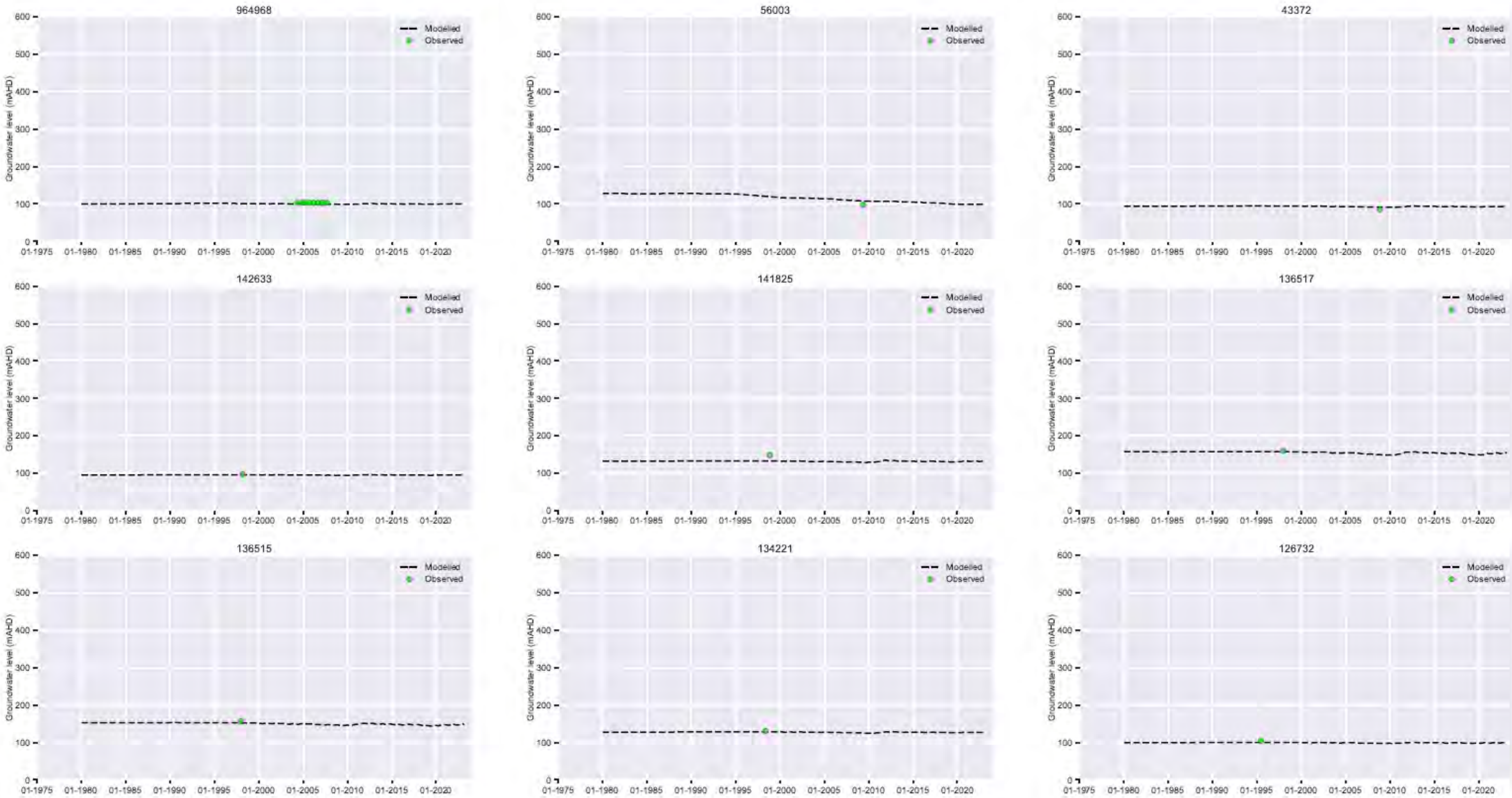


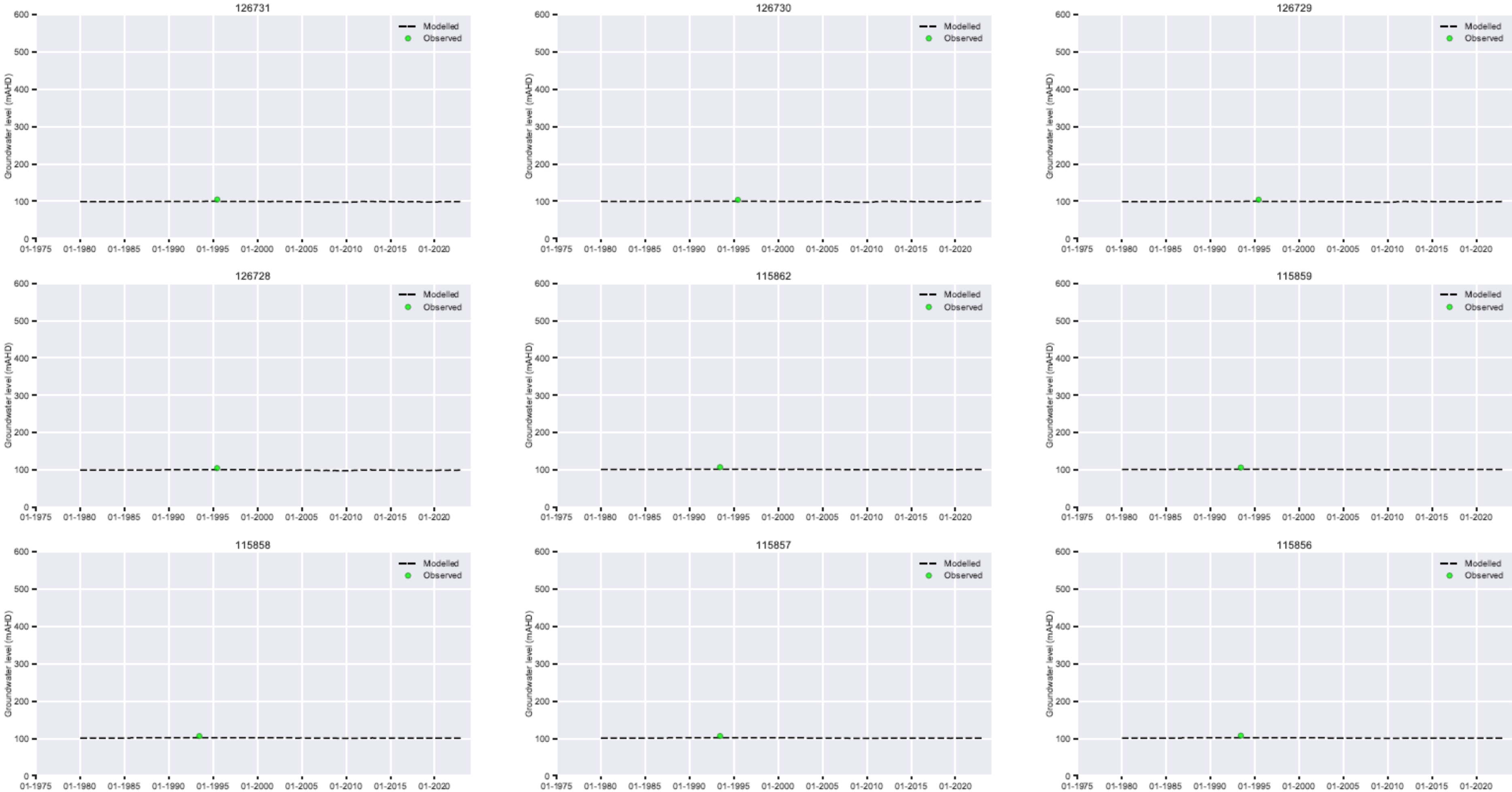
Model bottom – layer 19 to 23

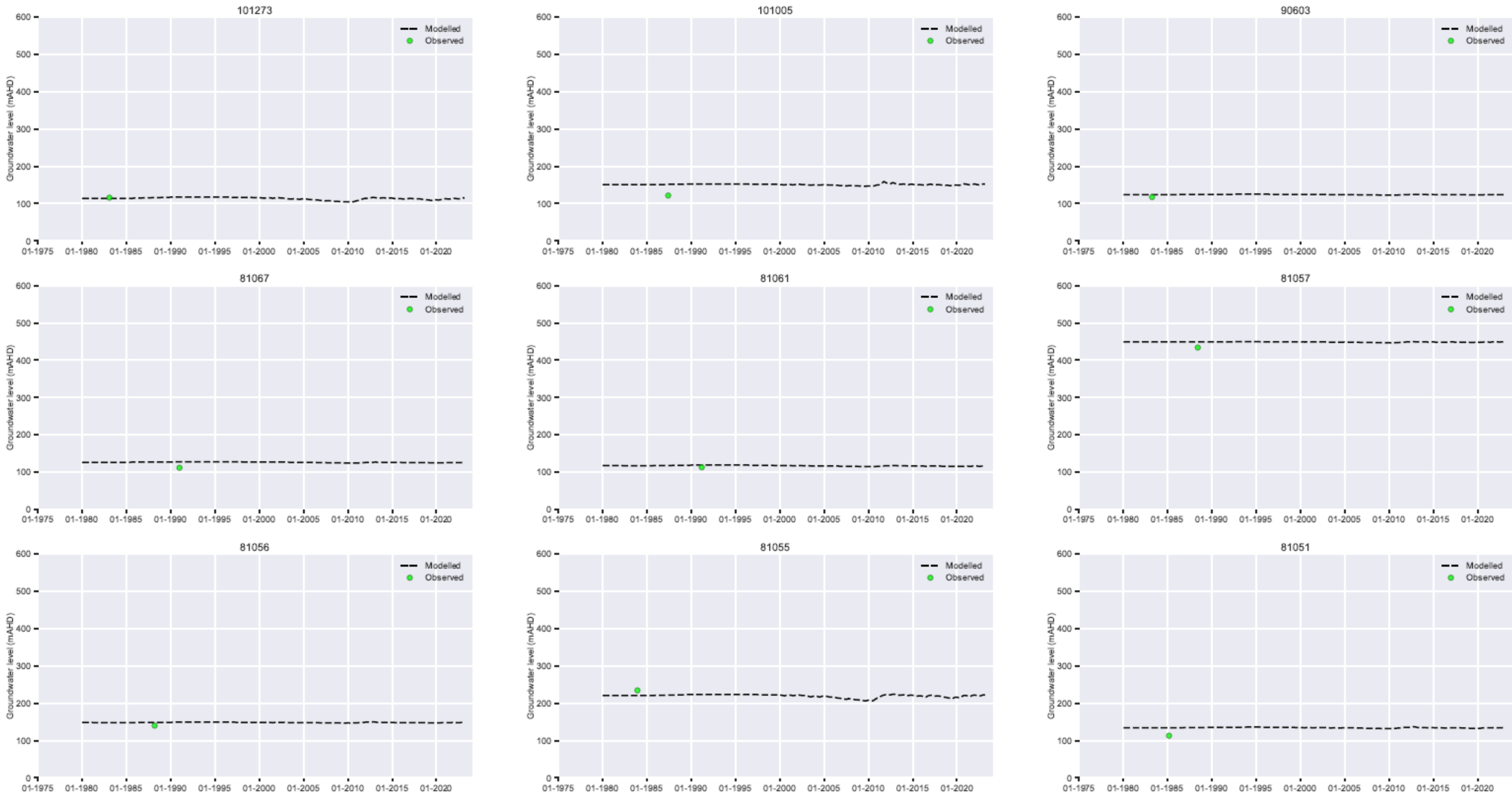
Appendix B

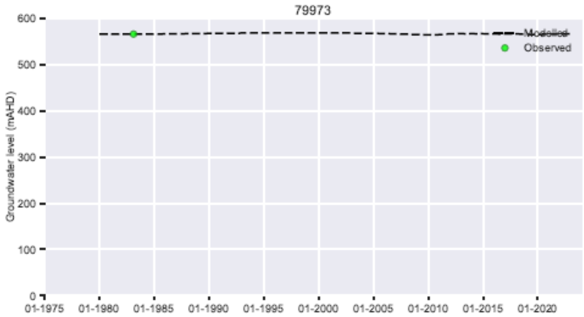
Regional bore calibration hydrographs

Bore ID	PEST ID
964968	964968
WRK056003	56003
WRK043372	43372
142633	142633
141825	141825
136517	136517
136515	136515
134221	134221
126732	126732
126731	126731
126730	126730
126729	126729
126728	126728
115862	115862
115859	115859
115858	115858
115857	115857
115856	115856
101273	101273
101005	101005
90603	90603
81067	81067
81061	81061
81057	81057
81056	81056
81055	81055
81051	81051
79973	79973


964968
56003
43372
142633
141825
136517
136515
134221
126732
Modelled
Observed
Groundwater level (mAHD)
0
100
200
300
400
500
600
01-1975
01-1980
01-1985
01-1990
01-1995
01-2000
01-2005
01-2010
01-2015
01-2020


126731
126730
126729
126728
115862
115859
115858
115857
115856
Modelled
Observed
Groundwater level (mAHD)
0
100
200
300
400
500
600
01-1975
01-1980
01-1985
01-1990
01-1995
01-2000
01-2005
01-2010
01-2015
01-2020


101273
101005
90603
81067
81061
81057
81056
81055
81051
Modelled
Observed
Groundwater level (mAHD)
600
500
400
300
200
100
0
01-1975
01-1980
01-1985
01-1990
01-1995
01-2000
01-2005
01-2010
01-2015
01-2020


79973
Groundwater level (mAHD)
Modelled
Observed
600
500
400
300
200
100
0
01-1975
01-1980
01-1985
01-1990
01-1995
01-2000
01-2005
01-2010
01-2015
01-2020

ghd.com

→ The Power of Commitment

Appendix M

Recommended Monitoring Program

Surface Water and Groundwater Monitoring Plan

Boral Montrose

Boral Resources (Vic) Pty Limited

10 August 2023

→ **The Power of Commitment**

Project name	Boral Montrose Quarry SWMP and GWMP
Document title	Surface Water and Groundwater Monitoring Plan | Boral Montrose
Project number	12570927
File name	12570927-REP-1_SW_GW_MonitoringPlan.docx

Status Code	Revision	Author	Reviewer		Approved for issue		
			Name	Signature	Name	Signature	Date
S4	0	T Anderson G Savage	G Foley	Genevieve Foley			10/8/23
[Status code]							
[Status code]							
[Status code]							
[Status code]							

GHD Pty Ltd | ABN 39 008 488 373

180 Lonsdale Street, Level 9

Melbourne, Victoria 3000, Australia

T +61 3 8687 8000 | **F** +61 3 8732 7046 | **E** melmail@ghd.com | **ghd.com**

© GHD 2023

This document is and shall remain the property of GHD. The document may only be used for the purpose for which it was commissioned and in accordance with the Terms of Engagement for the commission. Unauthorised use of this document in any form whatsoever is prohibited.

The Power of Commitment

Contents

Table index

Figure index

1. Introduction

This surface water and groundwater monitoring plan describes the monitoring requirements, trigger levels and trigger action response plans (TARP) for potential impacts to the water cycle by the operation, and ultimately closure and rehabilitation of the Boral Montrose quarry.

This report is subject to, and must be read in conjunction with, the limitations set out in section 1.2 and the assumptions and qualifications contained throughout the Report.

1.1 Purpose of this report

The objective of this Surface Water and Groundwater Management Plan (SW&GWMP) is to provide the groundwater level, groundwater quality, seepage pumping monitoring and management requirements for the Montrose quarry. It has been specifically prepared to address the risks identified as part of the surface and groundwater impact assessment completed to support a work plan variation for the quarry.

1.2 Scope and limitations

