APPENDIX B

Groundwater Assessment

Dendrobium Mine – Plan for the Future: Coal for Steelmaking

Groundwater Assessment

FOR

South32 – Illawarra Coal

BY

NPM Technical Pty Ltd

trading as

HydroSimulations

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Rev	Description	Authors	Date	Comments
A	Draft Groundwater Assessment Report	W Minchin (Watershed HydroGeo); S Brown (HGEO), B Rollins, A Skorulis, N Merrick (HydroSimulations)	12/12/2018	combined Conceptual and Numerical Modelling Report, incorporating comments by Kalf and Associates and the coordinating consultant.
B	Draft Groundwater Assessment Report	W Minchin (Watershed); S Brown (HGEO)	07/02/2019	updated Assessment, incorporating Tahmoor South Project and following review of IEPMC (2018)
C	Final Draft Groundwater Assessment Report	W Minchin (Watershed); S Brown (HGEO)	26/03/2019	updated Assessment, further tasks to address IEPMC recommendations
D	Final	W Minchin (Watershed); S Brown (HGEO)	09/05/2019	Incorporating comments from coordinating consultant and editorial corrections

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1 INTRODUCTION

Illawarra Coal Holdings Pty Ltd (Illawarra Coal), a wholly owned subsidiary of South32 Limited (South32), operates the underground Dendrobium Mine, in the Southern Coalfield of New South Wales (NSW) (**Figure 1-1**). Since the initial approval in 2001, underground mining has been carried out using longwall extraction within Areas 1, 2 and 3A, and is currently underway in Area 3B. South32 intends to seek the necessary approvals to allow for mining within two new areas, known as Area 5 and Area 6, located to the west and north of the current Dendrobium Mine, within Consolidated Coal Lease (CCL) 768. The development of these new areas is referred to as the Dendrobium Mine - Plan for the Future: Coal for Steelmaking ("the Project").

1.1 SCOPE

HydroSimulations (HS) was engaged by Illawarra Coal to prepare an assessment of potential impacts of longwall mining in Areas 5 and 6 on the hydrogeological system. This assessment report forms part of the application to the NSW Department for Planning and Environment (DPE) as part of the NSW State Significant Development assessment and determination process.

The broad scope is to '*conceptualise, model, assess and document the likely groundwater impacts of the development in support of a State Significant Development (SSD) Application to extend the Dendrobium Mine into…'* Areas 5 and 6.

This report describes the data analysis and conceptualisation of the existing conditions and the likely impacts of mining on the hydrogeological system, and subsequent numerical modelling and impact assessment.

Following a review of historical and future approved mine plans and of the proposed Area 5 and 6 plans (**Section 1.3**), the analysis of data is presented in **Sections 2, 3 and 4**, and includes the following tasks for the study area (**Figure 1-1**):

- Literature review.
- Review of geological data and mapping.
- Review of aquifer property data, including from core and packer testing.
- Review of groundwater level data from the extensive monitoring network at Dendrobium, including from swamps and 'deep' or hard-rock groundwater systems.
- Review of surface water flow data.
- Review of mine inflow estimates from Dendrobium's detailed mine water balance.
- Review of surface water and groundwater chemistry data.

Conceptualisation of the groundwater system (**Section 5**) has been carried out based on the data analysis, and previous experience with pre- and post-mining conditions at Dendrobium and other longwall mines.

Groundwater modelling has been documented in **Sections 6 to 9**, including predictions and sensitivity analysis. Conclusions and impact assessment are presented in **Section 11**, along with some recommendations for future monitoring and modelling.

1.1.1 SECRETARY'S ENVIRONMENTAL ASSESSMENT REQUIREMENTS

SEARs were issued by DPE on 06/02/2017. The items relevant to this Groundwater Assessment are listed in **Table 1-1**.

Table 1-1 Summary of DPE SEARs

ITEM	REF. IN SOURCE	ISSUE RAISED	REFERENCE IN THIS REPORT
Subsidence	SEARs p.3	..taking into consideration connective fracturing above longwall panels	Section 5.2.2 and SCT (2017, 2018b)
Water	SEARs p.3, point 1	An assessment of the likely impacts of the development on the quantity and quality of surface and groundwater resources, having regard to agency requirements and recommendations.	Impacts discussed in Sections 5.2 and 11. Agency requirements – see Table 1-2.
	SEARs p.3, point 2	An assessment of the likely impacts of the development on aquifers, watercourses, swamps, riparian land, water supply systems including Cordeaux Dam and Avon Dam, and other water users.	Impacts on aquifers and other water users – Section 8.4. Impacts on watercourses – Section 8.5 Impacts on reservoirs – Section 8.6.
	SEARs p.4, point 1	An assessment of any drinking water catchment issues from mining…	Reduction in water quantity - Sections 8.5 and 8.6. Effect on water quality – refer to Surface Water Assessment (HEC, 2019).

Agency advice (including from DoI Water, WaterNSW) to DPE and provided along with the SEARs is referred to in **Table 1-2**.

Table 1-2 Summary of Agency advice accompanying the SEARs

AGENCY	REF. IN SOURCE	ISSUE RAISED	REFERENCE IN THIS REPORT
WaterNSW	Attachment 1, **Item 1.**	Full description of the development and existing environment should include those aspects which have the potential to impact on the quantity and quality of surface and ground waters.	Description of existing environment – Sections 2, 3 and 4.
		The location, mapping and nature of geological structures including faults, dykes and sills and other intrusions.	Geological structures discussed in Section 3.3 and 3.4.
		Hydrogeological fluxes between surface and ground waters.	Analysis of fluxes discussed in Sections 4.4, 4.6.2, 4.6.3 and 4.6.4.
		Location and description of water monitoring locations/points (including surface and ground waters), noting that WaterNSW have not been satisfied with the design and implementation of surface and groundwater monitoring in previous mining domains.	Surface water flow monitoring – Section 2.4.1. Groundwater level and quality monitoring – Section 4.2. Monitoring is designed in consultation with WaterNSW through technical working group meetings, email correspondence and review during the activity approval process.
WaterNSW	Attachment 1, **Item 2.**	Impacts on Avon and Cordeaux Dams	Loss of water from reservoirs – Sections 8.6and 9.4.

AGENCY	REF. IN SOURCE	ISSUE RAISED	REFERENCE IN THIS REPORT
		Impacts on water quantity and quality of overlying and adjacent water resources including Avon and Cordeaux reservoirs and rivers and their tributaries, using scientifically sound and rigorously numerical modelling, and sufficient, appropriate and representative baseline data.	Numerical modelling described in Sections 6, 7, 8 and 9. Baseline data described in Sections 2.4and 4.2. Reservoirs losses – Sections 8.6 and 9.4. Take from watercourses – Section 8.5.
		Impacts of the proposed mining on receiving water quantity and quality, both surface and groundwater systems and associated impacts on interaction and baseflow of surface waters.	Reservoirs losses – Sections 8.6and 9.4. Take from watercourses – Section 8.5. Refer to Surface Water Assessment (HEC, 2019)
		Details of proposed monitoring of groundwater levels, surface water flows, groundwater and surface water quality, along with information as to how the proposed monitoring will be used to monitor and, if necessary, mitigate impacts on surface water and groundwater resources. Monitoring programs shall be designed in consultation with WaterNSW.	Recommendations for future groundwater monitoring – Section 11.2.1. Monitoring is designed in consultation with WaterNSW through technical working group meetings, email correspondence and review during the activity approval process.
DPI Water *(now DoI Water)*		Assessment on impacts on surface and ground water sources (both quality and quantity), adjacent licensed water users, basic landholder rights, watercourses, wetlands and groundwater dependent ecosystems, and measures proposed to reduce and mitigate these impacts.	Impacts quantified in Section 8, 9 and 11. 'Take' of water is dealt with via licensing of groundwater and surface water (Sections 1.5, 8 and 9) Bores predicted to be affected beyond AIP minimal harm threshold are documented in Sections 8.4.4 and 9.3.2.
		Annual volumes of surface water and groundwater proposed to be taken by the activity from each surface and groundwater source as defined by the relevant water sharing plan.	Inflow (groundwater take) and surface water take quantified for sources within *Greater Metropolitan Region Groundwater Sources Water Sharing Plan* (Sections 8.3, 8.5, 9.2 and 8.7).
		Assessment of any volumetric water licensing requirements (including those for on-going water take following completion of the project).	Recommendations for licensing – Section 8.7
		A detailed assessment against the NSW Aquifer Interference Policy (2012)	AIP assessment summarised in Section 11.1 (based on Section 8).
		Full technical details and data of all surface and groundwater modelling, and independent peer review of the groundwater model.	Numerical model development, calibration and predictions - Sections 6, 7, 8 and 9. Peer Review by Kalf and Associates.
		Proposed surface and groundwater monitoring activities to assess impact on surface and groundwater quantity and quality.	Existing monitoring – Sections 2.4 and 4.2. Recommendations for groundwater monitoring – Section 11.2.1.
		Assessment of any potential cumulative impacts on water resources, and any proposed options to manage the cumulative impacts.	Inclusion of other mines in numerical modelling for cumulative impact assessment – Section 6.8.7 and 8.1.

AGENCY	REF. IN SOURCE	ISSUE RAISED	REFERENCE IN THIS REPORT
		Assessment of whether the activity may have a significant impact on water resources, with reference to the Commonwealth Department of Environment Significant Impact Guidelines.	Assessment of significant impacts re: subsidence, surface water and groundwater effects is made in the EIS.
		If the activity may have a significant impact on water resources, then provision of information in accordance with the Information Guidelines for Independent Expert Scientific Committee advice on coal seam gas and large coal mining development proposals, including completion of the information requirements checklist.	Information provided in accordance with IESC Information Checklist. Completed checklist supplied accompanying EIS.
OEH	Water and soils, point 6	The EIS must map the following features relevant to water and soils including:	
		▪ b. Rivers, streams, wetlands, estuaries;	Sections 2.4, 2.5, 2.6 and 2.7.
		▪ c. Groundwater.	Section 4.1.
		▪ d. Groundwater dependent ecosystems.	Sections 2.6 and 2.7.
	Point 7.	The EIS must describe background conditions for any water resource likely to be affected by the development, including:	
		▪ a. Existing surface and groundwater.	Sections 2 and 4.
		▪ b. Hydrology, including volume, frequency and quality of discharges at proposed intake and discharge locations.	Section 4.6.
		▪ c. Water Quality Objectives including groundwater as appropriate that represent the community's uses and values for the receiving waters.	Section 10.
		▪ d. Indicators and trigger values/criteria for the environmental values identified at (c) in accordance with the ANZECC (2000) Guidelines for Fresh and Marine Water Quality and/or local objectives, criteria or targets endorsed by the NSW Government.	Section 10, noting that baseline data collection would occur following project approval, and triggers determined from that.
	Point 8	The EIS must assess the impacts of the development on water quality, including:	

AGENCY	REF. IN SOURCE	ISSUE RAISED	REFERENCE IN THIS REPORT
		▪ a. The nature and degree of impact on receiving waters for both surface and groundwater, demonstrating how the development protects the Water Quality Objectives where they are currently being achieved, and contributes towards achievement of the Water Quality Objectives over time where they are currently not being achieved. This should include an assessment of the mitigating effects of proposed stormwater and wastewater management during and after construction.	Discussion of effects on groundwater quality – Section 5.2.7. For effects on receiving waters in the drinking water catchment, refer to Surface Water Assessment (HEC, 2019)
		▪ b. Identification of proposed monitoring of water quality.	Monitoring of groundwater via sampling pumps in bores – Section 4.2.2.
Dams Safety Committee (DSC)	Item 2	The Environmental Impact Statement (EIS) must include a quantitative assessment of the hydrogeology of the system.	Sections 4 and 5.

1.1.2 CONTEMPORARY AGENCY REQUIREMENTS AND RECOMMENDATIONS

In preparing this report, HS has considered relevant legislation as well as contemporary advice and decisions, e.g. decisions by Department of Industry (DOI) Water, DSC, the Planning Assessment Commission (PAC) as well as advice from the Federal Independent Expert Scientific Committee (IESC). Key points relevant to the Project are summarised in **Table 1-3**.

Table 1-3 Summary of Requirements and Recommendations

SOURCE DOCUMENT	REF. IN SOURCE	ISSUE RAISED	REFERENCE IN THIS REPORT
11 September 2014 – IESC Referral and Assessment Advice for the “Russell Vale Colliery Underground Expansion Project”. (IESC 2015-057)	24	Assessment of swamp connectivity. Inclusion of swamps in groundwater model.	Illawarra Coal have commissioned paired monitoring piezometers Areas 3B, 5, 6. Sections 6.5 and 6.7.
	36	Swamp monitoring, assessment of connectivity.	Illawarra Coal have commissioned paired monitoring piezometers Areas 3B, 5, 6. Monitoring of swamps in Areas 3A, 3B will continue.
	37	Assessment of effects on swamps.	Swamps to be included in numerical model. Swamps are assessed in HEC (2019). A review of historical impacts presented in Watershed HydroGeo (2019).
	52	Numerical model: calibration and prediction of groundwater level and flux, hydraulic conductivities, subsidence parameters, uncertainty analysis.	Calibration to groundwater level, inflow, hydraulic conductivity (Section 7). Secondary calibration to surface flow (baseflow) where appropriate (Section 7.7). Uncertainty analysis (deterministic scenario analysis, as per Middlemis and Peeters, 2018) carried out (Section 9).
	59	Effects on stream	This is investigated with the

SOURCE DOCUMENT	REF. IN SOURCE	ISSUE RAISED	REFERENCE IN THIS REPORT
		'perenniality' (i.e. stream flow continuity)	groundwater model (Section 8.5), and the Surface Water Assessment.
	60	Diversion or re-direction of flow in surface fracturing zone.	Sections 5.2.4 and 6.9.2.
	82-85	Effects on water quantity.	Sections 2.4 (watercourses), 2.5 (reservoirs), 4.8 (effects on near surface strata), 4.6.2 (baseflow estimates), 5.2.4 (conceptual model of effects on streams) and Section 8.5 (numerical model predictions). See also HGEO (2018a) and Watershed HydroGeo (2019).
11 March 2015 – IESC Assessment Advice for the "Russell Vale Colliery Underground Expansion Project. (IESC 2015 065)	1, 2	Insufficient knowledge of faults, shear zones.	Discussion on faults, shear planes in Sections 4.8, 4.7.3, and 5.2.1, including advice from geotechnical engineers (SCT, 2015; Walsh *et al*. (2014).
	3	Baseflow estimation and use in model calibration. Installation of multi-level pressure sensors above and adjacent to longwalls. Understanding of pre- and post-mining permeability. Discussion of observed and modelled permeability and other calibration datasets. Uncertainty and sensitivity analysis.	Sections 4.6.2 (analysis) and 7.7 (calibration) Section 4.2. This is on-going. Section 4.7. Permeability: Sections 4.7, 6.7, 6.9. Calibration datasets: Section 7.1. Section 9.
	11	Assessment of seam to surface connectivity.	Discussion of enhanced permeability (Section 4.8), structures as conduits (Section 4.7.3), analysis of water quality of seepage entering the mine workings (Section 4.5.3, 4.5.4) and the conceptual model of longwall mines and their connectivity to adjacent strata and the surface (Section 5.2). Groundwater modelling relies on results from FLAC2D geotechnical modelling (SCT, 2017 and 2018b).
	17-21	Assessment of seam to surface connectivity, especially with respect to stored waters.	As above, and SCT (2015, 2018a), HGEO (2018e).
2 April 2015 – PAC Review Report of Russell Vale Colliery Underground Expansion Project (R030/14)	Sections 4.1.4.	Residual concerns at end of assessment regarding water loss impacts.	Water losses from surface discussed in Sections 5.2.4, 5.2.6. The numerical model has been used to estimate water losses from streams (Sections 8.5) and reservoirs (Sections 8.6, 8.7 and 9.4)

SOURCE DOCUMENT	REF. IN SOURCE	ISSUE RAISED	REFERENCE IN THIS REPORT
	Sections 4.1.5.	The risk of inflow from entering and then exiting the mine via the access adit and the associated risk that the mine workings/goaf and groundwater system not being able to recover/ re-pressurise when the mine entrance is via an adit.	Section 9 of the Dendrobium – Avon and Cordeaux Reservoirs DSC Notification Area Management Plan (Illawarra Coal, 2015).
	Groundwater advice from Dr Colin Mackie (Appendix 5)	Modelling deficiencies, mainly around height of fracturing, parameterisation of storage properties, unsaturated zone representation, prediction of near surface areas where desaturation will take place and for how long.	Dendrobium Mine has extensive data and analysis on these issues. Previous modelling at Dendrobium has dealt with most of the issues described. More recently there has been additional focus on water quality/geochemistry. Height of fracturing, the changes to aquifer properties above longwalls estimated in SCT (2017, 2018b). Storage properties described in Sections 4.7.2, 6.7.2 and 6.9.5. Water table drawdown in Section 8.4 and 9.3.
28 May 2015 – Draft Policy Framework for Biodiversity Offsets for Upland Swamps and Associated Threatened Species Impacted by Longwall Mine Subsidence.	"Where 'nil' or 'negligible' environmental consequences are predicted". "Monitoring the environmental consequences of mining on upland swamps and associated threatened species".		Modelling carried out in HEC, 2019. Historical review of impacted swamps at Dendrobium (Watershed, 2019). Swamp monitoring described in Section 4.2.3.
29 June 2015 – PAC Review Report of Springvale Mine Extension Project (SSD 5594)	Section 3.2.2 details the following items relevant to groundwater: ▪ simulated effects on swamps; ▪ estimation of the height of fracturing.		Subsidence effects to be dealt with by MSEC (2019), with surface fracturing to be included in the groundwater impact assessment and model, as discussed in Section 5.2.6. Groundwater modelling relies on results from FLAC2D geotechnical modelling (SCT, 2017 and 2018b), as recommended by IEPMC (2018), Mackie (2017).
24 July 2015 – "Further advice on impacts to swamps" (IESC 2015-068)	Items 1-6 and 8-14, regarding adequate monitoring of under-mined swamps and the use of reference swamps to allow comparison against a control site).		Separate advice provided to Illawarra Coal regarding Area 5 & 6 swamp monitoring. A summary is provided in Section 4.2.3.
20 August 2015 – SEARs for Hume Coal Project (SSD 15_7172)	Groundwater SEARs, EPBC Requirements and input from DPI Water and WaterNSW.		Details on baseline hydrogeology (Section 4), GDEs (Section 2.6), Water Sharing Plans and licensing (Section 1.5), monitoring (Section 4.2, 2.4.1), modelling and predictions (Section 6-8).
21 September 2015 – PAC Second Review Report of Springvale Mine Extension Project (SSD 5594)	See Section 4.3 for discussion of subsidence and swamps.		Section 4.2.3 discusses Area 5 & 6 swamp monitoring to achieve a long baseline of swamp water levels, moisture content in order to maximise the understanding of swamp responses to variable rainfall, evaporation prior to mining commencing.

SOURCE DOCUMENT	REF. IN SOURCE	ISSUE RAISED	REFERENCE IN THIS REPORT
1 April 2016 – PAC Second Review Report of Russell Vale Colliery Underground Expansion Project (R037/15)		Expert Advice on Groundwater and Subsidence (Appendix 6). Dr Mackie raised points on: ▪ Seam-to-surface connection; ▪ Streambed cracking; ▪ Licensing of groundwater and surface water take.	Fracturing in the shallow subsurface and seam-to-surface connectivity is considered by SCT (2016) [Section 4.8], water finger-printing analysis (Section 4.5.3). Surface fracturing is discussed in Section 5.2, and modelling will represent this process (Section 6.9.2), although this feature is not a regular inclusion in groundwater models. Licensing of groundwater and surface water take is addressed in (HS, 2016a) and communications with DPI Water. Groundwater modelling (Section 8.7) will provide estimates of licensing requirements for Areas 5 & 6.

DPE commissioned an independent review of the height of fracturing and associated environmental effects. That study, PSM (2017) and associated peer reviews, provided several recommendations relevant to this groundwater assessment. HS reviewed PSM (2017) 'Height of Fracturing' study and associated reviews. A summary of the implications for both the conceptual and numerical modelling is presented in **Table 1-4**. This has been extended with discussion following the release of the report by the Independent Expert Panel for Mining in the Catchment [IEPMC] (IEPMC, 2018). A table of responses to other IEPMC comments has been provided separately.

Table 1-4 Summary of Implications for Groundwater Modelling from PSM and IEPMC

#.	ISSUE	ACTION / RECOMMENDATION
1	Accounting for structures, specifically Elouera Fault	Illawarra Coal maps structures in the mining area and has commissioned studies to investigate the role of structures within and around Area 3B longwalls. Data available at the time of modelling has been incorporated. Geological structures currently identified around Areas 5 and 6 are documented in PSM (2019). The Elouera Fault is not relevant to Areas 5 and 6. Notwithstanding, studies on the Elouera Fault are underway as part of SMP applications for longwall panels in the approved Area 3B mining domain. Ongoing investigations into structures relevant to Areas 5 and 6 would continue, however, investment into these investigations would in part be dependent on approval of the Project.
2	Valley-bulging (valley-closure) around lakes	This item, and 3 and 4 below have been the subject of several investigations by Illawarra Coal in the past two years. Suggestions for incorporation into modelling are that this be dealt with by increasing the hydraulic conductivity of the strata along valley walls and beneath valley floors. The modelled increase in hydraulic conductivity used to represent this mechanism is described in Section 4.8.
3	Accounting for basal shears	Increased permeability resulting from basal shears around ends of longwalls and the potential to connect to Lake Avon has been incorporated into the model. Based on advice from SCT, and the PSM study, these occur around the claystones (BHCS and SPCS). PSM stated that "based on its general experience in sedimentary rock geological terrains, this shearing is likely to be continuous throughout the Dendrobium Mine region." Basal shears are modelled via an increase in hydraulic conductivity.

#.	ISSUE	ACTION / RECOMMENDATION
4	Off-goaf fracturing	The groundwater model needs to simulate off-goaf Kh enhancement, although this may be accounted for via the 'valley-bulging' mechanism described earlier (#2). Enhancement has been represented as: • occurring up to 500 m from longwalls; • being an increase of 2-3 times as a minimum, but up to 15 times based on recent testing at S2314A *(more discussion of this in HGEO, 2018b and Section 4.8*). PSM's claim of up to 3 orders of magnitude was not supported by data or literature; • being applied as declining with distance, based on S2313 and S2314A data.
5	Representation of fracturing through to surface in Area 3B	Neither the Tammetta (2013) or Ditton (Ditton and Merrick, 2014; DGS, 2016) models are supported by the PSM study or reviews. However, IEPMC (2018) recommended that, despite limitations, the method of Tammetta (2013) should be adopted over Ditton and Merrick (2014) for conservatism. There is clearly some form of fracturing at the surface above Area 3B, although the specific mode of fracturing is subject to some dispute. PSM assert there is vertical connection from seam to surface above Area 3B (e.g. based on the Longwall 9 investigations), although not all lines of evidence (i.e. water budgets, groundwater levels and inflow chemistry) consistently support this concept (Sections 4.5.3, 4.5.4). To carry out a conservative assessment of impacts, the baseline model now incorporates seam-to-surface connection (Sections 4.8, 5.2.2, 6.9.1) which is at least as conservative, if not more so, as IEPMC's recommendation to adopt the Tammetta method, while maintaining calibration (where possible) to inflow and groundwater levels.
6	Geotechnical modelling	Geotechnical modelling could be done prior to groundwater modelling (e.g. FLAC) or coupled (e.g. COSFLOW). FLAC2D modelling has been conducted by SCT (2017 and 2018b), and is summarised briefly in Section 4.8.3. The modelled hydraulic conductivity with height above the seam has been used to parameterise 'Drains' to represent the fracture network above extracted panels (Section 6.9.1).
IEPMC (2018) Comments and Recommendations		
4.5.3 e	Transition to an unstructured model mesh for MODFLOW-USG	IEPMC ("the Panel") noted that the transition to an unstructured model mesh had 'stalled', i.e. the model had been moved to MODFLOW-USG in 2015, but still used the structured (rectilinear) grid adopted in Coffey (2012b). The model mesh is now unstructured. Discussion in Section 6.4.
6	Estimation of height of connective fracturing	The Panel recommends "to err on the side of caution and defer to the Tammetta [2013] equation…". See response to PSM recommendation 5 (above).
6.ii	Use of geotechnical models.	The Panel recommends "geomechanical modelling of rock fracturing and fluid flow is utilised to inform the calibration of groundwater models.". This has been done. See response to PSM recommendation 6 (above).
8.i	Continued updates to groundwater models	The Panel recommends "that groundwater models should continue to be updated". The peer-reviewed modelling presented in this study represents a significant update to existing groundwater modelling, including the use of depth-related permeability constrained by field data, further calibration of recharge estimates, incorporation of results from FLAC2D and general improvement in model calibration of groundwater levels and inflows. The model will continue to be updated in future, as necessary.
8.iii	Disparity in Kh and Kv model parameters between groundwater models	IEPMC (2018) identified that there is disparity or inconsistency in Kh and Kv model parameters between groundwater models, with reference to the previous modelling conducted for Dendrobium and for Metropolitan Mine. In this model, the hydraulic conductivity values in the model are well constrained by field data from Dendrobium, BSO (both Illawarra Coal) and from Tahmoor Mine, as discussed in Sections 4.7.1, 6.7.1 and 7.2. Metropolitan Mine data is not compared in this report, but a separate study to analyse all available hydraulic conductivity for the Southern Coalfield is recommended.

#.	ISSUE	ACTION / RECOMMENDATION
s6.4, p.124	Estimate cumulative impacts on catchments to reservoirs	The Panel recommended a "useful and appropriate comparison would require the groundwater model to cover the groundwater catchment area of the reservoir and include cumulative losses due to mining." This is presented in Section 8.7.1, noting that the groundwater model in this study covers the catchments of Lake Avon, Lake Cordeaux, and parts of the catchment to Lake Nepean and Lake Cataract.

1.1.3 INFORMATION REQUIREMENTS AND GAPS

Table 1-5 lists the information requirements of the IESC in their assessment of large coal mining developments under the *Environment Protection and Biodiversity Conservation Act, 1999* (EPBC Act). Further detail of the requirements is in Appendix A of the IESC Information Guideline (2018). Each category of information and current gaps with respect to information requirements are indicated. The completed checklist is supplied separately.

Table 1-5 Information Requirements

IESC INFORMATION REQUIREMENT	WHERE ADDRESSED
1. Description of proposed project	This report, Section 1.
2. Description of impacts to water resources and water dependent assets	This report, Sections 2 to 5.
2.1. Conceptual model	This report, Section 5.
2.2. Numerical Modelling	Addressed in this report: ▪ Sections 6-7: model development and calibration. ▪ Section 8: model predictions. ▪ Section 9: sensitivity in model predictions (as per Middlemis and Peeters, 2018).
2.3. Water and salt balances	Water balance would be presented in the Modelling report
3. Data management and monitoring	Section 10 of this report
4. Cumulative impacts	Cumulative impacts are considered in the numerical model: Sections 6-9.
5. Risk assessment	A risk assessment is presented in a separate Risk Assessment report

1.2 DATA SOURCES AND INVENTORY

Data sources include previous studies and documentation commissioned for Dendrobium Mine, data from Dendrobium's exploration programmes and monitoring network, and from Dendrobium's mine water balance.

Additional data has been sourced from NSW government, including from the Geological Survey of NSW, Department of Industry (DOI) Water, and WaterNSW.

Further data has been sourced via data-sharing agreements, from neighbouring mines in the Southern Coalfield, namely Appin (also operated by Illawarra Coal), Tahmoor (Glencore/SIMEC) and Wongawilli and Russell Vale Collieries (Wollongong Coal).

1.3 PROJECT OVERVIEW

1.3.1 DENDROBIUM MINE

Dendrobium is an existing underground coking coal mine located between the Avon and Cordeaux Reservoirs in the Southern Coalfield (**Figure 1-1**). The Dendrobium Mine was approved by the NSW Minister for Urban Affairs and Planning on 20 November 2001 under the *Environmental Planning and Assessment Act, 1979* (EP&A Act). The existing mining operations are undertaken in accordance with NSW Development Consent (DA 60-03-2001), as well as the Approval Decision (EPBC 2001/214) granted on 20 December 2001 under the EPBC Act.

Key surface infrastructure supporting the underground mining operations include the Kemira Valley Coal Loading Facility (KVCLF), Kemira Valley Railway, Dendrobium Pit Top, Dendrobium Coal Preparation Plant (located within the Port Kembla Steelworks) and ventilation shafts. The Company has identified two proposed future mining areas within CCL 768 to extend the life of the existing operations of the Dendrobium Mine, namely Area 5 and Area 6.

Figure 1-1 shows the location of the mining areas and longwalls at Dendrobium and the relative location of nearby Avon and Cordeaux reservoirs and watercourses. On this figure the mining areas are labelled “A1” (Area 1), “A2” (Area 2), “A3A” (Area 3A) and so on.

Longwall mining has been conducted at Dendrobium since early 2005 (**Table 1-6**). Area 1 (Longwalls 1 and 2) was completed in 2007, followed by Area 2 (Longwalls 3, 4, and 5) in 2009, and Area 3A (Longwalls 6, 7 and 8) in 2012. Mining of Area 3B commenced in February 2013 and continues in 2018.

All mining in these areas was and will be within the Wongawilli Coal seam.

1.3.2 THE PROJECT

The locations of the proposed future mining areas, Areas 5 and 6, are shown on **Figure 1-1**.

IC is seeking the necessary approvals to allow for mining within Area 5 and Area 6 at the Dendrobium Mine. This involves the preparation of an Environmental Impact Statement (EIS) for the Project and associated documents required to obtain a new development consent and secure approval under the EP&A Act and EPBC Act. The proposed mine plan is shown on **Figure 1-2**, with details of the longwall panels provided in **Table 1-7**. Surface infrastructure, such as ventilation shafts, would be required within Areas 5 and 6 or near roadways.

Area 5 will target the Bulli Coal seam[1] (‘Bulli seam’). It is proposed that development would begin in 2019, with extraction sixteen panels through years 2024-2038, i.e. a 15-year life.

[1] Bulli Coal and Bulli Coal seam are the accepted formal names for these stratigraphic units, however based on usage by Illawarra Coal (e.g. ‘Bulli Seam Operations’, in stratigraphic logs etc) the informal term ‘Bulli seam’ is used by HS throughout this document.

Table 1-6 Details of Historical and Planned Longwalls – Areas 1-3C

MINE AREA	LONG-WALL	DATE START	DATE END	DAYS	LW WIDTH	VOID WIDTH	LW LENGTH	CUTTING HEIGHT MEAN		DEPTH OF COVER [m]		
			Historical Panels					Mean	Max	Min	Mean	Max
1	1	30/03/05	15/12/05	261	237	247	1750	3.2	3.70	170	262	316
1	2	09/02/06	22/01/07	348	237	247	2000	3.3	3.66	162	264	320
2	3	30/03/07	22/11/07	238	235	245	1560	3.6	3.75	138	211	282
2	4	17/12/07	30/09/08	289	235	245	1950	3.6	3.80	159	249	310
2	5	04/12/08	18/12/09	380	235	245	2300	3.7	3.90	213	252	293
3A	6	9/02/10	28/03/11	413	238.5	248.5	2610	3.5	3.60	287	345	389
3A	7	04/05/11	23/01/12	265	238.5	248.5	2220	3.4	3.50	288	338	379
3A	8	24/02/12	29/12/12	310	295	305	2220	3.5	3.70	261	321	373
3B	9	09/02/13	02/06/14	479	295	305	2150	3.9	4.50	314	381	409
3B	10	20/01/14	20/01/15	366	295	305	2200	3.9	3.95	325	383	406
3B	11	18/02/15	05/01/16	322	295	305	2190	3.9	3.95	327	381	404
3B	12	22/01/16	31/01/17	377	295	305	2590	3.9	3.95	329	376	404
3B	13	04/03/17	19/04/18	411	295	305	2210	3.2	3.70	299	375	400
3B	14	22/05/18	Dec-2018*		295	305	1980		3.9	325	378	395
				Approved (future) Panels						Min	Mean	Max
3B	15	Jan-2019	Sep-2019		295	305	1963	3.9		324	370	390
3B	16	Oct-2019	Jun-2020		295	305	1874	3.9		280	350	390
3B	17	Jul-2020	Mar-2021		295	305	2013	3.9		279	345	385
3B	18	Apr-2021	Nov-2021		295	305	1928	3.9		248	332	375
3A	19	Jan-2022	Jun-2022		295	305	1600	3.6		287	331	369
3C	20	Aug-2022	Mar-2023		245	270	2000	3.9		324	374	413
3C	21	Apr-2023	Aug-2023		245	255	800	3.9		380	408	418
3C#	-	2039	2043		295	305	~900-2400	3.9		300	350	405

Width and length all in metres (m). * proposed completion date
the mine plan for Area 3C has not been formalised, so a preliminary or generalised longwall plan is modelled.

Table 1-7 Details of Proposed Longwalls – Areas 5 and 6

MINE AREA	LONG-WALL	DATE START	DATE END	LW WIDTH	VOID WIDTH	LW LENGTH	CUTTING HEIGHT	DEPTH OF COVER [m]		
Area 5								Min	Mean	Max
5	501	Jan-2024	Dec-2024	295	305	3470	3.2	277	340	387
5	502	Jan-2025	Dec-2025	295	305	3990	3.2	302	345	371
5	503	Jan-2026	Dec-2026	295	305	3900	3.2	299	358	377
5	504	Jan-2027	Dec-2027	295	305	3900	3.2	322	362	385
5	505	Jan-2028	Dec-2028	295	305	3740	3.2	321	367	392
5	506a,b	Jan-2029	Dec-2029	295	305	1090, 2485	3.2	273	360	398
5	507a,b	Jan-2030	Dec-2030	295	305	650, 2710	3.2	288	360	397
5	509	Jan-2031	Jun-2031	295	305	1175	3.2	277	359	384
5	508a,b	Jul-2031	Jun-2032	295	305	1910, 1810	3.2	285	360	366
5	512	Jul-2032	Dec-2032	295, 195	305, 205	1850	3.2	318	364	388
5	511	Jan-2033	Dec-2033	295	305	1990	3.2	320	368	394
5	510	Jan-2034	Dec-2034	295	305	1830	3.2	318	364	388
5	513	Jan-2035	Dec-2035	295	305	2060	3.2	275	309	371
5	514	Jan-2036	Dec-2036	295	305	2270	3.2	272	331	374
5	515	Jan-2037	Dec-2037	275	285	1725	3.2	253	313	373
5	516	Jan-2038	Dec-2038	275	285	2100	3.2	266	347	385
Area 6								Min	Mean	Max
6	601a,b	Jan-2043	Dec-2043	295	305	1150, 870	3.9	374	425	455
6	602a,b	Jan-2044	Dec-2045	295	305	400, 2440	3.9	399	435	460
6	603	Jan-2046	Dec-2046	295	305	2640	3.9	419	438	453
6	604	Jan-2047	Dec-2047	295	305	2420	3.9	429	449	458
6	605	Jan-2048	Dec-2048	295	305	1150	3.6	417	449	458

Width and length all in metres (m). Dates are approximate, based on IC's yearly Development and Production schedule.
E:\DENDROBIUM\Tech\MinePlan\Longwall Geometry and Depth of Cover Summary_DND.xlsx

Area 6 will target the Wongawilli Coal seam[2] ('Wongawilli seam'). It is proposed that Area 6 will be mined following the approved Area 3C and that development would begin in Area 6 in 2029, with extraction of five panels through years 2043-2048, i.e. a 6-year life.

As noted in the tables above and shown on **Figure 1-3**, the longwall geometry is similar to previous areas. Area 5 has a smaller mining or cutting height (being in the Bulli Seam) but similar depth of cover to Area 3B. Area 6 has the same cutting height as for most of Area 3B, but a greater depth of cover.

1.4 NEIGHBOURING MINES

Figure 1-1 shows the extent of historical and recent mining around Dendrobium. Many of these mines undertook partial extraction, with a move to longwalls in about the 1970s. The major mines currently or recently operating around Dendrobium Mine are listed in **Table 1-8**.

Table 1-8 Other mines in the Southern Coalfield

MINE	OPERATOR	SEAM	DISTANCE FROM DENDROBIUM
Appin and West Cliff ('Bulli Seam Operations' [BSO])	Illawarra Coal	Bulli seam	This mine is about 8 km north of Area 6.
Tahmoor Mine	SIMEC	Bulli seam	Located approx. 10 km north-west of Area 5.
Wongawilli (Elouera)	Wollongong Coal	Wongawilli seam	Located immediately south of Area 3B.
Russell Vale	Wollongong Coal	Wongawilli seam	Located about 900 m east of Area 6.
Metropolitan Mine	Peabody	Bulli seam	Located 20 km north-east of Area 6.
Proposed operation			
Tahmoor South Project	SIMEC	Bulli Seam	EIS lodged early 2019. Located approx. 6 km north-west of Area 5. 9 longwalls proposed for extraction during 2023-2034.
Historical operations			
Cordeaux	Corrimal	Huntley	Avon
Kemira	Mt Kembla	Nebo	Port Kembla

Other than Metropolitan Mine (which is distant from Dendrobium), the other operations listed in **Table 1-8** are simulated in subsequent model scenarios for the purpose of model calibration and impact assessment.

1.5 WATER MANAGEMENT

NSW DoI Water manages water resources, including groundwater. This area is managed via the *Greater Metropolitan Region Groundwater Sources* Water Sharing Plan (WSP), which is divided into separate Groundwater Sources. Except for the entrance portal to the east of Dendrobium Area 1, all Dendrobium mine areas lie within the *Sydney Basin Nepean Sandstone* [Management Zone 2 (MZ2)] Groundwater Source. This Groundwater Source is classified by DPI as 'Highly Productive' under the *Aquifer Interference Policy* (AI Policy). The total assigned entitlement[3] for all users within the Nepean Sandstone (for both Management Zone 1 and 2) is 24,576 megalitres per year (ML/yr) (equivalent to 67 megalitres per day [ML/d]).

[2] As above, with the Wongawilli Coal and Wongawilli Coal seam referred to in this report as the 'Wongawilli seam'.

[3] http://www.water.nsw.gov.au/water-licensing/registers [accessed 14/10/2016]

IC currently hold shares of groundwater entitlement sufficient to cover their current and predicted take (for Areas 1-3B) from the Nepean Sandstone MZ2 and the incidental take from neighbouring Groundwater Sources:

- 3,962 shares (essentially ML/a) for the *Sydney Basin Nepean* Sandstone MZ2.
- 6 shares for the *Sydney Basin Nepean* Sandstone MZ1.
- 73 shares for *Sydney Basin South* Groundwater Source.

IC has successfully secured via controlled allocation additional shares to account or future predicted groundwater take from the *Sydney Basin Nepean* Sandstone MZ2 (Section 8.7).

Areas 5 and 6 are wholly within Nepean Sandstone MZ2 and mining in these areas is unlikely to significantly increase the incidental take from other Groundwater Sources.

2 TOPOGRAPHY, CLIMATE, DRAINAGE AND LAND USE

2.1 TOPOGRAPHY

Dendrobium Mine is located on the Woronora Plateau inland of the Illawarra Escarpment (**Figure 2-1**). The escarpment rises from the coastal plain to elevations in excess of 400 mAHD around Dendrobium. In Area 5, ground elevation ranges between 300 mAHD (northeast corner) to 450 mAHD (southern edge), averaging about 400 mAHD. Area 6 is slightly lower, with a minimum of 250 mAHD (along the western edge) to a maximum of 375 mAHD, averaging about 340 mAHD.

On the plateau, topography generally slopes to the north or northwest, toward the centre of the Sydney Basin. However, the plateau is dissected with the larger river valleys incised to between 50 m and 100 m into the terrain.

2.2 RAINFALL AND EVAPORATION

Daily rainfall observations are recorded by Illawarra Coal and long-term averages have been obtained from the Bureau of Meteorology (BoM). The distribution of BoM long-term average rainfall is presented in **Figure 2-2**. This figure shows that the average rainfall for the period 1961-1990 is about 1200-1400 mm/yr at Dendrobium. This compares with an average of 1100 mm/yr for the period 2003-2017 as recorded at the Dendrobium Mine weather stations.

Figure 2-3 shows the long-term rainfall trends, as defined by the cumulative departure from mean or cumulative rainfall deficit curve. This shows the historical occurrence of dry periods (downward trends on the rainfall trend), wetter than average periods (upward trends) and illustrates that the lower totals recorded by the Dendrobium weather stations for the recent period are the result of drier conditions in this period (e.g. including the recent April-2017 to October-2018 rainfall deficits assessed by BoM as 'lowest on record') than during the period of the BoM average (1961-90). Discussion of any relationship between groundwater levels and rainfall trends is presented in **Section 4.3**.

Potential evaporation (PE) is also available from BoM. Long-term average PE is approximately 1430 mm/yr at Dendrobium, and slightly higher at Wollongong on the coast (1520 mm/yr). Actual ET[4] at Dendrobium is approximately 920 mm/yr.

A comparison of average monthly rainfall and potential evaporation is presented in **Figure 2-4**. This shows that in late summer, autumn and winter there is a slight rainfall excess, while there is a rainfall deficit in spring and early summer.

2.3 LAND USE

As shown on **Figure 1-1**, land use in this area is primarily land reserved as part of Sydney's drinking water catchments (WaterNSW's Special Areas). These areas are primarily native forest and swamp vegetation, but include the major reservoirs of the upper Nepean system (see **Section 2.5**). More detail on vegetation types will be included in the Biodiversity Assessment for the Project (Niche, 2019).

Cleared areas or urban areas are primarily restricted to the coastal plain, or inland of Dendrobium, e.g. Bargo and Yanderra which are 6 km west of Area 5, and Wilton which is about 7 km north of Area 6.

[4] Actual ET is the ET that actually takes place, under the condition of existing water supply, from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average.

There are few transport links (other than fire trails) in the Dendrobium Mine area, although Picton Road passes through Area 6.

The distribution of groundwater bores, as registered in the NSW DoI Water *Pinneena* database, is discussed in **Section 4.6.5**. The bores around Dendrobium are all exploration and monitoring bores associated with mining. The non-mining bores are located on the coastal plain (east of the escarpment) and 10 km west and further south of Dendrobium, around Bargo/Yerrinbool and the Southern Highlands respectively. This highlights the lack of population immediately around the Dendrobium mining areas.

2.4 WATERCOURSES

The Dendrobium mining area is located within the catchment of the Upper Nepean River. Drainage is to the north-northwest, towards the Nepean River, with most of the local surface runoff initially captured in Nepean, Cordeaux, Avon, and Cataract lakes, before eventually flowing into the Nepean River (Coffey, 2012a). Additional information on these lakes (reservoirs) is presented in **Section 2.5**.

Approximately 40% of Area 5 lies within the catchment of Lake Avon, a further 35% within the catchment of the regulated Avon River downstream of the lake, and the remaining 25% within the surface water catchment of Donalds Castle Creek, which is tributary to the Cordeaux River (downstream of Lake Cordeaux).

Approximately 5% of Area 6 lies within the catchment of Lake Cordeaux, and 90% is within the catchment of the regulated Cordeaux River downstream of the lake. The remaining 4%, in the very north-eastern corner of Area 6, lies within the catchment of Wallandoola Creek, which is a tributary of the Cataract River (downstream of Lake Cataract).

Figure 2-5 shows the watercourses around Dendrobium, as well as the upstream catchment area for monitoring sites and for other selected sub-catchments. This allows identification of those sub-catchments potentially affected by mining.

2.4.1 MONITORING

Surface water flow monitoring sites are marked on **Figure 2-5**, including operational or active sites and some as-yet un-rated sites and proposed sites around Areas 3B, 3C, 5 and 6. Monitoring sites are to include gauging stations, rated for flow, where appropriate sites can be found (based on geomorphology and accessibility).

2.4.2 STREAM HYDROLOGY

This section presents the data from the existing monitoring network at Dendrobium, and then some specific discussion about the effects of mining.

Data

IC has been monitoring stream level and flow around Areas 3A and 3B since late 2007 (monitoring sites are marked on **Figure 2-5**). Gauging of streams within and downstream of the proposed mining areas has recently commenced and results are presented in Hydro Engineering and Consulting [HEC], 2019).

Hydrographs of flow in the gauged watercourses are presented in **Figure 2-6**. Flows in these watercourses are typically relatively flashy, although there is a consistent baseflow component. The catchments of some of these gauges have been undermined and show discernible effects of mining (e.g. WC21, DC13) (see below).

Figure 2-7 presents a summary of catchment yield (i.e. flow per catchment area, expressed in mm) at many of the gauging stations, where yield is defined as the flow per catchment area, and expressed as mm/d or mm/yr, which normalises the flow in each watercourse. **Figure 2-7A** presents a duration curve of yield for the gauged sites for the full gauged period, including the post-mining period for those catchments that have been mined under. This shows that flow in some watercourses is more reliable than others, although most fall to below 0.001 mm/d for 5-15% of the time. This includes WWL, which is the most-downstream gauging station from Areas 3A and 3B, which records naturally occurring cease-to-flow conditions about 5% of the time.

Figure 2-7B presents average or mean flow yield as mm/yr compared with gauging station elevation. Gauging stations in the Donalds Castle Creek catchment are coloured red, while those in the Wongawilli Creek catchment are coloured blue, and the yields have been calculated based on the approximate pre-mining conditions for each site. The Donalds Castle Creek catchments seem to have lower flow yields (<=100 mm/yr) than those in the Wongawilli Creek catchment (200-300 mm/yr), however **Figure 2-7B** does not suggest that there is any strong relationship between elevation and yield. The yield at the two main catchment outlets (WWL and DCU) is 110-220 mm/yr. This range in yield is approximately equivalent to 8-17% of long-term average rainfall (**Figure 2-7C**).

A brief description of water quality of watercourses is presented in **Section 4.5.1**, while analysis of groundwater-surface water interaction is discussed in **Section 4.6.2**.

Effects of mining

More detail on the effects of mining is provided in the Surface Water Assessment (HEC, 2019), as well as the Surface Water End of Panel reports (HydroSimulations, 2016c, HGEO, 2017a and 2018c), however the processes are relevant to the Groundwater Assessment and a brief discussion is provided here.

As noted above, some of the gauged watercourses have been undermined and show discernible effects of mining, e.g. WC21, DC13. These effects are due primarily to fracturing of the creek bed. Similar cracking effects have been observed in creeks offset from longwalls, notably some cracking in WC15 (without observed flow diversion) [HGEO, 2018a] and in tributary LA4 at about 290 m from mining (with loss of flow) [HGEO, 2017a].

Also, some watercourses which are not directly undermined, but are near to longwall areas, show the effects of baseflow capture, as discussed in Watershed HydroGeo (2018) and HGEO (2018d). Under average or wet conditions, the effects are not apparent, but during drought conditions such as the severe rainfall deficit during 2017-18 (**Section 2.2**), the effect may be revealed. In essence, the magnitude of baseflow capture is small compared to average flow, but may result in a loss of flow that is significant at low flows, even enough to result in the cessation of overland flow while dry conditions persist.

As discussed in HydroSimulations (2016d) and McMahon (2015), while the loss of surface flow observed in the streams such as WC21, DC13S1, DCS2 is significant enough to be discernible on hydrographs for those streams (HydroSimulations, 2016c), changes in surface water flow at downstream gauges are either not discernible/unclear (DCU) and are still not discernible at WWL (HGEO, 2018a). This is because of gauging accuracy and the small magnitude of loss compared to total flow at the downstream gauging stations. The current understanding is in line with earlier assessments which made similar statements about the observed loss of surface flow and possibility of re-emergent flow, e.g.:

"*Effects* (baseflow losses) *are not clearly observed in the downstream catchments to Donalds Castle Upper (DCU) and Wongawilli Creek Lower (WWL); this suggests that some or all flow lost in the headwater catchments is returned downgradient, but is not conclusive, as evapotranspiration (ET) might account for some fraction of that*." (HydroSimulations, 2016c).

This understanding is routinely re-assessed during the End-of-Panel process, and is assessed by HEC (2019). The current understanding is in agreement with both the findings on longwall-induced alteration of habitat by the NSW Scientific Committee and with work on Waratah Rivulet (e.g. Mclean *et al*., 2010), as discussed in Section 3.6 of HydroSimulations (2016d). The NSW Scientific Committee states:

"If the coal seam is deeper than approximately 150 m, the water loss may be temporary unless the area is affected by severe geological disturbances such as strong faulting. In the majority of cases, surface waters lost to the sub-surface re-emerge downstream".
(OEH, 2011). For context, the coal seam at Dendrobium Area 3B is typically >350 m deep, but is approximately 240 m deep under Wongawilli Creek. In Area 5, the Bulli seam is typically 330-370 m deep, while in Area 6 the Wongawilli seam is typically 350-430 m deep (**Section 3.2**).

2.5 RESERVOIRS

Lake Avon, Lake Cordeaux and Lake Nepean are water supply reservoirs formed by the damming of the upper Avon, Cordeaux and Nepean Rivers, and form part of the Upper Nepean Scheme (along with Lake Cataract). This forms part of the water supply for Sydney and the Illawarra. WaterNSW manages the water supply areas and infrastructure, with additional oversight by the NSW Dams Safety Committee (DSC). Key parameters are summarised in **Table 2-1**.

Table 2-1 Water supply reservoirs near Dendrobium

Reservoir	Area (km^2)	Operating Capacity (ML)	FSL (mAHD)	Deepest bed depth (mAHD)	Intersected Stratigraphy (from Moffitt, 1999)
Cordeaux	7.8	93,640	303.9	255.8	Hawkesbury Sandstone, Bald Hill Claystone, Bulgo Sandstone, Stanwell Park Claystone, Scarborough Sandstone
Avon	10.5	146,700	320.18	253.4	Hawkesbury Sandstone
Nepean	3.3	67,730	317.25	247.2	Hawkesbury Sandstone, Bald Hill Claystone, Bulgo Sandstone

Sources: http://www.waternsw.com.au/supply/visit/ . Bathymetry data obtained from WaterNSW.

As shown on **Figure 1-2**, Area 5 is immediately east and north of the northern section of Lake Avon. The average lateral distance between the edge of Area 5 longwalls and Lake Avon full supply level (FSL) is about 400-600 m. The nearest of the proposed Area 5 longwalls to Lake Avon is 300 m away. The western edge of Area 5 is located 2.9 km east of Lake Nepean.

Area 6 is located just north of the northern part of Lake Cordeaux. The nearest Area 6 longwall is proposed to be 600 m from the reservoir at its closest point, with the longwalls being an average of about 950 m away (lateral distance).

Lake Cordeaux is located 220 m west of Area 1 longwalls and 270 m east of Longwall 3 in Area 2. The Sandy Creek arm of Lake Cordeaux is 380 m east of Longwall 6 in Area 3A. Lake Cordeaux's FSL is 303.9 mAHD.

Surrounding shallow groundwater levels are typically higher in elevation, resulting in groundwater discharging to the lake (HydroSimulations, 2014c), although this is not always the case, and dependent on which geological formations are present along the lake shore and beneath the lakes. Drawdown in units at or below the base of the lakes can result in reversal of groundwater gradients.

Inflow to (as runoff) and evaporation from the reservoirs are significant parts of the regional water balance. BoM's National Water Accounts[5] provide estimates these, e.g.:

- Runoff into Avon Reservoir for 2009-10 = 19,446 ML or 53 ML/d.
- Runoff into Cordeaux Reservoir for 2009-10 = 21,650 ML or 59 ML/d.
- Evaporation loss from Avon Reservoir for 2009-10 = 8,410 ML or 23 ML/d.
- Evaporation loss from Cordeaux Reservoir for 2009-10 = 4,870 ML or 13.3 ML/d.

Review of WaterNSW's annual inflow data for 1909-2015 for Avon indicates that annual inflow ranges 6,005-279,000 ML (16.5-765.4 ML/d), averaging 68,875 ML/yr or 188 ML/d. The average inflow was about 30% less in the last decade of data reviewed.

Inspection of the accounts for other years (e.g. 2013) suggests similar magnitude evaporative losses, i.e. Avon 8,118 ML and Cordeaux 5,267ML. These equate to approximately 800 mm/yr lost to evaporation from the Avon and 630 mm/yr lost from Cordeaux.

2.6 GROUNDWATER DEPENDENT ECOSYSTEMS

The NSW State Groundwater Dependent Ecosystems Policy (DLWC, 2002) describes the five broad types of groundwater systems in NSW, each with associated dependent ecosystems as follows:

- **Deep Alluvial Groundwater Systems** – occurring under floodplains of major rivers west of the Great Dividing Range (e.g. Namoi, Macquarie, Lachlan, Murrumbidgee and Murray alluvium).
- **Shallow Alluvial Groundwater Systems** – coastal rivers and higher reaches west of the Great Dividing Range (e.g. Hunter, Peel and Cudgegong alluvium, and beds and lateral bars of the lower Macleay, Bellinger and Nambucca Rivers).
- **Fractured Rock Groundwater Systems** – outcropping and sub-cropping rocks containing a mixture of fractures, joints, bedding planes and faults that contain and submit small and occasionally large amounts of groundwater (e.g. Alstonville Basalt, Molong Limestone and the Young Granite).
- **Coastal Sand Bed Groundwater Systems** – significant sand beds along the coast of NSW (e.g. Botany and Tomago sand beds).
- **Sedimentary Rock Groundwater Systems** – sedimentary rock aquifers including sandstone, shale and coal (e.g. Great Artesian Basin, Sydney Basin and Clarence Moreton Basin).

Groundwater resources in the Dendrobium Mine area are located within the Porous (as the Nepean Sandstone Water Sources is classified – **Section 1.5**) sedimentary rock groundwater system.

The NSW State Groundwater Dependent Ecosystems Policy (DLWC, 2002) also recognises the four Australian groundwater dependent ecosystem types (Hatton and Evans, 1998) in NSW, namely:

- terrestrial vegetation;
- base flows in streams;
- aquifer and cave ecosystems; and
- wetlands.

A review of the BoM GDE Atlas[6] and relevant legislation and other literature has been conducted.

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5 http://www.bom.gov.au/water/nwa/2010/

The BoM GDE Atlas provides mapping of features that are potentially reliant on the surface expression of groundwater and other features that are potentially reliant on what the GDE Atlas refers to as 'subsurface groundwater', which is both the saturated zone and the vadose zone or capillary fringe. The BoM's mapping of these is presented on **Figure 2-8**, with the features classified to show their likely interaction with groundwater (low, moderate, high). BoM's mapping is based on remote sensing data[7] (and often not verified in the field) that "*indicates landscapes that are most likely to access additional water sources. The additional water source may be soil water, surface water, or groundwater*."

Of note on **Figure 2-8** are the following features depending on surface expression of groundwater:

- The Avon and Cordeaux Rivers downstream of the reservoir, and immediately adjacent to Areas 5 and 6. These features are both classified as having a 'moderate' potential for interaction with groundwater.
- The Nepean River is also classified as having a moderate potential for groundwater interaction, with the exception of a reach with a 'high' potential for groundwater interaction just downstream of the reservoir. This reach is about 2.2 km from Area 5. Another 'high' potential reach is located between Tahmoor and Appin in the north of the study area.
- The Cataract River downstream of Lake Cataract, located about 7 km north of Area 6, is classified as having a moderate potential for groundwater interaction.
- Lake Illawarra, located about 9 km from Dendrobium on the southwestern edge of the study area, is classified with a moderate potential for groundwater interaction.

There are numerous features that are also potentially dependent on 'subsurface groundwater' (i.e. either from the saturated zone or vadose zone) (i.e. 'terrestrial' GDEs), and these include:

- Areas of Coastal Sandstone Ridgetop Woodland (with a 'low' potential for interaction with groundwater), located on the ridgelines and interfluves.
- Areas of Coastal Sandstone Gully Forest and Hinterland Sandstone Gully Forest in the lower-lying areas (moderate potential for groundwater interaction). To the west and north of Area 5 there are areas of Hinterland Sandstone Gully Forest along the edge of gullies that are classified as having a high potential for groundwater interaction.
- Small areas of Nepean Shale Cap Forest (moderate potential for groundwater interaction).
- A number of Coastal upland swamps, with a 'high' potential for groundwater interaction. BoM's mapping of these features covers a subset of the mapping used by HS for this project (from Illawarra Coal and OEH mapping).
- Isolated areas of Sandstone Riparian Scrub – some with 'high' potential along Wongawilli Creek to the north of Area 3B, and more of this ecological class with low to moderate potential for groundwater interaction around Area 6.

The remote sensing data suggests that there is minimal potential for groundwater interaction across much of the study area (**Figure 2-8**), i.e. those areas not included in either of the datasets described above. This area generally corresponds to those parts of the landscape above 350-400 mAHD, and includes much of Areas 2, 3A, 3B, 3C and 6.

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6 http://www.bom.gov.au/water/groundwater/gde/map.shtml

7 http://www.bom.gov.au/water/groundwater/gde/faq.shtml

A search of legislation (see WSP in **Section 1.5**) was carried out to identify any High Priority GDEs in the region. The *Greater Metropolitan Region Groundwater Sources* WSP specifies a number of High Priority GDEs[8]. The nearest of these are:

- O'Hares Creek catchment: located 13-18 km northeast of Dendrobium Area 6. This includes "O'Hares, Stokes and Four Mile Creeks, downstream to the junction of O'Hares and Stokes Creeks".
- Thirlmere Lakes: located 16 km northwest of Dendrobium Area 5 and just west of Tahmoor Mine; and
- Macquarie Rivulet: located on the coastal plain 18 km south of Dendrobium in the Lake Illawarra catchment.

Although not defined as a 'High Priority', there are numerous swamps around the Southern Coalfield (**Section 2.7**).

2.7 UPLAND SWAMPS

Coastal Upland Swamps are prevalent in the eastern part of the Sydney Basin of NSW. They are listed as an endangered ecological community under the EPBC Act, and the NSW *Threatened Species Conservation Act, 1995*.

Upland Swamps are typically located at the headwaters of low order streams, on low relief plateau on low permeability Hawkesbury Sandstone. Swamp vegetation is highly variable, ranging from open graminoid (grassy) heaths and sedgelands to fernlands and scrub (TSSC, 2014). The location and extent of known swamps is shown in **Figure 2-5** and is derived from a combination of mapping by Illawarra Coal and the NSW Office of Environment and Heritage (OEH). Swamps within 400 m of the footprint of the existing and proposed mining areas at Dendrobium include:

- Area 5 - 27 mapped swamp areas, totalling 0.24 square kilometres (sq.km).
- Area 6 - 13 mapped swamps, totalling 0.28 sq.km.
- For comparison, Areas 2, 3A and 3B intersect 20 swamp areas, totalling 0.74 sq.km (within 400m of the mine footprint).

Potential effects on swamps are discussed in **Section 5.2.6**, and further discussion will be included after modelling and predictive scenarios have been completed.

8 http://www.austlii.edu.au/au/legis/nsw/consol_reg/wspftgmrgs2011739/sch4.html (accessed 1 November, 2016)

3 GEOLOGY AND RESOURCES

Dendrobium Mine is located within the (Southern) Sydney Basin, part of the Southern Coalfield, one of the five major coalfields that lie within the Sydney-Gunnedah-Bowen Basin.

3.1 STRATIGRAPHY

The stratigraphy of the Southern Coalfield is presented in **Figure 3-1**, with some additional information provided in **Table 3-1**. The Basin is primarily a Permo-Triassic sedimentary rock sequence and is underlain by undifferentiated sediments of Carboniferous and Devonian age.

Table 3-1 Summary of the regional Permo-Triassic stratigraphic sequence

Period	Group	Sub-group	Formation		Description	Typical thickness (m)
Triassic	Hawkesbury Sandstone (**HBSS**)				Massive or thickly bedded quartzose sandstone with siltstone, claystone and grey shale lenses up to several metres thick (Bowman, 1974; Moffitt, 1999).	<120
Triassic	Narrabeen Group		Newport Formation (NPFM)		Fine-grained sandstone (less than 3 m thick) interbedded with light to dark grey, fine-grained sandstones, siltstones and minor claystones (Bowman, 1974).	10
Triassic	Narrabeen Group		Garie Formation (GRFM)		Cream, massive, kaolinite-rich pelletal claystone, which grades upwards to grey, slightly carbonaceous claystone containing plant fossils at the base of the Newport Formation (Moffitt, 1999).	3
Triassic	Narrabeen Group	Clifton Subgroup	Bald Hill Claystone (**BHCS**)		Massive chocolate coloured and cream pelletal claystones and mudstones, and occasional fine-grained channel sand units (Moffitt, 1999).	12
Triassic	Narrabeen Group	Clifton Subgroup	Colo Vale Sandstone (**CVSS**)	Bulgo Sandstone (**BGSS**)	Thickly bedded sandstone with intercalated siltstone and claystone bands up to 3m thick (Moffitt, 1999).	95
Triassic	Narrabeen Group	Clifton Subgroup	Colo Vale Sandstone (**CVSS**)	Stanwell Park Claystone (**SPCS**)	Red-green-grey shale and quartz sandstone (Moffitt, 1999; BHP Billiton, 2013)	20
Triassic	Narrabeen Group	Clifton Subgroup	Colo Vale Sandstone (**CVSS**)	Scarborough Sandstone (**SBSS**)	Quartz-lithic sandstone, pebbly in part (Moffitt, 1999).	30
Triassic	Narrabeen Group	Clifton Subgroup	Wombarra Formation (WBFM)	Wombarra Claystone (**WBCS**)	Grey shale and minor quartz-lithic sandstone (Moffitt, 1999; BHP Billiton, 2013)	25
Triassic	Narrabeen Group	Clifton Subgroup	Wombarra Formation (WBFM)	Coal Cliff Sandstone (**CCSS**)	Fine to medium grained quartz-lithic sandstone (Moffitt, 1999). BHPB (2013) suggests CCSS is a sub-unit or facies grading into the Wombarra Formation.	15
Permian	Illawarra Coal Measures				Coal interbedded with siltstone, claystone, quartz-lithic sandstone and minor conglomerate (Moffitt, 1999). Includes the Bulli seam (**BUSM**/**BUCO**), Balgownie Coal, Wongawilli seam (**WWSM**/**WWCO**) and Tongarra Coal, plus Loddon/Lawrence Ssts (**LRSS**) and Kembla Sandstone (**KBSS**).	200-300

Table 3-1 includes abbreviations for the stratigraphic units. In this report, units are referred to by their full name in the text, but are often abbreviated on figures.

The Illawarra Coal Measures are the primary economic sequence of interest in the Sydney Basin, and consist of interbedded sandstone, shale and coal seams, with a thickness of approximately 200-300 m. The two main coal seams mined in the Southern Coalfield are the uppermost Bulli seam and the Wongawilli seam (Holla and Barclay, 2000). The vertical separation between the historically-mined Bulli and Wongawilli seams is about 30-50 m in the Dendrobium area.

The Illawarra Coal Measures are overlain by Triassic sandstones, siltstones and claystones of the Narrabeen Group (BHP Billiton, 2013), and the Hawkesbury Sandstone (HBSS). The Hawkesbury Sandstone is the dominant outcropping formation across the study site, as shown in **Figure 3-2** - *Southern Coalfield Geology* map – Moffitt, 1999. The key to the geological maps is shown on **Figure 3-3**.

To the north of Areas 5 and 6 are isolated shale cappings of the Wianamatta Group (WMFM). There are also small pockets of Quaternary-aged swamp deposits (‘Qs’ on the *Southern Coalfield Geology* map – Moffitt, 1999), located around the Southern Coalfield, including within Areas 5 and 6.

Figure 3-4 to **Figure 3-6** present a series of geological cross-sections through Areas 5 and 6 (cross-section lines plotted on **Figure 3-2**). These figures illustrate the relative thickness of the Hawkesbury Sandstone and Bulgo Sandstone in relation to the other units, as well as the layered nature of the geological sequence with alternating sandstones and claystones. These figures also show that the Stanwell Park Claystone is not fully extensive, or at least not sufficiently distinguishable from the underlying Scarborough Sandstone or overlying Bulgo Sandstone across the study area, resulting in ‘windows’ through this unit.

Figure 3-4 shows the degree to which the Avon Reservoir and major rivers (i.e. Cordeaux River) are incised into the Hawkesbury Sandstone. **Figure 3-5** and **Figure 3-6** show the degree of incision of Wongawilli Creek, Avon River and Lake Cordeaux.

3.2 COAL SEAMS

IC currently extracts coal from the Wongawilli seam at the Dendrobium Mine. Area 5 will target the Bulli seam and Area 6 will target the Wongawilli seam (**Section 1.3.2**). The Bulli and Wongawilli seams typically occur within a 30-50 m interval at Dendrobium. The geometry of the target coal seams is presented on **Figure 3-7** (Bulli) and **Figure 3-8** (Wongawilli).

The contours on **Figure 3-7** indicate that the dip of the Bulli seam is to the north toward the centre of the Sydney Basin with some warps and folds. The dip is about 1:50 through Area 5, similar through Area 6 and somewhat less (1:40) through Area 3C. **Figure 3-7** and the cross-sections (**Figure 3-4** to **Figure 3-6**) indicate the Bulli seam is located from 400 m to about 250 m below surface in the western part of Area 5.

The contours on **Figure 3-8** indicate some warps and folds in the Wongawilli seam and a dip to the north. The dip is similar to that of the Bulli Seam, being about 1:50 through Area 5 and Area 6, and slightly less (1:40) through Area 3C. **Figure 3-8** and the cross-sections (**Figure 3-4** to **Figure 3-6**) indicate the Wongawilli seam is generally 350-400 m below surface in Area 6, ranging from almost 450 m below surface on the eastern boundary to 360 m below surface in the western edge of Area 6. The cover depths described here are in excess of the 120 m minimum depth of cover described in DSC (2010) for longwall mining directly under stored waters, while proposed Area 5 and 6 longwalls are >500 m from reservoirs (**Section 2.5**).

The Bulli Seam has a thickness of up to 3.2 m in Area 5 with an average of approximately 2.5 m. Full extraction of this thickness is proposed.

The Wongawilli seam has a total thickness of 7-10 m; however, the proposal is that the working section would be a maximum of 4.2 m in Area 6 (**Section**). For modelling purposes, this is calculated from the floor of the deepest Wongawilli ply.

3.3 STRUCTURE

Figure 3-2 also presents regional structure, as mapped by Moffitt (1999)[9]. A large syncline runs through Area 3B and Area 6 (just east of Area 5), plunging to the north. Several north-south trending lineaments are also present in this area, including the Narellan Lineament, Cordeaux River lineament and Avon River Lineaments – these latter two are near to or pass through Area 5. To the west of Dendrobium and Lake Nepean, there are several 'domes', including the Mount Burke Dome located beneath Lake Nepean. These are usually associated with igneous intrusions (**Section 3.4**).

Smaller structures, typically faults and dykes have been mapped around the mine and documented in PSM (2019). Detailed mapping of geological structure would be carried out in Areas 5 and 6 as development extends into these areas.

3.4 IGNEOUS INTRUSIONS

Figure 3-2 presents IC's mapping of known and interpreted igneous intrusions. This includes the Cordeaux Crinanite around Area 2/3A, as well as sills and associated cindering to the north and west of Area 3B, around Area 5, and south of Area 3A. The mapping of intrusions is based on a half distance between bores where sills are detected and those where sills are absent, so is likely an overestimate of the continuity or extent of sills and heat-affected coal.

The cross-sections on **Figure 3-4** to **Figure 3-6** include IC's mapping of sills above and below the Bulli seam and Wongawilli seam in the vicinity of Areas 5 and 6.

3.5 SWAMP DEPOSITS

The structure and hydrological function of Coastal Upland Swamps have been well studied by Young (1982, 1986), Tomkins and Humphries (2006), Fryirs *et al*. (2014) and Cowley *et al*. (2016), and others. Upland Swamps form on accumulations of sandy and silty sediments on the broad and gently sloping headwater valleys. The geomorphic development of swamps is driven by positive feedback that operates when there is a significant excess of rainfall over evaporation (TSSC, 2014). Overland flow transports detritus from weathered sandstone exposed on the interfluves, which deposits and accumulates in the headwater valleys. High rates of precipitation, runoff and seepage from the sandstone substrate leads to waterlogging and an increased density of groundcover, thereby trapping more sediment and leading to the death of trees that are intolerant of high water tables.

[9] If necessary, refer to the original: http://www.resourcesandenergy.nsw.gov.au/__data/assets/image/0004/352858/Southern_Coalfield_regional_100K_Geology_Map_1st_ed_1999.jpg

Young (1982) and Tomkins and Humphries (2006) describe the structure of swamps on the Woronora Plateau. Young (1982) identifies four sediment types (**Figure 3-9A**): Organic fines, organic sands, grey-brown sands and sandy yellow earths (clayey sand). Similar sediment types are recognised by Fryirs *et al*. (2014) and Cowley *et al*. (2016). Measured cross-sections indicate a reasonably consistent structure: A basal layer of grey-brown, medium to coarse sand is overlain by increasingly organic rich sands and organic fines. There is commonly a lateral variation in facies caused by the fractionation of sediments during overland flow such that grey-brown sands accumulate at the swamp margins, whereas finer-grained sediments (silt, mud) and organic material accumulate towards the swamp axis (Young, 1982; *Figure 39*). Mottling of the sediments is common and indicative of waterlogging. Fibric mats of live and dead organic matter occur at the swamp surface to a depth of approximately 50 cm, providing some protection from erosion during runoff events.

The lithological sequence within the Quaternary swamp deposits has been investigated by multiple authors. A log from a Dendrobium swamp monitoring bore (piezometer site 01B_02 in Swamp 01B) is presented in **Figure 3-9B**, alongside a generalised classification of the lithology from Cowley *et al.* (2016). The log shows 1.8 m thickness of swamp sediments overlying sandstone saprolite (weathered sandstone). The deposits are fine to medium-grained sand to organic rich silts and clays, consistent with Upland Swamp deposits described elsewhere. The log also shows that the lithology is variable through the sequence but follows the classification of Cowley *et al*. (2016) and similar to that shown in **Figure 3-9A**:

- Surficial organic fines (SOF);
- Alternating beds of organics and sands (AOS);
- Fine cohesive sands (FCS);
- Basal sands or gravels (BSG), overlying
- Weathered or fresh rock.

Work by Tomkins and Humphries (2006) at Drillhole Swamp and Swamp 18, both located in the headwaters of the Avon Catchment, indicates a complex internal structure caused by episodes of rapid erosion and sediment flushing and relatively stable periods during which sediment and peat accumulate in low-lying areas. Radiocarbon dating of sediment from Drillhole Swamp indicates that episodes of erosion occur naturally with a periodicity of several thousand years. These episodes are thought to be caused by high intensity rainfall-runoff events, possibly following wildfires.

A common assertion is that upland swamps have a significant role in the catchment hydrology, i.e. they contribute baseflow to streams after rainfall – this is discussed more in **Section 4.6.2**. They are also an important trap and storage of nutrients and sediment.

3.6 REGIONAL GEOLOGICAL MODEL

The geological model provided by Illawarra Coal has been extended laterally beyond the Dendrobium area to form the basis for the groundwater model. This has been done using data from other sources, including the Illawarra Coal bore database which covers Appin, West Cliff, Cordeaux areas (to the north of Dendrobium), Wongawilli/Nebo areas (to the south) (**Figure 1-1**) and Tahmoor Mine bore data and the regional groundwater model constructed for Tahmoor (HS, 2018b) (to the north-west of Dendrobium).

One result of using the detailed stratigraphic interpretation in the data sources stated above, in combination with detailed topographic information, is that the regional outcrop mapping (**Figure 3-2**) has been updated in some areas. The outcropping geological units, based on the 3D mapping, is shown in **Figure 3-10**, which shows several differences from **Figure 3-2**:

- A greater area where the Bald Hill Claystone and Bulgo Sandstone outcrop around Areas 1 and 2 and near Sandy Creek.
- The Wongawilli Creek valley is incised through the Hawkesbury Sandstone into the Bald Hill Claystone and Bulgo Sandstone between Areas 3A and 3B.
- Similar incision through the Hawkesbury Sandstone into the Bald Hill Claystone and Bulgo Sandstone along the axis (thalweg) of the northern part of Lake Avon. While Moffitt (1999) suggested this for Lake Nepean (**Figure 3-2**), bathymetric data shows that the lake is more incised than the published outcropping mapping suggests. Sediment is likely to have accumulated and accreted behind the dam wall, so there may not be direct exposure of these rock units on the lakebed.
- Baseline swamp mapping on **Figure 3-10** is from National Parks and Wildlife Service (2003), which is updated in more detail around Dendrobium Mine by consultant botanists.

Some of the thicker stratigraphic units have multiple piezometers placed in them within a single bore (**Section 4.2**), and these piezometers frequently show some degree of head separation between upper, middle and lower portions of the Hawkesbury Sandstone, Bulgo Sandstone, and sometimes also within the Scarborough Sandstone. For this reason, it will be necessary to split or sub-divide these units for inclusion and representation in the groundwater model (**Section 6.5**).

The rules that have been used to sub-divide those three layers are as follows:

- Hawkesbury Sandstone: this unit is sub-divided into three layers; upper, mid and lower. The lower Hawkesbury Sandstone is defined as the lower 40 m above the Bald Hill Claystone, then the mid Hawkesbury Sandstone was defined as the next 50 m, and the upper Hawksbury Sandstone the remainder (variable thickness). Where erosion/topography has removed part of the Hawkesbury Sandstone, part or all of these sub-units may be removed (i.e. they are thinner or completely absent).
- Bulgo Sandstone: upper and lower layers based on the lower being defined as 50 m above the Stanwell Park Claystone, and the upper Bulgo Sandstone is the remainder (to the base of the Bald Hill Claystone). Again, this is topographically controlled, so that these sub-units may be thinner/absent.
- Scarborough Sandstone: upper and lower layers defined by the lower being 20 m above the Wombarra Claystone, and the upper Scarborough Sandstone is the remainder (to the base of the Stanwell Park Claystone). Again, this is topographically controlled, so that these sub-units may be thinner/absent.

These rules have been applied to the geological model, and the intersection of the different portions of these stratigraphic units with ground surface is the basis for the outcrop mapping of these layers shown on **Figure 3-10**.

4 HYDROGEOLOGY

This section describes the hydrostratigraphic framework at Dendrobium (based on the preceding geological data), the water-bearing properties (hydraulic conductivity and storage) and the characteristics and occurrence of groundwater in this area.

With respect to the hydraulic properties, **Section 4.7** outlines pre-mining or 'host' hydraulic properties, while **Section 4.8** discusses predictions and measurements of post-mining hydraulic properties.

4.1 HYDROSTRATIGRAPHY

The major hydrostratigraphic units within the study area are the Sydney Basin Permian and Triassic rock units, and within the Nepean Sandstone Groundwater Source these units are classified as 'Highly Productive' by DoI Water. This classification is based on groundwater yield (i.e. yield greater than 5 L/s and total dissolved solids [TDS] of less than 1,500 mg/L). Further discussion is given in **Section 4.5.2**. Within this broad classification of Permian and Triassic rock units (see stratigraphic column in **Figure 3-1**) the primary groundwater-bearing unit is the Hawkesbury Sandstone.

The Hawkesbury Sandstone is comprised primarily of sandstone, but also shales, mudstone and clay-rich lenses and horizons. The sandstone lenses have varying grain-size as is typical of a sedimentary sequence laid down under varying conditions. A geophysical log (from Coffey Geotechnics, 2012a) is presented as **Figure 4-1**, noting that a high gamma count is indicative of clay-rich horizons or laminae. This lithological variation and the thickness of the unit (up to 200 m thick) mean that although this unit is considered a single stratigraphic entity, it essentially forms a series of vertical layered aquifers. Each of these has a moderate resource potential, tending to higher resource potential in areas where secondary porosity (jointing and fracturing) is more developed.