This report: has been prepared by GHD for Boral Resources (Vic) Pty Limited and may only be used and relied on by Boral Resources (Vic) Pty Limited for the purpose agreed between GHD and Boral Resources (Vic) Pty Limited as set out in this report.

GHD otherwise disclaims responsibility to any person other than Boral Resources (Vic) Pty Limited arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

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

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

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

Accessibility of documents

If this report is required to be accessible in any other format, this can be provided by GHD upon request and at an additional cost if necessary.

GHD has prepared a numerical groundwater model ("Model") for, and for the benefit and sole use of, Boral Resources (Vic) Pty Limited to support the prediction of groundwater seepage, groundwater drawdown and impacts to Bungalook Creek baseflow and must not be used for any other purpose or by any other person.

The Model is a representation only and does not reflect reality in every aspect. The Model contains simplified assumptions to derive a modelled outcome. The actual variables will inevitably be different to those used to prepare the Model. Accordingly, the outputs of the Model cannot be relied upon to represent actual conditions without due consideration of the inherent and expected inaccuracies. Such considerations are beyond GHD's scope.

The information, data and assumptions ("Inputs") used as inputs into the Model are from publicly available sources or provided by or on behalf of the Boral Resources (Vic) Pty Limited, (including possibly through stakeholder engagements). GHD has not independently verified or checked Inputs beyond its agreed scope of work. GHD's scope of work does not include review or update of the Model as further Inputs becomes available.

The Model is limited by the mathematical rules and assumptions that are set out in the Report or included in the Model and by the software environment in which the Model is developed.

The Model is a customised model and not intended to be amended in any form or extracted to other software for amending. Any change made to the Model, other than by GHD, is undertaken on the express understanding that GHD is not responsible, and has no liability, for the changed Model including any outputs.

The opinions, conclusions and any recommendations in this report are based on information obtained from, and testing undertaken at or in connection with, specific sample points. Site conditions at other parts of the site may be different from the site conditions found at the specific sample points.

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

GHD has prepared this report on the basis of information provided by Boral Resources (Vic) Pty Limited and others who provided information to GHD (including Government authorities)], which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

2. Objectives

The objectives of the monitoring program are:

- Compliance with licence conditions
  - EPA discharge licence
  - SRW groundwater licence
  - Earth Resource Regulator work approval
- Verify the predictions derived from the numerical groundwater modelling completed for the work plan variation
- Understand the impact of quarry operations on the water environment, the timing of implementation and the effectiveness of the management measures to mitigate against drawdowns.

3. Legislation and Standards

3.1 Legislation

Victoria legislation that is relevant to the Montrose quarry has been summarised in Table 1.

Table 1 Purpose of Victorian legislation and relevance to the Quarry

Legislation/policy	Purpose of legislation	Relevance to Project
Water Act 1989	In the context of groundwater, the *Water Act* (1989) principally deals with the sustainable, efficient, and equitable management and allocation of the resource. It also provides a means for the protection and enhancement of all elements of the terrestrial phase of the water cycle. Under the Act approvals are required for: – Construction of bores for monitoring, dewatering, or aquifer recharge – Extraction of groundwater, or aquifer reinjection/recharge	*This Act is relevant where groundwater bores are required to be installed on the project site (for investigation or abstractive purposes). It is also relevant where groundwater is to abstracted for use on the project site.*
Environment Protection Act 2017	The Environment Protection Act 2017 and its subordinate legislation came into effect on 1 July 2021, transforming Victoria's environment protection laws and the Environment Protection Authority Victoria (EPA). The Act introduces a General Environmental Duty (GED) which requires all Victorians to take reasonable and practicable steps to reduce the human and environmental risks of their activities. This includes a duty to manage and notify of the presence of contamination.	*Provides the regulatory framework for environmental protection within the State of Victoria. As the Project is within Victoria, compliance with the Act is required. This Act is relevant when assessing and managing contaminated groundwater.*

3.2 Standards

Table 2 contains a list of standards, guidelines and best practice documents relevant to the groundwater monitoring program.

Table 2 Standards, best practices and guidelines

Instrument, guideline
Environment Reference Standard (ERS) (2021)
Australian Groundwater Modelling Guidelines (Barnett et al 2012)
Minimum construction requirements for water bores in Australia (NUDLC 2020)
Australian/New Zealand Standard on Water Quality Sampling - Part 1: Guidance on the design of sampling programs, sampling techniques and the preservation and handling of samples (AS/NZS 5667.1:1998), Standards Australia, New South Wales.
Australian/New Zealand Standard on Water Quality Sampling – Part 11: Guidance on sampling of groundwater (AS/NZS 5667.11:1998), Standards Australia, New South Wales.
ANZECC & AMRCANZ 2000, Australian Guidelines for Water Quality Monitoring and Reporting, National Water Quality Management Strategy Paper No 7, Australian and New Zealand Environment and Conservation Council (ANZECC) and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ), Canberra.

Instrument, guideline
ANZECC & AMRCANZ 2000, Australian and New Zealand Guidelines for Fresh and Marine Water Quality, National Water Quality Management Strategy Paper No 4, Australian and New Zealand Environment and Conservation Council (ANZECC) and Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ), Canberra
AS4482.1 – 2005 Guide to the investigation and sampling of sites with potentially contaminated soils
ISO21413:2005 Manual methods for the measurement of a groundwater level in a well
National Industry Guidelines for hydrometric monitoring, Part 2 (BoM)
EPA Publication 669.1 Groundwater sampling guidelines (February 2022)

4. Site background information

4.1 Site setting

The quarry address is described as 56 Canterbury Road Montrose and it is located at the intersection of Canterbury and Fussell Roads, Montrose. The northwestern corner of the site lies at an elevation of around 135 m AHD, and the southern batters have been excavated into a local topographical high. The southern parts of the site, which constitute the proposed expansion area for the quarry rise to over 200 m AHD. The site is shown in Figure 1.

4.2 Geology

Review of the Geological Survey of Victoria's 1:63,360 scale Ringwood mapsheet indicates that the quarry mines the hard rock of the Mount Dandenong Volcanics Complex. A geological contact passes through the quarry, aligned approximately southwest to northeast. The Coldstream Rhyolite lies to the west of the contact and the Mount Evelyn Rhyodacite is on the eastern side of the contact. These rocks intruded through Silurian – Devonian age indurated sediments, i.e. Melbourne Formation.

4.3 Hydrogeology

4.3.1 Hydrostratigraphic units

The aquifers present at the quarry are described as follows:

- Alluvial sediments, where saturated, laterally restricted to the present day drainage lines.
- Mount Dandenong Volcanics Complex (MDVC):
  - The MDCV have been differentiated locally into the Mount Evelyn Rhyodacite and the Coldstream Rhyolite. Hydrogeologically, these rocks are considered to have similar properties and have been grouped into a single fractured rock aquifer system, referred to as the MDVC aquifer.

Further removed from the quarry are the Silurian-Devonian mudstones and siltstones, which like the MDVC, also form a regionally extensive, low yielding fractured rock aquifer system.

4.3.2 Groundwater levels

Groundwater levels are variable across the site owing to the steep topography. Near Bungalook Creek groundwater levels can within 2 m of the surface, and to the east of the quarry the depth to water is over 100 m.

There is insufficient understanding to assess the seasonal groundwater level response.

Groundwater flow in the region is likely to be complex owing to the varied topography. The eastern and northern parts of the quarry are topographically higher compared to the southwest and northwest. Pre-quarry development the groundwater flow may have had components towards the north, but also towards the southeast and Bungalook Creek.

4.3.3 Groundwater quality

There has been limited characterisation of the onsite groundwater quality. Available information from previous studies indicates salinities between 1,000 mg/L TDS and 2,200 mg/L TDS. Regional hydrogeological mapping indicates salinities can be below 1,000 mg/L TDS at the site.

Based upon the segment classifications documented in the Environment Reference Standard (ERS), the groundwater is classified as falling within segments A to B.

Paper Size ISO A4

0 0.1 0.2 0.3 0.4

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

GHD

Boral Resources (Vic) Pty Limited
MONTROSE QUARRY

Site Location Plan

Project No.	31-1270927
Revision No.	A
Date	21/04/2023

FIGURE 1

\\ghdnet\ghd\AU\Traralgon\Projects\31\12570927\GIS\Maps\Working\31_12570927_01_Montrose_Location.mxd
Print date: 26 Apr 2023 - 17:09

Data source: VicMap Data, DELWP Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community. Created by: lgomez

4.4 Groundwater model predictions

Numerical groundwater modelling was undertaken of the quarry expansion to provide predictions of the groundwater inflows into the quarry, and their associated drawdowns, and the impact on leakage from Bungalook Creek (GHD 2023b). The model assumed the expansion would take 40 years to complete, and recovery was modelled for a period of 50 years. This section provides a high level summary of the numerical model findings.

4.4.1 Groundwater drawdowns

To address the issue of model non-uniqueness, uncertainty analysis was undertaken to assess the effect of parameter uncertainty on model predictions. This involved running the model using a range of alternative parameter combination whose predictions can be regarded as being equally plausible (based upon the existing calibration data set). The extent of drawdowns determined from the uncertainty analysis undertaken is shown in Figure 2 which plots the 95th percentile of drawdowns from 131 model realisations. The magnitude and extent of drawdown is shown to decrease over time as the quarry is backfilled and rehabilitated.

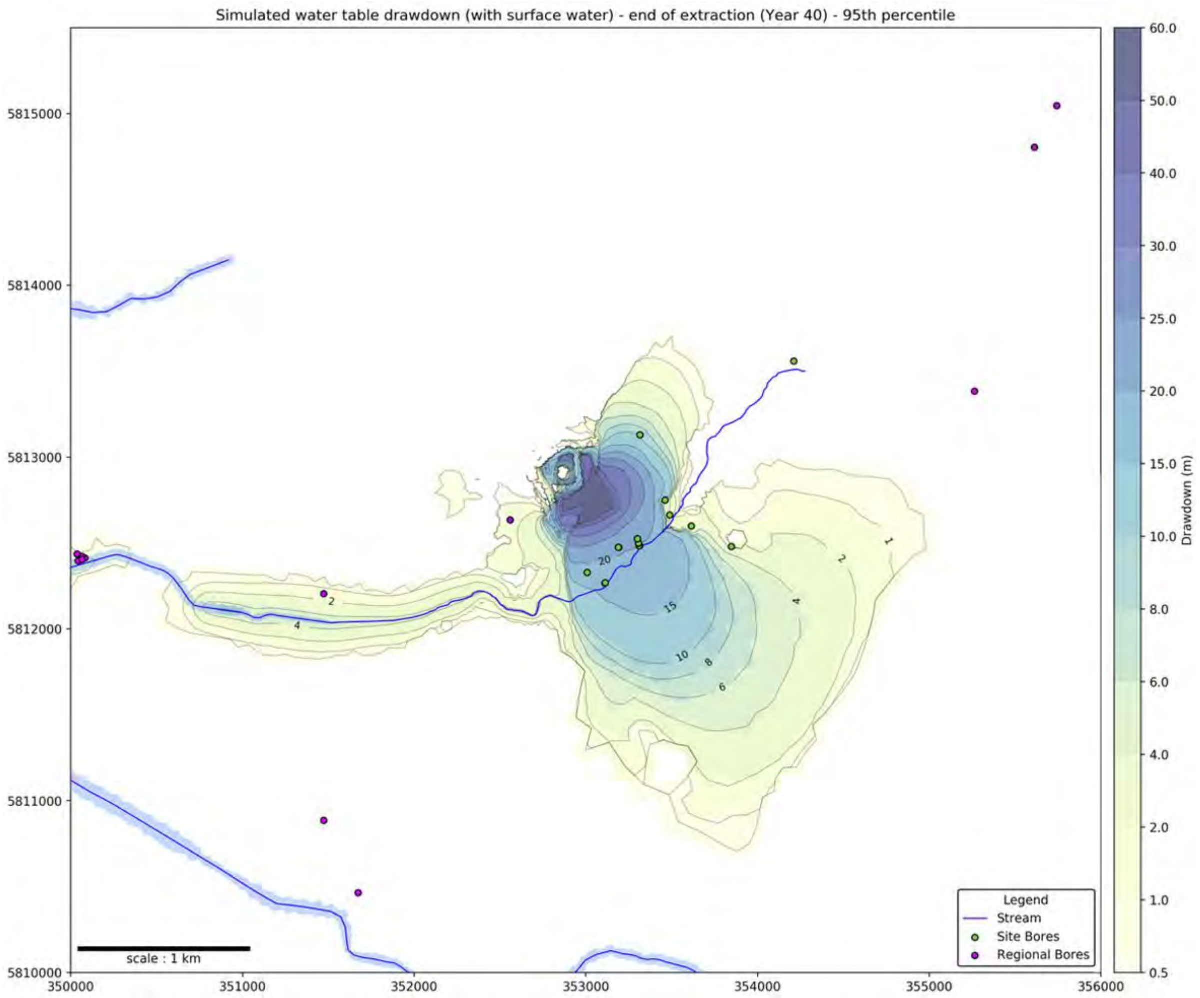


Figure 2 Predicted drawdowns (95th percentile)