Bore yields of >5 L/s (as per the 'Highly Productive' criteria) are possible, but yield is variable. For example, drilling and testing undertaken in 2005 by the NSW government near Lake Avon drilled two bores that produced quite different yields:

- GW040952: screened 80-145 mBG in Hawkesbury Sandstone, yield was 26 L/s.
- GW040946: screened 92-148 mBG in Hawkesbury Sandstone, yield was only 2 L/s.

Smaller quantities of groundwater can be extracted from parts of the Narrabeen Group, such as the Bulgo Sandstone, or from the Illawarra Coal Measures. The whole sequence comprises interlayered sandstone, claystone, siltstone, and, within the Permian strata, coal seams, to significant depth (>400-500 m).

North of Area 6 there are isolated outcrops or hill cappings of the Wianamatta Formation (**Section 3.1**). These shales are poorly permeable, with typically poor water quality. Springs can occur in the Wianamatta Formation, often at the contact with the Hawkesbury Sandstone.

There is very little mapped alluvium in this area.

There are many small pockets of unconsolidated material (upland swamps) throughout the study area (**Section 3.5**), although most swamps are located between Area 5 and the escarpment (**Section 3.6**). These features are generally oriented parallel to the direction of surface flow.

4.2 GROUNDWATER MONITORING

Figure 4-9 shows the location of monitoring locations around Dendrobium. The monitoring network is significant, and is expanding in size and scope.

4.2.1 GROUNDWATER LEVELS

IC operates an extensive groundwater monitoring network across the Dendrobium tenements. While this is focussed on the approved mining areas, some bores in Areas 5 and 6 have been monitored for over 5 years. A summary of the monitoring across Areas 3A, 3B, 5 and 6 is presented in **Table 4-1**. The VWP sites are labelled 'Deep (VWP) on **Figure 4-9**.

Table 4-1 Groundwater monitoring network– number of installation types

Status	Area 3A	Area 3B	Area 3C	Area 5	Area 6
VWP coal seams	2	21	7	6	3
VWP multiple units	6	12	6	9	
VWP special purpose	1	22		9	
Sampling pumps	5	9	3 (2 x HBSS 1 x BGSS)	3 (2 x HBSS 1 x BGSS)	0
Decommissioned	9	9	1		
Not monitored	2		3		

'special purpose' = e.g. installed post-mining above goaf, holes around Lake Avon to test off-goaf conditions, shallow sandstone piezometers near swamps.

A summary of the monitoring most relevant to Areas 5 and 6 is presented in **Table 4-2**, noting that S2116 and S2206 are within the bounds of Area 6 (the others are within Area 3C, about 500-3000 m south of Area 6).

Illawarra Coal operates many multi-level bores near to, but offset from, longwalls, which are being used for continuous monitoring before mining, during mining and the post mining period. This data is providing information on the near- and far-field influence of the underground mines. There are limited monitoring bores above the longwall panels, due to the safety risk of a possible lightning strike that could cause combustion in the mine. However, recently more monitoring bores have been installed above longwalls, usually as a process of installing bores before mining commences that are then decommissioned prior to undermining and then re-installed post-mining, but not installed to the full depth of the mine workings due to the risk described above. Currently, monitoring bores with multi-level piezometers have been installed above Longwalls 9, 10 (Swamp 1b, tributary WC21), and 12 (WC21).

The current network of groundwater monitoring sites at Dendrobium is shown on more detailed maps as **Figure A1** (Areas 1, 2, 3A and 3B) and **Figure A2** (Areas 3C, 5 and 6) in **Appendix A**.

Table 4-2 Summary of Groundwater Monitoring in Areas 5 and 6

AREA	S-INDEX	BORE NAME	NO. OF PIEZOMETERS								FIRST DATA	LAST DATA	COMMENT
			HBSS	BHCS	BGSS	SPCS	SBSS	CCSS	BUCO	WWCO			
Area 5	S2073								1	1	May 2010		active
	S2082	DEN155							1		June 2010		active
	S2312		3		3		2		1	1	July 2015		active
	S2064	DEN149	3		3		2		1	1	Apr 2012	Aug 2016	confirm status
	S2303		3		3		1				Jan-2016		active
	S2074	DEN152							1	1	May 2010		confirm status
	S2071	DEN151							1	1	May 2010		active
	S2007	DEN130						1		1	June 2009		active
	S2006	DEN129	3		3		2		1	1	June 2009		active
	S1908	DEN122							1	1	June 2009		active
	S2309		3		3		2		1	1	July 2015		active. suspect WWCO, 112-HBSS.
	S2291								1	1	Apr-2014		active
	S2076	DEN153							1	1	May 2010		active
	S2320		3		3		2		1	1	Aug-2016		active
	S2321										Aug-2016		active
	S2324		3		3		2		1	1			confirm status
	S2325		3		3		2				Aug-2016		active
	S2340	D-A5-25	3		3		2		1		Dec-2016		active
	S2341	D-A5-28	3		3		2		1		Dec-2016		active
	S2342	D-A5-12	3		3		2		1	1	Dec-2016		active
Area 6	S2116								1	1	Aug-2011	Sep-2016	confirm status
	S2206								1	1	Dec-2013		active
	S1154	Cordeaux 11							1?		Sep-2014		active. suspect data
Area 3C	S2011	DEN133							1	1	Jul-2009		active
	S2010	DEN132							1	1	Jul-2009		active
	S2270	Cx Hole-R								1			confirm status
	S2333		3		3		2		1	1	Oct-2016		active
	S2187								1	1	Oct 2012		active

AREA	S-INDEX	BORE NAME	NO. OF PIEZOMETERS								FIRST DATA	LAST DATA	COMMENT
			HBSS	BHCS	BGSS	SPCS	SBSS	CCSS	BUCO	WWCO			
near to Areas 5, 6, 3C	S1132	Cordeaux 7							1				no records available
	S1152	Cordeaux 9							1				no records available
	S1153	Cordeaux 10							1		Nov 1991	Nov 1991	one month only
	S1163	Cordeaux 14							1		1992	1992	no records available
	S1192	Cordeaux 16							1		Apr 1993	one reading 2011	
	S1193	Cordeaux 17							1		May 1993	Jan 2011	no records available
	S1194	Cordeaux 18							1		Apr-1993	May-1993	short record

KEY: = good data; = suspect or no data

4.2.2 GROUNDWATER CHEMISTRY

Table 4-1 shows that 3 groundwater sampling pumps have been installed in bores in Area 5 and in Area 6, focussing on the Hawkesbury Sandstone (HBSS) and Bulgo Sandstone (BGSS).

Monitoring of groundwater quality would be carried out with the primary objective to increase the existing baseline dataset, as described in **Section 4.5**. Monitoring would also be carried out to monitor chemical constituents and complying with the objectives outlined in **Section 10**.

In historical/current mine areas at Dendrobium, water quality of seeps and goaf areas in the mine works is analysed and reported on. The same would apply in Areas 5 and 6 if approved.

4.2.3 SWAMP MONITORING

Field investigations to identify appropriate sites to install piezometers and soil moisture probes in swamps commenced in January 2017. Monitoring in Areas 5 and 6 will be similar to Areas 3A and 3B with at least 2-years of baseline (pre-mining) groundwater level and soil moisture data in each swamp that is to be undermined and within 400 m of longwall areas, consistent with the OEH (2016) directive. Whilst piezometer transects are not planned at this stage; there would be two stages of piezometer installation:

1. A single piezometer in each relevant swamps in Areas 5 and 6 during 2017 to provide a long record of pre-mining baseline data. The first Area 5 longwall is proposed for 2023 (**Section 1.3.2**), so there should be a significant baseline record available.
2. Once the mine plan is finalised, all swamps above longwalls would have a piezometer installed, as well in those swamps situated within 400 m of the longwall footprints. This should provide sufficient multiple water level observations from each swamp to be undermined, as well as the ability to compare water level variations in 'swamps considered to be outside or beyond influence of mining.

In Areas 5 and 6 the data from shallow swamp piezometers would be compared against nearby 'shallow sandstone' piezometers, which would be installed to about 50 m depth. This would assist in understanding the connectivity or relationship with groundwater within the Hawkesbury Sandstone.

4.3 GROUNDWATER LEVELS

4.3.1 PERMO-TRIASSIC STRATA

Groundwater levels are monitored at numerous sites around the Dendrobium Mine. The data from many of the bores is analysed regularly as part of the End of Panel reporting process. This study has assessed the data from Areas 5, 6 and 3C, which are generally further from recent or active mining.

A series of hydrographs are presented in **Appendix C** – these show groundwater levels as reduced levels (mAHD) and as pressure head (m). Locations are in maps in **Appendix C**, and the rainfall trend (RMC – **Section 2.2**) is plotted on a selection of these. The key points to take from these hydrographs are:

- In Area 5 there are currently four bores monitoring water levels throughout the geological sequence (S2006, S2064, S2309, S2312), while the other bores monitor water levels in the Bulli and Wongawilli seams (**Table 4-2**).
- Some of the Area 5 bores are located near to Area 3B, which is currently being mined. Water levels in the coal seams at S1998 (DEN122) and S2007 (DEN130) show response to mining of recent longwalls in Area 3B. The observed depressurisation is about 20 m at S1998.

- There are no discernible signs of historical mining in the hydrographs from bores further west and north in Area 5.
- In Area 5 the head separation between the Bulli and Wongawilli seams is relatively small, being less than 25 m, and usually less than 15 m.
- In Area 6 water levels are currently only measured in the coal seams. The head separation between the two seams is typically about 100 m (heads in the Wongawilli are lower than in the Bulli seam). The exceptions to this are S2011 (which looks suspect as the two hydrographs are effectively the same), and both S2187 and S2206 where the heads in the Bulli are lower than those in the Wongawilli seam.
- In Area 6, the hydrograph from the Bulli seam at S2187 shows a significant recovery (90 m) since mid-2015. This might be due to changing operational conditions at another mine in this area (e.g. Russell Vale). There is no recent data from S2206 to confirm whether this response is observed in more than one bore, but this should be investigated further.
- The correlation between rainfall trends and groundwater levels is not strong. The hydrographs of many bores at Dendrobium were inspected, and two examples of piezometers where shallow water levels respond to rainfall trends are included at the end of **Appendix C**. These include two of the upper three piezometers at S1879 (DEN92), and for three shallow piezometers at S1892 (DEN99) – the rainfall trend (RMC) is shown on these charts. Other bores where shallow piezometers are observed to respond to rainfall trends include, but not limited to, S1577 (DEN38), S1867 (DEN84), S1870 (DEN85). However, there are many shallow piezometers where no correlation to rainfall trends can be discerned from the hydrographs, e.g. S2206 (DEN129), S2064 (DEN149). This seems to be due to either limited rainfall recharge or proximity to some discharge that limits water table fluctuation. (**Section 4.6.3**).

The water levels in three hydrostratigraphic units have been extracted for a particular date and used to produce a set of water level contour maps. **Figure 4-10** to **Figure 4-12** provide water levels for early 2016 within the lower Hawkesbury Sandstone, upper Bulgo Sandstone and Bulli seam. The Dendrobium data has been extended, where possible, with water level data from other sources in order to better represent the regional patterns of groundwater flow, although it should be noted that the data from other sources might be from a different time period.

Figure 4-10 presents contour water levels for the lower Hawkesbury Sandstone. This indicates that the dominant regional groundwater flow direction is to the north, with some contours converging on the Nepean River between the Tahmoor and Appin mine areas.

Figure 4-11 indicates contour water level data for the upper Bulgo Sandstone (or lower depending on availability of data from other sources). The regional pattern of groundwater flow in the Bulgo Sandstone appears less influenced by surface drainage than the shallower Hawkesbury Sandstone water levels in **Figure 4-10**, although groundwater flow directions remain towards the north toward the centre of the basin.

Figure 4-12 presents water level data for the Bulli Seam. This is shown here in instead of the Wongawilli seam because the data was more easily extended to the northwards and presents a more complete regional coverage. Northward groundwater flow is again apparent, with localised drawdown clearly apparent in bore water levels at Dendrobium, BSO and Tahmoor.

4.3.2 WATER LEVELS ABOVE MINED AREAS

Groundwater levels near to active mining areas show different amplitudes of drawdown, depending on the proximity to mining and the vertical position in the stratigraphic column (i.e. height above the mined seam).

The best example of water level behaviour above longwalls is the combined record of S2192-S2220 above the centreline of Longwall 9. This was discussed in HydroSimulations (2016d), and updated data is included here in **Figure 4-13A** (pressure head hydrograph) and **Figure 4-13B** (head vs depth).

Groundwater levels in the deeper parts of the stratigraphic column frequently exhibit significant drawdown, usually >50 m (e.g. piezometer 140 m-HBSS on **Figure 4-13** including the head contours for the Bulli Seam, **Figure 4-12**), that can result in complete depressurisation of fractures or zero pressure head in the deeper strata. For example, S1925-DEN108 (**Appendix C**) suggests that zero pressure might occur through much of the profile however VWP failure means it is not definitive, while S1930-DEN112 (at end of **Appendix C**) suggests that while there was significant drawdown after Longwall 9 passed in December 2013, most of the profile retained positive pressure heads (subsequent VWP failure after Longwall 10 passed means that only the upper three piezometers are functioning).

Drawdown in the shallower strata is in the order of tens of metres, such as in the Hawkesbury Sandstone (piezometer 95 m-HBSS on **Figure 4-13**) where the mining-related drawdown is in the order of 10-20 m. In the upper Hawkesbury Sandstone, there is usually much less drawdown, e.g. piezometer 50 m-HBSS (**Figure 4-13A**) actually shows little or no discernible drawdown (0-3 m), with recent water levels being near to or at pre-mining levels. Additionally, no mining related drawdown has been observed in the 10 m-HBSS piezometer at S1925-DEN108 (between Longwalls 11-12), while 65 m-HBSS at S1911-DEN106 (above Longwall 13) has so far exhibited about 6 m drawdown with the approach of mining in Area 3B.

Piezometers have been installed at the WC21 bores, and water level records from these would be analysed in future as data comes to hand.

4.3.3 SWAMPS

Swamp groundwater levels in the Dendrobium Mine area have been monitored since 2010, providing baseline data with which to assess the natural hydrological characteristics of swamps, and also the impacts of mine-related subsidence on swamp hydrology.

Baseline Conditions

Swamp hydrographs display a range of responses reflecting varying hydrological regimes at each swamp and at different locations within each swamp. At most locations, the shallow groundwater level rises sharply to within centimetres of the ground surface after a significant rainfall event (>75 mm in one day), particularly if the event is preceded by rainy days. The shape of the recession curve is characteristic of each swamp and location, with the following responses being common:

- In some swamps, a sharp peak lasting several days following a significant rainfall event, followed by a rapid recession as described below. The sharp peaks represent input from the rainfall itself and subsequent rapid runoff events. An example is marked on **Figure 4-14B**.
- In other swamps, a flat-topped or gently sloping peak with a duration of several weeks, indicating that groundwater levels are sustained near the ground surface following the rainfall event or that there is sufficient water entering the swamp (from rainfall or run-on from up-catchment) and the level of water in the swamp is maintained at a constant elevation by surface drainage (e.g. Swamp 01b piezometer 01b_01 - **Figure 4-14A**).

In many cases swamp hydrographs display characteristic combinations of the above responses, indicating a local hydrological (or hydrogeological) control that becomes dominant as the water supply declines after the rainfall event. Important factors are likely to include:

- rainfall intensity and duration;
- degree of saturation prior to a rainfall event;
- area, volume and structure of the swamp;
- connection with the sandstone groundwater system and head difference between the systems;
- the existence and characteristics of channel systems within the swamp deposits;
- the size of the catchment upstream of the swamp and the reliability of that flow through the swamp;
- the shape of the substrate and nature of the discharge point(s);
- the location of the piezometer; and
- high evapotranspiration from the water table at some fraction of potential evaporation rate.

Fryirs *et al.* (2014) describe four swamp hydrograph response types at an upland swamp on the Budderoo plateau which they attribute to varying responses to rainfall intensity and duration, the degree of saturation prior to the rainfall event, and the importance of contributions from the marginal swamp deposits. While useful in understanding the hydrological responses at the studied swamp, the response types do not appear to generalize to all swamps in the project area.

Stable isotope (2H / 18O) and radon analyses presented by Cowley (2016) indicate that swamps located in the Southern Highlands and the Blue Mountains contain groundwater with some contribution from adjacent groundwater systems. However, this is not generally supported for swamps in Areas 5 and 6, where the regional groundwater table is typically approx. 10 m below the swamp water level, indicating that baseflow from the surrounding regional groundwater system to the swamp is not occurring (HEC, 2019).

Mining responses

Swamps that have been undermined commonly display hydrological changes shortly following the passage of the longwall beneath the monitoring site. Hydrographs of piezometers at affected locations may show one or more of the following features:

- a decrease in the average shallow groundwater elevation;
- a decrease in the duration of saturation of the swamp sediments following a significant rainfall event; or
- a change in the shape of saturation peak and recession curves in response to significant rainfall events.

An example of a hydrograph from a piezometer that has not been mined under (Swamp 01b piezometer 01 – **Figure 4-14A**), compared to that of Swamp 05 piezometer 03 (**Figure 4-14B**), which has been directly mined under.

The most recent assessment of the effects of mining at Dendrobium under and near to swamps is in HGEO (2018a) and Watershed HydroGeo (2019). That analysis is summarised in **Table 4-3**.

This indicates that almost all piezometers mined under by Dendrobium Area 3A and 3B record a decline in shallow groundwater levels, increase in recession rate, and/or a decrease in wetting frequency. Additionally, swamps beyond the edge of longwalls were also affected. Observations at Area 3A and 3B indicate that shallow groundwater levels in Upland Swamps have been affected up to approximately 60 m from the extracted longwall footprint, with groundwater levels in other (non-swamp) piezometers affected at up to 125 m from a panel (Watershed HydroGeo, 2019). IEPMC (2018) noted that at other mines, i.e. Springvale, movement of or transmission of effects along geological structures had resulted in swamps being affected at much greater distances (e.g. over 700 m), however this has not been the case around the historically mined areas at Dendrobium.

Table 4-3 Number of swamp piezometers showing a mining effect

Swamp	Mine Area	No. of piezometers affected by mining	Comment (HGEO, 2018a)
01a	Area 3B	7 of 8	There is limited baseline (pre-mining) data for some piezos.
01b	Area 3B	2-4 of 6	There is limited baseline (pre-mining) data for some piezos.
03	Area 3B	1 of 1	Possible increase in recession rate and reduced response to rainfall after LW11 passed and LW12 undermined.
05	Area 3B	5 of 6	
08	Area 3B	2 of 3	Piezometers are outside mapped swamp boundary
10	Area 3B	1 or 1	Mined under by LW12
11	Area 3B	1 or 3	Partially mined under by LW13
12	Area 3A	3 of 3	
13	Area 3B	0 or 1	Low water levels in 2017-2018 likely related to very dry conditions; no significant change in recession rate.
14	Area 3B	0 or 2	Yet to be mined under; no change in characteristics
15a	Area 3A	0 of 1	There is limited baseline (pre-mining) data at this swamp
15b	Area 3A	12 of 13	
23	Area 3B	0 of 2	Yet to be mined under
35a	Area 3B	0 of 1	Yet to be mined under
35b	Area 3B	0 of 1	Yet to be mined under

The hydrological changes are most likely due to the development of surface fracturing and bedding plane openings in the sandstone substrate of the swamp. The surface fracturing has two main hydrogeological implications:

- it forms fracture networks that allow drainage of the swamp and re-direction of the stored waters to down-gradient locations; and
- increases the fracture storage in the sandstone substrate.

In essence, the formation of fractures in the substrate may change the swamp from a perched system that is poorly connected with the sandstone groundwater, to a connected system where water can migrate from the swamp to the sandstone at shallow depth (10 to 20 m, possibly more) and flow horizontally to emerge downstream. The upper part of the sandstone groundwater system is itself likely to be perched above the regional sandstone water table. The impact on the swamp would be dependent on the head difference between the swamp sediments and the sandstone substrate. Where the hydraulic gradient is downwards (into the sandstone, which is common) then the fracturing will lead to greater flows of water from the swamp and a decline in average swamp groundwater levels. It is not yet known whether this outflow would decrease as fractures are filled with fine sediments. On-going monitoring will allow assessment of longer-term behaviour of the swamp and shallow sandstone interaction.

4.4 INFLOW TO MINES

4.4.1 DENDROBIUM

Groundwater inflow to mine workings cannot be directly measured but is determined through a detailed mine water balance. The accounting of water via pumping stations is monitored and controlled in real-time through the System Control and Data Acquisition (SCADA) system and used to calculate a daily Mine Water Balance. The water balance measures all water that enters, circulates and leaves the mine, including via air moisture and coal moisture, and groundwater inflow is determined by mass balance for each goaf area. Key metrics of the water balance are reported against Trigger Action Response Plan (TARP) levels to the DSC.

Estimates of groundwater inflow to each mine area are plotted in **Figure 4-15** alongside longwall timings and rainfall trends (residual mass). Modelled recharge has been added to the charts in response to IEPMC (2018 - Section 4.2.2 of that report) who stated there was a "*need to consider the runoff-infiltration component in a cumulative way*". The modelled recharge series shows that we do consider the infiltration component as a function of accumulated rainfall versus antecedent soil moisture, as described in Section 4.6.3.

The average Water Balance (groundwater inflow) for each area for the previous 12 months are shown in **Table 4-4** with a summary of any trends or correlations. The pattern of inflow has also been the subject of analysis and review by Mackie (2016), HS (2016a,d), HGEO (2018c), and IEPMC (2018). Key points from those authors are included here.

Table 4-4 Mine Water Balance (Feb 2018-Feb 2019)

AREA	AVERAGE INFLOW	COMMENTS ON APPARENT TRENDS IN INFLOW
1	328 m^3/d *	After two significant peaks correlating to rainfall events in 2007-2008, inflow has been relatively consistent, typically fluctuating between ~200 and ~800 m^3/d. Since those early peaks there has been a weak correlation with residual rainfall trends (also identified by Ziegler and Middleton, 2011), with broad inflow peaks delayed by several months. This mild correlation appears to continue into 2016, other than an unexplained peak (up to 1900 m^3/d) in September 2016. **The Area 1 flow meter failed in Sept-2016. Due to the low rate of inflow in this area, average inflow (328 m^3/d) is reported after that date*.
2	330 m^3/d	Highly variable inflow, with peaks of between 4000-9000 m^3/d that are strongly correlated with large recharge events. The largest inflow peaks in recent times were 6400 m^3/d (2014), 4600 m^3/d (2015) and 4500 m^3/d (2017). Baseline inflow is between ~200 and 1000 m^3/d, but has declined in the past 18 months. Peak inflow is delayed by 8 to 10 days after heavy rainfall events.
3A	950 m^3/d	Inflow increased linearly with area mined during active mining (2010 to 2012). This hydrograph appeared to be more correlated to rainfall, including to individual events, during mining, i.e. Longwalls 6-8 and the first 'half' of Longwall 9. From mid-2012 inflows have fluctuated between ~1000 and ~4000 m^3/d, with average inflows correlated with residual rainfall trends. Since 2013 (when mining moved to Area 3B) 'baseline' inflow has reduced from about 3000 to approx. 1500 m^3/d or lower, likely correlated with recent dry conditions. An inflow spike in mid-2018 is not correlated with rainfall. The weakened correlation of inflow to rainfall from about August 2013 may have more to do with the onset of mining in Area 3B than the cessation of mining in Area 3A.
3B	4,380 m^3/d	Area 3B is located across the axis of a syncline, and water naturally drains toward the Area 3B sump at TG9 (Longwall 9). IEPMC (2018) report that the correlation to rainfall is 'moderate' and we generally agree with this, at least from Longwall 12. HGEO (2018c) noted: *Groundwater ingress to Area 3B has increased steadily since the start of mining (2013), and correlates approximately with the total area mined. However, the overall rate of increase appears to have slowed during the mining of Longwalls 12 and 13, representing a possible departure from the area-inflow relationship, as was seen at Area 3A after Longwall 7.* *As of Longwall 12 there is an apparent correlation between periods of high inflow to Area 3B and periods of high rainfall with a lag time of between two and three months. Peak inflow rates to Area 3B following high rainfall events is one to two ML/d higher than during low rainfall periods. The inflow peak that followed the* [sustained recharge period] *of early 2017 accounts for approximately 20% of the total inflow for the 2017 year. The peak component in 2016 was approximately 12%.*

Correlation to rainfall trends in Area 3B are possible due to review of hydrograph behaviour. But these are not considered completely definitive when considering the use of chemical methods to assess the relationship to rainfall (**Section 4.5.3 and 4.5.4**).

Since the commencement of Longwall 9 in Area 3B the total groundwater inflow to the Dendrobium Mine has varied between about 4,000-12,000 m^3/d (i.e. 4-12 ML/d) (average 6.8 ML/d). In the 12 months November 2017-18 it has totalled 2270 ML, equivalent to an average of 6.2 ML/d. The highest water-year total was 3040 ML in 2016-17.

Analysis of the water captured in the mine workings is presented in **Sections 4.5.3 and 4.5.4**. Discussion with site staff at Dendrobium indicates that upward flow through the floor of the underground mine is a significant source of groundwater entering the workings. While this is expected due to the pressure difference between groundwater in underlying strata and the zero pressure in the workings, this component of flow needs to be recognised. A recommendation regarding the possibility of characterisation (i.e. “finger-printing”) of this water analysis is included in **Section 11.2.1**.

4.4.2 NEIGHBOURING MINES

Table 4-5 presents a summary of the available historical inflow data for nearby Southern Coalfield mines. Some of this information has been sourced from Geoterra (2015), Coffey (2012a) and Annual Environmental Monitoring Reports (AEMR) for Tahmoor.

Table 4-5 Summary of Inflows to neighbouring mines

MINE	AVAILABLE RECORD	INFLOW [ML/d]		
		Minimum	Mean	Maximum
Tahmoor	1995-2002, 2009-2015	--	2.5	4.2
Appin & Tower	2007-2009	0.06	1.85	2.8
	2016-17	0.9	1.2	1.75 *
Cordeaux	1992-2002	--	1.2	--
Bellambi / NRE No1 / Russell Vale	2005-2009	0.05	0.4	0.7
	2010-2015	0.15	0.8	1.45

* Likely an over-estimate due to ‘make up’ pumping in Jul-Sep 2016 to remove additional stored water.

The inflow at other mines has typically been lower than Dendrobium’s inflow. This is conceptualised as being related to several factors:

- Dendrobium Mine extends for a distance of about 10 km in the east to west direction, cutting across groundwater flow paths;
- Longwalls at Dendrobium are consistently wider than elsewhere; and
- Panel widths (W) are also consistently larger compared to depth of cover (D), i.e. a lower ratio of D/W, at Dendrobium than at other mines.

4.5 WATER QUALITY

The quality and chemical characteristics of surface and groundwater in the general vicinity of Areas 5 and 6 is well understood from numerous water samples collected since 2004. Samples are collected from the mine, groundwater bores, streams and swamps in the Dendrobium Mine area. Further characterisation would be possible once additional bore pumps are installed (**Section 4.2.2**). Surface water sampling is being carried out in Areas 5 and 6. Groundwater and surface water monitoring in the Project area needs to meet the objectives set out in **Section 10**.

More than 3,280 water samples have been collected and analysed at Dendrobium Mine since 2004, providing an extensive database with which to assess mine water chemistry against baseline surface and groundwater chemistry. The database currently includes 1,008 analyses of Tritium providing an indication of the presence of modern water (<70 years) in any given sample. This is particularly useful for detecting recent recharge and components of modern water in groundwater entering the mine.

A comparison of the water quality parameters from surface water, groundwater and mine seepage (deep groundwater), in terms of EC, is shown in **Figure 4-16** and the major ion composition of all samples is represented in a Piper plot in **Figure 4-17**. **Section 4.5.1** (surface waters) and **Section 4.5.2** (groundwater) describe the overall water characteristics.

4.5.1 SURFACE WATER QUALITY

Surface water samples are collected from several stream locations and from the Avon and Cordeaux reservoirs. Surface water is characteristically fresh (typically less than 100 µS/cm or 60 mg/L TDS), with a median pH of 5.7 (tends to be mildly acidic), reflecting their derivation from rainfall runoff. The major ion composition is dominated by Na^+ and Cl^- with minor Mg^{2+} and HCO_3^-. Iron and manganese concentrations are low (median Fe 0.12 mg/L; median Mn 0.04 mg/L). Watercourses that have been affected by subsidence (e.g. WC21 during mining of Longwalls 10 and 11) have shown temporary increases in dissolved Fe and Mn, and an increase in pH to near neutral (pH 7) at sampling locations immediately down-gradient of the affected area. These changes are evident as localised iron staining in creek beds.

4.5.2 GROUNDWATER QUALITY

Groundwater quality is highly variable depending on the geological unit and sampling depth. In general, the salinity of groundwater increases with stratigraphic age, reflecting the longer groundwater residence times in the deeper units. The Hawkesbury Sandstone hosts water that is generally fresh (EC < 1000 µS/cm; **Figure 4-16**), with a mixed major ion composition. The relatively fresh nature of groundwater in Hawkesbury Sandstone is indicative of relatively recent rainfall recharge via fracture networks in the weathered zone. Groundwater in progressively deeper stratigraphic units (Bulgo Sandstone, Scarborough Sandstone), become both more saline (**Figure 4-16**) and dominated by Na^+ and HCO_3^- ions. There is a corresponding increase in the concentration of minor and trace ions.

The range of EC shown on **Figure 4-16** indicates that groundwater in this area, and throughout the sequence, typically has salinity less than 2,500 µS/cm (= 1,500 mg/L), which is one of the AI Policy criteria for 'Highly Productive' groundwater.

Deep groundwater samples are collected from development roadway roof seepages, mining faces and designated sampling points from the goaf during mining. Roof seepage samples are considered representative of the Wongawilli seam and adjacent shales. Deep groundwater in the Wongawilli seam is geochemically dominated by Na^+ and HCO_3^- ions, across the three existing mine areas, and spatial variation in salinity (electrical conductivity) can primarily be related to changes in the concentrations of these two major ions. Spatial variations are evident; the highest salinities are in Area 1 and the western end of Area 3B.

Within Area 3B, the salinity of roof drippers increases from east to west (i.e. fresher near the Wonga Mains).

At Dendrobium, there are no major pyrite deposits, and pH conditions are near-neutral to alkaline, hence hydrogeochemistry is dominated by species mobilised during natural silicate weathering and carbonate dissolution processes (e.g. Si, Na, Ca, Mg, Fe and minor ions Ba, Sr, Li).

4.5.3 WATER SOURCE DISCRIMINATION

Background and operational water quality monitoring carried out at Dendrobium to date has shown a number of dissolved constituents that are useful in discriminating that is “finger-printing” waters derived from different sources. The most useful indicators are found to be:

- **Tritium** (indicating the average time elapsed since the water fell as rain).
- **Electrical Conductivity** (EC, an indicator of salinity or total dissolved salts).
- **Na/Cl ratio** (an indicator of sodium enrichment as a function of aquifer processes).
- **Si** (dissolved silica derived from weathering of silicate minerals).
- **Li, Ba, Sr** (minor or trace ions liberated during silicate weathering or carbonate dissolution).

Of these, tritium, EC and Na/Cl are identified as the most useful indicators for routine monitoring and reporting. In addition, the Li/Cl ratios allow discrimination of some deep groundwater sources. Tritium specifically identifies waters derived from rain within the last ~50 to 70 years (or mixing with a young source). Illawarra Coal is currently investigating other isotopic tracers such as ^{14}C, ^{36}Cl, $^{7}Li/^{6}Li$ and $^{87}Sr/^{86}Sr$ to better understand mine inflow pathways and water-rock interactions.

A plot of EC versus Li/Cl is shown in **Figure 4-18** as an example of water source discrimination using water chemistry. The plot distinguishes water types (including groundwater types) on the basis of salinity and lithium (normalised to Cl) which is a sensitive indicator of deep groundwater. It is apparent that deeper groundwaters have distinctly different characteristics in terms of dissolved metal ions. The deeper groundwater (e.g. mine seepage) is characteristically higher in minor ions such as Li, Ba and Sr compared to surface water and shallow groundwater (when normalised to chloride). These characteristics reflect long residence times and equilibrium established with the host aquifer minerals. Furthermore, different mine areas can be distinguished using water fingerprinting. Mine seepage and goaf drainage from Areas 3A and 3B have distinctly higher Li/Cl ratios than seepage and goaf water from Areas 1 and 2.

4.5.4 POTENTIAL FOR MODERN WATER IN MINE INFLOW

Potential sources of modern water ingress to the mine include modern water within strata and from surface waters and nearby reservoirs where there is a hydraulic connection to the goaf. The likelihood of modern water, i.e. surface water, contributions to mine inflow have been assessed using the mine water balance together with measurements of tritium in mine seepage samples.

Tritium is used as the key indicator for binary mixing models. Tritium (^{3}H) is a short-lived isotope of hydrogen with a half-life of 12.43 years. It is constantly replenished in the atmosphere through cosmic radiation and is directly incorporated into the water molecule ($^{1}H^{3}HO$ or ^{1}HTO) and so is the only radioisotope that directly dates groundwater (rather than a dissolved constituent). Tritium levels elevated above background specifically identify waters derived from rain within the last ~50 to 70 years (or mixing with a young source).

Assuming that the component of surface water inflow to the mine is rapid in comparison to the tritium half-life and that there is negligible tritium loss via diffusion along the fracture network pathway, the minimum proportion of modern water can be assessed by assuming a binary mixing relationship:

$$f_{mw} = (T_x - T_{gw})/(T_{sw} - T_{gw})$$

where f_{mw} is the fraction of modern water in the sample, T_x is the tritium concentration in the sample, T_{gw} is the tritium concentration in groundwater and T_{sw} is the tritium concentration in surface water.

The most recent 12 analyses were used so that the estimate of % modern water reflects the most recently measured inflow to the mine, rather than representing a long-term average. In order to express the uncertainty in the estimate of modern water the analysis was carried out using a statistical resampling technique whereby 10,000 calculations were carried out for each mine area based on random combinations of modern surface water and deep groundwater end-members (**Table 4-6**).

Table 4-6 Summary of modern surface water and groundwater end-members used

Tritium		Deep groundwater (Scarborough Sandstone)	Surface water (all samples from streams and reservoirs)
Count of samples (n)		70	242
Tritium (TU)	Mean	0.08	1.73
	Standard Deviation	0.06	0.48
	10th percentile	0.01	1.33
	50th percentile (median)	0.08	1.63
	90th percentile	0.14	2.32

The resulting probability distributions are shown in **Figure 4-19**. Binary mixing calculations indicate that the total percentage of modern water entering Area 1 is in the order of 10%, in Area 2 is 26% and Area 3A 11% (**Table 4-7**), and <1% in Area 3B goaf. Although the confidence intervals are large, the analysis indicates that the fraction of modern water is significantly greater than zero in goaf samples from Areas 1, 2 and 3A, but is not significantly greater than zero in goaf water from Area 3B. In assessing the modern water content of mine inflow using tritium it is important to consider the following factors:

1. town supply water (modern surface water) is used in some parts of the mine, and some goaf water is recycled through the Nebo mine storage for water supply to the mining areas. Therefore, elevated tritium in mine goaf waters may, in part, be derived from those sources.
2. tritium may be retarded in groundwater through diffusion towards stagnant zones (with 'old' groundwater) as it percolates through a fracture system. Although current literature suggests that this effect is very small (ANSTO, 2018), it would be prudent to consider the measured tritium concentrations in groundwater as an underestimate.
3. Groundwater can comprise mixtures of waters of different ages (or a continuum of ages). Using a single tracer such as tritium in binary mixing models may under-represent other water components in the sample such that the derived modern water component should be considered a minimum.

Applying the 50th and 90th percentile minimum modern water contents, the minimum flow-weighted mean for all mine inflows is in the range of 4% to 11 % (**Table 4-7**). As a comparison, the surface water component was calculated using a hydrograph base-flow separation technique. For that approach it is assumed that mine inflow peaks (which are variably correlated in Areas 2, 3A and 3B) represent additional mine inflow that is induced by heavy rainfall events, surface flooding and associated groundwater level changes. The hydrograph separation technique, when applied to mine inflows for the last three years (2016-2018) yields slightly higher estimates of surface water input with a weighted average for all mine areas of 18%. The percentages in **Table 4-7** do not support the separate estimates reported in IEPMC (2018), made via hydrograph separation, from HGEO (2017c) and Mackie (2017), which were that up to 78% or even 90% of inflow to Area 2 could be due to direct rainfall/surface water ingress.

Table 4-7 Estimated % Modern Water entering Dendrobium Mine

MINE AREA	AVERAGE DAILY BALANCE (m^3/day) in 2018	Tritium in groundwater		Water Balance hydrograph separation	
		% MODERN WATER 50TH %ILE	% MODERN WATER 90TH %ILE	RAINFALL PEAK COMPONENT (%)	FLOW (m^3/day)
Area 1	330	10.3	17.4	24	127
Area 2	350	25.6	33.9	44 to 78	331
Area 3A	990	10.9	27.2	22	306
Area 3B	4,460	0.5	4.8	12	572
Flow-weighted mean		**4 %**	**11 %**	**18-22%**	**1336**

% modern water based on binary mixing and assumed conservative behaviour of tritium in groundwater.

Analysis of tritium (TU) and EC measured in the underground mine, groundwater inflow and rainfall is provided in **Appendix D**. Note that 'BG tritium' is background tritium, defined by the approximate upper limit of tritium concentration in samples from the Scarborough Sandstone which is assumed to contain no modern water (but may contain trace amounts of geogenic tritium).

Despite apparent correlations between inflow and large rainfall events and the detection of tritium above background levels in mine inflow, there is apparently little correlation between tritium content and 30-day rainfall (**Chart D1)** or between tritium and mine inflow rate (**Chart D2)**. There is an apparent correlation between tritium content and mine seepage water samples from Area 2, but there is no correlation for goaf water samples. Tritium measured in Area 2 is higher, 0.5 TU compared to 0.1 TU, than in Area 3B (**Chart D3**).