The numerical modelling has shown that along Bungalook Creek is likely to be supplying recharge to the water table via stream leakage, particularly during periods of high flow. The modelling suggests that the historical extraction at the quarry is likely to have resulted in some drawdown towards Bungalook Creek, albeit temporary and limited to periods of low flow when there is insufficient leakage to top up the water table. As the quarry expands southwards, inflows into the quarry increase, and water levels are drawdown beneath Bungalook Creek. This can result in a further leakage from Bungalook Creek, and as streamflow is lost due to leakage, groundwater drawdowns can extend westwards further downstream of the quarry.

4.4.2 Groundwater seepage

Figure 3 presents the predicted groundwater seepage rate into the quarry, based upon the 131 model realisations applied as part of the uncertainty analysis. The seepage rate is predicted to increases over time, as the quarry undergoes expansion and deepening. The seepage rate is also sensitive to the assumed climate condition, which influences recharge and streamflow that feeds water into the groundwater system.

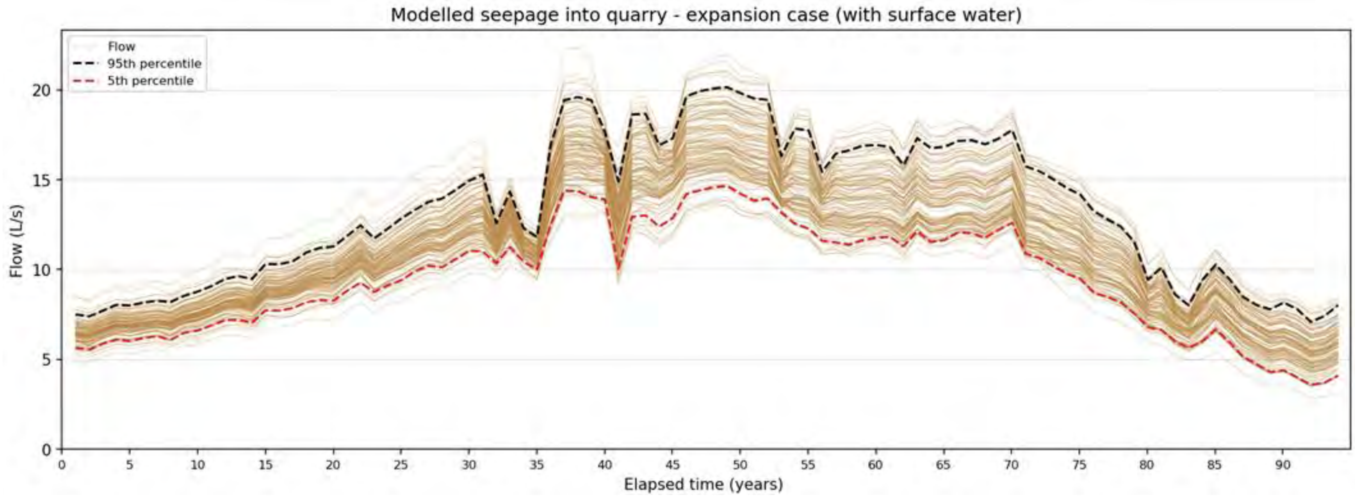


Figure 3 Predicted inflows into the expanded quarry

4.4.3 Impact to baseflow

Figure 4 compares the time series of predicted total streamflow at gauge 228369A for the base case and expansion case. The figure also shows the percentage of streamflow reduced by the quarry expansion. The modelling indicates that during dry periods, when the total streamflow is less than 10 L/s, all of the streamflow is lost as leakage due to the expansion of the quarry and associated drawdown of the water table.

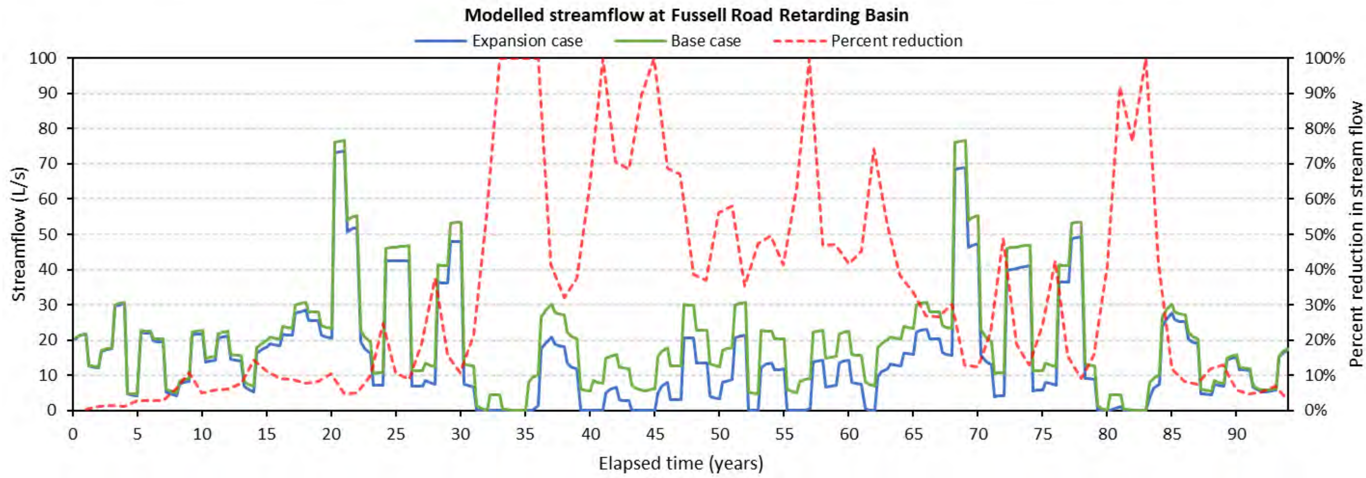


Figure 4 Predicted changes to Bungalook Creek streamflow

The uncertainty analysis (not shown herein) determined that uncertainty in streamflow due to model parameter uncertainty is less than that arising from the uncertainty in future climate.

4.5 Climate change

The numerical groundwater model was used to assess the potential impact of climate change. This assessment suggests that changes in stream flow and recharge due to climate change has the potential to result in large differences in the water table drawdown along Bungalook Creek (GHD 2023), with the maximum water table drawdown ranging from around 27 m for the low (wet) climate change condition to around 37 m for the high (dry) climate change condition (and occurring more frequently under this dry condition). This means the uncertainty in future climate has a similar (if not, bigger) contribution to the uncertainty in modelled water table drawdown compared to that arising from the uncertainty in model parameters.

4.6 Environmental values

4.6.1 Groundwater dependent ecosystems

This section is to be updated when ecological studies have been completed by Boral.

4.6.2 Existing groundwater users

Neighbouring groundwater users, as identified from the DEECA Water Measurement Information System (WMIS) have been summarised in Table 3. A census of these bores has not been undertaken to determine if they bores are operational or otherwise.

Table 3 Registered bores within predicted area of influence

Bore ID	Registered use	Depth (m)	Zone 55 MGA55 Co-ordinates		Approximate distance from quarry (m)
			Easting	Northing	
139907(1)	Dewatering	90	352673.2	5813184.1	80
WRK056003	Industrial	108	352560	5812634	570
81043	Stock & domestic	51.8	353953.2	5811984.1	950
81044	Stock & domestic	73	353953.2	5811984.1	950
81045	Stock & domestic	64	353873.2	5812004.1	880
81061	Stock & domestic	121	351473.2	5812204.1	1,340
81067	Stock & domestic	112	351673.2	5810464.1	2,330
WRK032565	Industrial	100	351611	5811577	1,500
134221	Stock & domestic	91.3	351193.2	5809664.1	3,250
WRK983590	Not specified	24	351660	5812926	940
WRK967196	Stock & domestic	45	350277.2	5812832.1	2,330
WRK968757	Stock & domestic	19	350680	5814860	2,620
81055	Stock & domestic	64.57	355263.2	5813384.1	2,000

Note: 1. Plots on Boral land

4.6.3 Mitigation

Groundwater seepage into the base of the quarry is currently returned to Bungalook Creek under an EPA discharge licence. This has some effectiveness in reducing drawdowns, however, only a proportion of returned volume leaks from Bungalook Creek to the underlying aquifers. The numerical groundwater model (GHD 2023b) was applied to assess the benefit of incorporating a groundwater recharge system to mitigate against drawdown. This confirmed that a system that returns the water directly to the aquifer, e.g. via injection bores or a soakage trench would be more effective in mitigating against drawdowns.

The need to the implement such an active system to manage groundwater levels near Bungalook Creek is to be determined through further ecological assessment.

4.7 Summary of water risks

The expansion of the quarry may have an effect on groundwater, but groundwater may have an effect on the project. Details of these potential impacts are discussed in the following sections, and have been summarised in Table 4.

Table 4 Aspects and impacts

Environment	Aspect	Impact
Surface water	Effect of the project on surface water.	– Aquifer dewatering required to maintain safe and stable working conditions may result in reductions in baseflow to waterways such as Bungalook Creek. – Spills / hazardous materials handling could contaminate waterways.
	Effect of surface water on the quarry expansion.	– There will be an increase in the quarry size and therefore an increase in the volumes of run-off generated into the quarry void. Quarry has existing stormwater / run-off control measures.
Groundwater	Effect of the project on groundwater.	– Deep excavations intersecting groundwater will require on-going dewatering throughout the quarry life span. This can affect: • Existing groundwater users. Many of the groundwater bores on the WMIS have been installed for investigation or observation purposes e.g. contaminated land investigations. • GDEs - Aquatic ecosystems in Bungalook Creek - Riparian vegetation - Terrestrial vegetation • Generation and release of acidic leachates (not considered relevant to Montrose based upon regional soil mapping / geological setting) • Subsidence (not considered relevant to Montrose given the consolidated rock geology) • Dislocation or displacement of contaminated groundwater plumes A registered contaminated site has been identified on Fussell Road. Part of this site (Lot 1) has been verified by a statutory environmental audit. • Take on the resource Boral is required to hold a take and use licence for the groundwater extracted from the quarry.
	Effect of groundwater on quarry expansion	An increase in quarry seepage volumes will occur. This would require Boral to have the necessary infrastructure to manage, handle, treat and dispose of these flows.

5. Proposed monitoring network

5.1 Groundwater

5.1.1 Existing

The Boral groundwater monitoring network is comprised of 17 groundwater bores (some with dual installations), however, a number of bores have been lost from the monitoring network since its establishment circa 2000s. Concerning the existing network and these missing bores:

– Bores MB9 and MB7 are located remote from the quarrying activity and unable to be located. There are bores nearer to the quarry that are operational
– Bore MB5 (a and b) is between the quarry and Bungalook Creek. Bore MB4 is located nearer to the pit, however, it leaves a spatial gap in monitoring in an area where the quarry is proposed to expand towards.

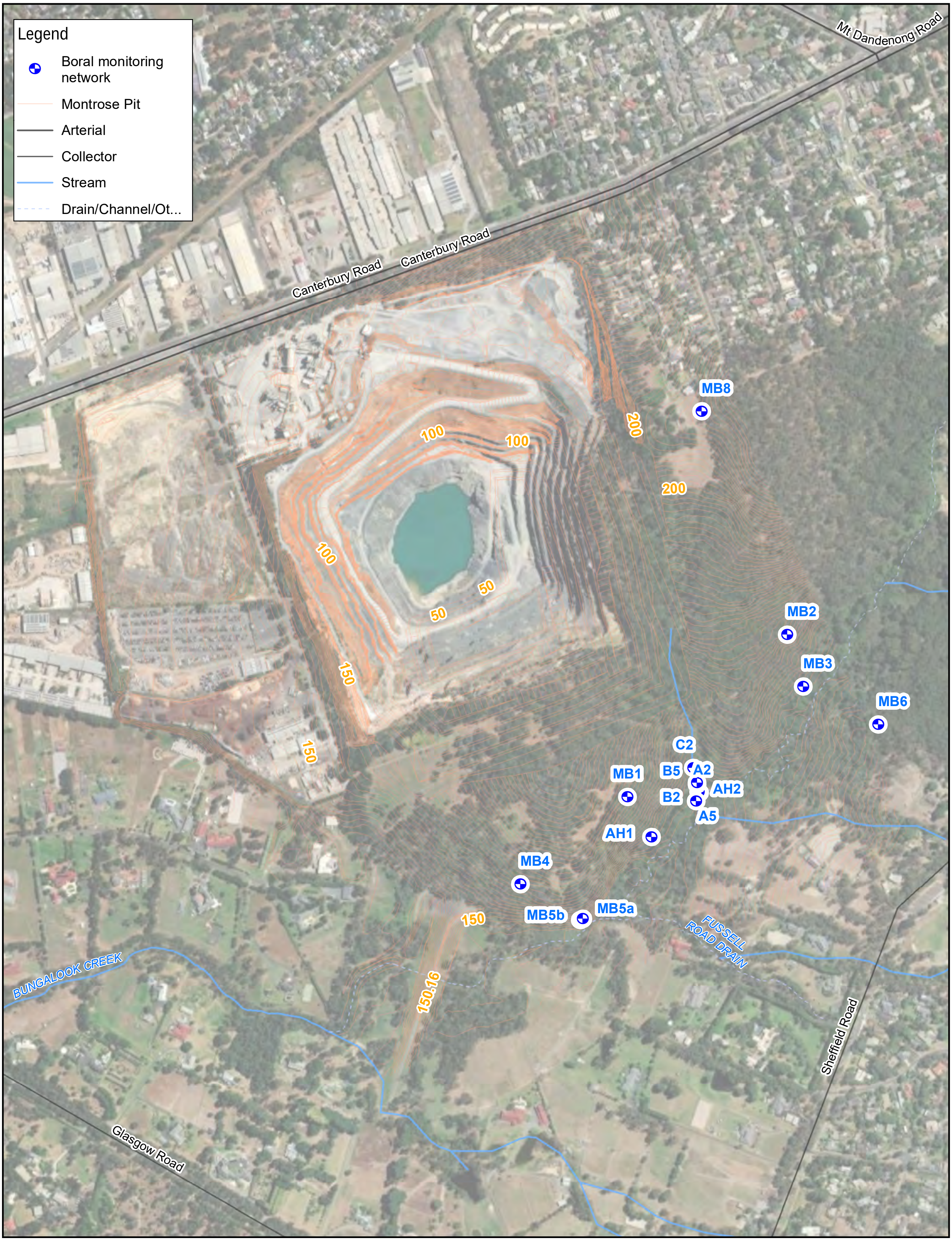
There is an absence of groundwater monitoring information on western boundary (Fussell Road) and northern boundary (Canterbury Road).

5.1.2 New monitoring sites

Additional monitoring site have been proposed as per Table 5. The monitoring bore network should be reviewed following the findings of the ecological assessment, i.e. whether target monitoring is required adjacent ecologically sensitive sites.

Table 5 Proposed additions to the monitoring network

Location	Rationale
Short term	
Northern end of Fussell Rd	Understanding of potentiometry and water quality to the north of the quarry (and industrial zone of the Boral site).
Southern end of Fussell Rd	May be a nested site. Understanding of potentiometry and water quality to the west of the quarry and potential impacts to existing groundwater users.
Replacement to bore MB5	Provide an understanding of potentiometry between the expansion area and Bungalook Creek, towards the southwest of the Boral workplan area.
Long term	
	The timing of these installation is subject to further discussion with Boral regarding the development, as well as access for bore installation. A minimum 6 months, preferably 2 years of monitoring data is recommended prior to the commencement of the expansion: – West: Bungalook Creek, near Liverpool Road. To assess the extent of drawdown downstream of the quarry. The site would need to consider access and presence of any sensitive groundwater dependent ecosystem in this area. – South: Sheffield Road / Glasgow Road. To assess the extent of drawdown extending southwards beyond Bungalook Creek.



Paper Size ISO A4

0 0.06 0.12 0.18 0.24

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

N

GHD

Boral Resources (Vic) Pty Limited
MONTROSE QUARRY

Project No. 31-1270927
Revision No. A
Date 28/04/2023

Boral monitoring network

FIGURE 8

\\ghdnet\ghd\AU\Traralgon\Projects\31\12570927\GIS\Maps\Working\31_12570927_08_Boral_Monitoring_Network.mxd
Print date: 01 May 2023 - 09:36

Data source: VicMap Data, DELWP Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community. Created by: lgomez

5.1.3 Monitoring bore construction

To ensure the integrity of monitoring data, monitoring bores will be constructed consistent with the NUDLC (2020) minimum requirements. Key considerations include:

- Bores are licensed with SRW
- Adequate seals are incorporated into the bore construction to ensure that the screen zone is representative of the formation being monitored.
- Monitoring bore construction (and lithological) information is stored in a centralised database.
- Monitoring bores need to constitute long term monitoring assets, e.g. ability to remain functional for periods of over 40 years.

Monitoring sites will comprise one of the following configurations:

- Standpipes to measure water levels in both aquifers, either as two “nested” bores or as one bore with two standpipes, suitably sealed between the screened layers
- A single bore/standpipe targeting a particular zone of the aquifer system
- A single bore with one, two, three of four vibrating wire piezometers (VWPs) installed at different levels of interest

Selected VWPs will be fitted with data loggers for continuous (pore pressure) monitoring whereas open standpipes will be used when periodic water sampling is required. Sites are to have a known construction i.e. screen depth & seals and are to be recorded in a centralised database.

5.1.4 Monitoring bore survey

Survey of the monitoring bores will be to the specification summarised in Table 6. This is for new bores, or existing bores where headworks modifications have occurred.