Chart D4 shows EC through time against inflow to each area. There are no significant trends in the EC hydrograph in any area. After mining in Area 1 (Longwalls 1-2) and in Area 2 (Longwalls 3-5), EC is relatively consistent through time in all four areas, including during recent/current extraction of Longwalls 9 to 14 of Area 3B.

These charts support the analysis of **Figure 4-19** and **Table 4-7** above.

4.6 GROUNDWATER PROCESSES

The following sections describe and provide some quantification of the key groundwater recharge and discharge processes (noting that discharge to mines is discussed in **Section 4.4**).

4.6.1 REGIONAL GROUNDWATER FLOW

Based on the contouring of groundwater levels, the groundwater flow is predominantly in a northerly direction, similar to stratigraphic dip, toward the centre of the Sydney Basin. However, some groundwater close to the Illawarra Escarpment flows east to become spring flow or be evapo-transpired along the escarpment or flowing to the sea.

The water level contours developed for the lower Hawkesbury Sandstone (**Figure 4-10**) do not have the required detail in the observed water level dataset to indicate the expected "sinks" zones at conceptualised springs that would occur along the escarpment to the east of Dendrobium. However, the contour map does clearly show that the regional groundwater flow around Dendrobium is northerly, converging on the Nepean River between the Tahmoor and Appin mine areas. Groundwater flow in deeper units (**Figure 4-11**, **Figure 4-12**) is also in a northerly direction based on available bore data .The only significant change to this direction is caused by the localised mines (e.g. at Dendrobium, Tahmoor, Appin [BSO]). It should be noted most data is concentrated around Dendrobium, Tahmoor, Appin mines.

4.6.2 STREAM BASEFLOW

HS has analysed surface stream flow and electrical conductivity (or chloride) data from some of the gauging stations around Dendrobium and applied the following two methods to calculate baseflow near Dendrobium Mine:

- digital filters (also referred as to as analytical methods), such as the HYSEP method (Sloto and Crouse, 1996), which use local minima and 'turning point' concepts; and
- a chloride (or electrical conductivity [EC]) mass balance method, which uses baseflow estimates of river salinity (chloride or EC) data; an estimate of groundwater salinity', and a record of river flows, and combines these in a mass balance approach.

All baseflow separation techniques have strengths and weaknesses. A good summary is presented in SKM and CSIRO (2012), who state "*Chemical hydrograph separation is probably the most suitable method for estimating mean annual groundwater discharge rates, although uncertainty in end-member concentrations can produce significant uncertainties in estimated groundwater inflow rates".* Thus, while the specification of the end-member chloride or EC can be uncertain, as discussed in Cartwright *et al.* (2014) and based on HS' experience elsewhere in comparing such methods, the EC-constrained estimates are typically more reliable, and usually lower than estimates produced using digital filters.

Cartwright *et al*. (2014) state: "...*geochemical and analytical methods of estimating baseflow yield contrasting results. While all the techniques used are subject to uncertainty, the systematic nature of the differences (especially the observation that the difference between the analytical techniques and chemical mass balance is greatest during winter high-flow periods) implies that the uncertainties in the techniques alone do not explain the contrasting results. We conclude that the contrasting results reflect how the different methods characterise the water sources to rivers. The analytical methods probably aggregate all delayed water sources as baseflow components. Many of these delayed water sources (such as bank flow, interflow, or floodplain storage) will have a geochemistry that is similar to that of surface runoff, and geochemical mass balance techniques aggregate them with the surface runoff...".* While there is uncertainty associated with the choice of end-member chemistry, the choice of a chemically-constrained method at least allows some attempt to identify water sourced from regional groundwater as opposed to that entering a stream from bank storage.

Cartwright *et al*. (2014) concluded with "...*the use of analytical methods alone may result in overestimation of regional groundwater inputs to rivers if a significant part of the base-flow component is from transient water stores such as bank return flow or draining of surface pools on the floodplain*". This is in agreement with HS' experience in comparing the results of digital filters and chemically constrained methods.

Baseflow separation analysis carried out at Dendrobium is summarised in **Table 4-8**. Geological abbreviations are listed in **Table 3-1**.

Table 4-8 Baseflow Separation at Dendrobium

Watercourse	Baseflow Index (BFI)			Input parameters for chemically-constrained	
	Best estimate	Method: Digital filter	Method: Chemically constrained	Groundwater End-member (mg/L)	Choice of groundwater end-member
Wongawilli Creek	10-16 %	30-40 %	10 %	52	Max HBSS Chloride
			15 %	38	Median HBSS Chloride
			16 %	36	Max watercourse Chloride
			38 %	22	Min HBSS Chloride
Donalds Castle Creek	1-6 %	25-30 %	0.1 %	6900	Max HBSS EC
			1 %	634	Mean HBSS EC
			4 %	200	Median HBSS EC
			6 %	170	Max watercourse EC
			27 %	82	Min HBSS EC
Sandy Creek	8-20 %	50-60 %	1 %	6900	Max HBSS EC
			8 %	858	Mean HBSS & BGSS EC
			11 %	634	Mean HBSS EC
			20 %	360	Max watercourse EC
			37 %	200	Median HBSS EC
			98 %	82	Min HBSS EC

At Dendrobium, the correlation between chloride (mg/L) or EC (µS/cm) and flow (ML/d) is only moderate for Wongawilli Creek, but better for Sandy and Donalds Castle Creeks.

Table 4-8 shows the range of input end-members (i.e. chemistry of the assumed 100% groundwater end-member), which are based on statistics derived from Dendrobium's groundwater chemistry database. The Sandy Creek catchment incorporates an area of outcropping Bulgo Sandstone, so Hawkesbury Sandstone and Bulgo Sandstone chemistry have been used in the assumed end-member. The different end-members are shown to be sensitive input parameters, resulting in a range of possible BFI.

It is clear from **Table 4-8** that the BFI generated by digital methods are considerably higher than those using a chemical constraint, and are roughly equivalent to the BFI produced by using an extreme end-member (e.g. minimum Hawkesbury Sandstone chloride or EC).

The BFI estimates produced here are a good match to the estimates of BFI by Coffey (2012a), and also compare well with similar EC-constrained analysis done by HS for watercourses near Tahmoor: Hornes Creek (BFI = 4-15%) and Bargo River (6-20%).

The BFIs estimated here have been converted to yield (mm/yr) and % long-term average (LTA) rainfall and summarised in **Table 4-9**. These are similar to those in Coffey (2012a).

Table 4-9 Summary of calculated BFI and Baseflow Yield

Watercourse	BFI	Baseflow yield [mm/yr]	%LTA rainfall
Wongawilli Creek	10-16 %	31 to 50	2.5 to 4.2%
Donalds Castle Creek	1-6 %	1.5 to 10	0.1 to 1%
Sandy Creek	8-20 %	22 to 55	1.8 to 4.6%

X:\HYDROSIM\DENDROBIUM\Tech\SurfaceWater\Baseflow\Summary.xlsx

The lower BFI and baseflow yield in Donalds Castle Creek is consistent with the lower overall flow and catchment yield identified in **Section 2.4.2**, and is conceptualised as being due to the generally more elevated, less-incised nature of this creek compared to Wongawilli Creek.

This analysis suggests that baseflows in the Dendrobium area are equivalent to about 2-60 mm/yr (with a mean of about 20-50 mm/yr), or approximately 1-4% of long-term average rainfall.

The higher porosity of swamp deposits (**Section 4.7.5**) means that these features are considered to supply reliable baseflow to watercourses for an extended period after rainfall. NSW Minerals Council (2015) asserts that "*not all upland swamps provide the contribution to base flow, as is commonly assumed*". Analysis of two similarly size gauged catchments at Dendrobium, SCU and WC15 (**Figure 2-5**) suggests that WC15 has more consistent recession flows than does SCU, which may be a result of Swamp 14 covering about 5% of the WC15 catchment, while SCU has no mapped swamp deposits in its catchment.

However, subsequent analysis of water levels from Swamp 14 is not definitive. A calculation of swamp area and water level decline indicates that this swamp could contribute as much as about 20% of the daily flow in WC15 during a recession period, but when evapotranspiration is taken into account as a cause of water level decline in the swamp, this could be significantly lower, with the potential contribution by the swamp to flows in WC15 being anywhere from 0-20%.

It seems likely that swamps do contribute some baseflow to downstream watercourses; however, the significance of that baseflow would be dependent on swamp-specific factors (sediment type, position in the catchment), catchment-specific factors (topography, slope, geology, rainfall). Also, the thickness of swamp deposits also limits the volume of water that can be stored in them, despite their higher porosity. HS understand that detailed water balance studies on Upland Swamps in this area are in progress by UNSW/WRL.

4.6.3 RAINFALL RECHARGE

Table 4-10 presents a summary of several studies and their estimates of recharge to the outcropping hard-rock units of the Southern Coalfield. These estimates were made by different authors for studies for Illawarra Coal (HS, Coffey), and a variety of independent estimates. These estimates are usually expressed in one of two different ways; as a % of long-term average rainfall or as mm/yr. In light of comments in Advisian (2016), the method of analysis has been noted in the table where it is available.

Table 4-10 shows that HS' previous recharge estimates compared favourably to those of Crosbie (2015), DPI (2011), Pells and Pells (2013), EMM (2015) and the higher estimate of Coffey (2012a), which was based on analysis of water table fluctuation.

Table 4-10 Summary of Recharge Estimates

REFERENCE	ANALYSIS METHOD	RECHARGE	
		% LTA rain	mm/yr
URS, 2007	water table fluctuation ("WTF")	3-10%*	n/a
DPI, 2011	unknown	6%	n/a
Coffey, 2012a,b	Baseflow separation, WTF	2.7 or 6%	n/a
Pells, 2013	unknown	5%	50
Crosbie, 2015	Chloride mass balance in shallow groundwater.	3-8.5%	40-100
HS, 2016b	Chloride mass balance baseflow separation, WTF	6.5%	65
EMM, 2015	Sydney Basin-wide estimate, based on review of Crosbie, modelling assessments. Table 5.1 indicates 1% to Permian, 5% to HBSS/Narrabeen Group, <5% Wianamatta Group.	5 % Triassic 1 % Permian	
BoM, 2016	AWRA-L model (2005-2018)	6.9%	83

LTA: Long-term Average. BFI : Baseflow Index. * URS stated that local variation might be 2-16%, but "realistic range" is 3-10%.
AWRA-L model results for (~5x5 km) model cell at Lat -34.39, Long 150.71

HS' estimates mentioned in **Table 4-10** are from a 'water balance model' constructed by HS. It is a time-series (daily) water balance model of the Wongawilli Creek catchment, including inputs of rainfall, potential evaporation, simulating runoff, interflow, recharge, and producing estimates of evapo-transpiration from the soil zone, evapotranspiration from shallow groundwater, and baseflow, and calibrated against measured river flow (baseflow + Interflow + runoff) in Wongawilli Creek and in Donalds Castle Creek. Matching of hydrographs in these two catchments suggests that Wongawilli Creek receives more baseflow than Donalds Castle Creek – this is likely to be primarily due to the lower elevation of Wongawailli Creek compared to Donalds Castle Creek. It could also be due to slightly lower recharge to the Donalds Castle Creek catchment, although a reason for that to occur is not obvious or apparent.

This provides checks on the average recharge, as well as estimation of the historical sequence of rainfall recharge to the outcropping Hawkesbury Sandstone in this catchment. The advantage of this water balance method over methods employing a constant recharge as a percentage of rainfall the relation between wet and dry periods are better (i.e. it captures 'elasticity' of rainfall-recharge relationship' as described in Barron *et al.*, 2012), due to the simulation of a soil moisture deficit.

Swamp recharge

These features are composed of unconsolidated sands, silts, clays, organic matter (**Section 3.5**). As such they behave as "sponges" during drier spells, and also accept more infiltration during rainfall periods. It is difficult to isolate recharge from direct rainfall and infiltrating run-on from upslope areas. As a result, it is estimated or assumed that the swamps would accept more rainfall than the hard-rock outcrop areas (based on HS' experience in landscapes where unconsolidated sand deposits occur at surface), and so have a higher average applied recharge of 25-30% of rainfall.

4.6.4 EVAPOTRANSPIRATION

Evapotranspiration by vegetation is controlled by rooting depth. A review of a number of literature sources, including Canadell *et al.* (1996), Florabank[10], Lamontagne *et al.* (2005), Allen *et al.* (2006) and Zolfaghar (2013) was carried out.

A compilation of reported maximum rooting depth of sclerophyllous shrubland and forest (Canadell *et al.*, 1996) indicates an average for such species is 5.2 m (±0.8 m). Rooting depth is also likely controlled by the geomorphology and depth of soil deposits.

[10] http://www.florabank.org.au/

Based on recent research carried out in the southern part of the Sydney Basin, 9 m has been adopted as the likely depth to which water is accessed by the potentially deeper-rooted sclerophyllous trees (based on Zolfaghar, 2013), i.e. this will be used as the initial estimate in subsequent groundwater modelling but may be modified during model calibration.

The rooting depth of the swamp deposits is likely controlled by the geomorphology of these deposits. The unconsolidated peat and sand deposits are typically 1-2 m thick above the underlying rock stratum. The rooting depth of the swamp vegetation is very likely to be the same or less than the thickness of the unconsolidated deposits, therefore probably in the range 0.5-2.0 m.

A review of data in Allen *et al.* (2006) provides information on the likely maximum rooting depths of grasses and agricultural crops. Grasses are the dominant vegetation type in the cleared/grassland areas to the north, west and east of the study area and along the coastal plain. The mean of these reported maximum rooting depth of the grasses in Allen *et al.* (2006) is 1.2 m (range 0.9 to 1.5 m).

4.6.5 GROUNDWATER USE

Figure 3-2 shows the groundwater bores registered on DoI Water's Pinneena database. There are about 900 registered groundwater bores within the study area (**Figure 1-1**), and 650 within the boundary of the groundwater model (**Section 6**), although these are almost all located some distance from Dendrobium Mine. There is essentially no groundwater bore use near to (i.e. within about 4-5 km) Dendrobium Mine due to the lack of population and the areas being reserved as drinking water catchment (i.e. "Special Areas" - **Figure 1-1**).

Based on a review of Water Access Licence (WAL) information on the NSW Water Register, over 700 bores within the study area returned matches with the WAL register, of which a subset of 309 are considered to be 'water supply works' as per the AIP. Based on this search, there is a licensed groundwater entitlement of 3,272 ML/yr for private or small-scale government use. There is some additional 981,000 ML/yr associated with unregulated river licences held by government agencies, although these licences are also associated with licensed groundwater works. Additionally, there is approximately 1,000 ML/yr of unlicensed groundwater use for stock and domestic purposes, which is based on the assumption that use for these purposes is 1-2 ML/yr.

Almost 90% of the groundwater (bore) usage in the area to the west, north and south of Dendrobium Mine is from the Hawkesbury Sandstone or from surficial alluvium and basalt aquifers well to the west and south of Dendrobium. About 10% of the total entitlement is from the Bulgo Sandstone. This is probably due to generally lower bore yields, poorer water quality, and increased drilling costs for accessing deeper units.

The NSW Water Register sometimes provides estimates of actual groundwater use for Water Sources. For the Nepean Sandstone Groundwater Source, the reported usage is:

- Zero for all water years from 2004-05 to 2016-17, and
- non-zero only in the most recent 'water years' 2017-18 and 2018-19.
- The records of usage are considered unlikely to be accurate.

Along the coastal plain to the east of Dendrobium, most of the bores extract from the outcropping early Permian strata, i.e. the Cumberland Subgroup (i.e. the 'lower' Coal Measures) and the older Shoalhaven Group.

4.7 HYDRAULIC PROPERTIES

This section outlines pre-mining or 'host' hydraulic properties, while **Section 4.8** discusses predictions and measurements of post-mining hydraulic properties.

As described in **Sections 3.1 and 4.1**, the Triassic and Permian rock strata around Dendrobium and of the Sydney Basin in general show significant lithological variation. The Hawkesbury Sandstone, for example, shows many clay-rich horizons within a dominantly sandstone matrix (**Figure 4-1**). As a result of the lithological variation, as well as the variable presence of weathering and secondary porosity (e.g. naturally occurring joints and bedding planes) the hydraulic properties, namely hydraulic conductivity and porosity or storage, can show significant variability, as discussed in the following sections.

The database of hydraulic properties, most of it from packer testing, discussed here is a sound basis for modelling. The modelled properties are discussed in **Section 7.2**.

4.7.1 HYDRAULIC CONDUCTIVITY (K)

In order to determine the influence of mining, characterisation of both the horizontal (Kh) and vertical hydraulic conductivity (Kv) is required. Packer testing is most commonly used to measure *in situ* Kh, accounting for the permeability due to both matrix (primary) and secondary porosity. Laboratory analysis of core samples is used to assess and estimate Kv.

Figure 4-2 illustrates the range in pre-mining Kh measured by packer testing at Dendrobium, overlain with the data from Tahmoor. This shows that Kh is typically greater at shallower depths, which is expected due to the greater prevalence of open joints, bedding planes and degree of weathering in the near surface. In the deeper subsurface it is joints and bedding planes are more likely closed due to the overburden pressure, as noted in AGC (1984) and subsequently outlined by various authors.

This figure also classifies each packer test interval by stratigraphy (see **Table 3-1** for abbreviations). Comparison of Kh within stratigraphy units compared to Kh with depth suggests that depth is the primary modifying factor or control on the magnitude of Kh, while lithology is a secondary modifying factor. This is because each stratigraphic unit is comprised of facies of differing coarse- versus fine-grained sediment composition.

Figure 4-2 shows the arithmetic and geometric mean of the pre-mining Kh hydraulic conductivity data from Dendrobium and BSO, grouped in 50 m intervals. The arithmetic mean of the data from Tahmoor is also presented in 50 m intervals. These series confirm the trend of decreasing Kh with depth.

Figure 4-2 includes the post-mining Kh data for two bores S2331 and S2220, just to illustrate the potential changes in this parameter as a result of subsidence-induced fracturing. Other post-mining data and discussion of changes to Kh due to mining is presented in **Section 4.8**.

A database of drillstem test data at Dendrobium and BSO was compiled and added to **Figure 4-10**. This is for all coal seams within the Illawarra Coal Measures (85% of tests are in the Bulli and Wongawilli Seams). These coal seam drillstem test data shows higher hydraulic conductivities, typically 10-100 times higher, than the other data.

Figure 4-3 presents a summary of horizontal hydraulic conductivity (Kh) as determined by packer testing in each stratigraphic unit, with the box and whisker plots showing the range, quartiles, median and arithmetic mean. The count of tests is listed on the right-hand side of the chart. **Figure 4-3A** presents this data based on packer testing at Dendrobium (with a summary of the coal seam drillstem testing also shown), while **Figure 4-3B** presents a similar summary of data from Tahmoor Mine. The drillstem testing on **Figure 4-3A** further illustrates the higher K of the seams better than the packer testing, and suggests that coal seam Kh is 1-2 orders of magnitude greater than the other lithologies.

HS also reviewed the spatial variation in Kh as determined from packer tests at the Dendrobium Mine. **Appendix B** presents a summary of this analysis[11]. This, along with the summarised packer results from Tahmoor (**Figure 4-3B**) suggests that there is some variation in Kh through the Southern Coalfield, including the Dendrobium area. This variation may be a result of difference in lithology, weathering and the depth of the interval tested. For example, Bulgo Sandstone Kh is greater in the east of Area 3A than to the west (Area 3A west and Area 3b). This is likely due to the shallower depth to the Bulgo Sandstone (and areas of outcrop) in the east of Area 3A than to the west.

Vertical hydraulic conductivity (Kv) is difficult to measure in the field, and laboratory measurements on core samples are one way to characterise Kv, although these values may be somewhat lower than field values because of much smaller sample volume available from boreholes, i.e. this technique may not capture hydraulic conductivity due to secondary porosity. For determining the effective Kv within a sequence of strata the harmonic mean is the correct statistic (Domenico and Schwartz, 1998). At Dendrobium, core testing of the Hawkesbury Sandstone, Newport Formation, Bald Hill Claystone and Colo Vale Sandstone has been carried out, and the results are summarised in box-and-whisker format on **Figure 4-4A**. This has been augmented with a summary of similar core testing at BSO (taken from Heritage Computing, 2010) – this is presented as the harmonic mean and the minimum and maximum range in vertical hydraulic conductivity. **Figure 4-4B** presents the extensive core testing dataset from Tahmoor.

The data (in **Figure 4-4A**) suggests there is a significant variance in Kv in some units, but the harmonic means for most units other than the Hawkesbury Sandstone tend to be less than 1E-5 m/d, and frequently in the range 2E-7 up to 1E-5m/d.

The combined datasets suggest that there is also a general decrease in Kv with depth, and that the claystone units have generally lower Kv than the sandstones. The sandstone units (i.e. Hawkesbury, Bulgo and Colo Vale and Scarborough) all exhibit a wide range in measured K, no doubt due to the presence of fine-grained sandstone, mudstone and claystone facies (lenses) within the broader sandstone unit.

These extensive datasets provide a sound basis for developing the conceptual model (**Section 5**) and setting the Kh and Kv hydraulic properties of the hydrostratigraphic units of the subsequent groundwater model (Section 6). The results of previous modelling studies (Heritage Computing, 2010; HS, 2014a; HS, 2016a) are also presented on **Figure 4-3** and **Figure 4-4** – these show good agreement with packer Kh and core Kv data, although the data on **Figure 4-4A** suggests that modelled Kv for deeper strata could have been too high in previous modelling at Dendrobium (HS, 2016a).

4.7.2 STORAGE PROPERTIES (SY AND SS)

Testing of porosity (total) percentage has been completed for Dendrobium core from the upper stratigraphic units, such as the Hawkesbury Sandstone, Newport Formation, Bald Hill Claystone and Colo Vale Sandstone (essentially the equivalent of the Bulgo Sandstone). Specific yield (Sy) has not been measured directly. In the long term Sy is close to drainable porosity. Effective porosity is considered a better approximation of Sy, although some practitioners consider that laboratory-determined effective porosity may be an overestimate of the porosity that is ‘drainable’ in the field. **Table 4-11** provides total and effective porosity results from laboratory testing of core samples.

[11] A similar analysis could have been carried out with Kv (from core testing, below) but it was considered that this would be too skewed by micro-scale differences in Kv to make it useful to check spatial variability in the overall Kv of relatively thick stratigraphic units.

This dataset from Dendrobium has been augmented with a summary of data from BSO (Heritage Computing, 2010), which includes average porosity and effective porosity for some geological units, where effective porosity is a reasonable approximation for specific yield.

Table 4-11 Summary of porosity (%) determined from Dendrobium and BSO core samples

GEOLOGICAL UNIT	Total Porosity (%)				Effective Porosity (%)	
	Min	Mean	Max	Count	Mean	Count
Hawkesbury Sandstone	3.8	15.4 (14.9)	23.6	68 (4)	11.2	2
Newport Formation	2	2.4	2.6	3		
Bald Hill Claystone	4.1	6.1	9.9	6		
Colo Vale Sandstone	3.7	9.4	18.1	10		
upper Bulgo Sandstone		(8.2)		(5)	3.3	5
lower Bulgo Sandstone		(5.6)		(4)	0.7	4
Stanwell Park Claystone		(8.2)		(3)	0.2	2
Scarborough Sandstone		(8.5)		(4)	1.5	2
Wombarra Claystone		(3.7)		(1)	0.2	1
Coal Cliff Sandstone		(7)		(2)		

Total porosity data in parentheses () is from BSO. All Effective Porosity measurements are from BSO.

Source: X:\HYDROSIM\DENDROBIUM\Tech\AquiferProperties\Packer\Dendrobium_AquiferPropertiesDatabase_20161219.xlsx

A review of the porosity data shows that this hydraulic parameter varies, and like hydraulic conductivity, decreases approximately with depth.

As expected, the values of total porosity, and even the effective porosity from BSO, are higher than those suggested for specific yield in studies conducted in the Sydney metropolitan area and elsewhere, which indicate a specific yield of between 0.01 and 0.02 is reasonable for typical Hawkesbury Sandstone (Tammetta and Hewitt, 2004). Specific yields for Sydney Basin sedimentary strata in the context of drainage due to longwall subsidence generally vary between 0.005 and 0.015.

Illawarra Coal has been using Nuclear Magnetic Resonance (NMR) imaging in selected drillholes to provide continuous logging of density, gamma count, porosity and hydraulic conductivity. The porosity estimates are made on a 0.1 m interval, with estimates of total porosity and three constituents: clay-bound water, capillary water, and 'free water'. Of these constituents, free water + capillary water = effective porosity, while we consider that free water = drainable porosity or Sy.

Figure 4-5 presents the porosity trace down bore S2324. This particular bore has been chosen because it has a log for the full sequence, down to the Kembla Sandstone (KBSS), below the Wongawilli Seam (WWSM). Raw NMR data is at 0.1 m intervals, however, the data presented in this figure is a 1 m moving average to make it somewhat less variable and easier to interpret. Stratigraphy is shown on the right-hand side of the porosity chart.

Figure 4-6 presents the average of each of the porosity components by stratigraphy. **Figure 4-6A** shows the averages for the broad stratigraphic units. These broad stratigraphic units correspond to the units of the model layers, with the exception of the more detailed subdivision of the Hawkesbury Sandstone (HBSS) and Bulgo Sandstone (BGSS). For those units, which are subdivided into multiple model layers, **Figure 4-6B** shows the average porosity for the sub-layers.

From these charts, it can be seen that the NMR 'free water' results indicate that Sy is in the range 1% to 6.3%. For the Hawkesbury Sandstone, the NMR free water volume (approx. 6%) and estimated effective porosity from NMR (6 + 4 = 10%) compare well against the effective porosity from the laboratory (11%, **Table 4-11)**. For the Triassic units, from the Bulgo

Sandstone and below, the NMR free water values are typically higher than the effective porosity values in **Table 4-11**.

The information from the core tests and NMR and from previous modelling will been used as the basis for the initial parameterisation of the groundwater model (**Sections 6.7 and 7.2**).

Direct test data is not generally available for confined storage, namely the specific storage (Ss). The specific storage of Hawkesbury Sandstone has been estimated to be approximately:

- 1E-6 m^{-1} in the shallower zones where fracture flow is the dominant flow process (Kelly *et al.,* 2005); and
- 1.5E-6 m^{-1}, for intervals between ground surface and 300 m depth based on pumping tests in Hawkesbury Sandstone from Tammetta and Hawkes (2009).

Model calibration at other mines in the Southern Coalfield suggest that Ss is in the order of 1E-7 to 3E-5 m^{-1} for the coal seams, and about 1E-6 m^{-1} for overburden or interburden.

Estimates of Ss can also be made based on Young's Modulus and porosity, based on calculations in Mackie (2009), and methods utilising porosity determined from core testing are recommended (Evans *et al*., 2015). Calculations for this Project suggest that for interburden (sandstones, claystones) Ss generally lies in the range from 1.7E-6 (unfractured, fresh rock) to 8E-6 (fractured rock), while for the coal seams, Ss is approximately an order of magnitude higher. These ranges are generally consistent with the findings of Rau *et al*. (2018) who suggested a range of Ss of approximately 1.3E-5 to 2E-7 for fine-grained rocks.

For the model developed in this study, a range of generally decreasing Ss with depth is be used, representing the concept that overburden pressure at depth steadily decreasing the 'elastic storage' of the rock formation.

4.7.3 ROLE OF GEOLOGICAL STRUCTURE

Faults and other water-bearing structures (**Sections 3.3, 3.4**) are considered potential pathways between the underground mine and surface water, for example supply reservoirs, streams. Structures that may provide potential preferred groundwater pathways (excluding the goaf and fracture zones, as described in **Section 5.2**) include:

- major faults or fault zones comprising one or more pervasive sub-vertical fractures;
- minor fractures identified from underground mapping or advance drilling that are oriented in such a way as to provide a potential pathway between the mine and a surface water body;
- unknown and/or unidentified fractures that are intersected by mining;
- bedding plane fractures and openings, including horizontal shear planes that form in response to valley closure movements (both natural and mine related); and
- igneous intrusions such as dykes and sills; particularly at their margins where fracturing is likely to be more intense.

Detail of mapped geological structures in Areas 5 and 6 is provided in PSM (2019). This document presents the current level of knowledge of the interpreted position, type (e.g. fault, dyke, etc) and characteristics of structures. Pending approval of the Project, more investment would be made into understanding the structures within the proposed mining areas.

Experience at Dendrobium Mine and other studies (e.g. Wilson, 1985) suggest that fractures and faults are typically not associated with large mine inflows, provided that there is adequate separation between the panel and the water source e.g. a reservoir. The proposed longwalls in Areas 5 and 6 are deeper than 120 m (DSC, 2010). Area 5 longwalls are 300 m from Lake

Avon (at their nearest), while Area 6 longwalls are further than 500 m laterally from stored waters (**Sections 2.5 and 3.2**).

Faults

Tonkin and Timms (2015) carried out a peer-reviewed study of data on geological structures in the Southern Coalfield and their role in transmitting groundwater. This study found that more than 95% (1580/1660) of structures near reservoirs and underground mines were not associated with any groundwater flow. Groundwater flow at the other 5% was less than 0.001 ML/d, with the exception of two where flows were 0.01 ML/d. Structures were found to be relatively short compared to the depth of cover and often infilled with weathered materials. Horizontal stresses typically close rather than open such structures, and so reduce the effective hydraulic conductivity. This assessment is based on analysis of dyke and fault systems at Dendrobium.

Larger structures, similar to the Nepean Fault near Tahmoor are known to have resulted in increased inflow to adjacent mine workings. If and when such structures are identified by Illawarra Coal they should be included in future revisions of the numerical model.

One such large structure is the Elouera Fault located south of Dendrobium Area 3B between proposed Longwall 18 and the previously mined Longwall 8 of the Elouera Mine. Current mining at Area 3B has not intersected the Elouera Fault. However, investigations are on-going to characterise the fault in terms of its structure and permeability. The fault was previously intersected by drill holes and mine headings in the Elouera Mine. As of February 2019, drilling had intersected a broad fracture zone within the lower Narrabeen Group assumed to be the fault, and packer testing was being carried out and analysed.

Horizontal Fractures and Shear Planes

As discussed in **Section 4.8**, recent drilling investigations carried out between Area 3B and Lake Avon have identified fracturing and associated increased in strata beyond the longwall footprint. TDR monitoring in two holes identified movement on structure(s) within the Newport Formation which are interpreted by SCT (2018a) as a basal shear associated with valley closure. Repeated packer testing carried out after longwall extraction identified increases in permeability at and above that horizon.

Summary

With respect to this groundwater modelling study, horizontal shears and other structures are considered common and result from natural processes and mining related subsidence. Model Kh parameters are derived from the analysis of numerous packer tests and pumping tests which include measurements taken across discrete and connected fractures in bores. The selected model hydraulic parameters are therefore assumed to be representative of the rock mass, including the secondary porosity (i.e. joints, fractures), at the model scale which is regional and therefore small-scale geological structures (e.g. faults, joints, bedding planes) do not need to be explicitly included in a numerical model.

Predictive modelling will include scenarios (**Section 9**) to test the sensitivity of model predictions to the (potential) presence of horizontal shear planes connecting the mine, goaf and reservoirs.

4.7.4 INTRUSIONS AND HEAT-AFFECTED COAL

There has been no field testing of igneous features (sills) around Dendrobium (**Figure 3-2**), so the effects of these features on hydraulic conductivity are not quantified. However, commentary is based on discussion with Illawarra Coal geologists and literature review.

Dykes and sills within the coal measures and other units are thought to enhance hydraulic conductivity along their upper and lower cindered and fractured margins (Wilson, 1985). Based on core data interpretation this is thought to be a localised effect. The main igneous rock mass and sills are likely to be less permeable than surrounding sedimentary units.

Horizontal hydraulic conductivity of the crinanite has been assessed via packer testing. Depending on dominant lithology, the median Kh was 2E-5 to 4E-4 m/d (Geoterra, 2010).

4.7.5 SWAMP DEPOSITS

Upland Swamps comprise a range of unconsolidated deposits from medium – coarse quartzose sands to organic-rich silts and clays. Fryirs *et al*. (2014) investigated the structure and hydraulic properties of an upland swamp on the Budderoo plateau, in the Southern Highlands of NSW. The swamp sits directly on Hawkesbury Sandstone substrate and from a hydrogeological perspective is analogous to the Upland Swamps in the Project area. **Table 4-12** summarises slug tests by Fryirs *et al.* (2014), as based on Hvorslev (1951) analysis.

Table 4-12 Hydraulic conductivity (K) of swamp sediments (after Fryirs *et al*., 2014)

Sedimentary layer	Average organic content (%)	Grain size (mm)	K (m/s)	K (m/d)
Fibricorganic fines (FOF)	48	0.063 – 0.125	1.6 x 10-4 (upper) 2.2 x 10-6 (lower)	13.8 (upper) 0.2 (lower)
Sapricorganic fines (SOF)	33	0.063 – 0.125	1.9 x 10-7	0.02
Dark sands (DS)	3.8	0.5 – 0.7	3.4 x 10-6	0.3
Gravels and sands (GS)	1.4	0.5 – 0.7	3.5 x 10-5	3.0

When viewed in the context of the conceptual cross sections of upland swamps developed by Young (1982) and Fryirs *et al.* (2014), these results suggest that saturated hydraulic conductivity is higher in the near-surface deposits (FOF) and the basal grey sands and gravels, and also in the sandier medial slope-wash facies. The organic-rich silty sediments that characterise the swamp axis deposits have saturated hydraulic conductivity values that are 2 to 3 orders of magnitude lower. This implies that the coarser basal deposits provide effective under-drainage to the swamps and facilitate the interaction between groundwater levels in the sandstone substrate and shallow swamp groundwater.

Glamore and Rayner (2016) state "*Specific yield of swamp surface soils (0 m to 0.2 m) ranged between 15-20%, with deeper sediments (0.2 m to 0.4 m) approximately 10% greater*". These values appear reasonable based on the lithic sediments encountered at swamps around Dendrobium, although are lower than the approximate 40-50% in peat and 10-25% in fine sands suggested by Morris and Johnson (1967). It is therefore likely that the mix of peat and lithic sediments in swamps is likely to have a specific yield of 20-30%.

4.8 EFFECTS OF MINING ON HYDRAULIC PROPERTIES

Extraction of coal using longwall methods commonly results in ground subsidence and associated deformation and fracturing of overlying and adjacent strata (Peng and Chiang, 1984; Whittaker and Reddish, 1989). While authors differ in their terminology, there is general agreement on the overall fracture zonation patterns. Fracturing is most intense and vertically connected immediately above the collapsed longwall (goaf), and grades upwards through zones of less fractured strata (Booth, 2002). Fracturing of the overburden can cause significant changes in aquifer characteristics such as hydraulic conductivity and storage, and potentially can provide pathways for vertical groundwater movement between shallow groundwater and surface water systems and underground mines (Advisian, 2016; McNally and Evans, 2007).

The height to which vertically-connected and potentially free-draining fracture networks extend above the mined seam and the hydraulic properties (hydraulic conductivity and drainable porosity) in this area are therefore important in assessing potential impact of longwall mining on groundwater and surface water systems.

Discussion of the effects, including the height of fracturing and the effects on strata permeability, are presented in the following subsections.

4.8.1 PREDICTIVE MODELS FOR FRACTURE PROPAGATION

Several authors have developed empirical approaches to the likelihood of water ingress problems for longwall mines (e.g. Gale, 2006 and 2008), and for the specific issue of estimating the height of connected fracturing or groundwater drainage above longwalls (e.g. Forster, 1995; Guo *et al*., 2007; Mills, 2011; Tammetta, 2013; Ditton and Merrick, 2014).

These methods have been used at numerous coal mines in NSW to provide guidance on water ingress and the height of fracturing. The latter estimates have been used in recent times for the development of numerical groundwater impact models.

These models for estimating the behaviour of overburden above longwalls rely on the following longwall geometry parameters:

- W = panel (void) width [m];
- D = depth of cover [m]; and
- T = mining or cutting height [m].

The mine geometry parameters at Dendrobium are summarised in **Section 1.3**. Some analysis of the mine geometry is provided in **Section 4.8.2.**

At Dendrobium, the methods of Ditton and Merrick (2014) and Tammetta (2013) yield estimates that are substantially different from each other. A review of longwall subsidence fracturing at Dendrobium was commissioned by the DPE. The review by consultants PSM (2017), with peer review by Emeritus Professor Jim Galvin (2017a) and Dr Col Mackie (2017). The study had several key conclusions with respect to the height of connected fracturing:

- empirical approaches carry significant uncertainty and limitations related to the data on which they were based and were not robust. The result is that while they are not universally accepted, these methods still provide useful estimates (Galvin, 2017b).
- fracturing above the (305 m wide) panels in Area 3B likely extends to the surface (PSM, 2017; Galvin, 2017a). The latter conclusion is generally consistent with the predictions of the Tammetta model at Dendrobium Area 3B.
- Further review by the IEPMC (2018) recommended that, in the absence of better data is available, the height of connected fracturing be assumed to be to the height predicted by the Tammetta model. Further, IEPMC concluded “that irrespective of whether the Tammetta equation is predicting the height of complete drainage reasonably accurately, its outputs can be useful as an indicator of the potential for water ingress from the surface” (see use of empirical methods as a ‘screening tool’ - **Section 4.8.3**).

In relation to the above points, the review of Mackie (2017) and IEPMC (2018) recommended that geotechnical modelling, such as FLAC2D, could be employed to predict the height of fracturing, and as a result this has been conducted for Areas 5 and 6 (see **Section 4.8.3**).

4.8.2 RATIO OF PANEL WIDTH TO DEPTH OF COVER (W/D)

The ratio of panel width (W) and depth of cover (D) is often used as a preliminary guide to the risk of connected fracturing extending from the goaf to the surface. It is relevant that if the mean and minimum values of W/D are calculated, based on **Table 1-7**, they yield the following ratios for Areas 5 and 6:

- For the mean values:
  - Area 5 W/D: 0.80-0.95;
  - Area 6 W/D: 0.65-0.69.
- For the minimum values:
  - Area 5 W/D: 0.92-1.09;
  - Area 6 W/D: 0.69-0.79.

Gale (2006 and 2008) developed empirical relationships based on mine geometry, subsidence which serve as a screening or indicative tool for understanding the potential for issues associated with mine inflow.

The W/D ratios for Area 5 are relatively high (as shown on **Figure 1-3**). Comparing these with the relationship developed by Gale (2006) [see **Appendix E, Figure E1a**] without other data such as predicted strain for comparison would indicate probable cracking to the surface. Area 6 ratios are lower, due to the greater depth of cover at Area 6 and are in the range that would suggest to toward/near surface, but likely to result in lower rates of inflow to mine workings than in Area 5 (or Area 2 and 3B).

Gale (2008) also developed a relationship using surface subsidence. The observed and predicted subsidence (MSEC, 2019) for each area has been plotted in **Appendix E, Figure E1b**. This also suggests lower risk of 'water inflow issues' in Area 6 than in Area 5 and other Dendrobium areas.

4.8.3 EMPIRICAL METHOD – TAMMETTA H (2013)

As noted by IEPMC (2018), the calculation of H using the method of Tammetta (2013) can be used as an indicator or screening tool for the potential of water ingress from the surface and potential for seam-to-surface connection. This method is an alternative to the W/D method described in **Section 4.8.2**.

H is "the height of complete groundwater drainage" (Tammetta, 2013), and could be considered a proxy for the height of connected fracturing. H is a function of panel (void) width, cutting heights and depth of cover. A spatially-distributed calculation of this has been made using the relevant parameters at Dendrobium. **Figure E4** (**Appendix E**) presents this in terms of the depth to the top of this zone, and the stratigraphic unit in which the connected fracturing zone is estimated to extend to.

The colour scale has been set to identify areas where the Tammetta H rises to the surface, or near to the surface and likely to intersect the cracking that extends downward from the surface (see Section 5.2.1). The areas shown in red, orange and yellow on **Figure E4** have the greatest potential for seam-to-surface connection.

Figure E4 suggests that, with the exception of Longwalls 6 and 7 in Area 3A, the historical and approved areas of Dendrobium Mine have a greater potential for connection to the surface than the proposed longwalls in Areas 5 and 6. All historical areas are indicated by a high potential for seam-to-surface connection, with the presence of historical workings above Area 1 likely to have been the cause of relatively low inflow to that part of the mine.

Within Area 5, it is generally the areas closest to Lake Avon that would have the greatest potential for connection to the surface (**Figure E4**). It is expected that the zone of connected fracturing would extend into the mid-HBSS (right-hand pane on **Figure E4**).

Area 6 would have only a moderate probability of seam-to-surface connection, except in the areas closest to Cordeaux River, where the valleys of the tributaries to Cordeaux River cause the depth of cover to decrease and the potential for connection to the surface to increase.

These results are slightly different to that implied by the W/D ratios (**Section 4.8.2**), which suggest that Area 6 would have a low potential for water inflow issues.

4.8.4 GEOTECHNICAL MODELLING OF FRACTURE PROPAGATION

Geotechnical modelling of the overburden using FLAC2D software has been carried out by SCT (2017 and 2018b) for representative 305 m wide panels as proposed in Areas 5 and 6. This modelling suggests that fracturing would extend from seam to surface in most of the cases modelled by SCT (**Table 4-13**), given that the mine does not proposed individual longwalls but a series of neighbouring panels.

Table 4-13 Summary of FLAC2D model seam-to-surface connection

Depth of cover	Mine area modelled	Single panel	Multiple panel
375	Area 5 (Bulli Seam)	Fracture network extends to surface	Fracture network extends to surface
400	Area 6 (Wongawilli Seam)	Fracture network extends to surface	Fracture network extends to surface
450	Area 6 (Wongawilli Seam)	Fractures do not extend to surface	Fracture network extends to surface

Results from SCT (2017 and 2018b)

A summary of SCT's work, and that most relevant to deriving inputs to the groundwater model, is shown on **Figure 4-20** (A – Area 5 and B – Area 6).

The hydraulic conductivity estimates produced by the FLAC2D modelling are noted to be conservative (SCT, pers comm.): strain within the strata could be more widely distributed than estimated, resulting in a wider distribution of lower hydraulic conductivity, rather than the more intensely-focussed strain predicted by the FLAC2D model.

4.8.5 OBSERVED CHANGES DUE TO MINING

Over the last few years, Illawarra Coal has carried out studies to quantify hydraulic properties and hence understand those changes in two contrasting settings:

1. directly overlying the workings at Longwall 9, Longwall 10 and Longwall 12 in Dendrobium Area 3B (investigations at Longwalls 13, 14, 15 and 6 are currently underway); and
2. between Longwalls 12-14 and Lake Avon reservoir.

Boreholes were drilled before and/or after longwall mining and packer testing carried out to quantify the changes in Kh due to mining subsidence. The study above Longwall 9, carried out by Parsons Brinckerhoff [PB] (2015), also included tracer tests to place constraints on the Kv of fractured overburden, and to identify any preferred pathways between the shallow groundwater systems and the mine goaf. The results of these studies are summarised below.

Effects above extracted longwalls

The effect of mining subsidence strata hydraulic characteristics above longwalls have been investigated by Illawarra Coal in the following locations at Dendrobium:

- Above Longwall 9: Pre-and post-mining investigations were carried out in 2013 to 2015 and reported by PB (2015);
- Above Longwalls 10 and 12: Geotechnical and permeability testing of holes during investigations of tributary WC21 (SCT, 2016; HGEO, 2017a and 2017b).

Investigations into mining effects above longwalls are currently underway and/or in the process of being reported at:

- Longwalls 9 and 10, post-mining investigations at Swamp 1b;
- Longwalls 12, 13, 14, 15 and 6, in fulfillment of condition 18 of the LW14-15 Subsidence Management Plan Approval by DPE dated 17/5/2017.

Results of the completed investigations are summarised below.

Longwall 9

Four diamond core holes were drilled at a location along the mid-line of Longwall 9 in Area 3B, prior to any mining in that area. A series of pumping and packer tests, down-hole flow tests and dye and salt tracer tests were used to characterise the pre-mining conditions at the site. Following the passage of Longwall 9 beneath the test site, five new holes were drilled and tested in a similar manner. Vibrating wire piezometers (VWPs) and extensometers were installed at the site to monitor the approach and passing of the longwall. Results are reported by PB (2015), and also reviewed as part of PSM (2017) and associated peer reviews (Mackie, 2017 and Galvin, 2017a). The main findings of these studies include:

- Down-hole camera surveys identified a significant increase in horizontal and inclined fracturing after mining. Drill core intersected inclined and sub-vertical fractures in the lower Bulgo Sandstone.
- Post-mining test bores indicated steep downward hydraulic gradients, particularly in the lower Bulgo Sandstone due to lower vertical hydraulic conductivity in this unit. A VWP installed after the investigation at bore AQ5 (S2220) indicated depressurisation at the base of the Hawkesbury Sandstone. However, groundwater levels in the shallow Hawkesbury Sandstone (AQ10) remained perched.
- Horizontal hydraulic conductivity, as measured via packer tests (as shown in **Figure 4-7A**), increased by between one to three orders of magnitude due to mine subsidence and strata fracturing. Increases in Kh are observed in every geological unit, but are greatest below the base of the Hawkesbury Sandstone. Some intervals, including a 30-40 m thick interval at 175-220 m, show consistently lower enhancement to Kh than elsewhere in the column.
- Tracer tests designed to measure the Kv of fracture networks did not detect tracer breakthrough between the Hawkesbury Sandstone and Bulgo Sandstone both before or after mining. On the other hand, horizontal cross-hole tracer tests showed rapid breakthrough consistent with high Kh/Kv ratios.
- Despite the steep downward gradients, salt (KCl) and Rhodamine dye tracers were not detected at the main discharge point of the Longwall 9 goaf up to 6 months after mining. Therefore, the experiments provided no direct evidence for significant connection of flow via fracture networks with a tracer transit time of less than 2 years (2014-2016), between shallow groundwater systems and the goaf.
- Extensometer data indicates dilation of the rockmass during subsidence of approximately 2.5 m (over ~400 m depth), with the strain accommodated mainly by opening of bedding planes. These observations imply an increase in fracture storage in the overburden. Estimates from Longwall 9 data suggest that the increase in fracture storage for a single panel could be in the order of 750 ML from the ground

surface to the base of the Bulgo Sandstone, and in the order of 1.5 GL in the strata below the Bulgo Sandstone.

- Despite there being no tracer detected in the mine workings, the packer testing results showing the presence of fractures and bedding separation through the whole geological sequence led PSM to conclude that seam-to-surface connection (i.e. enhanced Kv) above Longwall 9. This conceptual model has been adopted for subsequent conceptualisation and numerical modelling (for longwalls with a similar geometry (**Section 1.3**).

Investigations at WC21

Illawarra Coal carried out investigations into the shallow groundwater conditions adjacent to tributary WC21. Four bores were drilled and packer tested; two (S2335 WC21-1 and S2336 WC21-2) above Longwall 12, and two (S2336 WC21-3 and S2338 WC21-4) above Longwall 10. The tested bores were drilled to a depth of 51-52 m. **Figure 4-7B** shows the packer test results and stratigraphy at these sites. Note that the pre-mining packer tests are from a different site to the post-mining (about 700 m away from one another), and with about 30 m difference in topographic elevation. This testing suggests that there is a two-order of magnitude increase in Kh in this upper 50 m section of the Hawkesbury Sandstone. This is consistent with the testing in the uppermost section (0-80 m) of the strata by PB at Longwall 9 (**Figure 4-7A**).

Effects outside longwall footprint

Between 2015 and 2018, Illawarra Coal installed a series of investigation boreholes and piezometers within the “barrier pillar” between the Avon Reservoir and the longwalls at Dendrobium Mine Area 3B. These were partly in response to the discussion of valley-bulging or valley-closure in PSM (2017).

The investigation was designed to assess geological strata (fracturing and permeability) and groundwater conditions both before and after longwall mining adjacent to Lake Avon, thereby allowing calculation of potential rates of seepage through the pillar zone. Investigations were carried out at eight locations (initially named locations AD1 to AD8) at varying distances from mined and planned longwalls. The results were summarised in a number of reports, the most recent being SCT (2018a) and HGEO (2018b).

Time-domain reflectometry (TDR) monitoring identified anomalies related to movement on fractures in bores S2314 (site AD2) and S2377 (AD3) associated with longwall subsidence. In both cases the anomalies developed progressively at a specific depth and increased in magnitude as mining progressed, suggesting reactivation along a discrete fracture zone or horizon within the Newport Formation. The anomalies correspond to increases in strata permeability at, and above the anomaly depth.

Strata permeability was assessed at each of the Avon Dam investigation sites using packer tests (**Figure 4-8**). Testing at sites AD2, AD3 and AD7 indicated an increase in strata permeability due to mine subsidence of at least an order of magnitude (10 times) over the depth interval between the reservoir full supply level (FSL) and the lake bed (~285 m AHD). The remaining two sites, AD1 and AD6 indicated minor, if any, increase in permeability compared with pre-mining testing. At site AD6, just 10 m from Longwall 13 goaf, there is no significant change in strata permeability. At AD1, average permeability in the post-mining hole (S2331) is approximately 0.2 log units higher than the pre-mining hole (S2313), but the difference is not statistically significant at the 95% level. There is no simple correlation between permeability increase and proximity to goaf, implying that strata fracturing (including bedding plane shear) is influenced by other factors such as topography and associated phenomena (valley closure) as was suggested by SCT (2015).

5 HYDROGEOLOGICAL CONCEPTUAL MODEL

A hydrogeological conceptual model provides the framework for the development of a numerical groundwater model to assess the impacts of the proposed development on groundwater and connected surface water resources. This section provides a framework for the subsequent numerical modelling.

The conceptual framework and model design were all reported on and presented to the Peer Reviewer (Frans Kalf of Kalf and Associates) before work commenced on the numerical model. The sections on model planning and model design are now incorporated into **Sections 6 and 7**. The conceptual model is present in the following sub-sections.

5.1 PRE-MINING HYDROGEOLOGY

The key features of the hydrogeological system are assessed and described in more detail in **Section 4**. The main pre-mining conceptual features and processes are as follows:

1. The Southern Coalfield (south-eastern Sydney Basin) groundwater system:
    - The boundary of the groundwater systems relevant to the model is not far below the base of the Permian Illawarra Coal Measures. Below that level, the hydraulic conductivity and groundwater velocity is assumed to be so low as to have little influence on the shallower groundwater systems. To the east, the coal measures are truncated (eroded) along the Illawarra Escarpment, where springs occur at the discharge boundary. To the south groundwater flow enters the study area from areas of higher elevation (the Southern Highlands), and flow to the north beyond the study area and into the centre of the Sydney Basin. To the west, the coal measures are also truncated by the gorge of the Nattai River and Lake Burragorang, however the study area does not extend that far, as groundwater flows to the north and is approximately parallel to the study area boundary.
    - The hydraulic conductivity and porosity of the rock strata vary with both depth and due to some lithological controls. The variation with depth is considered to be the overarching or dominant control on horizontal hydraulic conductivity (Kh), while differences caused by lithology, i.e. the dominance of sandstone or claystone/mudstone or coal in particular units or layers, is a secondary control. Vertical hydraulic conductivity is considered to be more controlled by lithology, particularly the increased frequency of fine-grained laminations and horizons in the dominantly claystone units.
    - The primary groundwater source (‘aquifer’) in the area is the Triassic Hawkesbury Sandstone. Due to its considerable thickness (up to 200 m), and the presence of numerous high and low permeability horizons or lenses, this unit essentially comprises or acts as a series of multiple, variably connected and sometimes perched aquifers.
    - Less productive ‘aquifers’ are the Bulgo Sandstone and Scarborough Sandstone. The coal seams are also relatively permeable compared to the Narrabeen Group and interburden units of the coal measures.
2. The dominant recharge process is via distributed rainfall recharge through the unsaturated zone to the water table. Additional sources include river recharge from losing sections of streams and during flood events, some natural leakage from impounded water (in the reservoirs). There is also some minor inflow from upgradient areas beyond the ‘study area’, mainly from the south and southwest.

3. Rivers, creeks and lakes are the main natural discharge features within the basin. However, they can also act as recharge features (noted above) depending on the river stage relative to the adjacent groundwater levels. These factors can vary both spatially and temporally across the basin.
4. Evapotranspiration (ET) from shallow water tables. This is likely to occur to<10 mbg for areas vegetated by trees, and at even higher ET rates down to 1-2 mbg in swamp areas and is therefore also a significant mechanism of groundwater discharge from this these zones.
5. There is very little groundwater extraction (bores) on the plateau around Dendrobium Mine due to this area being a Special Area for water supply.
6. There is a long history of coal mining in the Southern Coalfield, so few areas are in a true 'pre-mining' state. Area of the Bulli, Balgownie and Wongawilli seams have been extracted, typically depressurising target seams and the strata above.

5.2 EFFECTS OF LONGWALL MINING

Longwall panels proposed for Area 5 are 305 m wide, 700 to 2,850 m long, with an extraction height of 2.5 to 3.2 m (average 2.8 m). The proposed longwalls for Area 6 are 305 m wide, 1,150 to 3,000 m long, with an extraction height of up to 3.9 m) (see **Section 1.3**). In order to develop roadways and then extract a longwall panel, the coal seams must be dewatered, and this dewatering generally continues during operation to prevent flooding of roadways, longwalls and also to maintain air circulation.

Ultimately, mine inflow draws groundwater from the surrounding geological strata and potentially from the surface water systems. In regulatory terms, this can constitute capture ("take") from one or more water sources and across management zones (**Section 1.5**).

After the panels of coal are extracted the overlying strata immediately above the extracted seam collapses into the void (forming the goaf). The strata above the goaf deform and fracture in response, and some level of subsidence can occur at the ground surface.

In 2016 DPE commissioned an independent 'Height of Fracturing Study' to assess the height of fracturing and related behaviour above longwalls at the Dendrobium Mine. This was conducted by PSM (2017), and the chief findings of that are summarised and discussed in **Section 5.2.1**. Where relevant, findings have been incorporated into the conceptual model (detailed in the latter parts of **Section 5.2**) and subsequent numerical model (**Section 6**).

Section 5.2.1 describes the zones and modes of deformation. The effects of these geotechnical and hydraulic processes can influence various receptors. Each of the broad classes of receptors is discussed in the following sections, including the geological strata (**Section 5.2.1**) including specific attention of the height of connected fracturing (**Section 5.2.2**), groundwater levels (**Section 5.2.3**), watercourses and waterbodies (**Section 5.2.4**) and upland swamps (**Section 5.2.6**). Effects on water quality, surface water and groundwater are described in **Section 5.2.7**.

5.2.1 SUBSIDENCE AND FRACTURING

Forster and Enever (1992) carried out studies at pillar and longwall mines in NSW and developed a conceptual model to describe a sequence of deformational zones (**Figure 5-1A**) existing above longwall and pillar extraction areas. Another conceptual model was provided by the Department of Planning (2008) (**Figure 5-1B**), and other authors have developed similar or alternative conceptual schemes.

The zones adopted by HS, both in terms of the geomechanical behaviour and groundwater response, are listed in **Table 5-1**. As other authors (e.g. PSM, 2017, Mackie, 2017) have noted, these 'zones' are a construct to allow identification of dominant processes. In reality, these are unlikely to occur as discrete zones, but as a continuum depending on the lateral or vertical location above or offset from a longwall panel and the geometry of the longwalls in relation to the depth of cover, and their geological and topographic setting.

Based on review of the existing conceptual models, e.g. Booth, 1986 and 2002; Holla and Barclay, 2000; Guo *et al.,* 2007; Mills, 2011; Tammetta, 2013; Ditton and Merrick, 2014, as well as analysis of data from Dendrobium, and discussion between HGEO, SCT, HS and Illawarra Coal, a conceptual model diagram has been developed (**Figure 5-2**). This is consistent with **Table 5-1** and is based mainly on the geotechnical zones proposed by Mills (2011), but with consideration of other published works.

This figure, the summary in **Table 5-1**, and the following supporting text in this section would be used in the development of a numerical groundwater impact assessment model to simulate the changes that occur to the hydraulic conductivity and storage properties of the strata around Dendrobium Mine. In the following text, numbers in circles, e.g. ①-⑳, correspond to the zones on **Figure 5-2**.

Table 5-1 Conceptual Zones of Deformation adjacent to Longwalls

	CONCEPTUAL ZONE		MILLS (2011)	TAMMETTA (2012)	DITTON (2014)	GEOMETRY
⑦	Surface Fracture Zone (i.e. surface cracking)				D-zone	Depth of increased surface fracturing (due to lower depth of cover/confinement) <=20 m, with enhanced horizontal hydraulic conductivity. HS has assumed depth = 10 x *t*, typically extending from the surface down to the Fractured Zone (**Section 4.8**).
③	Zones of mostly horizontal shear **offset from the longwall panel footprint**			Disturbed Zone		Offset from goaf, extending approx. 500 m from longwall edge.
	Constrained Zone		Zone of no disturbance (#5)		C-zone	Based on packer tests (**Section 4.8**), <u>not considered to occur above Area 3B, and therefore unlikely at Areas 5 & 6.</u>
③	Fractured Zone:	upper zone of Disconnected Fracturing	Zone of stress relaxation (#4) Zone of bedding plane dilation, some fracturing (#3)		B-zone	▫ 1.6 x panel width (W) (Mills, 2011) ▫ B/B95 – Ditton and Merrick (2014).
②		Lower zone of Connected Fracturing	Zone of large downward movement (#2)	Collapsed Zone	A-zone	▫ 1 x panel width (W) (Mills, 2012) ▫ H - Tammetta (2013) or ▫ A/A95 – Ditton and Merrick (2014).
①	Caved Zone		Zone of chaotic disturbance (#1)			▫ 5-10 x *t* (Forster & Enever, 1992, Guo *et al.*, 2007) ▫ 5-20 m (Mills, 2011)
	Mined Zone (extracted seam)					Mined seam thickness (***t***) = 2.5-3.9 m at Dendrobium Areas 5 & 6
⑧	Buckling/heaving of 'floor' strata, caused by unloading after panel extraction (Meaney, 1997; Karacan *et al.*, 2011)					Assumed to be in the order of 10-30 m.

Numbers in circles, e.g. ①-⑧**,** correspond to zones on **Figure 5-2**.

The strata in the connected part of the fractured zone ①② will have a substantially higher vertical hydraulic conductivity⑱ than the undisturbed host rocks ⑤. This would encourage groundwater to move out of rock storage (elastic storage and drainable porosity) and drain downwards towards the goaf ⑬⑭⑮. Fracturing becomes gradually less well-connected (i.e. declining continuity between separate fractures) with increasing height above the seam, tending toward being vertically 'disconnected' ③; Kh increases due to the parting of bedding planes being enhanced more than Kv due to reduced frequency of (sub-)vertical fractures to act as vertical pathways. As a result, the vertical movement of groundwater would be enhanced but may not be significantly greater than under natural conditions ⑫. This is borne out by observations:

- at the Tahmoor Longwall 10A "HoF" (height of fracture investigation) borehole (SCT, 2014), it was clear that a downward gradient existed in the lower Hawkesbury Sandstone, but the vertical connectivity was not sufficient to alter groundwater levels in the mid/upper Hawkesbury Sandstone to any observable degree; and
- at Dendrobium, where water levels in shallow strata have been more affected than those at Tahmoor Longwall 10A, but positive pressures can still be maintained in the shallow strata (see **Section 5.2.3**), indicating an indirect connection (or a slow or low transmissivity pathway) to the fractured zone and goaf. That is, any fracturing below is insufficiently continuous or connected, or insufficiently transmissive, to cause drainage of groundwater from the upper zone via recharge or other sources.

At distances exceeding approximately 500 m from the mine, strata are assumed to be relatively unaffected ⑤, although minor enhancements to Kh may arise at specific horizons due to shearing on bedding planes. This enhancement is considered more likely in the upper parts of the strata offset from longwalls; in the lower sections above chain pillars the compression of overlying strata ⑥ is likely to restrict the potential for secondary porosity to develop, and may even reduce Kh in these areas.

At mines where the depth of cover greatly exceeds the longwall width, strata overlying the fractured zones may sag but not significantly fracture, resulting in a degree of hydraulic isolation of those fracture zones from the surface and near surface (⑦ - see below). This is referred to as the 'constrained zone' by Booth (1986) and others (**Figure 5-1**) and the zone of vertical stress relaxation by Mills (2011). However, longwall geometries and depths of cover at Dendrobium are such that a constrained zone does not occur above the goaf, i.e. packer testing has shown fracturing through the sequence above these longwalls (see **Section 4.8**, **Figure 4-7A**). Similar longwall geometries are proposed in Area 6, while the cutting height would be lower in Area 5 (**Section 3.2**). In the proposed areas the depth of cover is typically similar to (in Area 5) or greater (in Area 6) than in Area 3B and other areas (**Section 3.2**). Therefore, the possibility is that there would be less connective fracturing and more disconnected fracturing above these mine areas than in Area 3A, 3B (**Section 4.8.2**). However, for the purpose of modelling and impact assessment, connection between the goaf and surface cracking zone ⑦ is assumed for the 305 m panels (**Section 5.2.2**), as based on SCT's geotechnical modelling in **Section 4.8.3**.

In the surface zone ⑦, fracturing of the surficial and near-surface strata can occur due to the effects of compression and tension on unconfined strata within and near to the subsidence trough.

Fracturing in the base or bed of watercourses has occurred at Dendrobium, most notably within streams directly mined under by Area 3B, e.g. WC21, as well as at other mines in the Southern Coalfield, e.g. along the Bargo River and Redbank Creek above Tahmoor and at Waratah Rivulet above Metropolitan Colliery. Down-slope movements and valley closure will enhance these strains and result in an increase in fracture frequency and/or width at these locations. Experience at Dendrobium and Appin mines suggests that 95% of observed fracturing occurs within the longwall footprint, about 99% within the footprint plus a further 50 m buffer, i.e. above or within the chain pillars, and a remaining 1% occur beyond that distance. E.g. cracking at tributary LA4, at approximately 290 m from the longwall (MSEC, 2019). The likelihood of surface fracturing and upsidence above Dendrobium Areas 5 and 6 is discussed in the assessment by MSEC (2019).

Surface fracturing may result in persistent or permanent changes to hydrology ⑨, such as WC21 ceasing to flow during recession periods. Leakage of water into the surface fracturing zone can result in water quality impacts (McNally and Evans, 2007).

Surface water flow that is redirected into and through near-surface fractures ⑨ may either be returned to surface drainage somewhere down-gradient ⑩, (in which case the net loss from the catchment is minimal), migrate downwards towards the goaf ⑬, or some combination of both. Tracer tests are planned to further investigate this behaviour – a related recommendation is made in **Section 11.2.1**.

The strata movements and deformation that accompany subsidence would alter the hydraulic and storage characteristics of the host strata. As there would be an overall increase in rock hydraulic conductivity ⑱, groundwater levels can fall either due to actual drainage of water into the goaf ⑬⑭⑮⑯ or by an increase in storage capacity due to an increase in porosity ⑳ (Tammetta, 2016).

Fractures that are directly connected to the goaf would rapidly depressurise and form a pathway for seepage of pore water downwards towards the goaf. This does not mean that these areas contain no groundwater, but that there can be free drainage through the cracks and fractures ⑬. Desaturation can occur over time in this zone. As the matrix drains due to the presence of fractures, the declining moisture content in the matrix may result in lower (primary) hydraulic conductivity ⑲. Where the downward drainage of water in the fracture system encounters restrictions (partially closed fractures or fracture terminations), the fractures may fill or perch and would then drain at a rate dependant on the rock matrix or fracture hydraulic conductivity.

The zones of enhanced K, i.e. the deformation zones ①②③⑦, above the mine void/goaf on **Figure 5-2** is a schematic representation of monitoring data of post mining strata conditions at Dendrobium Mine and the conceptualised ‘likely’ case for future mining areas at Dendrobium (i.e. Areas 5 and 6). There are a number of models for estimating the height of the zone of connected fracturing, and these are discussed further in **Section 5.2.2**. There are also methods and schemes for estimating change in K (e.g. Tammetta, 2014, Guo *et al.*, 2007), although the method employed in numerical modelling (**Section 6.9.1**) relies primarily on the FLAC2D geotechnical modelling of SCT (2017 and 2018b). The enhanced hydraulic conductivities were tested during model calibration (**Section 7**) bearing in mind previous modelling at Dendrobium (e.g. HydroSimulations, 2014a, 2016a) and elsewhere in the Southern Coalfield, such as at Russell Vale, Metropolitan and Tahmoor.

Basal shear planes ④, as identified in the analysis of Walsh *et al*. (2014) and SCT (2015), can extend laterally in strata at an elevation of or just beneath the base of incised valleys. These features can be natural or a result of or enhanced by mining subsidence. It is possible that shear planes may act as a conduit for groundwater flow ⑪, and that these might enhance horizontal connection between watercourses and waterbodies (specifically the Avon and Cordeaux Reservoirs) with the fractured zone extending upward from the longwall goaf, therefore providing a rapid and transmissive pathway for surface water to enter the mine. It is unclear at what distance such shear planes might be able to connect a valley, including a reservoir, with the fractured zone above the goaf. However, data from Sandy Creek indicated that shear planes were mobilised when Longwall 8 was some 670 m from the valley (Walsh *et al*., 2014), so conceptually there may be connection when the longwall edge is about 600 m from a watercourse or reservoir.

Aside from the discrete basal shear features ⑪, there is potential for the development or enhancement of Kh ④⑱ beyond the mine footprint. The extraction of a longwall results in the collapse and subsidence of overlying strata, causing both vertical and horizontal movement of overlying and nearby strata. Outside the longwall footprint, where such horizontal movements occur, the effect can be an enhancement of Kh through horizontally-bedded strata, especially in areas where the topographic relief is such that parts of the landscape (strata) are not supported or buttressed against such horizontal movements (SCT, 2016). Hydraulic conductivity testing at bores S2313 and S2331, located between Longwall 12 and Lake Avon suggests that Kh might be enhanced 2-3 times the host (pre-mining) value (~0.3 log units). However, this is not definitive (**Section 4.8**, HGEO, 2018b) and possibly not significant as the post-mining permeabilities measured at S2331 lie within the expected range of (pre-mining) K. While the degree of enhancement of Kh in areas offset from a longwall is unclear and subject to further research, it is considered prudent that the effects of an increase in Kh of 2-3 times the host value, in line with SCT (2015) and **Section 4.8** is considered by model sensitivity analysis (**Section 9**).

The distance from the longwall footprint that this effect occurs is not clear – bores S2313-S2331 are approximately 80 m from the nearest longwall edge. For the purpose of modelling, HS would assume that this effect could occur with declining strength or significance to about 500 m from the edges of the longwall footprint.

Within the mine workings, heave and buckling of the floor are relatively common observations during the removal of the coal seam or other strata. As noted in **Section 4.4.1**, upward flow through the floor is observed around the mine, and this is likely exacerbated by the deformation within and beneath the floor of the workings ⑧⑱.

This conceptual framework is in broad agreement with observed chemistry trends. The concentration of tritium in mine water samples relative to that seen in modern surface water can be used to estimate the proportion of mine water that is derived from modern water sources. Estimates of the modern water content for each mine area (see graph in **Figure 5-2**) indicate that, to a first order approximation, the degree to which modern water contributes to the mine water balance (i.e. a measure of the degree of connection to the surface – more discussion in **Section 5.2.2**) decreases with increasing depth of cover, assuming constant mining parameters. The depth of cover at Area 2 (median = 240 m) is such that it would suggest connected fracture networks ② intersecting with surface fracturing which would lead to greater connection (i.e. direct transfer of larger volumes of water/solute) and hence a greater proportion of modern water detected in the mine. By contrast, the depth of cover at Area 3B is significantly greater (median = 365 m), and it follows that although connection is concluded based on packer test data (as per PSM, 2017), this is a slower, less transmissive pathway between the goaf and surface water systems (supported by the lack of tritium detected in the Area 3B workings).

Based on these observed relationships and estimates of depth of cover at Area 5 and 6 (more analysis in **Section 5.2.2**), it is expected that the "degree of connection" between the mine and the surface in those areas would be similar to, or less than that seen at Area 3B.

5.2.2 DEGREE OF CONNECTED FRACTURING

Based on the FLAC2D modelling (**Section 4.8.3**) seam-to-surface connection has been enforced for all multiple (adjacent) 305 m wide panels, noting that it is based on the 'void width' (**Table 1-6** and **Table 1-7**). This is consistent with the Width/Depth of Cover ratio (W/D), as noted in **Section 4.8.2** and separately by the Peer Reviewer, that are closely approaching a value of 1. Furthermore, it is consistent with the interpretation by PSM (2017) for Longwall 9 (**Section 4.8.5**).

While fracturing to the surface is therefore expected in both Areas 5 and 6, the different W/D ratios discussed in **Section 4.8.2** and comparison of these with the empirical relationships developed by Gale (2006, 2008) suggest that inflow rates are likely to be lower in Area 6 than in Area 5, mainly due to the greater depth of cover.

The adopted conceptual model (and the numerical model) assumes that the profile of connected fracturing shown in **Appendix G**, which shows the simulated height of this zone intersecting the surface cracking zone, if not ground surface, for most of the area within the longwall footprint at Dendrobium, specifically for longwalls with a void width of >300 m. For longwalls that are narrower, the conceptual and numerical models rely on the use of the Tammetta (2013) method to estimate the height of connected fracturing.

These assumptions mean that the modelling-based assessment is consistent, and at least as conservative, as the approach suggested by IEPMC (2018) who concluded that the Tammetta (2013) model be used at Dendrobium in the absence of other data or geotechnical modelling.

5.2.3 EFFECTS ON GROUNDWATER LEVELS

Based on the depth of cover and longwall geometry, groundwater level responses in Areas 3A and 3B offer the evidence on which to base predictions of groundwater level responses in the proposed Areas 5 and 6.

Observed groundwater drawdown due to mining is discussed in **Section 4.3.2**. In general, the most severe drawdown effects occur in the strata immediately above the mined coal seam. Within and adjacent to the connected fracture zone ② which, at Area 3B includes the Scarborough and Bulgo Sandstones, and in the Hawkesbury Sandstone. The drawdown is often > 50 m or the strata become completely depressurised (pressure head is zero). Drawdown in the mid Hawkesbury Sandstone is about 10-20 m, and in the shallower horizons of the Hawkesbury Sandstone it has been observed to be <5 m (e.g. at S2192-S2220 directly overlying Longwall 9). The declining drawdown might be due to decreasing fracture connection③, although PSM (2017) concluded that the fracturing above Longwall 9 is connected right through to the surface.

Drawdown in Hawkesbury Sandstone decreases with distance from the extracted panels to approximately 5-10 m at a distance of 1 km from the longwall (based on observations in HydroSimulations, 2014b or review of DEN131-S2009 or the head contours in **Figure 4-10**). Deeper in the sequence, e.g. the Bulli Seam, the 5-10 m drawdown occurs at about 2-3 km from extracted longwalls (**Figure 4-12**). Note that the responses described here are considered general or average responses only; responses in individual piezometers can vary depending on the conditions from one location to another.

There are no areas in the Dendrobium Mine where inflow has ceased, however it is expected that drawdown would persist until inflow ceases, and the mine re-fills after the sealing of the adit entrance, and an equilibrium is finally re-established.

5.2.4 IMPACTS TO STREAM AND CATCHMENT YIELD

As noted in the analysis of observed data from Area 3B (**Section 2.4.2**), a reduction in surface water flow may occur:

- via some depressurisation of shallow (outcropping) strata due to the depressurisation of deep strata. This has been observed or inferred in the middle reach of Wongawilli Creek (HGEO, 2018d and Watershed HydroGeo, 2018), where the recent drought conditions have reduced incoming stream flow to a point that this drawdown effect is clearly observed.
- via surface fracturing (**Figure 5-1**, **Figure 5-2**).

Offset (i.e. not directly above) from longwalls, the first of these two is the more likely, although fracturing of stream beds associated with flow loss can occur to a distance of approximately 290 m (as observed at LA4) and predicted by MSEC (2019). Above and adjacent to a longwall footprint, while the first behaviour will occur, it is the fracturing of the creek bed and subsurface that is likely to be the primary cause of a loss of flow.

Based on longwall geometry and depth of cover it is likely that the effects that would occur in streams directly above mining in Areas 5 (in particular) and 6 would be similar to the responses observed in streams directly mined under in Areas 3A and 3B. Likewise, effects on streams that are located offset or away from longwalls will be similar at similar distances to those observed near Area 3B.

Fracturing of creek and river beds is an observed phenomenon around the Southern Coalfield (e.g. at Dendrobium, Tahmoor, Appin, and Metropolitan). At Dendrobium, the stream known as WC21 (in the north-eastern part of Area 3B) has had a fracture network develop sufficient to divert all but flood flows. Other streams e.g. tributaries LA4 and DC13, and the upper part of Donalds Castle Creek, have also experienced changes or reductions in flow, as reported in the End of Panel Reports (HS, 2016c; HGEO, 2017a and 2018a). The effects are typically seen most clearly on recession flows or low flows – it is not possible to discern effects on high flows following storm events.

It has been suggested that the observed surface flow loss from the tributaries is lost from the catchment either via downward migration to the mine workings or to evapo-transpiration from deep-rooted vegetation. However, the catchment-wide effects of surface fracturing on flow and yield are difficult to accurately assess (McMahon, 2015). The experience at Dendrobium is that the loss of flow that is clear in the upper tributaries, e.g. WC21, Donalds Castle Creek tributaries, is not evident as a reduction in flow in the hydrographs from downstream flow gauging sites (HGEO, 2018a). This situation may change as more longwalls as extracted or if mining moves closer to the WWL gauge.

Additionally, water chemistry analysis (“finger-printing” – see **Section 4.5**) indicates that very little, if any, of the flow lost as a result of mining and subsidence from these watercourses in Area 3B enters the mine workings within the period of monitoring to date (greater than 4 years). The hypothesis that the flow is captured by deep-rooted vegetation cannot be easily tested. In any case, it is clear that any reduction in down-catchment yield from Area 3B mining has been small compared to the natural variation in the flow in those watercourses, i.e. too small to discern an effect at down-stream gauging stations.

More discussion and quantification of effects on streams is presented in **Section 8.5** and HEC (2019).

5.2.5 INCREASED INFILTRATION RECHARGE

Conceptually, the presence of fracturing at the surface could or would allow additional recharge to occur to the groundwater system (as in Table 5.2 of Advisian, 2016). This could occur via:

- increased infiltration of diffuse rainfall, leading to either or both a reduction in the amount of rainfall that becomes runoff or a reduction in the amount of rainfall that is evaporated or transpired in the soil zone or at the surface; or directly from the water surface.
- capture of surface flow (runoff and/or baseflow), as observed in tributaries above Area 3B (refer to HGEO, 2018a).

HS has attempted to analyse groundwater level and salinity data in areas where mining has occurred to try to confirm and quantify the first of these processes. However, the salinity data is not definitive, and groundwater levels fluctuations are affected by multiple processes which increase Kh, Kv, Sy and (possibly) recharge, meaning that it is not possible to isolate the recharge and quantify any change.

As a result, while we conceptualise it as a possible or probable process, the magnitude is uncertain. In the numerical modelling, an estimate of a 50% increase in infiltration recharge has been adopted for areas within the footprint of an extracted longwall.

5.2.6 EFFECTS ON UPLAND SWAMPS

Based on earlier assessments (e.g. HGEO, 2017a, 2018a), almost all undermined swamps were affected by mining. Swamps that are offset from longwall panels have typically been affected up to a distance of 60 m as described in Watershed HydroGeo (2019). Based on other data from Dendrobium, shallow water tables in non-swamp features were affected at 125 m.