Table 6 Monitoring bore survey

Element	Precision	Unit
Location	Field GPS ±5 m	m Australian Map Grid (AMG)
Elevation	Differential GPS ±0.05 m or better	m Australian Height Datum (AHD)

5.2 Surface water

Monitoring of surface water is required at the following locations as summarised in Table 7

Table 7 Surface water monitoring sites

Location	Rationale
Discharge point within the quarry processing area	Characterise the water quality exiting the quarry and compliance with EPA discharge licence
Bungalook Creek upstream of the retarding basin	Characterise the health of the aquatic environment and catchment
Sump of the operating quarry	Characterise the bulk groundwater quality (and run-off) entering the quarry

6. Monitoring method and requirements

6.1 Groundwater levels

6.1.1 Method

Groundwater levels will be gauged using a combination of methods:

- Manual water level gauging, e.g. using a dip meter
- Automated monitoring, e.g. using automated pressure transducers and dataloggers.

Boral would develop a Standard Operating Procedure (SOP) for water level monitoring.

6.1.2 Frequency

The bores monitored (and the monitoring frequency) may change over time subject to periodical reviews completed by a hydrogeologist. The frequency will depend upon the stage of the development and/or operation and the risk profile.

Initially water level monitoring will be at an increased frequency of xx to build up a time series of water level information that could inform the 'baseline condition'. Groundwater has been disturbed by historical mining conditions, and the baseline would represent the conditions prior to the expansion.

Under long term operation, a quarterly water level monitoring frequency will be adopted as a minimum. More frequent monitoring may be undertaken nearer to waterways.

6.1.3 Timing

The groundwater level monitoring program should be implemented immediately irrespective as to whether Boral proceeds with the expansion or otherwise.

6.2 Groundwater quality

6.2.1 Method

The groundwater monitoring program will target three key objectives:

- Evaluate changes in the water quality over time.
- Map the radius of influence as the quarry expansion grows
- Map the initial conditions (prior to expansion).

Monitoring bores will be sampled using industry approved methods e.g. Vic EPA Publication 669.1 (2022). Sampling procedures will need to consider:

- Preservation and holding times
- QA/QC procedures
- Field monitoring of purging
- Representativeness of the sample

Automated logging of Electrical Conductivity (EC) and pH would be considered for bores that are in areas that are difficult to access. Boral will develop an SOP for groundwater sampling (production and observation bores).

Groundwater levels can be influenced by barometric pressure. Barometric pressure should be collected with groundwater level data to enable compensation of groundwater levels, i.e. barometric efficiency. Automated dataloggers should be vented, or if non-vented, barometric compensation completed.

6.2.2 Frequency

Frequency of the sampling will depend upon the phase of the development, and groundwater risks specific to each monitoring bore location:

- Initially bores would be sampled on a quarterly frequency, in order to build an understanding of water quality behaviour will be undertaken for the first 2 years. Monitoring sites close to Bungalook Creek should be equipped within automated water level dataloggers.
- After 2 years, bores would be tested biannually (6 -monthly basis) subject to their risk profile (and groundwater model predictions).

6.2.3 Sampling and analysis plan

Field monitoring of water quality parameters will be undertaken as part of any groundwater monitoring event, and will include:

- Installation of new bores (production or observation) e.g. monitoring of development water quality
- Prior to collection of a groundwater sample (assessment of purging)
- As required by Boral to assess the water condition.

All field monitoring equipment is to be calibrated and appropriate records of calibration are to be maintained.

Samples for laboratory analysis will collected in laboratory supplied containers and submitted to NATA registered analytical laboratories. Analytical suites will vary depending upon the objective of the sampling, as summarised in Table 8.

Table 8 Indicative analytical plan: groundwater

Type	Analytical Plan
Water quality verification (rapid check / low risk)	TDS, EC, pH
Observation bores	Major cations and anions (Ca, Na, Mg, K, SO4, Cl, NO3, HCO3, CO2-) Nutrient screen (speciated N, P) Physico-chemical (TDS, EC, alkalinity, fluoride, hardness, turbidity) Heavy metal screen Plant toxicity (e.g. Boron, Sodium, Chloride etc)
	Optional (diagnostic) Organic contaminants e.g. Fussell Road contaminated sites

6.3 Surface water volume

6.3.1 Method

Calibrated flow meter (mechanical or Magflo™) to be equipped at the EPA discharge point. Calibration should be checked at frequency recommended by manufacturer.

6.3.2 Frequency

Daily flow rates to be recorded at EPA discharge point.

6.4 Surface water quality

6.4.1 Method

Grab samples would be collected from Bungalook Creek and the quarry sump, e.g. using telescoping sampling pole or equivalent devices.

It is recommended that automated logging for turbidity, EC and pH is implemented at the EPA discharge point.

6.4.2 Frequency

Quarterly frequency for Bungalook Creek and quarry sump.

Daily frequency for EPA discharge point (where equipped with automated logging).

6.5 Adopted screening criteria (quality)

6.5.1 Groundwater

Based upon the existing information, the groundwater has been classified as Segment A, and the protected environment values of groundwater at and local to the quarry are summarised in Table 9

Table 9 Relevance of Segment A environmental values

Environmental Value	Existing in Work Plan Area	Neighbouring Areas	Discussion
Water dependent ecosystems and species	Possibly	✓.	**Relevant** Groundwater quality must be maintained to protect aquatic ecosystems at the point of groundwater discharge. The study area falls within the Central Foothills and Coastal Plains segment which are considered to be a slightly to moderately modified water dependent ecosystem.
Potable water supply (desirable)	×	No	**Potentially relevant** Such low salinity groundwater has been identified regionally, but not local to the quarry itself. Groundwater is not used on site for such purposes. Stock and domestic bores have been identified in the broader area, however, the likelihood of use for potable supply is considered limited given the relatively low yields of bores, but also the availability of reticulated mains water throughout the region.
Potable water supply (acceptable)	×	No Urban bores ✓ Domestic	
Potable mineral water supply	×	No	**Not Relevant** The groundwater is not within a recognised mineral water province and there are no identified mineralised bores close to the site. There is a limited likelihood of groundwater being used for this purpose.
Agriculture and irrigation (irrigation)	N/A	✓	**Relevant** One bore (WRK983171) at the Mooroolbark bowls club with an irrigation use has been identified. Bore yields in the MDVC aquifer system are not likely to be capable of supporting large scale commercial irrigation enterprises.
Agriculture and irrigation (stock watering)	N/A	✓	**Relevant** Nearby stock bores have been identified. The groundwater salinity is suitable for a wide range of livestock types. The urbanised land development within

Environmental Value	Existing in Work Plan Area	Neighbouring Areas	Discussion
			the study area is not conducive to livestock e.g. agriculture/farming land which would suggest that such an environmental value is unlikely to be realised in the future.
Industrial and commercial use	Seepage used by quarry	No	**Potentially Relevant** There are no existing bores within a commercial or industrial use type, however, this environmental value could be realised in the future. Bore yields in the MDVC aquifer system are not likely to be capable of supporting large scale commercial irrigation enterprises.
Water-based recreation (primary contact recreation)	N/A	✓	**Relevant** Bunglaook Creek borders the quarry and groundwater is expected to discharge to waterways. It is noted that based upon the site inspection, there are limited deep pools or access to the creek for bathing purposes.
Traditional Owner cultural values	N/A	✓	**Relevant** No specific engagement with the local traditional owners has been undertaken as part of this work. In the absence of the such engagement, it has been assumed that protection of groundwater that discharges into nearby waterways is required to maintain traditional owner cultural values.
Buildings and structures	N/A	✓	**Possibly** There are some buildings, including residential properties, located within the study area, however these are assumed to have shallow foundations. The estimated deep water levels are likely to limit the interaction between groundwater.
Geothermal properties	N/A	N/A	**Not relevant** The groundwater is too shallow to have an elevated temperature and therefore this value is not considered relevant to this assessment.

The screening criteria for groundwater would be based mainly upon those required to assess the protection of water dependent ecosystems and species, i.e. Australian and New Zealand Water Quality Guidelines (ANZG 2018). These tend to have the most conservative water quality objectives of all the relevant environmental values of the groundwater identified in Table 9.

No consultation has been undertaken with Traditional Owners. It has been assumed that application of the ANZG (2018) guidelines for the protection of water dependent ecosystems would be a suitable interim measure to protect Traditional Owner cultural values that may be associated with Bungalook Creek.

It is noted that there may be some constituents occurring in groundwater that are naturally elevated above the ANZG (2018) guidelines. However, it may be difficult to differentiate what is elevated and what could have been the result of the historical and existing operation of the quarry. More frequent sampling has been proposed (refer 6.2.2) prior to the expansion to characterise groundwater conditions prior to the expansion.

6.5.2 Surface water

Samples from the site discharge are to be compared against the EPA discharge licence. The EPA discharge licence limits are summarised in Table 10.

Table 10 Discharge limits

Discharge Point No	Description of Discharge Point	Indicator	Limit Type	Unit	Discharge Limit
DPB	DPB as shown in Schedule 1B	Flow Rate	Max Daily Flow	ML/D	0.86
		Electrical conductivity	Annual Median	μS/cm	1,600
		Electrical conductivity	Maximum	μS/cm	2,000
		Turbidity	Annual median	NTU	25
		Turbidity	Maximum	NTU	40
		pH	Maximum	pH	9
		pH	Minimum	pH	6

6.6 Adopted screening criteria (volumetric)

Boral’s operations are required to comply with licenses which both specify volumetric criteria:

– Groundwater: 120 ML per annum
– Discharge to surface water: 0.86 ML/day (equivalent to 314 ML per annum)

The discharge to surface water is metered, however, it represents a total volume of water harvested from the site, i.e. stormwater occurring both within the quarry footprint, but also the rock and concrete processing areas at the northern end of the site.