Given the similarity in geology and longwall geometry, the effects of longwall mining on the Upland Swamps in Areas 5 and 6 (see **Section 2.7**) are likely to be similar to those observed in Areas 3A and 3B. I.e., it is expected that swamps that are located directly above or within the distances described above will be at a high risk of being affected by a reduction in water levels and/or an increase in the rate of drainage of these features after heavy rainfall events. These effects are a result of fracturing of the sandstone base of swamps and enhanced rates of groundwater shallow drainage beneath the swamp deposits (**Figure 5-3**).

As noted on **Figure 5-3**, the presence of the basal sands and gravels (see **Section 3.5**) means that the intersection of even a small number of fractures within the surface zone (**Figure 5-1**) with the base of a swamp would result in enhanced drainage of groundwater from the swamp. The main effect observed in swamp hydrographs in mined areas is an increase in the groundwater recession rate (i.e. the rate with which water drains from the swamp), and this is facilitated by the basal sands and gravels acting as a ‘drainage blanket’.

It may be possible for shallow cracks and fractures to fill with sediment over time, however the responses observed in Area 3A and 3B swamp piezometers do not suggest this has occurred in the time since these swamps have been mined over a period of approximately seven years.

5.2.7 INFLUENCE ON WATER QUALITY

Longwall subsidence can result in fracturing of streambeds and this fracturing can lead to changes in stream water quality because of the following processes:

- diversion of surface flows through shallow fractures (possibly up to 40 m depth);
- oxidation and dissolution of minerals in the freshly fractured bedrock (notably marcasite [FeS_2], ankerite [$Ca(Mg,Fe^{2+},Mn)(CO_3)_2$] and siderite [$Fe^{2+}CO_3$]); and
- leaching of ions from the bedrock strata present within the surface fracturing zone.

Oxidation of Fe^{2+} in sulphide and carbonate minerals can result in a decrease in pH and release of Fe, Mn and Mg into solution. This can manifest as ferruginous springs within and near streambeds, and the formation of iron staining of stream beds and rock faces. The release of hydrogen ions (decrease in pH) may be offset or buffered by pH increases caused by CO_2 outgassing from turbulent stream sections and by ankerite dissolution.

Watercourses that have been affected by subsidence (e.g. WC21 during mining of Longwalls 9, 10 and 11) have shown temporary increases in dissolved Fe and Mn, and an increase in pH to near neutral (pH 7) at sampling locations immediately down-gradient of the affected area. The overall salinity of stream waters (as estimated from EC) is controlled largely by rainfall patterns, with EC tending to increase during periods of low rainfall, but there is no discernible change in EC as a result of mining subsidence.

It is therefore expected that changes to water quality due to mining would be minor in stream reaches within subsidence affected areas. Local discolouration of streambeds and rock faces by iron hydroxide precipitation is a temporary impact. Water quality effects on stored waters of the reservoirs are expected to be negligible or undetectable, with further assessment being undertaken as part of the separate Surface Water Assessment (HEC, 2019).

Deeper groundwater is unlikely to be significantly affected over the long term. Mine inflows at Dendrobium are typically brackish, having similar chemical characteristics to deep groundwater. After mining is completed, the underground mine would flood and hydraulic head would eventually reach an equilibrium level, over a period of decades or longer. Until equilibrium is attained hydraulic gradients and therefore groundwater flow would be directed towards the mine. Based on pre-mining water levels and later modelling, the ultimate gradient should be downward in Area 6, but possibly ‘neutral’ or upward in Area 5 in the long-term. This could cause some upwelling of poorer quality water in the area above the goaf. Discharge to the surface environment may only occur via the mine portal, and possibly via old workings (Illawarra Coal, 2015), once the hydraulic head has recovered.

6 GROUNDWATER MODEL DEVELOPMENT

It is a requirement of the AI Policy (NSW Government, 2012) that a numerical model be used for licensing predictions, particularly partitioning of groundwater capture (“take”) between Groundwater Sources.

The broad objectives of the modelling are the prediction or estimation of project-specific and cumulative impacts, that is drawdown, water quality, water balance changes and influence on GDEs. Specifically, these are:

- Simulate the main features of the basin water balance, groundwater systems and contributions to surface water systems and groundwater dependent ecosystems.
- Predict the effects of Areas 5 and 6;
    - Mine inflows;
    - Partitioning of groundwater capture (”take’) from declared Groundwater Sources;
    - Reductions in watercourse flows (impact assessment and for licensing);
    - Leakage from adjacent reservoirs (impact assessment);
    - mine influence on swamp water tables (although given scale issues of the regional groundwater model, this is dealt with via local-scale modelling in the Surface Water Assessment [HEC, 2019] and via an assessment based on impacts observed at Dendrobium [Watershed HydroGeo, 2019]);
- Predict the cumulative effects of Areas 5 and 6 in combination with activities at other Dendrobium Mine areas (Areas 1, 2, 3A, 3B and 3C), as well as other mines in the area.

The following sections describe the development of a groundwater model for assessing potential drawdown and consequent effects of Dendrobium Areas 5 and 6 and the cumulative effects due to the combination of mining at Dendrobium and at other nearby mines.

6.1 PREVIOUS MODELS

Groundwater modelling has been conducted for Illawarra Coal’s Dendrobium operation since 2007, documented in GHD (2007), Coffey (2012b), HS (2014a; 2016a, 2016d; 2018). These have included the development of the model configuration and software, changes as discussed in Advisian (2016) as new data, such as the expansion of the monitoring network, changes in conceptualisation, and as new modelling software becomes available.

This current model is an extension of the previous modelling work.

6.2 SOFTWARE

Earlier models (Coffey, 2012b and HS, 2014a) used the MODFLOW-SURFACT software. HS (2016a) adopted MODFLOW-USG. The current model also uses the relatively new MODFLOW-USG computer code which is a recent addition to the United States Geological Survey’s (USGS) family of software. USG means “unstructured grids” that provides flexibility in setting the mesh geometry. MODFLOW-USG uses a control volume finite difference approach (CVFD), rather than the traditional MODFLOW’s rectilinear finite difference (FD) approach. The USG code offers significant advantages for modelling of longwall mines as follows:

- Allows complete deactivation of model cells that are not needed in the simulation, and hence are not included in the simulation thereby improving and reducing computation execution time and improving efficiency.

- MODFLOW-USG also allows for model layers to extend only in part of the model domain if required, whereas 'structured' Finite Difference MODFLOW models are required to have fully-extensive model layers.
- Allows simulation of transient changes in material properties using the Time-Variant-Materials (TVM) package developed by HydroAlgorithmics Pty Ltd.
- Possibility to include mesh elements called connected linear networks (CLNs) that simulate the connection of groundwater model cells to the goaf via 1D conduits. These can be used to represent, as a proxy, vertical connected fractures or boreholes.

HydroSimulations has undertaken extensive research to compare results from MODFLOW-SURFACT (by HydroGeoLogic) and MODFLOW-USG models (Merrick and Merrick, 2015). It has been found that the results for simulated groundwater heads, drawdown and inflows are closely comparable between these codes both spatially and temporally.

The model in this study uses the 'upstream weighting' method for simulating unsaturated conditions (similar to the 'pseudo-soil' function in MODFLOW-SURFACT), preventing problems with variably saturated strata and 'dry cells'.

6.3 MODEL EXTENT

The left-hand pane of **Figure 6-1** shows the model boundary on the right-hand map, shown in relation to Dendrobium mine areas, other mines, registered 'groundwater works' (bores) and water features such as reservoirs and major watercourses. The model covers slightly larger active domain than the previous versions of the regional groundwater model (first developed by Coffey, 2012b). The model has been designed to incorporate neighbouring mines in each direction (for the purpose of cumulative drawdown and any water quality assessment).

The model boundary is typically 10-15 km from the edge of the mining footprint at Dendrobium. This distance sufficiently far enough to minimise boundary effects at the critical features (namely the reservoirs and Areas 5 and 6). However, because of the extent and history of mining in the Southern Coalfield, some boundary effects may be unavoidable.

6.4 MESH DESIGN

Both panes on **Figure 6-1** show the 'unstructured' mesh employed in this groundwater model. This is the first of the line of models of Dendrobium that an unstructured mesh has been employed. The mesh has been designed using AlgoMesh (by HydroAlgorithmics), incorporating the following features:

- Uniform grids imposed within mine areas to better represent longwall geometry and progression. This includes rotating these uniform grids in different mine areas. This is visible on the right-hand pane on **Figure 6-1**.
- Unstructured 'voronoi' nodes or cells that follow the shoreline of the Avon Reservoir near to Areas 3B and 5 for improved representation of the shoreline and the distance from the reservoir to the nearest mine area.
- Nodes that follow the course of creeks for watercourses close to mining.

The constraints imposed and the optimization techniques within AlgoMesh have resulted in a mesh that has a maximum of 44,800 cells per layer. Given that there are 17 layers, this yields a total of 761,600 cells. However, MODFLOW-USG allows for model layers that are not fully extensive (unlike 'traditional' or structured versions of MODFLOW) thereby reducing the total number of nodes active in a model simulation. Hence consistent with the geological model constructed for this project, erosion and absence of stratigraphic units in certain locations means that many layers are not fully extensive, and that therefore there are only 698,211 active cells in the model simulation.

The smallest cells are 100-200 m^2 (i.e. approximately 10x10 m, 15x15 m, although usually not perfectly square), ranging up to 545,000 m^2 (i.e. approximately 740x740 m). Cells within the historical longwall areas are 60x60 m (= 3600 m^2), while those in the proposed longwall areas (Areas 5 and 6) are 50x50 m (= 2500 m^2).

6.5 MODEL LAYERS

The 17 model layers are based on the stratigraphy of the Southern Coalfield. **Table 6-1** sets out the model layering along with typical thicknesses for each, with reference back to the more detailed stratigraphy shown in **Table 3-1**, **Figure 3-1** and **Figure 3-3**.

These model layers are similar to those used in HydroSimulations (2014a, 2016a, 2018 and are based on the geological model supplied by Illawarra Coal which is defined by a large number (~hundreds) of exploration drill logs, as well as data shared with Tahmoor Mine and publicly available geological logs.

Table 6-1 Groundwater Model Layering

LAYER	STRATIGRAPHY		SECONDARY STRAT / LITHOLOGY	TYPICAL THICKNESS
1	Regolith		Swamp deposits Alluvium Wianamatta Formation (shales)	Regolith 5 m, swamps 2 m, WMFM 10-30 m
2	HBSS	Hawkesbury Sandstone (upper)		25-40 m
3		Hawkesbury Sandstone (middle)		40-50 m
4		Hawkesbury Sandstone (lower)	Crinanite	30-40 m
5	BACS	Bald Hill Claystone (includes Garie [GRFM] and Newport Formations [NPFM])	Crinanite	20-30 m
6	BGSS	Bulgo Sandstone (upper)	Colo Vale Sandstone (Area 3B and west) and crinanite	40-60 m
7		Bulgo Sandstone (lower)	Colo Vale Sandstone (Area 3B and west) and crinanite	40-60 m
8	SPCS	Stanwell Park Claystone	Colo Vale Sandstone (Area 3B and west) and crinanite	10-20 m
9	SBSS	Scarborough Sandstone	Crinanite	30-40 m
10	WBCS	Wombarra Claystone	Crinanite	20-30 m
11	CCSS	Coalcliff Sandstone	Wombarra Formation (Area 3B and west)	15 m
12	BUSM	Bulli Coal seam	Fault zones, cindered coal, intrusions	2-4 m
13	LDSS	Lawrence & Loddon Sandstones	Fault zones, cindered coal, intrusions	20-30 m
14	WWSM	Wongawilli Coal seam	Fault zones, cindered coal, intrusions	4-10 m (~4 m working section)
15	KBSS	Kembla Sandstone		15-25 m
16		lower Permian Coal Measures		20-30 m
17		Shoalhaven Group and older		modelled as 100 m

Layer 1 is fully extensive across the model domain, and is used to represent swamps, Wianamatta Formation, and alluvium where these are present, and otherwise simulates regolith where those other units are absent. The thickness of the swamp deposits is based on Illawarra Coal data. The thickness of the Wianamatta is based on Illawarra Coal's geological model and bore logs and published outcrop mapping. The thickness of the regolith in the Illawarra Coal geological model is in the range 0-18.5 m, with an average thickness of 5.1 m. Hence the thickness of model layer 1 has been set at a uniform thickness of 5 m.

The Hawkesbury Sandstone and Bulgo Sandstone units have been subdivided into three layers and two sub-layers respectively to better represent groundwater level (head) gradients across these thick units.

6.6 MODEL TIMING

The temporal discretisation is based on the need to simulate longwall progression for all Dendrobium mine areas, as well as simulation of some historical mining at neighbouring mines, in order to capture the inflow variability to Area 2.

The resulting stress period schedule (**Appendix F**) has 211 stress periods. The schedule shows that most historical longwalls are simulated across at least 3-4 stress periods and future longwalls across 2-3 stress periods. For the purpose of simulating or matching inflow variability there are three short stress periods to capture the rainfall event (typically 4-8 days long), a period of a week or so after rainfall and then a third stress period for the next 2-3 weeks across which the inflow pulse has been recorded in the Area 2 mine workings.

Of the 211 stress periods, the first (SP1) is the steady state period to initialize water levels, followed by two long stress periods to simulate long-term depressurization caused by decades of mining in this area. The first longwall at Dendrobium Mine commences in SP15. The historical period ends in SP110, with the commencement of Longwall 14 in Area 3B.

The predictive period runs from SP111 to SP211, incorporating the period where mining progresses through the approved areas before progressing into Areas 5, 3C and 6. This is followed by period SP193-211 represents post-mining recovery, which is simulated to 2200.

6.7 HYDRAULIC PROPERTIES

6.7.1 HYDRAULIC CONDUCTIVITY

The conceptual model (**Section 5.1**) developed, based on the analysis of hydraulic conductivity (**Section 4.7.1**), is that depth and lithology are the two primary controls on horizontal hydraulic conductivity (Kh). HS has adopted a 'Kh with depth' relationship, and the initial parameterisation of the model used an approximation of the arithmetic mean based on datasets from Illawarra Coal (Dendrobium plus BSO – black line) and Tahmoor (dashed orange line) on **Figure 4-2**. Data from the more distant Metropolitan Mine has not been used at this time, however the analysis across three sites addresses the issue raised by IEPMC (2018) regarding differing hydraulic conductivity values in different groundwater models. That is, with respect to this version of the Dendrobium groundwater model, the relationship of Kh with depth is consistent and well-constrained by the field data from Dendrobium, BSO and Tahmoor. Hydraulic conductivity of coal versus rock (sandstone/siltstone) has been made distinct due to the lithological differences.

The conceptual model is that vertical hydraulic conductivity (Kv) is governed more by the dominant lithology than depth. The initial parametrisation of the groundwater model relies on the calculated harmonic mean Kv per layer.

6.7.2 POROSITY AND STORAGE

The information from literature, core tests, NMR and previous modeling outlined in **Section 4.7.2** has been used as the basis for the parameterisation of natural or 'host' confined and unconfined storage (Ss and Sy, respectively) in the groundwater model. This includes approximate trends of:

- decreasing Sy and Ss with depth;
- higher Sy and Ss in units that are dominantly sandstones and the coal seams compared to units that are dominantly claystone/mudstone.

6.8 MODEL STRESSES AND BOUNDARY CONDITIONS

The following sections detail the numerical model boundary conditions used to simulate stresses or recharge/discharge processes in the MODFLOW-USG simulation. **Figure 6-2** shows the extent of the groundwater model along with many of the boundary conditions used.

6.8.1 MODEL BOUNDARY

A number of model boundary condition types are employed around the edge of the model. **Figure 6-2** shows that Constant Head Boundary conditions are set where the model extent intersects the coastline around Wollongong. The constant head elevation is set to sea level.

A series of General Head Boundary (GHB) set around other parts of the model domain where groundwater flow is conceptualized as being into or out of the model (rather than predominantly 'parallel' to the edge of the model). Typically this is along the southwestern boundary to represent northward groundwater from the Southern Highlands entering the active model domain, and along the northern boundary to represent the continued northward flow toward the centre of the Sydney Basin (**Section 4.3.1**).

In these areas GHBs are set to allow groundwater flux in the more transmissive parts of the groundwater system, typically layers 2, 3, 4, 6, 7, 9, 10, 12 and 14 (refer to **Section 6.5**). The elevation of these is based on nearby groundwater levels from observation bores (where available), otherwise extrapolated levels from contouring or previous modelling.

Inactive or 'no flow' boundaries are not used in this model. This is different to previous modelling at Dendrobium. This is an advantage of the MODFLOW-USG code. Instead of having a rectangular model area and inactivating cells to create a more hydrologically-correct boundary, the areas that would previously have been inactivated are simply not written to model files, with a consequent reduction in file size and some advantage in terms of computation time. Furthermore, where geological units have been eroded away, these are also not inactivated – that is the 'pinch-out' capability of MODFLOW-USG allows groundwater model layers to be only partially extensive across the model domain.

6.8.2 WATERCOURSES

MODFLOW 'River' boundaries have been employed to represent watercourses (**Figure 6-2**).

The watercourses simulated include variable stream stage, based on a time series of runoff from the water balance model (**Section 6.8.5**), for simulating gaining/losing conditions. The stage (water depth in the stream) is varied along each watercourse, i.e. smaller headwater creeks may have a stage of 0-2 m applied across dry/wet periods, while for larger watercourses (e.g. Nepean River) the stage varies from 0-8 m applied across dry/wet periods.

River conductances are based on the approximate width of the watercourse combined with streambed hydraulic conductivity. Smaller creeks have been set with a width of 1.5 m, while for larger rivers widths of up to 25 m have been used. Hydraulic conductivities for the streambeds are estimated in range 0.001 to 0.3 m/d, depending on outcrop geology (rock, alluvium, swamps) based on the data analysis (**Section 4.7.1**) and the conceptual model (**Section 5.1**). This means that streambed conductances range between 8-1800 m^2/d, for a uniform bed thickness of 0.25 m.

6.8.3 ESCARPMENT SPRINGS

The Wollongong Escarpment is the major topographic feature in this area. The topographic elevation ranges from about 300 to 400 mAHD across the plateau inland of the escarpment, up to 450 mAHD at the top of the escarpment down to about 100 mAHD at the base. There is a gentler surface gradient east from there down to the coastline. This significant change in topographic slope causes all stratigraphic units from the Hawkesbury Sandstone down to the Coal Measures, including the Wongawilli Coal seam (i.e. model layers 2-14) to be truncated by erosion. MODFLOW 'River' cells have been set along the escarpment (**Figure 6-2**) to allow groundwater discharge along this feature.

Stream stage is set based on local topography, and conductances in this area are set in the range 40-100 m^2/d.

6.8.4 LAKES / RESERVOIRS

A number of water storage reservoirs are located in this region, such as the Avon Reservoir. While they are technically 'reservoirs', being man-made impoundments of water, they are typically identified by the name 'lake' (e.g. Lake Avon), as in much of the government mapping and documentation. Therefore, in this report they are identified as both interchangeably.

MODFLOW 'River' boundaries have been employed to represent the reservoirs, as in previous modelling at Dendrobium. The historical record of water levels in the Avon and Cordeaux Reservoirs has been employed to specify the stage of the lake or reservoir for the historical period, while the full storage level (FSL) has been used to specify reservoir stage in the predictive period. Conductance was calculated based on cell area, an assumed 2 m thick lake bed and hydraulic conductivity of 0.001 m/d, based on horizontal and vertical hydraulic conductivity of the Hawkesbury Sandstone. A sensitivity run (**Section 9**) has been run to test the effect of increasing this to represent a more permeable lake bed (using an effective K of 0.02 m/d). A 20-fold increase in lake bed conductance resulted in a 5% change in predicted reservoir losses due to Dendrobium, indicating that this parameter is not very sensitive.

Runoff into, flows and evaporation out of reservoirs are not simulated. These are taken into account by using historical stage data where available. For predictive modelling, the Full Storage Level is used to maximize the head gradient from lake to adjacent groundwater systems and so provide a conservative estimate of leakage from reservoirs.

6.8.5 RECHARGE

Infiltration recharge

The MODFLOW Recharge (RCH) package is used to simulate diffuse rainfall recharge. As in HydroSimulations (2016a, 2018), temporal variation in rainfall recharge has been calculated based on a water balance determined on a daily time step and accounting for runoff, soil moisture deficit and recharge based on inputs of rainfall and potential evaporation.

The water balance model has been calibrated to match estimates of average or long-term recharge obtained from a number of literature sources and from analysis of Dendrobium data (**Section 4.6.3**, **Table 4-10**), noting that an additional source for recharge estimates was presented in that table, and is used to compare to the updated water balance model here. This recent source is the BoM (2016) AWRA-L 'landscape' model, which produces areal estimates of rainfall, evaporation, runoff, deep drainage (infiltration).

The HS water balance model has been modified from previous modelling (HS, 2016a) to better match the AWRA model results, noting the modification was only slight as the estimates were already quite similar. In order to fully compare the two models, AWRA runoff was also compared to the runoff and interflow (i.e. 'quickflow', as in Brodie and Hostetler, 2005 or Gordon *et al*, 2004) generated by the HS water balance model. That comparison is favourable, with mean AWRA runoff = 306 mm/yr and HS quickflow = 323 mm/yr (5% variance). **Table 6-2** presents the latest HS modelling against external references.

Table 6-2 Calibration of rainfall recharge model

REFERENCE	ANALYSIS METHOD	RECHARGE	
		% LTA rain	mm/yr
Crosbie, 2015	Chloride mass balance in shallow groundwater.	3-8.5%	40-100
Coffey, 2012a,b	Baseflow separation, water table fluctuation.	2.7 or 6%	n/a
DPI, 2011	unknown	6%	n/a
Pells, 2013	unknown	5%	50
URS, 2007	water table fluctuation	3-10%*	n/a
AWRA-L	Model (2005-2018)	6.9%	83
HS, 2018	**Model** (2005-2018)	**7%**	**84**

LTA: Long-term Average. BFI : Baseflow Index. * URS stated that local variation might be 2-16%, but "realistic range" is 3-10%. AWRA-L model results for (~5x5 km) model cell at Lat -34.39, Long 150.71.

The average recharge as calculated by the water balance model for the areas of rock outcrop is equivalent to about 7% of long-term average rainfall. As Advisian (2016) concluded, the weight of evidence from multiple studies is that recharge to the Hawkesbury Sandstone is within a range of 5-8.5% of LTA rainfall.

Figure 6-3 presents the zonation of recharge in the model. As in Coffey (2012b) and HydroSimulations (2014, 2016a, 2018), these zones have been defined based on:

- presence of lakes or reservoirs (no infiltration recharge simulated due to presence of a permanent waterbody, as per Zone 1 in **Table 6-3**);
- outcrop geology – swamps vs hard-rock vs Wianamatta Formation; and
- long-term average rainfall – using bands of rainfall <1000 mm/yr, 1000-1200 mm/yr and >1200 mm/yr. Average rainfall declines with distance from the coast.

The average recharge simulated in the various zones is summarized in **Table 6-3**. The trend of declining recharge in line with declining long-term average rainfall away from the coast was included in previous models by Coffey and HS, but also seen in Crosbie (2015).

Table 6-3 Average recharge calculated by water balance model (2000-2018)

ZONE	1	2	3	4	5	6	7	9
		HBSS-SE	HBSS-Centre	HBSS-NW	Swamp-SE	Swamp-Centre	Swamp-NW	Wianamatta Fm
Recharge	0	90	71	25	245	223	79	13

Units in mm/yr

Figure 6-4 presents the modelled time series of infiltration recharge and potential evapotranspiration from groundwater (see **Section 6.8.6** for discussion of evapotranspiration) at Dendrobium. Estimates of rainfall recharge to the swamps are not available due to the difficulty in isolating diffuse infiltration from run-on from upslope but conceptualised as being significantly more than to the rock outcrop. As a result, the water balance model for the swamp areas was set to produce a time series of recharge of about 330 mm/a, equivalent to 25-30% of long-term average rainfall. This is an assumption, based on the conceptual model and higher hydraulic permeability of these sediments compared to that of the surrounding rock outcrop.

Enhanced recharge within longwall footprint

The conceptual model of this process is discussed in **Section 5.2.5**.

Mining-induced increase in diffuse recharge has been simulated using the MODFLOW Recharge package. As noted earlier, the rate of increase is uncertain. A 50% increase in infiltration recharge has been adopted for some of the calibration and predictive modelling. This has been applied to hard-rock areas above Dendrobium longwall panels following extraction of underlying section of panel. This can cause two effects:

- an increase the hydraulic gradients above longwall panels, potentially leading to more groundwater entering the workings (e.g. at Area 2);
- faster recovery of groundwater levels post-mining, although that is complicated by enhanced hydraulic conductivity and (drainable) porosity of strata above longwalls.

6.8.6 EVAPORATION AND EVAPOTRANSPIRATION

The water balance model described in the previous section also includes estimates of actual evapotranspiration in the soil zone (‘AE_{soil}’) (or, the notation of Doble and Crosbie, 2017, $E_{uz} + T_{uz}$, where E = evaporation, T = transpiration, and the UZ subscript denotes the unsaturated zone, i.e. ‘soil zone’), and whether there is excess potential evaporation (PE) available on each day during the modelling sequence. Any excess in PE is available to remove groundwater from the saturated zone (the water table), provided the water table is shallow enough and/or directly from any open body of water. This excess PE is then averaged across each model stress period and applied to the MODFLOW model using the Evapotranspiration (EVT) package. The potential rate of evapotranspiration from groundwater has been set at approximately 350-550 mm/yr for the outcropping rock at Dendrobium, and the groundwater model simulates the rate of actual ET_{gw} (evapotranspiration from the water table) as a fraction of the potential rate based on the simulated depth to water.

Figure 6-4 shows the modelled transient ‘excess PE’ sequence applied to swamps and to the sclerophyll forests on rock outcrop, based on the zonation in **Figure 6-3**.

Plant rooting depth governs the extinction depth parameter required for the MODFLOW EVT package. The extinction depths specified are based on previous modelling conducted at Dendrobium (HS, 2016a, 2018) and guided by literature including Canadell *et al.* (1996) and Zolfaghar (2013). Extinction depth was set at 4.5 m for woodland/forest areas.

IESC (2014a) states that the upland swamps can include a range of vegetation with differing heights and rooting depths. However rooting depths swamp species are not well known or quantified. As a result, extinction depth was set 1.9 m for swamp areas based on the approximate sediment thickness for the swamps.

The potential rate of evapotranspiration from shallow water tables and the extinction depths were not changed in the post-mining environment.

6.8.7 MINE WORKINGS

MODFLOW 'Drain' boundaries conditions have been employed to represent mining, specifically simulating the removal of any groundwater entering and collected within the workings, usually done by pumping from a series of sumps. Drains were activated to fit the latest mine schedule as per **Table 1-6**, **Table 1-7**, **Figure 1-2** or **Figure 6 2**, with overall modelled longwall progression as shown in **Appendix F**. Drains applied within the mined seam are set at 0.1 m above the base of the layer, with conductances set to 2.5 m^2/d for longwalls and 0.025 m^2/d for other mine workings. These were set to ensure drainage of the model cells representing the mine workings.

Additionally, Drains have been employed for representing flow to the mine workings through the connected fracture zone above the goaf. More discussion on the use of Drain boundary conditions for this is presented in **Section 6.9**.

6.9 REPRESENTATION OF FRACTURING AND DEFORMATION

Within groundwater models, simulation of mining-induced changes to the hydraulic properties of rock strata within and above the mined zone has typically been limited to simulating the connected fracture zone. HS are aware of three methods for simulating the connected fractured zone in groundwater models, and these are discussed in **Section 6.9.1**.

Other zones and mechanisms are simulated in this groundwater model, based on conditions of approval at Dendrobium and the PSM (2017) study into the fracturing above longwalls. The representation of these is discussed in **Sections 6.9.2 to 6.9.5.**

All the methods tested, and the combination of methods for different processes, have some weakness, either in conceptual terms, or with software/model stability and performance.

6.9.1 ZONE OF CONNECTED FRACTURING

The presence of a network of connected fractures extending up from the longwall as a result of mining subsidence can be simulated in a number of ways. Broadly, the three primary methods adopted are:

- Time-varying hydraulic properties, using the MODFLOW-SURFACT TMP package or MODFLOW-USG TVM package.
- Connected Linear Networks (CLN) package in MODFLOW-USG. This method simulates flow in a discrete conduit. This method was used in HS (2016a).
- 'Stacked Drains', where a set of Drain boundary conditions are imposed in each layer within the connected fracture zone to represent the free-draining fracture network.

Each of these methods has been used in modelling at Dendrobium, and often a combination must be used to capture all the subsidence and deformation processes. A summary of the advantages and disadvantages of each is provided HS (2018).

During previous phases of groundwater modelling at Dendrobium it was found that while each method could be calibrated to inflow during the active longwall extraction phase in each separate mine area (see discussion of inflow character in **Section 4.4.1**), it was difficult to match inflow in the period after longwalls had been extracted but while significant inflow and often significant variation in inflow was still evident. Specifically, the inflow with strong peaks to Area 2 (*after* Longwall 5) and muted peaks in Area 3A (*after* Longwall 8) were difficult to simulate – consequently for the current degree of calibration, the 'Stacked Drains' method has been employed for this study. As a result, the model was found to be more stable, with better convergence and also gave better results during calibration runs for matching the variability of Area 2 inflows.

It is considered that the use of ‘Stacked Drains’ to simulate the connected fracture zone should provide a suitable and more conservative assessment as this method has been used successfully by other modelling consultants (e.g. AGE, 2017).

Geotechnical modelling of the overburden using FLAC2D software has been carried out by SCT (2017 and 2018b) for representative 305 m wide panels in Areas 5 and 6 (**Section 4.8.3**). This modelling suggests that fracturing would extend from seam to surface in most of the cases modelled by SCT.

Based on that analysis seam-to-surface connection has been enforced for all multiple (adjacent) 305 m wide panels, noting that it is based on the ‘void width’ (**Table 1-6** and **Table 1-7**). This is consistent with the interpretation by PSM (2017) for Longwall 9. In addition, it is also in line with the Width/Depth of Cover ratio (W/D) approaching a value of 1, as noted in **Section 4.8.2** and separately by MSEC (2019) and the Peer Reviewer.

For panels narrower than 305 m, the Tammetta (2013) empirical model has been used to estimate the height of connected fracturing for all modelled longwalls, based on the local conditions (panel width, depth of cover (considered separately but not together), cutting height). Despite weaknesses of the main empirical models used to estimate the height of fracturing (as stated in PSM, 2017 and Galvin, 2017a), the Tammetta model has been used as it is typically the more conservative than the alternative models by Ditton (Galvin, 2017b). As noted previously, this is consistent with the recommendations of IEPMC (2018).

The resultant modelled profile of seam, surface and the height or depth of the main fracturing zones are shown in **Appendix G**. There are areas where the calculated fracturing (Tammetta H) extends high enough to intersect the estimated surface cracking zone or ground surface, even without the enforcement of seam-to-surface fracturing for the 305 m wide longwalls.

Within the MODFLOW software, the parameter COND is the conductance of a Drain. This parameter is the combination of the dimensions of the drain, and the hydraulic conductivity of and the distance across “the interface between the aquifer and the drain” (Panday *et al*. 2013). In this application, the Drain is the fracture network (assumed to be desaturated), and the interface is represented by the hydraulic conductivity of the host strata, the dimensions of the drain are based on the cell geometry and total fracture network aperture or density, and the distance across the interface is based on the cell geometry.

The ‘Stacked Drains’ have been set with a conductance that is variable, depending partly on height above the mined panel, but on a number of other factors as outlined below. HS adopted the following steps from a method first employed by AGE (2017).

- HS reviewed the FLAC2D geotechnical modelling developed by SCT (2017 and 2018b) for 305 m wide longwalls in Areas 5 and 6 and used SCT’s modelled post-mining hydraulic conductivities (using the data shown on the two left-hand charts on **Figure 4-20**) in the following step. The use of the FLAC2D modelling results meets one of the recommendations of PSM (2017) and Mackie (2017).
- Estimate the effective fracture aperture (*a*), based on the modelled hydraulic conductivity (K) with height above the panel. SCT’s (and others) analysis and modelling relies on a modified cubic relationship between hydraulic conductivity [*K*] of the fracture network and hydraulic aperture [*a*] (m):

$$K \sim a^3 \times 10^6 m/s \quad \textbf{Equation 1}$$

- Re-arranging the relationship allowed estimation of the effective fracture aperture from the hydraulic conductivities calculated by the FLAC2D modelling (SCT, 2017 and 2018b – see **Section 4.8.3** of this report or Figure 15a of SCT, 2018b for a summary of modelled K with height above the panel). The relationship derived for aperture versus height above the seam [*h*] is:

$$a = -0.001ln(h) + 0.01 \qquad \textbf{Equation 2}$$

- AGE (2017) found that using the Thiem equation to calculate the conductance of groundwater model cell connecting to a conduit (as described for CLNs in Panday *et al*., 2013, but used elsewhere for other MODFLOW packages) provided a good estimate of the conductances for the 'Stacked Drains'. I.e. it resulted in improved simulation of inflow and groundwater levels. We have adopted the same approach, and therefore drain conductance [α_{fn}] was calculated based on the Thiem equation:

    - $$\alpha_{fn} = \left[\frac{\ln\left(\frac{r_{oz}}{r_n}\right)+S_f}{2\pi l K_{xz}\sqrt{1/R_{rz}}}\right]^{-1} \qquad \textbf{Equation 3}$$

- where,

r_{oz}	= effective external radius of MODFLOW cell to fractured network.	*= model cell dimensions x 0.208 (calibration factor, as per AGE, 2017)*
r_n	= effective radius of the fracture network.	*= a (from* **Equation 2**.*)*
S_f	= skin factor.	*= 1*
l	= effective thickness of fracturing within the model cell.	*=vertical thickness of model cell*
K_{xz}	= host hydraulic conductivity.	*= calculated as geometric mean of the horizontal and vertical host hydraulic conductivity*
R_{rz}	= x:z anisotropy ratio (Kx / Kz).	

- The key difference to the original method of Panday *et al* (2013) and AGE (2017) is that the original calculation considered either horizontal or vertical flow as dominant, and for this problem HS has conceptualised flow to be both horizontal (when entering vertical fractures) or vertical (when entering shears, dilated bedding planes), so conductance needs to account for this.
- The inputs to **Equation 3**, e.g. skin factor and the use of different methods of incorporating hydraulic conductivity (K_x, K_z), were varied during calibration. The 'baseline' or calibration groundwater model has 'Stacked Drain' conductances varying from 3.5E-5 to 0.67 m^2/d, averaging 0.047 m^2/d. The incorporation of the cell thickness (*l*) and host hydraulic conductivity parameters into **Equation 3** means that modelled drain conductance is not governed so much by height above the panel. In fact, the greatest conductances typically occur in model layers 3, 4 and 6, corresponding to the higher host hydraulic conductivity and greater thickness of these units. This method is an improvement on the configuration in recent modelling (i.e. HS, 2018) in terms of the ability to replicate groundwater inflow and drawdown.

After the mine ceases removing water from the workings at the end of the mine life, the MODFLOW Drains in the workings and the 'Stacked Drains' representing the fracture network are inactivated. At this point Kv needs to be increased in order to simulate the fracture network and allowing the groundwater model to simulate groundwater recovery around the mine. The model increases Kv by 25 times in the top of the facture zone to more than 4-5 orders of magnitude in the caved zone (guided by SCT, 2018b and then with further groundwater model calibration).

Enhanced specific yield (Sy) is discussed in **Section 6.9.5.**

6.9.2 SURFACE CRACKING ZONE

Estimates of surface cracking depths above extracted longwall panels include:

- 20-30 m at Springvale, based on a mined thickness of 3 m (Guo et al, 2007);
- up to 15 m ("50 ft") in Kendorski (2006);
- 10-15 m (Ditton and Merrick, 2014).

In order to make the assessment conservative, a greater depth of surface cracking has been simulated. We have adopted a surface cracking depth of 10 x longwall cutting height (t) above longwall panels. This means that the surface cracking zone above Dendrobium is simulated as being about 34 m (Area 1), up to 45 m (Longwalls 10-12) in Area 3B, and about 32 m above longwalls in Area 5 and 39 m for proposed longwalls in Area 6 (**Appendix G**). There will be some difference in the model application given the thickness of model layers compared to the scale of 10 x t.

This representation of the surface cracking zone was set as having a horizontal hydraulic conductivity as 3 times that of the host material and vertical hydraulic conductivity that is 50% greater than the host strata. Higher factors were initially tried during model calibration, and these resulted in modelled inflow hydrographs with fewer inflow peaks.

6.9.3 OFF-GOAF (VALLEY CLOSURE)

The development of shear planes because of valley closure is discussed in SCT (2015). In the groundwater model, the process has been tested in the Sensitivity Analysis (**Section 9**) and is simulated by increasing horizontal hydraulic conductivity of the strata between the longwalls and the nearest 'deep' valley. This has been done by selected model cells within a certain distance or buffer (less than 100 m from the longwall, less than 300 m and less than 600 m) and assigning a Kh multiplier to each buffer area, with the multiplier decreasing with distance from the longwall. The modelled timing of the hydraulic conductivity enhancement is based on the timing of the nearest longwall.

The Kh factors adopted were x4, x3 and x2, based on previous modelling (HS, 2018). Kh enhancement is simulated as occurring in the strata from the base of the nearest valley, e.g. in the lower Hawkesbury Sandstone (and above) between Area 3B and Lake Avon, between Area 5 longwalls and Lake Avon, and between Area 6 and Lake Cordeaux.

6.9.4 UNDERLYING (FLOOR) STRATA

Deformation (buckling) in floor strata is caused by unloading. This has been simulated with a horizontal hydraulic conductivity increased by a factor of 5, and vertical hydraulic conductivity increased by a factor of 2. This is applied to the layer immediately below the mined seam.

6.9.5 DISTRIBUTION OF INCREASED POROSITY

The extraction of the longwalls can cause an increase in porosity, specifically the drainable porosity or specific yield (Sy) property, in the subsurface, and this can influence groundwater storage and flow. For example, the removal of 3.9 m of coal at Dendrobium (**Table 6-4**) causes an increase in the void space or porosity through the strata. The strata volume then reduces due to goaf collapse and subsidence at the surface (see example on the left-hand side of **Table 6-4**). The consequent reduction in strata volume between the seam floor and the surface results in some re-distribution of porosity (total and 'drainable' Sy) throughout the profile.

Advisian (2016) has indicated that: "In areas nearer the zone of extraction, such as the caved zone, both vertical and horizontal cracking is substantial and therefore significant increases in vertical and horizontal hydraulic conductivity are expected, as well as increases in porosity." PB (2015) stated that the greatest strain occurs below their lowest extensometer (i.e. below the Bulgo Sandstone).

Table 6-4 Modelled Enhancement of Porosity / Specific Yield

POROSITY CALCULATION	
PARAMETER	VALUE
Mined height	3.9 m
Subsidence	0.8 m (pillar);^ 2.5 m (centre)^
Porosity created	1.5 m (averaged)
	= 3.9-1.5 = 2.4 m
Depth of Cover	350 m
Average increase in drainable porosity	=2.4 / 350 = 0.007 = 0.7%

MODELLED POROSITY ENHANCEMENT					
		HOST		POST-MINING	
Layer	Thickness*	Sy	Void (m)	Sy	Void (m)
Wombarra Fm (L11)	15 m	0.004	0.06 m	0.033	0.495 m
Bulli Seam (L12)	2.5 m	0.016	0.04 m	0.06	0.15 m
LRSS (L13)	28 m	0.005	0.14 m	0.05	1.5 m
Wongawilli Seam (L14)	4 m **	0.015	0.06 m	0.15	0.6 m
Total			0.3 m		2.65 m
Difference			=2.65-0.3 = 2.3 m		

^ taken from MSEC, 2017. *End of Panel for LW12*; * example thickness; ** working section only

In the current model, the specific yield (Sy) increase occurs within the mined seam, the caved zone and the lower parts of the connected fractured zone, as a shown in the right-hand columns of **Table 6-4**.

Table 6-4 shows good agreement between the 'calculation' of porosity created and the example distribution of void space (m) or Sy enhancement in the groundwater model. It is acknowledged that porosity can be created or enhanced higher in the profile, and possibly in a non-systematic manner (e.g. as in PB, 2015). However, HS considers that most of the Sy enhancement will occur in the zones nearer the mined seam (as per Advisian, above) and the Sy enhancement would slow the rate of groundwater level recovery after mining. This delay is because of the increased pore space that can be filled. However, the delay due to this process is possibly negated or overwhelmed by increased hydraulic conductivity.

6.9.6 OTHER WORKINGS

Within roadways and bord and pillar areas, the horizontal hydraulic conductivity was set to 10 m/d, and vertical hydraulic conductivity to 0.002 m/d. These are assumptions, both based on using values that are higher than the available data for the host hydraulic conductivity suggests for conservatism, but not so high as to introduce model convergence and mass balance issues.

7 GROUNDWATER MODEL CALIBRATION

7.1 APPROACH TO CALIBRATION

Calibration targets were for mine inflow and groundwater levels, while constraining the hydraulic conductivity based on the large dataset of packer and core test results. These were available at Dendrobium supported by data from neighbouring mines (BSO, Tahmoor).

The model uses many available values of hydraulic conductivities and storage parameters, recharge, boundary conditions and conductances. Manual calibration methods were used to modify the hydraulic conductivity (horizontal and vertical), and specific yield of modelled layers or zones, and the conductances of the stacked drains to match the inflow and groundwater level targets.

Calibration has been attempted for inflow to each mine area (Areas 1, 2, 3A and 3B). This is viewed as important as the different character of inflow at each area, particularly different situations in Area 2 and Area 3B as assessed by HS.

The conductance of the 'Stacked' Drain boundary conditions, which are used to represent the connected fracturing above the longwalls, proved to be very effective in achieving calibration of the groundwater inflow.

7.2 CALIBRATED HYDRAULIC PROPERTIES

Table 7-1 presents the K and S parameters used in the calibrated 'base case' model.

7.2.1 HOST OR NATURAL HYDRAULIC CONDUCTIVITY

During model calibration, changes were made from using constant horizontal hydraulic conductivity (Kh) within a number of strata units (as used in previous modelling at Dendrobium) to using variable Kh with respect to depth. Some units were still used to allow some additional lithological controls, but generally all units within Layers 2-17 have been modelled using the accepted Kh-depth relationship estimated from analysis of packer tests of all stratigraphic units (**Section 6.7.1**). This relationship modified during calibration, but based on the formulation presented in AGC (1984):

$$\mathrm{K} = \mathrm{K}_o . \exp(-cz)$$ **Equation 4**

- where,

c = gradient; z = depth [m].

The broad Kh-depth relationship at Dendrobium was calculated to be:

$$\mathrm{K} = 0.022 \exp(-80 - z)$$ **Equation 5**

- where,

the hydraulic conductivity K calculated by this relationship is limited to the range 2E-4 to 2.5E-2 m/d

This relationship (red line) is compared against field data from Illawarra Coal's database on **Figure 7-1**, alongside the calculated arithmetic mean (black) and geometric mean (purple) for each 50 m depth interval. The final relationship is similar to the arithmetic mean of all data down the sequence. The orange series on **Figure 7-1** is the arithmetic mean of the data from Tahmoor Mine, and the derived Kh-depth relationship for the model is generally consistent with that data too, as per the discussion in **Section 6.7.1**.

No depth relationship was applied to any of the units in Layer 1 (**Table 7-1**).

Table 7-1 Calibrated Modelled Hydraulic Parameters

Layer	Zone#	Geology	abbrev.	Kh	K_h m/d	K_v m/d	Ss m-1	Sy
1	11	Swamps		n/a	1	0.05		0.3
	1, 3	Alluvium		n/a	10, 3	0.3, 5e-3		0.1
	2	Wianamatta Formation	WMFM	n/a	0.015	2.0E-05		0.1
	10	Regolith		n/a	0.03	0.03		0.1
2	20	Hawkesbury Sst (upper)	HBSS	1.3	*K-depth*	1E-05	5E-03	0.05
3	30	Hawkesbury Sst (mid)	HBSS	0.6	*K-depth*	1E-04	1E-06	0.025
4	40	Hawkesbury Sst (lower)	HBSS	1	*K-depth*	3E-05	1E-06	0.012
5	50	Bald Hill Claystone	BACS	0.1	*K-depth*	3E-06	1E-06	0.006
	51	Crinanite (weathered)		0.8	*K-depth*	3E-03	5E-04	0.01
6-11	multiple	Crinanite		0.25	*K-depth*	5E-05	5E-04	0.01
6	60	Bulgo Sst (upper)	BGSS	1	*K-depth*	1E-04	9E-07	0.008
	61	Bulgo Sst (upper)	BGSS	1	*K-depth*	5E-05	9E-07	0.008
	62	Bulgo Sst (upper) / CVSS	BGSS	0.7	*K-depth*	1E-06	9E-07	0.008
	64	Bulgo Sst (upper) (A2 outcrop)	BGSS	0.8	*K-depth*	2E-06	9E-07	0.008
7	70	Bulgo Sst (lower)	BGSS	1	*K-depth*	2E-05	8E-07	0.007
	71	Bulgo Sst (lower)	BGSS	1	*K-depth*	5E-05	8E-07	0.007
	72	Bulgo Sst (lower) / CVSS	BGSS	0.7	*K-depth*	2E-06	8E-07	0.007
	74	BGSS (lwr) near A2/crinanite	BGSS	2	*K-depth*	6E-06	8E-07	0.007
8	80	Stanwell Park Claystone	SPCS	0.25	*K-depth*	3E-05	7E-07	0.005
	81	Stanwell Park Claystone	SPCS	0.25	*K-depth*	2E-06	7E-07	0.005
	83	SPCS, near A2	SPCS	2	*K-depth*	4E-06	7E-07	0.005
9	90-92	Scarborough Sst	SBSS	1	*K-depth*	1E-06	6E-06	0.01
10	100	Wombarra Claystone	WBCS	0.25	*K-depth*	5E-06	5E-07	0.0035
11	110	Coalcliff Sandstone	CCSS	1	*K-depth*	7E-06	4E-07	0.004
	111	Coalcliff Sandstone	CCSS	0.5	*K-depth*	5E-06	4E-07	0.004
12	120	Bulli Seam	BUSM	20	*K-depth*	1E-06	2E-07	0.004
	121	Bulli Seam – cindered	BUSM	0.3	*K-depth*	6E-06	1E-06	0.016
	123	Bulli Seam – faulted (mylonite)	BUSM	0.4	*K-depth*	3E-05	1E-06	0.016
13	130	Lawrence and Loddon Ssts	LDSS	1	*K-depth*	1E-06	2E-07	0.004
	131	Nepheline syenite		0.4	*K-depth*	2E-06	3E-07	0.005
	132	Fault/mylonite		0.5	*K-depth*	9E-06	3E-07	0.005
14	140	Wongawilli Seam	WWSM	40	*K-depth*	1E-06	2E-07	0.004
	141	Nepheline syenite		0.4	*K-depth*	3E-06	4E-06	0.02
	142	Wongawilli Seam – cindered	WWSM	0.5	*K-depth*	2E-06	3E-06	0.012
	143	Fault/mylonite		0.5	*K-depth*	9E-06	1E-06	0.015
15	150	Kembla Sandstone	KBSS	1	*K-depth*	3E-05	3E-07	0.0045
	151	Kembla Sandstone – outcrop	KBSS	1	*K-depth*	1E-05	1E-04	0.02
	152	Kembla Sandstone – outcrop	KBSS	1	*K-depth*	8E-04	1E-04	0.02
16	160	lower Permian Coal Meas.	lPCM	1	*K-depth*	1E-05	3E-07	0.004
	161	lower Permian Coal Meas.	lPCM	1	*K-depth*	8E-04	3E-06	0.03
17	170	Shoalhaven Group		1	*K-depth*	2E-06	3E-07	0.005

K-depth = means that Kh is primarily determined by depth of mid-point of model cell (see **Equation 5**).
Kh factor used to provide additional control based on lithology, facies variation. DND4_mesh_Kwdepth_4v71.xlsx

An additional part of the parameterisation of Kh was the use of a lithological factor. These are reported as 'Kh factor' in **Table 7-1**, and are a multiplier to the relationship in **Equation 5**. These incorporate some additional variation in Kh, based on facies mapping (e.g. from BHP, 2013), and based on the conceptual model. E.g. the coal seams are more permeable than the surrounding siltstones and sandstones even though they occur at similar depths, so the calculated Kh for these have been multiplied by 20-40 times (see **Table 7-1** above), which is consistent with the drillstem test dataset described in **Section 4.7.1**. Another example is that intrusions and cindered coal are considered less permeable than surrounding coal (based on discussion with Illawarra Coal geologists).

The resultant distribution of horizontal hydraulic conductivity for each layer is shown in **Appendix H**. White space on each figure represents where that particular stratigraphic layer is absent.

Generally vertical hydraulic conductivity (Kv) is not varied with depth, except in the shallow subsurface. If a model cell lies within 10 m of the surface, then the Kv for that layer is specified as the regolith Kv (0.03 m). Otherwise model Kv is as per **Table 7-1**.

7.2.2 SUBSIDENCE-ENHANCED PROPERTIES

As discussed in **Section 6.9.1**, connected fracturing is primarily dealt with via 'Stacked Drains'. At the end of all mining at Dendrobium (i.e. the end of Area 6) the drains are inactivated, and hydraulic conductivity is modified via the TVM package of MODFLOW-USG. In this instance, Kv is increased by a factor of 100 in the 'caved zone', by 25 in the connected fracture zone. At the same time, Kh is increased by a factor of 10 in both instances, although this is a less sensitive parameter.

Deformation in other zones (e.g. surface cracking zone, underlying strata) are discussed in **Sections 6.9.2 and 6.9.4** respectively. Specific storage (Ss) has not been enhanced in simulations. David *et al*. (2017) made some estimates of enhanced Ss above longwalls, however we consider that this parameter is likely the least sensitive of the four parameters (kh, Kv, Sy and Ss) given that it occurs within or above the connected fracture zone of which the lower 'half' is at low or zero pressure. Furthermore, David *et al*. (2017) concluded "*drawdown and inflow estimation could be overestimated if constant Ss is assumed*". Therefore, constant S would mean that an assessment of drawdown would be conservative, which seems an appropriate approach for this assessment.

7.3 MODEL PERFORMANCE

Earlier during calibration, the model required about 2-3 hours per run, however as more complexity was added (e.g. surface cracking and other subsidence-related deformation) calibration improved, but with increasing run times. The calibrated groundwater model required 8-9 hours to run through the historical calibration period.

At the end of that calibration period (mid-2018, model stress period 110), the modelled mass balance error was less than 0.01%, which is within the 1-2% error recommended by the *Australian Groundwater Modelling Guidelines* (Barnett, *et al*, 2012). This performance is achieved using the MODFLOW-USG 'SMS' solver with a head close criterion of 0.01 m.

7.4 WATER BALANCE

The modelled regional groundwater balance is summarised in **Table 7-2**, which presents the average water balance for 1940-2018. This includes Dendrobium (up to Longwall 13), historical mining around Dendrobium (e.g. Nebo, Elouera, Wongawilli, Kemira etc.), and the parts of BSO, Tahmoor and Cordeaux Mines within the active model domain (**Figure 6-1**).

Rainfall recharge is the dominant input, while evapotranspiration and baseflow to watercourses/springs/reservoirs are the dominant outputs. The model simulates historical mine inflow for all mines in the model domain equal approximately 4% of the recharge. Water balance error was computed to be less than 0.01%.

Table 7-2 Modelled Water Balance for Calibration Period (1940-2018)

MODFLOW component	Process	In	Out
RECHARGE	rainfall recharge	257.9	
RIVER LEAKAGE	watercourses, reservoirs	16.8	54.0
ET	evapotranspiration		216.4
DRAINS	mine inflow		9.6
HEAD DEP BOUNDS	regional GW flow	4.6	1.1
CONSTANT HEAD	flow to ocean, estuaries	0.1	1.0
STORAGE	groundwater storage	44.4 (decline in GWLs)	41.0 (rise in GWLs)
	Total	**323.73**	**323.71**

Units are in ML/d. Results are from model run 4v57 to SP110.

7.5 CALIBRATION – GROUNDWATER LEVELS

The location of boreholes and piezometers used for groundwater level calibration are depicted in **Figure 4-9**. As required in previous Conditions of Approval for Dendrobium, all available groundwater level data was used in the model. This means that data from 698 groundwater bores and piezometers is to assess the calibration of observed and modelled groundwater levels.

About 600 of these are piezometers, in ‘deep’ bores. From the sub-daily or daily data recorded at those sites, HS has calculated the median groundwater level for each month, resulting in over 38,250 ‘deep’ groundwater level targets.

HS has used water levels from 98 ‘shallow’ piezometers, almost all of which are located in swamp deposits (as mapped for Illawarra Coal or based on OEH mapping), although some are not located in such features. From this dataset, given that these shallow bores are responsive to short-term rainfall events, we have derived target values for calibration by taking a value within the first third, second third and last third of each month resulting in over 2,500 ‘targets’ for calibration.

7.5.1 GROUNDWATER LEVELS – SUMMARY OF SIMULATED AND OBSERVED LEVELS

All the modelled heads are plotted versus observed heads on **Figure 7-2A**. **Figure 7-2B** shows the same type of chart but only for the Hawkesbury Sandstone and shallow (swamp) groundwater levels. **Figure 7-2A** shows significant scatter (error) between modelled and observed, and comparison against **Figure 7-2B** shows that much of this scatter is in the deeper groundwater levels, which are more affected by mining – depressurization in the coal seams and caving effects.

The key reasons for the scatter in **Figure 7-2** are as follows:

- difficulty in matching the timing of drawdown. The model may match the pre-mining head quite well, and also the final post-mining head reasonably well, but during the period of drawdown, it is easy for the model to be in error by 100 m or more because the drawdown is too rapid or too slow. E.g. the WWCO hydrograph (and others) on **Figure 7-6** shows this effect. This is particularly the case in deeper units, as shown by the comparison of the scatter on **Figure 7-2A** compared to **Figure 7-2B**.

- longwall progression and therefore commencement of drawdown at a monitoring device occurs over short time increments compared to the longer model stress periods.
- potentially incorrect layer assignment. Some VWPs located in the mid-Bulgo Sandstone may be within the lower Bulgo Sandstone model layer rather than the upper Bulgo Sandstone.
- vertical head gradients between piezometers can be considerable. However, in many parts of the stratigraphic sequence, the model uses relatively thick model layers (greater than 50 m) and the groundwater model simulates only a single groundwater level (i.e. the average) across the vertical thickness of each model cell or layer. This means that it may not be possible to simulate the vertical variation in pressures if two or more VWPs are assigned to the same model layer.
- incorrect or suspect data (within the > 40,000 calibration targets) which has not been identified.
- incorrect or imperfect parameterization of the model re: K and S parameters, either on a local or larger-scale.
- If the drain conductance of the ‘Stacked Drains’ method is set too high, the model fixes the head in the connected fracture zone at zero pressure, whereas the vertical head profiles (see later in **Section 7.5**) show that positive pressures are sometimes maintained. Earlier versions of the groundwater model (e.g. the Longwall 16 model; HS, 2018) were too conservative with respect to this behaviour and over-estimated drawdown through much of the sequence. The current model does a better job of simulating pressures through the sequence while maintaining a conservative approach to the representation of the vertical extent of fracturing upward from the goaf and down from the surface.

While HS has worked through the dataset to remove groundwater level targets that are clearly erroneous, the size of the dataset has meant that thorough data ‘cleaning’ or the application of ‘weights’ has not occurred. We have made steps to have clearly erroneous data corrected (e.g. provided instructions to the data managers to fix some calculated heads obtained from some of the VWPs, such as occasional miscalculation between groundwater level, mAHD and pressure head, m).

The mean residual groundwater level is 5.4 m. The SRMS error for the correlation between observed data and the transient model groundwater levels is 8.7% and inside the often-quoted example of 10% (MDBC, 2001; Barnett *et al*., 2012), however considered acceptable for a model of this scale and complexity, in a fractured rock environment, and considering the accuracy of the VWPs and the size of the dataset.

7.5.2 GROUNDWATER LEVELS – CALIBRATION HYDROGRAPHS

Because of the size of the groundwater level data, a selection of bores was chosen based on spatial coverage, proximity to historical longwalls, importance for monitoring (e.g. TARP bores), use in research (‘Longwall 9’ or WC21 bores), number of piezometers and period of record. These bores were used as the primary or priority calibration targets along with groundwater inflow. Hydrographs comparing the modelled and observed groundwater levels are presented in **Figure 7-3** to **Figure 7-20**.

Some of these show a good fit to observed data (most piezometers at S1885 [**Figure 7-8**] the HBSS and SPCS piezometers in S2192-S2220 [**Figure 7-9**]), some poorer (two piezometers at S1557 [**Figure 7-3**], while most show some well-matched piezometers and poorly-matched piezometers at the same site (S1932 has a mix of good and poorly matched piezometers [**Figure 7-13**]. **Figure 7-20** illustrates that in Area 5 (bore S2345), the upper units are well simulated (HBSS, BGSS) but there is some variance between modelled and observed water levels in the coal measures. This highlights the difficulty in simulating water levels in a fractured rock environment and the potential issues with VWPs and size and complexity of the data given the precise unknown timing of the local mining and external mining sequence.

Some hydrographs show good match between the timing of mining-related drawdown (e.g. HBSS-135 m at S1911 [**Figure 7-10**], upper BGSS piezometer at S2313 [**Figure 7-12**], while other piezometers show a significant different in the timing of the modelled drawdown compared to observed (e.g. WWCO piezometer at S1577 [**Figure 7-5**], SBSS piezometer at S1870 [**Figure 7-6**], BUCO piezometer at S1992 [**Figure 7-7**]), although typically the overall magnitude of drawdown is correct, just that the model is faster or slowed than observed.

Other hydrographs suggest that some data is suspect (some spiky data at S1885 [**Figure 7-8**], WWCO piezometer at S2309 [**Figure 7-19**], some unusual behavior in the HBSS 96 m piezometer at S1932 among others [**Figure 7-13**]). Others need to be considered in light of the thickness of model layers compared to the distribution of piezometers (e.g. the numerous HBSS piezometers in S2335-S2336 [**Figure 7-11**]), where it is not possible for the model to match multiple piezometers that are located within the same model cell.

Hydrographs for all bores are presented in **Appendix I**. There is a variable degree of model calibration – some groundwater level records are well-matched but some are poor. Overall, these hydrographs represent an improvement on the modelled hydrographs produced by other modelling (e.g. HS, 2018), which generally over-estimated drawdown from mining.

7.5.3 GROUNDWATER LEVELS – VERTICAL PROFILES

An alternative method of visualizing groundwater levels or pressures is to plot the downhole sequence as a vertical profile. The pressure at each piezometer has been plotted and compared to modelled pressures at four piezometers:

- S1557 in Area 1 [**Figure 7-21A**]: Pressures in the upper units (WBCS and above) are available for this bore. The modelled pressures are a good match to observed pre- and post-mining pressures in this bore.
- S1870 between Areas 2 and 3A [**Figure 7-21B**]: Pressures are available right through the sequence, from WWCO to HBSS for this bore. The modelled pressures are a very good match to observed pre- and post-mining pressures in this bore, except that in reality the coal seams depressurised faster than the modelled predicted.
- S1911 in Area 3B [**Figure 7-22A**]: Pressures are available for the entire sequence, from WWCO to HBSS for this bore. The modelled pre-mining pressures are too high compared to observed, while the modelled pressures are a very good match to observed post-mining pressures in this bore.
- S2309 in Area 5 [**Figure 7-22B**]: The trend in modelled pressures is a good match to observed pressures in this bore, with this representing essentially pre-mining conditions in this area.

Overall, the trends in vertical pressures are good, suggesting that the modelled vertical hydraulic conductivity (Kv) is suitable. Water table or shallow groundwater pressures are often slightly over-estimated by the model, which may be due to the configuration of the regolith layer (model layer 1) being fully extensive regolith across the model domain, which may impede discharge around areas of steep topography (cliff lines), although significant effort has been made to counter this along the Illawarra Escarpment.

7.5.4 GROUNDWATER LEVELS – CONTOUR MAPS

A selection of contour maps has been produced from the groundwater model to illustrate the groundwater system around Dendrobium Mine. These show groundwater levels in four different layers and at two different times, a pre-mining case and 'present day' (i.e. mid-2018).

Figure 7-23 shows modelled pre-mining groundwater levels in Layer 1 (regolith, swamps) and in Layer 4 (lower Hawkesbury Sandstone) and **Figure 7-24** presents Layer 6 (upper Bulgo Sandstone) and Layer 14 (Wongawilli Seam). Vectors have been added to most of these maps to illustrate dominant groundwater flow direction, with the exception of the water table where there is too much variation. In general, the pre-mining water levels on **Figure 7-23** and **Figure 7-24** show that the dominant flow direction is to the north, except around the escarpment, where groundwater discharges toward the southeast.

The water level contours for the water table (**Figure 7-23**) are tightly bunched and are strongly influenced by local topography, bending around valleys (watercourses, reservoirs), and decline from over 500 mAHD on the escarpment to sea level (0) in the south-eastern corner of the model.

The other model layers show progressively smoother contouring down through the geological sequence. The lower Hawkesbury Sandstone (layer 4) outcropping or being close to surface in many areas, e.g. along Wongawilli Creek, Cordeaux and Avon Rivers (**Figure 7-23**).

The Bulgo Sandstone water levels show signs of strong topographic control around the upper or southern parts of s Cordeaux Reservoir and Avon Reservoir (**Figure 7-24**). Wongawilli Seam water levels are similar but show more variation in flow direction around the escarpment, with a ground divide being simulated through Dendrobium – north of that divide groundwater flows to the north while south of that line it discharges along the escarpment.

Modelled groundwater levels for mid-2018 are shown on **Figure 7-25** (Layer 1 and Layer 4) and **Figure 7-26** (Layer 6 and Layer 14). The general patterns of flow remain similar, except in the Wongawilli Seam where mining has clearly disrupted the groundwater system. Note that mining effects can be difficult to discern at the regional scale shown on these figures, and that the hydrographs present earlier are often better for this purpose.

Figure 7-25 shows localized effects of longwall mining, i.e. above Dendrobium Area 2 and 3B in particular it is possible to identify areas where the contouring shows drawdown in the water table. Deeper in the sequence, in the lower Hawkesbury Sandstone, effects are easier to discern (**Figure 7-25**), with head contours bending around Areas 3A and 3B.

Drawdown is more pronounced in the Bulgo Sandstone (**Figure 7-26**), being visible around Areas 2, 3A and 3B, as well as around mines to the north of Dendrobium (e.g. Tahmoor in the north-west). As noted above, the Wongawilli Seam water levels on **Figure 7-26** show drawdown occurring around all the current Dendrobium workings, as well as Cordeaux, South Bulli/NRE, Kemira and Wongawilli/Elouera workings around Dendrobium. The depressurization influence of Tahmoor and Bulli Seam Operations (both extracting from the Bulli Seam) workings to the north is also evident.

7.6 CALIBRATION – MINE INFLOW

Figure 7-27 and **Figure 7-28** present the model calibration of the groundwater inflow to the Dendrobium underground mine, as calculated by Illawarra Coal's detailed site water balance. The groundwater model results have been calculated considering time-weighted averages, with reference to model output periods (Section 6.6 and Mackie, 2013).

A general observation is that in Areas 1, 2 and 3B the inflows presented on **Figure 7-27** are an improvement in accuracy compared to previous modelling at Dendrobium. The following points are made for each area:

- Area 1 – modelled inflows are well matched through the mining period and the post-mining period. The model generally simulates higher peaks than observed in the post-mining period. Note that the peak and subsequent flat-lining of the observed inflow record midway in 2016 to the end of the record is due to a malfunction and failure of the flow meter in Area 1, which is now out of operation.
- Area 2 – the model provides a good representation of the inflow during Longwall 3, but simulates too much groundwater inflow during Longwalls 4-5. After the active extraction phase. The model does however simulate the inflow peaks in Area 2 up to 2.5 ML/d, although it does not always capture the peak inflow rate, and then often overestimates the inflow in the following recession period.
- Area 3A –the model overestimates inflow to the underground workings while longwall extraction is in progress, and also does not capture the inflow peaks, typically one or two per year, after the active phase. However, the general magnitude of inflow in the post-mining phase is quite reasonable.
- Area 3B – The model presents a very good match for the trend and magnitude of historical inflow to Area 3B, with the exception during Longwall 13 when the modelled inflow is approximately 20% higher than observed.

The modelled total mine inflow **Figure 7-28** appears to be a reasonable match to observed inflow. While it is generally higher than the observed data (i.e. conservative), many of the peaks and troughs are simulated to an acceptable level. On the scale of the whole mine, the results are an improvement on previous modelling HS (2016a and 2018).

7.7 CALIBRATION – BASEFLOW

Model results for groundwater discharge to streams were extracted and a comparison was made against baseflow estimates made for two key watercourses around Dendrobium (**Table 7-3**). The baseflow estimates are those made via chloride (or EC-) -constrained estimates (HS, 2016d). The use of the chloride mass balance approach provides more reliable estimates of baseflow than estimates made solely from digital techniques (Cartwright *et al*, 2014), although uncertainty remains, hence why a range of estimated baseflow contribution is provided in **Table 7-3**.

Table 7-3 Comparison of baseflow estimates

SITE / WATERCOURSE	MEAN FLOW	BASEFLOW ESTIMATE	MODELLED BASEFLOW	COMMENT
WWL / Wongawilli Creek	16	1.6-2.5 ML/d	1.1 ML/d	Modelled baseflow slightly low
DCU / Donalds Castle Ck	2.3	0.02-0.15 ML/d	0.35 ML/d	Modelled baseflow high

The modelled baseflow estimates shown in **Table 7-3** are in one instance less and in the other slightly higher compared to that derived from the baseflow separation. However, both are of the correct order of magnitude.

7.8 SUMMARY OF MODEL PERFORMANCE

7.8.1 MODEL CONFIDENCE

Groundwater modelling has been conducted in accordance with the National Guidelines sponsored by the National Water Commission [NWC] (Barnett *et al*., 2012). The 2012 NWC document has replaced the model complexity classification of MDBC (2001) by a "model confidence level".

An assessment of this model, using the example template provided in Barnett *et al*. (2012) is provided in **Appendix J** where a green tick indicates a valid characteristic or indicator for the model used in this study. This suggest that some elements of the modelling, such as data quality, data availability and complexity of processes to be simulated, belong to different confidence levels, typically levels 2 or 3. Overall, the Dendrobium Next Domain model, according to this classification, is a Class 2 model (effectively yielding "medium confidence"), which is an appropriate level for this project. The 2012 guidelines indicate that a model of this class would be suitable for:

- Prediction of impacts of developments in medium value aquifers; and
- Providing estimates of dewatering requirements for mines and the associated impacts.

These criteria are a good description of the groundwater system at Dendrobium with the Illawarra Coal Measures underlying the Hawkesbury Sandstone with medium and variable value groundwater potential.

7.8.2 SUMMARY

Considerable effort has gone into calibrating the modelled hydraulic conductivities (K) of the large dataset Illawarra Coal, data that includes the relationship with depth and dominant lithology through the geological sequence. Modelled storage values are based on analysis of results from core testing and downhole NMR surveys and consistent with literature (e.g. Rau *et al,* 2019). HS has calibrated the recharge estimates against multiple literature sources, notably Crosbie (2015) and BoM's AWRA-L model.

Given complexity of the physical system (including the effects of neighbouring mines, and the difficulties of representing hydraulic conductivity and water levels in a fractured rock environment, and the changes to hydraulic properties around longwalls), this model is considered to be suitable for simulating the proposed development of Dendrobium Areas 5 and 6, and predicting drawdown and associated environmental effects that may occur as a consequence of longwall mining.

The simulated mine inflow provides an acceptable match for the trends in observed inflow, although generally higher than the observed data. It is reasonable to conclude that the results are conservative. The baseflow estimates are also a reasonable match to inferred baseflow on Wongawilli and Donalds Castle Creeks. The model is therefore considered to be suitable for determining the drawdown distribution and groundwater inflow from the geological sequence and associated baseflow reduction from watercourses.

8 PREDICTIVE MODELLING AND IMPACT ASSESSMENT

This section presents results from the calibration or 'base case' model, which is the calibrated model presented in **Sections 6 and 7**. The results presented here include estimates of mine inflow to Areas 5 and 6, and resultant drawdown, reduction in stream flow and induced reservoir losses. **Section 9** presents results of sensitivity analysis conducted to understand possible variance or range in selected predictions.

8.1 PREDICTIVE SCENARIOS

To assess the effects of the proposed Areas 5 and 6 several predictive scenarios have been applied and these are summarised in **Table 8-1**. Comparison of the outputs of these runs allows quantification of the effect or impact of the development(s), and assessment of project-specific and cumulative impacts.

Table 8-1 Summary of Predictive Scenarios

Scenario	RUN	NAME	DENDROBIUM				OTHER MINES	COMMENT
			A1-3B	A3C	Area5	Area6		
A	4v71*	Full Impact	Y	Y	Y	Y	All	Refer to **Section 1.4** for a list of other mines.
B	4v59	Baseline – Approved	Y	Y	N	N	All	Comparison against A gives effects of Areas 5 and 6.
C	4v60	Baseline – Other Mines	N	N	N	N	All	Comparison against A gives effects of Dendrobium (all areas).
D	4v61	Baseline – Natural ('Null')	N	N	N	N	None	'Null run' as per Barnett *et al*, 2012. Comparison against A gives cumulative impacts.
E	4v74	Historical mining	Y (to end LW14)	No	No	No	Y (to end 2018)	Represents the mining effects already within the hydrogeological system

During the study, the Tahmoor South EIS was issued, and an earlier version of the Full Impact run (4v57) was superseded with a run that included the Tahmoor South Project.

Each predictive run simulates the period to the year 2200, which is detailed in **Appendix F**, with a sequence of climatic inputs (recharge, evapotranspiration) based on historical average conditions.

8.1.1 CLIMATE CHANGE

Climate change is predicted to affect rainfall and other climatic variables, of which rainfall has the most significant effect on recharge to groundwater. Two sources of projected changes in rainfall have been reviewed:

- NARCliM (NSW / ACT Regional Climate Modelling)[12] for the 'Illawarra, Metropolitan Sydney and South East and Tablelands' area.
- Climate Change in Australia Technical Report[13] ['CCiA'] produced by the CSIRO and BoM covering Australia's NRM regions, including the 'Eastern Australia' region.

Table 8-2 presents the median projection for change in rainfall from these sources for 2030 and longer-term projections for 2070 and 2090.

[12] http://www.climatechange.environment.nsw.gov.au/Climate-projections-for-NSW/About-NARCliM
[13] https://www.climatechangeinaustralia.gov.au/media/ccia/2.1.6/cms_page_media/168/CCIA_2015_NRM_Technical Report_WEB.pdf

Rainfall projections are somewhat similar, at least on an annual basis, for 2030, but quite variable for the 2070-2090 forecast (**Table 8-2**). NARCliM projections suggest a wetter climate, while 'CCiA' projections suggest a drier climate.

Table 8-2 Climate Change Projections – Percentage Change in Rainfall

PERIOD	2030				2070			2090	
	NARCliM			'CCiA' RCP 4.5	NARCliM			'CCiA' RCP 4.5	'CCiA' RCP 8.5
	Illawarra	Metropolitan Sydney	South East and Tablelands		Illawarra	Metropolitan Sydney	South East Tablelands		
Summer	+1.5	-0.2	+0.8	-2.0	+10.9	+12.3	+8.8	-2.0	4.0
Autumn	+5.6	-9.7	+6.5	-4.0	+15.1	+13.6	+11.0	-7.0	-8.0
Winter	-4.9	+0.0	-2.6	-3.0	-6.6	-0.1	-4.1	-10.0	-16.0
Spring	-1.5	-2.6	-7.5	-2.0	-1.3	+3.1	-11.2	-10.0	-16.0
Annual	**-0.4**	**-1.7**	**-1.8**	**-1**	**+6.5**	**+8.9**	**+1.4**	**-7.0**	**-10.0**

Baseline for NARCliM = 1990-2010 period; baseline for CCiA projections = 1986-2005 period.

Based on experience and literature, a general rule is that changes in rainfall are typically magnified 2-4 times when converted to rainfall recharge ('rainfall elasticity in recharge'), as described in Barron *et al* (2012). Using this, the tabulated changes in rainfall are predicted to result in changes in rainfall recharge similar to:

- NARCliM 'recharge scenario': -1.2%, -5.1% and -5.4% in 2030, increasing to +19.5%, +26.7% and +4.2% in 2070 (for the Illawarra, Metropolitan Sydney and South East and Tablelands areas).
- CCiA 'recharge scenario': -3% in 2030, falling to -25.5% in 2090. Note that the CCiA 'recharge scenario' uses the mean from the RCP4.5 and RCP8.5 projected change in rainfall for 2090 (**Table 8-2**).

The effect of the predicted climate change has not been specifically assessed for the Project groundwater inflow as the average change in inflow over the remaining life of the Dendrobium Mine is likely to be minor, given that there is only a small change in average rainfall by 2030 based on the NARCliM and CCiA projections (**Table 8-2**). In the short-term, climate variability, rather than climate change, will govern whether rainfall is similar to the long-term average or not. During the recovery period (i.e. relying on the 2070 and 2090 predictions) from NARCliM and CCiA differ in their prediction with respect to the likely changes in rainfall. If rainfall were to increase, this would result in quicker recovery, while conversely if rainfall were to decrease this would result in slower recovery.

Over the life of the Project, the sensitivity analysis conducted for the Groundwater Assessment (**Section 9**) has considered climate variability, specifically prolonged drought conditions.

The Surface Water Assessment (HEC, 2019) has considered the implications of climate change on the potential surface water losses from the catchment.

8.2 MINE SCHEDULES

The mine plan for Areas 5 and 6 and the schedule are presented in **Table 1-7** and **Appendix F**, along with the future workings of Areas 3A, 3B and 3C in **Table 1-6**.

8.3 PREDICTED MINE INFLOW

Figure 8-1 presents the predicted calibrated model or 'base case' rate of inflow (i.e. ML/d) of groundwater entering different areas of Dendrobium Mine inflow from 2005 until the proposed end of Area 6 (~2049).

The model indicates that inflows would rise from the current rate until the end of Area 3B, with a maximum inflow of just over 13 ML/d After that, a small peak would occur in Area 3A (Longwall 19) of up to 4 ML/d, and then relatively small rates of inflow into Area 3C Longwalls 20-21 (up to 2 ML/d). At about 2039 and during the 2040s, further development of Area 3C could see a second, larger peak of up to 7 ML/d.

Inflow to Area 5 is predicted to rise to a maximum of about 18 ML/d in 2033 and again in 2037, averaging approximately 12 ML/d during the life of that area.

Inflow to Area 6 is predicted to rise to a maximum of almost 4 ML/d in 2047, averaging approximately 3 ML/d during the life of that area. The lower inflow in Area 6 than in Area 5 is consistent with the conceptual model based on panel width and cover depth (**Section 4.8.2**).

The results, in particularly those for Area 5, represent a significant increase compared to recent inflows recorded at Dendrobium, which have been up to 6-10 ML/d (averaging 8 ML/d) in the period 2015-2018.

Initially, HS questioned the magnitude of predicted inflow; however, the observed inflow for historical areas was checked by plotting inflow against the total longwall footprint for each mine area. For areas that have not yet been mined, the modelled mean inflow was used, plotted against the total longwall area proposed for that mine area. The results are shown on **Figure 8-2**. These results suggest that, when accounting for differences in mined area (i.e. area in sq.km), the predictions of inflow to Areas 5 and 6 are consistent with the conceptualisation and inflow behaviour of recent workings.