6.7 GDE Health

The requirement for monitoring GDE health is understood to be a recommendation of the ecological assessment prepared by GHD (2025).

7. Trigger Action Response Plan (TARP)

7.1 General

The expansion of the quarry will result in a decline in groundwater levels. It is therefore necessary to understand whether the change in groundwater levels relative to the numerical groundwater model's predictions, i.e. is the change occurring at a rate faster, sooner, or at a greater magnitude, and what does this mean to the receptors:

– Neighbouring groundwater users
– Streamflow in Bungalook Creek
– Sensitive ecosystems dependent upon Bungalook Creek flows, or access to groundwater.

An example flow chart of actions is provided in Figure 6.

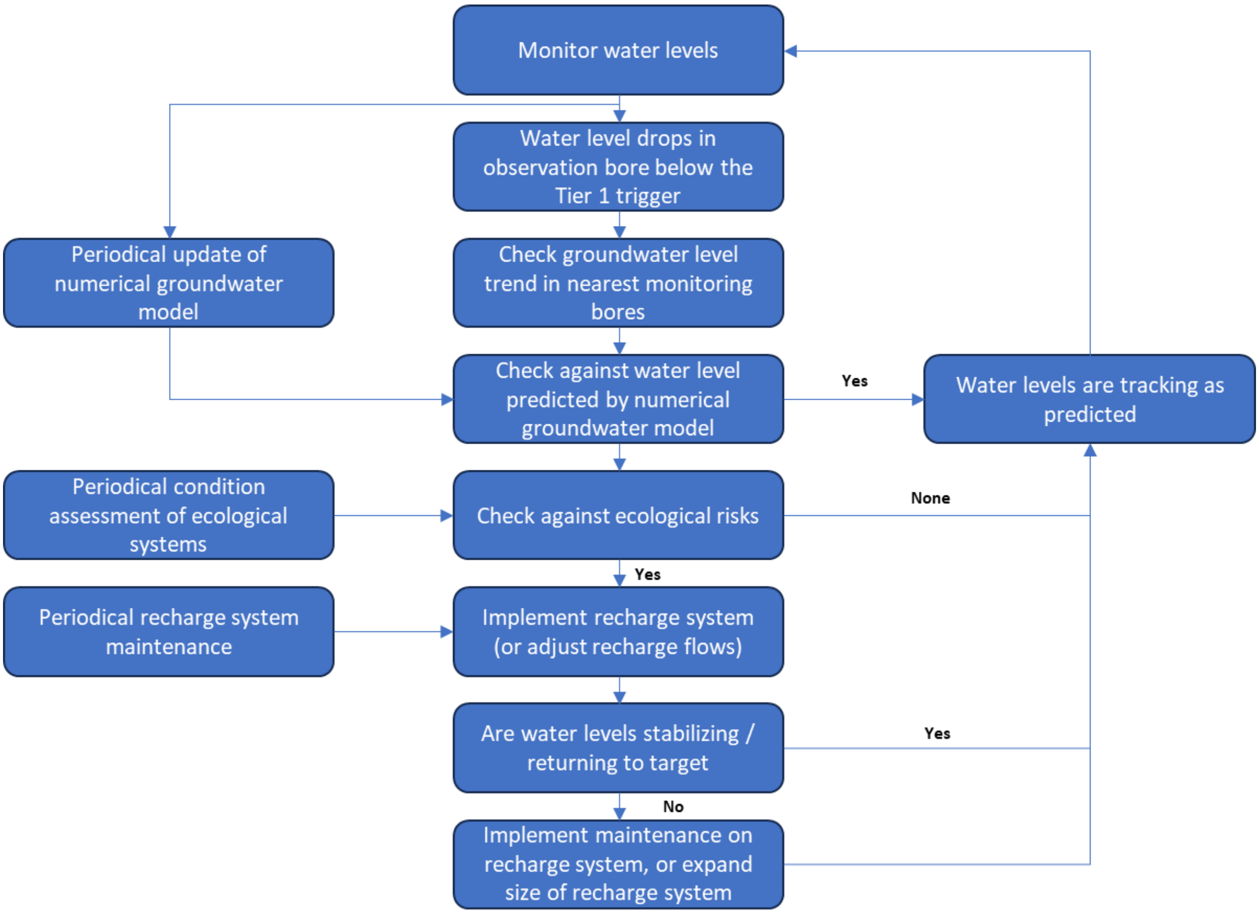


Figure 6 Actions arising from monitoring response

7.2 Approach

The Boral approach to adaptive management is by applying a Trigger – Action - Response system. This system comprises three basic tiers of action:

– Trigger 1 – usually a prompt to investigate, implement further monitoring or analysis, data checks etc
– Trigger 2 – specific mitigation actions
– Trigger 3 – Actual impacts e.g. GDE health impacts.
Objective of the tiered approach is to avoid the Trigger 3 circumstance, and provide sufficient time for Boral to implement corrective actions to prevent unacceptable impacts.

A generic example of this tiered approach is shown below in Figure 7, which relies on using water levels to establish the triggers. Water levels are considered a lead indicator of potential risks as these will respond more rapidly compared to quarry inflows, or groundwater quality monitoring.

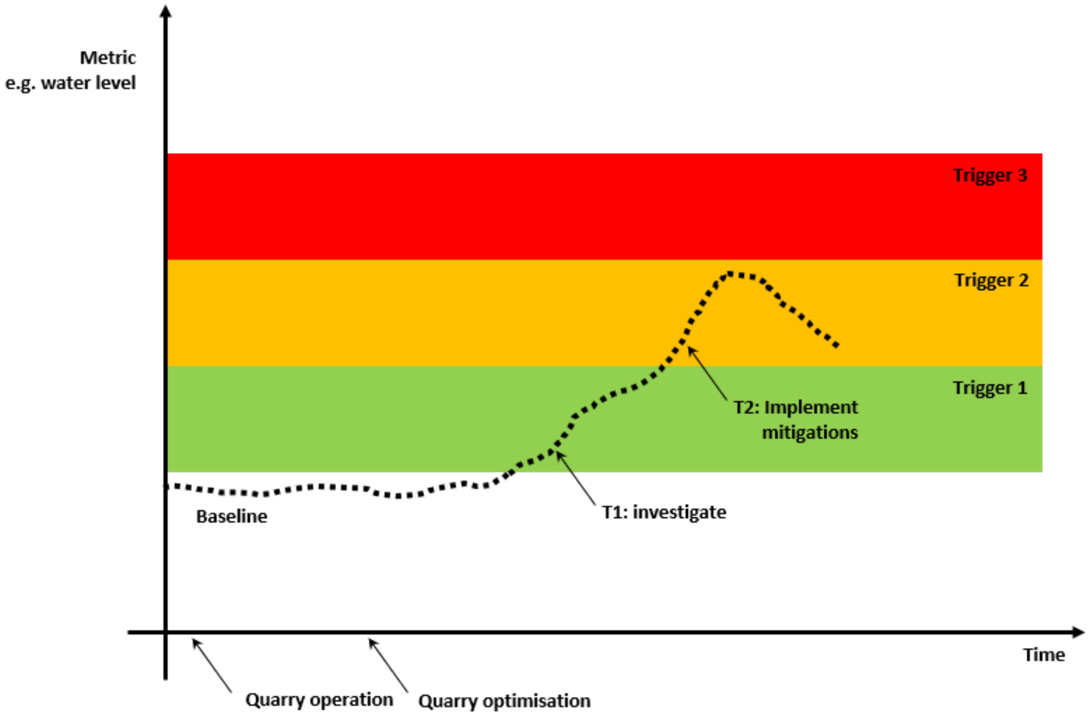


Figure 7 ***Boral tiered Trigger – Action – Response approach***

Boral will need sufficient time to implement remedial measures, and therefore the tiered approach allows time to review:

– Baseline conditions, observed magnitude and rate of departure from the baseline or existing conditions of the operating quarry i.e. trend
– Verification of the monitoring results
– Adopting an appropriate monitoring frequency, and adjustment of the frequency as necessary
– To consider new monitoring sites
– Monitoring program adjustments e.g. analytes or water level monitoring frequency
– Technical, financial and logistical assessment of the possible mitigation measures
– Likelihood of continued departure from baseline without further action
– Preparation to implement mitigation measures
– Informing management and compliance authorities

Different risks can be assessed on a case by case basis, allowing for tailoring of management responses that are specific to the observed scenarios.

7.3 Triggers

Tier 1 (alert) trigger to be set at a conservative value to allow for sufficient review and increase in monitoring to determine in the change in groundwater level, quantity or quality, or GDE condition represents an isolated departure, natural variation, or the indication of a trend away from the baseline conditions. At the Tier 2 (action) trigger, mitigation processes will then be implemented in response to a trigger exceedance.

The Tier 1 (alert) and Tier 2 (action) triggers levels are based on inputs such as the observed baseline conditions, and consideration of the risk profile. Whilst historical monitoring data is available, an improved understanding of quarry conditions should be established by Boral prior to commencing the expansionn works.

Trigger levels are summarised in Table 11 and the trigger levels or values will be agreed with the compliance agency / State prior to the commencement of quarry expansion. Trigger levels shown in Table 11 are considered preliminary only and will be revised as the hydrogeological understanding of the aquifers and quarrying optimisation improves.

Table 11 Trigger Action Response Plan

Trigger	Management measures	Contingency Plan
Normal No change in groundwater levels or quality outside of seasonal ranges	– Monitoring as per the surface water groundwater management plan (SW&GWMP) – Confirm monitoring program QA/QC	– Review SW&GWMP annually.
Groundwater volumes pumped from sump are consistent with previous pumping & seasonal climate response.	– Monitoring as per the SW&GWMP – Track use against entitlement at 50% and 75% of water year.	– Review monitoring equipment – Review risk profile and trigger values – Review and update site water balance as monitoring data set increases.
Discharge water volume	– Monitor as per Discharge Licence conditions	– Review monitoring equipment (operation, calibration, data collection)
Discharge water quality	– Monitor EC, pH, Turbidity as per Discharge Licence conditions	– Review monitoring equipment (operation, calibration, data collection)
GDE condition	– Monitoring as per the SW&GWMP	
Trigger Level 1 Water levels in alluvial bores have decreased by 1 m. Water level decrease of 1 m in any non alluvial bore in any 6 month period.	– Re-testing or repeat monitoring as a QA/QC check. – Review monitoring data (groundwater level and Bungalook Creek gauging data).	– Review monitoring equipment – Review monitoring frequencies – Review risk profile and trigger values – Review response relative to predicted response from numerical groundwater model. – Assess need for GDE assessment / ecological inspection – Assess need to implement groundwater recharge system, and data / design requirements.
Groundwater volumes pumped reach 50% of licence with <40% water year remaining	– Monitor as per the SW&GWMP. – Confirm monitoring program QA/QC, metering data.	– Review site water balance and proportion of surface water / groundwater. – Review response relative to predicted response from numerical groundwater model. – If trend in discharge tracking to exceed annual entitlement, apply for licence amendment i.e. increase entitlement. – Assess need for GDE assessment / ecological inspection
Discharge water volume daily volume is 75% of permissible licence or periodical, short term exceedances.	– Monitor as per Discharge Licence conditions. – Review treatment systems – Review monitoring equipment – Increase monitoring frequency – Verify inflows deviate significantly from numerical model predictions.	– Identify opportunity to increase pit storage
Discharge water quality has occasional exceedances of EPA licence conditions	– Monitor EC, pH, Turbidity as per Discharge Licence conditions – Check treatment system / maintain	– Identify need to augment or update existing treatment. – Identify opportunities for increasing in quarry storage.

Trigger	Management measures	Contingency Plan
Trigger Level 2 Water levels in alluvial bores have decreased by 1.5 m / outside of seasonal fluctuation range. Water level decrease of 2 m in any non alluvial bore in any 6 month period.	– Re-testing or repeat monitoring as a QA/QC check – Review monitoring data (groundwater level and Bungalook Creek gauging data). – Review climate – Review response relative to predicted response from numerical groundwater model.	– Review SW&GWMP – Undertake ecological assessment to identify evidence of stress – Implement groundwater recharge system and update SW&GWMP
Groundwater volumes pumped reach 80% of licence with <30% water year remaining	– Review response relative to predicted response from numerical groundwater model. – Review site water balance	– Apply for increase in SRW entitlement – Undertake ecological assessment to identify evidence of stress
Significant evidence of GDE stress	– Monitor as per the SW&GWMP – Adjust / review efficacy of irrigation (if already installed)	– Construct and commission irrigation / recharge system – Review and update SW&GWMP as appropriate to enable assessment of effectiveness of the irrigation system, e.g. need for additional monitoring bores etc.
Discharge water volume daily volume is 90% of permissible licence or multiple exceedances each month.	– Re-testing or repeat monitoring as a QA/QC check – Notify EPA, seek short term exemption on licence condition (if anomalously high rainfall etc).	– Identify opportunity to increase pit storage – Apply to EPA to amend Discharge Licence conditions.
Discharge water quality exceeds the EPA licence conditions multiple times each month.	– Re-testing or repeat monitoring as a QA/QC check – Notify EPA of any non-compliances – Undertake sediment basin maintenance	– Upgrade site treatment capacity (volume and quality) to ensure – – Discharge Licence conditions. – Apply for EPA licence increase

8. Resources

Boral will, as a minimum, make provision for:

- Adequate groundwater modelling capacity
- Adequate groundwater monitoring systems, including monitoring tools and equipment in accordance with the monitoring program requirements
- Other resources, as required to undertake the monitoring, or report on the monitoring as required.

8.1 Digital management

Data gathered during the monitoring program will be securely stored in a comprehensive data base designed for the purpose. This will include:

- A site plan showing all monitoring locations
- Sampling and monitoring procedures
- Data collected:
- Groundwater levels
- Groundwater quality
- Extraction volumes (dewatering)
- Monitoring results compared to trigger levels
- Laboratory analysis certificates and chains of custody
- Monitoring program reports
- Asset maintenance
- Monitoring bore issues / repair requirements etc
- Calibration reports (flow meter, field water quality meters)

8.2 Compliance reporting (monitoring and adaptive management).

This reporting will be aimed at providing a concise summary of monitoring information for Boral and potentially external stakeholders e.g. SRW, community environmental groups. Such reporting will include:

- Monitoring bore results:
  - Hydrographs
  - Interpreted contours of drawdown
- Flow metering / volumes pumped
- Groundwater quality
- Rainfall / evaporation data
- Non-compliances
- Mitigation actions implemented (where appropriate) to rectify non-compliances
- Look ahead of works in next 12 months
- Summary of investigations / hydrogeological understanding improvements that may have been obtained from drilling programs during last 12 months
- Recommendations regarding update to the monitoring program and/or monitoring plan.

8.3 Complaints / non-conformances

Boral will maintain a complaints register which will document incidents relating to general site operations, including those related to the water environment. The benefits of the complaints register include:

- Resolving complaints is important part of ongoing relationship management with neighbouring landholders and other stakeholders
- Legal protection
- Use to demonstrate the consistent issues in Boral procedures / detect patterns in operation.

Non-conformances may arise from auditing of the monitoring program, inspections, monitoring, incidents and *ad hoc* observations made during site visits. This will be recorded by Boral and corrective and preventative actions undertaken as required, and any subsequent confirmation of rectified and completed actions. Rectifications arising from incident investigations may result in update of the monitoring plan.

8.4 Review and audit

Monitoring data should be reviewed on a monthly based to confirm that the results are broadly consistent with those of the last 6 months. If there is a significant deviation, then the monitoring data should be reviewed, and regauged or resampled accordingly.

This would be triggered for:

- Groundwater levels provided:
  - ±0.5 m from the seasonal water level response in the hydrograph
  - ±0.5 m from the predicted water level response as determined from the numerical groundwater model.
- Groundwater salinity ±200 µS/cm provided:
  - There has been a change in groundwater level ±0.5 m from the seasonal water level response in the hydrograph of the monitoring bore sampled.

The risk register should be reviewed on an annual basis.

Where the monitoring indicates deviation from baseline conditions, the review may prompt the need for:

- Additional monitoring bore installation
- Amendments to the monitoring frequency and monitored parameters
- Review of site water balances
- Update of the numerical groundwater model.

8.5 Continuous improvement

Continuous improvement of the SW&GWMP will be achieved through on-going evaluation of environmental performance against environmental policies, objectives and targets for the purpose of identifying opportunities for improvement. The continuous improvement process is designed to:

- Identify areas of opportunity for improvement of environmental management and performance;
- Determine the cause or causes of non-conformances and deficiencies;
- Develop and implement a plan of corrective and preventative action to address any non-conformances and deficiencies;
- Verify the effectiveness of the corrective and preventative actions;
- Document any changes in procedures resulting from process improvement; and
- Make comparisons with objectives and targets

The key to capturing these opportunities will be the ability to identify, assess and respond to emergent issues, science and technologies. To achieve this, Boral will adopt the following actions:

– Regular and routine interrogation of the scientific literature to remain abreast of scientific Australian and international developments
– Periodical management reviews and environmental team reviews
– Peer review available information to ensure it is scientifically sound and consistent with the recognised Australian framework, including the National Environment Protection (Assessment of Site Contamination) Measure 1999, as updated 2013 (ASC NEPM)
– Continue to organise and participate in industry forums on new and emergent risks, assessment methods and management technologies, sharing lessons learnt and learn the information gathered within the team.
– Interrogate scientific documents and new technologies to understand the potential effectiveness, sustainability and efficiencies, and describe the likely opportunities presented by these advancements in plain English so they can be understood by other stakeholders.
– Provide an honest assessment of uncertainty of the science and technology presented and the conclusions reached.
– Changes in environmental regulation, e.g. EPA Amendment Act (2018).
– Continual improvement is achieved through constant measurement and evaluation, audit and review of the effectiveness of the SW-GWMP and adjustment and improvement of the quarry's Environmental Management System.

9. References

ANZG 2018. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Governments and Australian state and territory governments, Canberra ACT, Australia. Available at **www.waterquality.gov.au/anz-guidelines**

EPA Victoria, 2022: *Environment Reference Standard*. No.S245 Gazette 26 May 2021

GHD, 2023a: *Surface water and groundwater assessment of the Boral Montrose Quarry*. Report prepared for Boral Resources Australia Limited. GHD reference 12570927-301350-2

GHD, 2023b: *Numerical Groundwater Modelling Report, Boral Montrose Quarry.* Report prepared for Boral Resources Australia Limited. GHD reference 12570927-92403-6

ghd.com

The Power of Commitment