The total inflow for each of the mine development scenarios listed in **Table 8-1** is presented on **Figure 8-3**, based on 6-monthly intervals and the 'base case' model. The maximum annualised inflow to the mine, including Areas 5 and 6, is predicted to be approximately 26 ML/d or 9490 ML/yr, occurring in approximately 2032 and 2036 (both during Area 5) and a slightly lower peak of approx. 25.5 ML/d in 2043 (early during Area 6). The average modelled inflow for the period 2023-2049 is 22 ML/d (of which about 10 ML/d is predicted to be due to inflow to approved Areas 1-3C). Under a scenario of an extended drought peak inflow is about 22 ML/d.

These inflow predictions are considered further in discussion on water 'take' in **Section 8.7**.

8.4 PREDICTED GROUNDWATER LEVELS

A variety of methods of presenting modelled groundwater levels are provided in the following sections, including groundwater level hydrographs, contour maps of groundwater levels at particular time intervals, as well as contours of the maximum predicted drawdown (at various times) in a selection of model layers.

8.4.1 GROUNDWATER LEVEL HYDROGRAPHS

Hydrographs of modelled groundwater levels in the geological sequence are provided for two locations for each of Area 5 (**Figure 8-4**) and Area 6 (**Figure 8-5**). These figures show groundwater levels over time at two monitoring bore locations (S2064 and S2206 – **Figure 4-9**) and at two nominal locations near to the proposed mining areas (these two are labelled as 'MW' indicated on **Figure 4-9**, but are simply nominal locations used to inspect model groundwater level results). These nominal locations are adjacent to significant features which are the Avon Dam wall for Area 5 and Cordeaux River for Area 6.

These figures show the degree of drawdown due to mining and illustrate that the recovery of water levels is predicted to be partial (in many cases), recovery being relatively quick in the upper layers but more slowly in the lower units (e.g. typically in all the layers below the Bald Hill Claystone).

The key points from each hydrograph are as follows:

- At monitoring bore S2064, which is in the footprint of proposed Longwall 502 in Area 5 (**Figure 8-4A**):
  - Water levels in the Bulli and Wongawilli Seams are predicted to drawdown around ~300 m as a result of the extraction of Area 5 longwalls. Maximum drawdown is predicted to occur for about 30 years before recovery begins in about 2050. Water levels are predicted to recover to above pre-mining levels in about 2100 due to increased hydraulic conductivity above extracted longwalls. This establishes pathways to the surface and allows continued infiltration after longwall extraction, resulting in a higher water table.
  - Above the seams, all layers up to the Bald Hill Claystone (BHCS) are predicted to experience significant drawdown (>100 m) due to extraction of Area 5 longwalls. Recovery to pre-mining levels is predicted to be occur by ~2100.
  - Drawdown within the Hawkesbury Sandstone is predicted to be up to 80 m, including peak drawdown of 70 m in the water table. Although the model simulates recovery of lower Hawkesbury Sandstone water levels to greater than pre-mining levels, the model simulates incomplete recovery in the water table at this location, by about 15 m.
- At a location adjacent to the Avon dam wall, 900 m west of Area 5 (**Figure 8-4B**):
  - Water levels in the Bulli and Wongawilli Seams are predicted to drawdown around ~150 m as a result of the extraction of Area 5 longwalls. Maximum drawdown is predicted to occur for about 40 years before recovery begins in about 2080. Water levels are predicted to recover to above pre-mining levels due to increases hydraulic conductivity and resultant continued infiltration from the surface.
  - Above the seams, all layers up to the Bald Hill Claystone (BHCS) are predicted to experience significant drawdown due to extraction of Area 5 longwalls. Recovery to pre-mining levels is predicted to occur by ~2080-2120.
  - Drawdown in the lower Hawkesbury Sandstone due to Area 5 extraction is predicted to be about 2-3 m. Recovery is predicted to be about 30 m (approximately 50%) of the total drawdown.
  - The model predicts drawdown of 0.9-1.8 m in the upper and middle Hawkesbury Sandstone and less in the regolith at this location.
- At monitoring bore S2206, which is on the eastern edge of proposed Longwall 601B in Area 6 (**Figure 8-5A**):
  - Some drawdown is predicted to have occurred prior to 2020, due to neighbouring mines, up to about 30 m in the coal seams.
  - Drawdown in the Bulli and Wongawilli Seams is estimated to be about 320-350 m due extraction of Area 6. Water level recovery is predicted for the seams by about the year 2100 (i.e. after 50 years).
  - The Bulgo Sandstone is predicted to experience between 140-180 m drawdown with greater drawdown estimated for the lower Bulgo. These units are predicted to recover to greater than pre-mining levels due to changes in hydraulic

    - conductivity in and above the goaf, and continued surface infiltration, although recovery would take over 50 years.
    - Drawdown in the Hawkesbury Sandstone is predicted to be 10 m to 40 m, with greatest drawdown in the lower horizons.
- At a location adjacent to the Cordeaux River, 400 m north of Area 6 (**Figure 8-5B**):
    - The model predicts gradual drawdown in the Wongawilli and Bulli Seams due to historical mining to the east of Area 6. Following extraction of Area 6 longwalls, more rapid drawdown (up to about 120 m) is predicted to occur. Water levels are predicted to remain depressed for about 20 years at this location before commencing recovery. Recovery to pre-mining levels (and then above those levels) is simulated to occur in about year 2150 (i.e. take almost 100 years).
    - The Bulgo Sandstone is estimated experience incremental drawdown of 80 m (following extraction of Area 6. As above, recovery of water levels to pre-mining levels would take about 100 years.
    - The lower Hawkesbury Sandstone is predicted to experience ~25 m of drawdown due to the extraction of Area 6. Recovery is predicted to occur to above pre-mining water levels.
    - Drawdown of 4 m is predicted for the mid-Hawkesbury Sandstone, while mining-related drawdown of up to 0.9 m has been predicted to occur in model layer 1 (regolith), which is adjacent to the Cordeaux River.

8.4.2 GROUNDWATER LEVEL CONTOUR MAPS

Figure 8-6 to **Figure 8-9** present modelled water levels for four 'layers' in the geological sequence at two different times in the model simulation: 2049 (the end of mining at Area 6) and in 2200. These layers are:

- Water table (calculated as the water level in the uppermost saturated model layer, i.e. uppermost saturated stratigraphic unit);
- lower Hawkesbury Sandstone (model layer 4);
- upper Bulgo Sandstone (model layer 6); and
- Wongawilli Coal seam (model layer 14).

These can be compared against **Figure 7-23** to **Figure 7-26**, showing simulated pre-mining and present day water levels, in the Model Calibration chapter (**Section 7.5**) of the report.

Comparison of **Figure 8-6** and **Figure 8-7** with the earlier figures allows assessment of the effects of the approved and proposed areas of Dendrobium Mine, including Areas 3C, 5 and 6, on groundwater levels in those units. This includes significant drawdown in the Wongawilli Seam (up to 340 m within Area 6 and the eastern part of Area 5), upper Bulgo (approx. 150 m) and lower Hawkesbury Sandstone (20-40 m, possibly greater).

Comparison of **Figure 8-8** and **Figure 8-9** with **Figure 7-23** and **Figure 7-24** suggests the water table would recover to pre-mining levels in some locations, but remnant drawdown would exist in other locations above and around longwall areas. These figures also suggest that water levels in lower Hawkesbury and upper Bulgo Sandstone would eventually recover to close to or above pre-mining levels (the hydrographs discussed in **Section 8.4.1** provide more on this). The water levels in the Wongawilli Seam are predicted to remain depressed compared to pre-mining conditions in some areas (e.g. around Area 3B), but may recover to above pre-mining levels in other locations, e.g. Area 6 (see **Section 8.4.1**).

8.4.3 MAXIMUM DRAWDOWN CONTOUR MAPS

The groundwater level contour maps presented above are useful for illustrating the simulated pattern of groundwater levels, and the inferred direction of flow, as a result of mining and other processes. HS has calculated the maximum drawdown predicted in every model cell in a series of layers: the water table (whichever layer that is located in), the lower Hawkesbury Sandstone (Layer 4) and upper Bulgo Sandstone (Layer 6). These were selected because they are layers in or systems that are typically in contact with or near to the surface and the associated 'receptors' (i.e. watercourses, reservoirs or lakes, swamps, bores).

Comparison of Scenario A and Scenario C (see **Table 8-1**) allows estimation of the maximum head difference at any time in the model period (see **Appendix F**), with the difference between those two scenarios representing the drawdown due to Dendrobium Mine as a whole. The maximum drawdown for each model cell was then interpolated and contoured, as shown on **Figure 8-10** and **Figure 8-11**. This has been done to show the influence of Dendrobium (all mine areas) on the groundwater system. Furthermore, the results of the sensitivity runs have been summarised and included on these figures (see **Section 9.3.1**).

Figure 8-10A shows the simulated maximum drawdown of the water table for the 'base case' or calibrated groundwater model. This shows that within the longwall areas themselves, the model predicts drawdown of up to 70 m four zones within Area 5; up to about 20 m in the southern part of Area 6. Maximum predicted drawdown in earlier mine areas is about 65 m in Areas 2 and 3B.

Water table drawdown is typically restricted to within about 200 m of the longwall footprint for most of the Dendrobium mine areas, with greater extent from the longwall footprint occurring where there is a lower depth of cover. Area 2 is the best example where the 2 m drawdown contour extends up to 750 m west of Longwall 5. Similar drawdown is shown on **Figure 8-10A** for the area between the southern part of Area 5 longwalls and Lake Avon.

The converse is predicted in Area 6, where the inference is that the greater depth of cover (see calculated width to depth ratios calculated in **Section 1.3**) here does mitigate the drawdown in the water table to a greater degree than in other areas (although still up to 20 m in places), despite the simulation of fracturing through to the surface.

Figure 8-11 shows that same information but condensed to show the maximum predicted drawdown for the lower Hawkesbury Sandstone (HBSS) on the left-hand pane and for the upper Bulgo Sandstone on the right. In these figures, the position of the 2 m contour been highlighted. See **Section 9.3.1** for discussion model sensitivity.

For the lower Hawkesbury Sandstone, a maximum drawdown of approximately 90 m is predicted in Area 5, 100 m in Area 6. By comparison, the maximum was 85 m in Area 3B and >100 m in Area 2 (difficult to see due to small area of HBSS outcrop).

The extent of the base case 2 m drawdown contour is significantly larger than it was for the water table, with the main extension of this being downgradient, to the north. It is predicted to extend 3-4 km to the north of the mine workings, but is more constrained to the east, west and south by geological boundaries and hydrological features (reservoirs, watercourses).

For the upper Bulgo Sandstone (right-hand pane on **Figure 8-11**) a maximum drawdown of approximately 140 m is predicted in both Area 5 and Area 6. By comparison, the maximum was 140 m in Areas 2 and Area 3B, and >100 m in Area 3A.

As expected, the extent of the base case 2 m drawdown contour is larger than it was for either of the shallower layers discussed above. The base case 2 m contour is predicted to extend extent 3.5 km to the east and north of Area 6, and 7 km north and west of Area 5. The increased eastward and westward extent of the 2 m contour in the BGSS compared to the HBSS is due to the extent of the BGSS and it being deep enough not to be exposed and eroded away in the base of the Nepean/Avon/Cordeaux valleys.

8.4.4 DRAWDOWN AT GROUNDWATER BORES

NSW Government keeps a database of registered 'Groundwater Works' which can generally be assumed to be bores, but also includes wells and excavations, that have been registered with them over time. 650 'works' are located within the bounds of the groundwater model. Of these, 309 have been classed as 'water supply' works[14], with locations shown on **Figure 8-12**. Each of these has been assigned a model layer, based on known geology or, more often, water-bearing zones, bore construction details or bore depth – whichever are recorded in the NSW government database.

The AI Policy deems the threshold for 'minimal harm' at a water supply work to be 2 m drawdown due to the proposed activity or activities.

Comparison of scenarios A and B (see **Table 8-1**) suggests that none (0) of the 309 water supply works would be affected beyond the 2 m drawdown threshold by the Project, i.e. the extraction of Areas 5 and 6.

The number of 'water supply' bores predicted to be affected by the 'whole of Dendrobium' and cumulative mining scenarios has been assessed by comparing Scenarios A versus C and Scenarios A and D, respectively (**Table 8-1**).

Appendix L summarises the model results for all 'water supply' works in the model domain and for the various mine development scenarios.

Table 8-3 summarises the 'base case' model estimate of the number of bores affected by Dendrobium and cumulatively, and includes some further information to assist in understanding the source of the cumulative effects, i.e. are they due to the effects of mining that has already occurred (to the end of 2018), or are these cumulative effects due to the likely effects of mining that is yet to occur.

Figure 8-12 summarises the 'base case' estimate of the number of bores affected by Dendrobium, while **Figure 8-13** presents the results of the cumulative impact assessment. The results of the suite of sensitivity scenarios are presented in **Section 9.3.2**.

Table 8-3 >2m Drawdown at 'water supply' works – Dendrobium and Cumulative

Case	No. of GW works affected > 2 m			
	Historical mining (to end 2018)	**Cumulative mining** (excluding Dendrobium)	**Cumulative mining** (including Dendrobium)	**Dendrobium Mine only** (Areas 1-6)
'Base case' model	145	165	165	0

Note that Tahmoor Coal has indicated that the proposed mine plan for Tahmoor South, as documented in the Tahmoor South EIS and modelled here, is subject to review and likely to be modified via a Preferred Project Report. The mine plan modelled here is considered conservative with respect to subsidence-related parameters.

As shown in **Table 8-3** there are no water supply works that are predicted to experience greater than 2 m drawdown due to the Dendrobium Mine. The maximum predicted drawdown due to the Dendrobium Mine at any water supply work is 1.5 m, and only 4 are predicted to have more than 0.5 m due to operations at Dendrobium (**Appendix L**).

165 water supply works are predicted to experience greater than 2 m drawdown cumulatively (**Table 8-3**), however, more than 2 m drawdown is predicted to occur regardless of the Project or the Mine as a whole, due to other historical/approved/proposed operations. Furthermore, as shown in **Table 8-3** and **Appendix L**, 145 water supply works are predicted to experience >2 m drawdown predicted due to mining that has already occurred (i.e. mining

[14] Registered groundwater works considered as 'water supply' works are those where the registered purpose is irrigation, water supply, stock and domestic, commercial/industrial, other or unknown. Other purposes, such as exploration, dewatering and monitoring are not considered 'water supply'.

to the end of 2018, as per Scenario E in **Table 8-1**). **Figure 8-13** shows that most of the cumulatively-affected bores are located along the coastal plain (affected by the numerous historical mining operations along the edge of the escarpment) or around Tahmoor and BSO.

8.5 PREDICTED REDUCTION IN SUBCATCHMENT STREAM FLOW

Longwall mining can cause a reduction in stream flow via two mechanisms:

- groundwater depressurization or drawdown in the groundwater system that is connected to the watercourse (i.e. outcropping beneath the watercourse); and
- cracking, fracturing and deformation (e.g. 'surface cracking', upward extension of the 'connected fracture zone' to the surface, or development of basal shears) can enhance the hydraulic conductivity of stream beds and valley bottoms and result in loss of flow (if there is head gradient away from the stream).

The numerical model has been used to estimate loss from watercourses for the modelled scenarios. This is presented spatially on **Figure 8-14**. This figure shows the calculated change in groundwater-surface interaction for each MODFLOW River cell, with grey/blue indicating effectively neutral (no change) or a few cells where a slight increase in flow is predicted (due to changing hydraulic conductivity), and yellow-red cells indicating a reduction in flow. The figure shows that the model suggests that most of the mines included in the simulation have some influence on nearby streams and any springs that occur along the escarpment. The results are consistent with the 'maximum drawdown' extents presented in **Section 8.4**.

The results indicate that streams directly above longwalls are affected (via surface cracking), while outside the longwall footprint, the watercourses in more deeply-incised valleys are affected due to depressurization of connected groundwater system layers. Above Dendrobium, the predicted reduction in baseflow on streams appears to be greater above Areas 3A and 3B, however this is due to the different period for mining (i.e. historical versus future/predictive period). The figure is meant to illustrate the spatial distribution of the effects more than the exact magnitude of the effect (see below).

Note that **Figure 8-14** also includes the results for the reservoirs, which are also simulated using MODFLOW River cells (more discussion on reservoir losses in **Section 8.6**).

On the basis of the defined Groundwater Sources, the modelling suggests that losses from surface water would peak in the period 2040-2046. Maximum annual average losses are reported in **Table 8-4**. During that time, average annual losses would depend on wet or dry conditions, so the predicted wet year peak has been reported for the Nepean Sandstone MZ2 (the Groundwater Source that Dendrobium is in).

Table 8-4 Predicted maximum losses from watercourses by Water Source (ML/yr)

GROUNDWATER SOURCE	DENDROBIUM MINE (incl. Areas 5 & 6)	INCREMENTAL – AREAS 5 AND 6
Sydney Basin Nepean Sandstone MZ2	2761 (wet year peak 3319)	1622 (1928)
Sydney Basin Nepean Sandstone MZ1	11	7
Sydney Basin South	10	3

source: E:\DENDROBIUM\Model\GWModel\Processing\ZoneBudgetU\GWTake&SWTake_Zbud_DND4v58-61.xlsx

The model suggests that as a fraction of total groundwater inflow, surface water losses in 2016-18 are 10-20% of total inflow, and would average 15% to the end of Area 3A (Longwall 19). IEPMC (2018) state that "it is plausible that an average of around 3 ML/day of surface water and seepage from reservoirs is currently being diverted into the mine workings". The modelling here suggests that the recent rate is approximately 1-1.65 ML/d (range from 2016-18).

For Areas 5 and 6 (and 3C), the predicted average reduction in surface water flows is almost 25% of total mine inflow to the end of Area 6, peaking at approximately 35% in 2043-46. This percentage is dependent on weather conditions; the modelling suggests it could be 43% in wet conditions, or 25% in dry conditions.

The higher proportion of predicted surface water losses compared to predicted total mine inflow under the case of the approved mine plus the Project compared to that simulated for the historical mine (see previous paragraph) is due to the higher proportion of the mine footprint covered by longwalls of 305 m width in Areas 3C, 5 and 6 compared to Areas 1, 2 and 3A (Section 1.3). The wider panels mean there is a greater degree of connection to the surface, based on the geomechanical modelling (**Section 4.8.4**).

The predicted loss of flow from watercourses has been passed to hydrologists for inclusion in the Surface Water Assessment (HEC, 2019), and the key statistics are summarized in **Table 8-4**. These losses can be considered as an upper estimate as the groundwater modelling assumes water is available to be lost from the ephemeral drainage lines overlying Areas 5 and 6 at all times, whereas in reality many of these drainage lines naturally cease-to-flow during dry periods. HEC (2019) estimates potential losses of surface water based on the groundwater modelling predictions and stream flow modelling (which incorporates varying rainfall and evaporation data). The sites for which these estimates were made are shown on **Figure 4-9** (labelled as "Surface water assessment sites").

The overall conclusion is that Dendrobium Mine as a whole is likely to result in the loss of up to approximately 1300-1400 ML/yr of stream flow from the Cordeaux River catchment and a similar amount from the Avon River catchment (including the reservoirs). Refer to HEC (2019) for further discussion of these losses.

Table 8-5 Predicted maximum reduction in flow in key sub-catchments and watercourses

Cumulative Impact																		
Sub-catch	LA13/ LA13A	LA 14	LA 8	LA 12	LA 15	LA 17	AR32	AR31	AR19 S1	DC10	DC8	DC9	CR31	CR29	Wonga-willi Ck	Donalds Castle Ck	Site A (AR19)	Site B (Cordeaux)
Catch-ment	Avon Reservoir (LA) tribs						Avon River tribs			Donalds Castle Creek tribs			Cordeaux River				Avon River trib	Cordeaux River
ML/yr	330	47	68	29	20	45	118	274	192	71	214	66	5	46	739	505	203	1379
ML/d	0.90	0.13	0.19	0.08	0.05	0.12	0.32	0.75	0.53	0.19	0.59	0.18	0.01	0.13	2.02	1.38	0.56	3.78
approx yr	2046	2031	2044	2042	2031	2032	2032	2044	2046	2046	2046	2038	2049	2049	2046	2046	2046	2046
Dendrobium Impact																		
Sub-catch	LA13/ LA13A	LA 14	LA 8	LA 12	LA 15	LA 17	AR32	AR31	AR19 S1	DC10	DC8	DC9	CR31	CR29	Wonga-willi Ck	Donalds Castle Ck	Avon Trib to Site A	Cordeaux to Site B
ML/yr	330	47	68	29	20	45	118	274	192	71	214	66	5	46	735	504	203	1371
ML/d	0.90	0.13	0.19	0.08	0.05	0.12	0.32	0.75	0.53	0.19	0.59	0.18	0.01	0.13	2.01	1.38	0.56	3.76
approx yr	2046	2031	2044	2042	2031	2032	2032	2044	2046	2046	2046	2038	2049	2049	2046	2046	2046	2046
Project Impact (A5, A6)																		
Sub-catch	LA13/ LA13A	LA 14	LA 8	LA 12	LA 15	LA 17	AR32	AR31	AR19 S1	DC10	DC8	DC9	CR31	CR29	Wonga-willi Ck	Donalds Castle Ck	Avon Trib to Site A	Cordeaux to Site B
ML/yr	329	48	68	29	20	45	118	275	193	72	213	66	5	47	293	379	203	588
ML/d	0.90	0.13	0.19	0.08	0.05	0.12	0.32	0.75	0.53	0.20	0.58	0.18	0.01	0.13	0.80	1.04	0.56	1.61
approx yr	2046	2032	2046	2040	2031	2032	2032	2046	2046	2046	2046	2038	2049	2049	2052	2046	2046	2049

Notes: “approx yr” is the year of predicted peak flow reduction.

Data source:
E:\DENDROBIUM\Model\GWModel\Processing\Baseflow\BaseflowCaptureSummary to HEC_Runs4v58-61v3_wMeanBaseflow.xlsx
E:\DENDROBIUM\Model\GWModel\Processing\Baseflow\Baseflow_HEC_Zbud_DND4v58-61v3_additionalcatch.xlsx

8.6 PREDICTED LEAKAGE FROM RESERVOIRS

Two of WaterNSW's reservoirs are close to Areas 5 and 6, with Avon Reservoir situated about 300-900 m from the southern and western edge of Area 5 longwalls and the Cordeaux Reservoir situated about 630 m-1.5 km from the southern end of Area 6 longwalls.

Nepean Reservoir lies 3.2 km west of the nearest Area 5 longwall, while Cataract Reservoir is situated further away from Area 6, with historical mining located between the lake and those proposed longwalls.

Model results were extracted to assess the likely loss from the reservoirs that would occur as a result of Dendrobium as a whole (including Areas 5 and 6 and 3C). Results are shown on **Figure 8-15** (Cordeaux Reservoir) and **Figure 8-16** (Avon Reservoir). The results of sensitivity runs are presented on these figures and discussed in **Section 9.4**.

8.6.1 CORDEAUX RESERVOIR

Figure 8-15 shows that the model predicts a maximum loss of approximately 0.29 ML/d due to the Dendrobium Mine. This is predicted to occur in about 2050, just after the end of Area 6. The incremental loss from Areas 5 and 6 is estimated to be up to approximately 0.1 ML/d, due primarily to mining in Area 6.

8.6.2 AVON RESERVOIR

Figure 8-16 shows that the base case model predicts a maximum loss of 0.48 ML/d for the whole of the Dendrobium Mine.

The maximum incremental loss from Areas 5 and 6 is estimated to be up to approximately 0.36 ML/d, due primarily to mining in Area 5. The model also suggests that the maximum loss due to approved areas, primarily Area 3B, is 0.22 ML/d.

8.6.3 NEPEAN RESERVOIR

A figure or hydrograph has not been prepared for simulated losses from the Nepean Reservoir. The base case model predicts losses of up to 0.02 ML/d.

8.6.4 SUMMARY

These losses are of a similar magnitude to other estimates made previously for Areas 1-3B, such as in, Coffey (2012b), HS (2016a and 2018), HGEO (2018e) and SCT (2018a).

This is due to the different methods of representing Kh with depth and revised representation of the connected fracture zone, which have led to a better calibration to inflow and to groundwater levels than, for example, the Longwall 16 groundwater model (HS, 2018). Furthermore, this study incorporates sensitivity or uncertainty bands, and the majority of runs in the sensitivity suite and the average suggest that losses from the reservoir are <0.4 (Cordeaux) and <0.6 ML/d (Avon), as discussed in **Section 9.4**.

8.7 WATER 'TAKE' OR CAPTURE

The AIP requires estimation of 'take' or groundwater and surface water captured or lost from the environment or hydrological systems. This is done on the basis of Groundwater Sources defined within the Water Sharing Plan (WSP) for the *Greater Metropolitan Region Groundwater Sources 2011*. Dendrobium lies almost wholly within the *Sydney Basin – Nepean Sandstone Management Zone 2*, thus most of the water removed from the natural system by mining operations is from that Groundwater Source.

Table 8-6 presents recommendations for water licensing, based on the estimates of 'take' derived from maximum mine inflow (**Section 8.3**) and reduction in stream flow/baseflow capture (**Section 8.5**), as well as partitioning of groundwater 'take' or inflow from nearby Groundwater Sources (e.g. Sydney Basin South). Note that the maximum predicted inflow to the mine is approx. 9,400-9,500 ML/yr (**Section 8.3**) is not the same as the sum of the licensing recommendations in **Table 8-6**. This is because the peak take from different Water Sources are not simultaneous.

Table 8-6 Recommendations for Licensing

WATER SOURCE / MANAGEMENT ZONE	PREDICTED PEAK INFLOW OR TAKE		COMMENT
	DENDROBIUM MINE (incl. Areas 5 & 6)	PROJECT INCREMENT	
Groundwater: *Water Sharing Plan for the Greater Metropolitan Region* ***Groundwater*** *Sources 2011*			
Sydney Basin – Nepean MZ2	6700	5700	Groundwater take via mine inflow minus simultaneous take from connected SW and adjacent GW Sources
Sydney Basin – Nepean MZ1	32	7	Take from adjacent Groundwater Sources minus contemporary SW losses
Sydney Basin South	4	3	
Surface Water: *Water Sharing Plan for the Greater Metropolitan Region Unregulated* ***River Water*** *Sources 2011*			
Upper Nepean and Upstream Warragamba Water Source	3330	1935	Maximum 'incidental surface water take'. Peak surface water losses may not be contemporary with peak groundwater takes listed above.
Illawarra Rivers Water Source	10	3	

source: E:\DENDROBIUM\Model\GWModel\Processing\ZoneBudgetU\GWTake_to IllawarraCoal_DND4v58-61.xlsx

Dendrobium currently hold entitlement for 3,963 units for Nepean MZ2. HS understands that Illawarra Coal has successfully obtained additional groundwater entitlement via a Controlled Allocation to meet the peak predicted direct take from *Sydney Basin – Nepean MZ2*.

8.7.1 CUMULATIVE LOSSES FROM WATER SUPPLY CATCHMENTS

IEPMC (2018) suggested that it would be appropriate to use the groundwater model to estimate cumulative losses from the groundwater catchment to the water supply reservoirs. The groundwater model (**Figure 6-1**) covers the full catchment to Lake Cordeaux, but does not quite cover the full catchment of Lake Avon, and only smaller fractions of the catchments to Lake Nepean and Lake Cataract (**Table 8-7**). The model includes most, if not all, the significant mining operations with the catchment of Lake Cordeaux and Lake Avon, but does not include Hume Project (which could possibly affect Lake Nepean) or mining to the northwest of Lake Cataract (which may affect that catchment).

Nevertheless, the model has been used to provide estimates of the cumulative loss of baseflow in the modelled parts of these catchments due to mining operations.

Results are shown on **Figure 8-17** and summarized in **Table 8-7**.

Table 8-7 Modelled cumulative losses from reservoir catchments

Reservoir	Catchment Area (km2)	% catchment in model	Period 2000-2018		Period 2018-2070	
			Mean	Peak	Mean	Peak
L. Cordeaux	91	100 %	0.32	0.85	0.80	1.20
L. Avon	142	97 %	0.16	0.32	1.56	2.67
L. Nepean	320	33 %	0.01	0.10	0.01	0.04
L. Cataract	130	73 %	0.10	0.17	0.11	0.12

Losses in ML/d, based on simulated mining at all mines in **Section 1.4**.

source: E:\DENDROBIUM\Model\GWModel\Processing\Baseflow\CumulativeLosses_Reservoirs_4v73_v_4v72.xlsx

The losses reported in **Table 8-7** are the annualised losses. The periods in **Table 8-7** were selected based on lower reliability in simulating mining operations before 2000, based on 'present day' (i.e. 2018), and an approximate 50-year period into the future (i.e. to 2070).

Figure 8-17 shows these, along with simulated losses across shorter intervals, where wet and dry seasons are simulated. Those short-term losses give some estimate of losses at high flows (greater losses) compared to those at low flows, noting that in the modelled period after 2018, most model periods are typically 3- or 6-months long (**Appendix F**).

9 SENSITIVITY AND UNCERTAINTY ANALYSIS

There is no specific requirement in SEARs specifying uncertainty analysis (either the need or the method). The size and complexity of this model is governed by the processes required to be simulated, the stratigraphic layer framework and the need for cumulative impact assessment. This has implications of model run-time and memory requirements, and means that there are practical limits on the amount and type of uncertainty analysis that can be carried out.

The *Update to IESC Information Guidelines* (IESC, 2018) and *Draft Explanatory Note on Uncertainty* (Middlemis and Peeters, 2018) indicate that there are three possible methods, of which the first is adopted here:

1. *Scenario Analysis (i.e. Deterministic Scenario Analysis with Subjective Probability)*

HS has carried out the suite of 'deterministic scenarios' outlined in **Table 9-1** investigating the effects on a number of predicted behaviours. The detail of the parameters used in the high and low K or Sy scenarios is presented in **Appendix K**. These runs were agreed with the peer reviewer prior to the simulations being carried out.

Table 9-1 Sensitivity run design

Sens. Run	Model ID	Key feature / recharge	Kh	Kv	Sy
Sens. Run 1.	4v57	Base case, with enhanced recharge simulated in longwall footprint *	Base case Kh	Base case Kv	Base case Sy.
Sens. Run 2	4v62	Inclusion of basal shears** (using average recharge)	Higher Kh to 600 m	Base case Kv	Base case Sy.
Sens. Run 3	4v63	Extended drought (1992-03)#	Base case Kh	Base case Kv	Base case Sy.
Sens. Run 4	4v64	High Kh | base case recharge	**High Kh** [x5]	Base case Kv	Base case Sy.
Sens. Run 5	4v65	Low Kh | base case recharge	**Low Kh** [/10]	Base case Kv	Base case Sy.
Sens. Run 6	4v66x5	High Kv | base case recharge	Base case Kh	**High Kv** [x5]	Base case Sy.
Sens. Run 7	4v66x10	High Kv | base case recharge	Base case Kh	**High Kv** [x10	Base case Sy.
Sens. Run 8	4v67	Low Kv | base case recharge	Base case Kh	**Low Kv** [/10]	Base case Sy.
Sens. Run 9	4v68	High Sy | base case recharge	Base case Kh	Base case Kv	**High Sy**.
Sens. Run 10	4v69	Low Sy | base case recharge	Base case Kh	Base case Kv	**Low Sy**.
Sens. Run 11	4v70	Higher lakebed permeability^ (base case recharge)	Base case Kh	Base case Kv	Base case Sy.

* enhanced recharge via surface cracking simulated at +50% of natural recharge.

** basal shears have been simulated via enhanced Kh to a distance of 600 m from longwalls. Zones were such shears occur have been restricted to areas of deep/incised valleys e.g. around reservoirs, as indicated in Section 6.9.3 and as also simulated in HS (2018).

extended drought is simulated as modified recharge and potential evaporation, based on the conditions experienced between **1993-2002**, which had an average rainfall of 926 mm/yr compared to 1120 mm/yr. This rate represents the 10%-ile for decadal rainfall across the historical record back to 1889. The 'drought' recharge rates are then applied for the entire predictive period 2018-onward. Potential evaporation rates were unchanged.

^ reservoirs/lakes are modelled using MODFLOW Rivers (Section 6.8.4), which require the estimate of 'conductance'. In this sensitivity run, the conductance is increased in line with an assumed lakebed hydraulic conductivity of 0.02 m/d, i.e. increased by a factor of 20 over the baseline.

Two versions of 4v66 have been run, due to trouble achieving model convergence, a problem which was later solved, so the results of both runs have been included.

IESC states that the selected method is to be tied to risk. Because the model uses the conservative approach recommended by PSM (2017) and simulates vertical fracturing to surface as well as basing the parameterisation on FLAC2D modelling (SCT, 2017 and 2018b – see **Section 4.8.3**), the risk of that has been covered and is conservative, so uncertainty is more about the lateral spread of drawdown and the effects that may have on hydrological and environmental features at the surface, particularly the potential leakage from reservoirs.

9.1 ASSESSMENT OF SENSITIVITY RUN SUITABILITY

The aim of the deterministic scenarios is to provide quantification of the maximum and minimum likely inflows. HS compared the simulated mine inflow under the various sensitivity runs plus the base case (the predictive 'suite') versus annual totals from the observed record of inflow. This is presented in **Figure 9-1**.

This figure shows that the calibrated model, the base case, is slightly higher than observed, typically 10-25% higher, and that the observed inflow is better matched by the 30th percentile of the suite of inflow estimates presented here. The runs with higher Kh, Kv and Sy (in particular) all produce higher inflows than the base case, while the runs with lower Kh, Kv, Sy, and the run with the basal shears are more similar to the observed or the base case.

Runs with high Kh, Kv and Sy are all used to derive subsequent results from the suite of runs (along with the other runs in **Table 9-1**), e.g. estimates of maximum drawdown, change in reservoir inflow/outflow, those specific runs are however considered less realistic, especially for estimating drawdown at private bores and for changes in reservoir inflow/outflow, given their calibration to the mine inflow target.

9.2 MINE INFLOW SENSITIVITY

Figure 9-2 has been drawn to show the total mine inflow for the base case, for all areas and for Dendrobium without Areas 5 and 6. Alongside these hydrographs are the bounds (minimum and maximum) calculated from the suite of runs. In addition, based on the discussion in **Section 9.1**, the 30th percentile inflow from the suite is also plotted on **Figure 9-2** due to it being a better match to observed inflow.

The min-max range for the maximum annualised inflow is 21 to 38 ML/d, and the average is approximately 26 ML/d (similar to the 'base case' model). The likely range is considered to be 21.5 to 26 ML/d, which is based on the '30th percentile' and the base case model. Note that these predictions are averages across 6-12 months, and inflows are likely to reach a maximum above these estimates (and below) for shorter periods.

9.3 DRAWDOWN SENSITIVITY

9.3.1 MAXIMUM DRAWDOWN CONTOURS

As discussed in **Section 8.4.3**, the maximum simulated drawdown was calculated from the difference between mine development scenarios for any time in the model period. Each of the sensitivity runs in the suite was run with scenario A and C to allow estimation of the effects of Dendrobium as a whole. The results have been summarised as the minimum (best case) and maximum (worst case) estimates of 2 m maximum drawdown calculated from the predictive suite (see **Table 9-1**) and mapped on **Figure 8-10** and **Figure 8-11**. The reason for focussing on the 2 m contour is that the AI Policy specifies this drawdown as the limit of 'minimal harm'.

Figure 8-10B shows the same 2 m maximum drawdown contour (red line), as calculated from the base case model as shown on **Figure 8-10A**. The minimum and maximum drawdown was calculated, and the position of the 2 m contour is marked in orange (minimum/best case) and purple (maximum/worst case). This shows similar patterns of drawdown, with the minimum contour lying closer to or within the longwall footprint, while the maximum contour lies further from the footprint.

The maximum drawdown estimate (purple contour on **Figure 8-10B**) suggests that all of the Area 6 footprint would experience >2 m drawdown, compared to about 50% under minimum (orange contour) and about 60% under base case (red contour). There is some, relatively minor expansion of the 2 m drawdown contour outside the panel footprint in the ‘worst case’/maximum estimate.

The sensitivity runs suggest that around Area 5 there are more areas where additional drawdown might occur than under the ‘base case’. The maximum estimates such areas to the east (near Donalds Castle Creek), and to the south and west (near Lake Avon, the Avon River, and tributaries such as LA6-LA13, and others in that area). Drawdown estimates between sensitivity runs are more consistent to the north of Area 5.

Figure 8-11 shows that same information but condensed to show the maximum predicted drawdown for the lower Hawkesbury Sandstone (HBSS) on the left-hand pane and for the upper Bulgo Sandstone on the right. In these figures, the position of the 2 m contour, for the base case, minimum and maximum drawdown estimates have been highlighted.

For the lower Hawkesbury Sandstone, the extent of the 2 m drawdown contour is significantly larger than it was for the water table, with the main extension of this being downgradient, to the north. It is predicted to extend 2-6 km to the north of the mine workings (the range based on the sensitivity results), but is more constrained to the east, west and south by geological boundaries and hydrological features.

For the upper Bulgo Sandstone (right-hand pane on **Figure 8-11**) the extent of the 2 m drawdown contour is larger than it was for either of the shallower layers discussed above. The base case 2 m contour is predicted to extend extent 3.5 km to the east and north of Area 6, and 7 km north and west of Area 5, while the maximum/worst case contour is significantly larger and is not shown on the map north of about Northing 6,205,000. The increased eastward and westward extent of the 2 m contour (all cases) in the BGSS compared to the HBSS is due to the extent of the BGSS and it being deep enough not to be exposed and eroded away in the base of the major valleys.

9.3.2 PREDICTED DRAWDOWN AT GROUNDWATER BORES

The suite of sensitivity scenarios has been used to estimate the range in the drawdown and the number of ‘water supply works’ that could be affected by Dendrobium Mine (approved areas plus Areas 5 and 6). **Table 9-2** summarises the number of bores affected by Dendrobium as a whole, and the base case and worst-case results are mapped on **Figure 9-3**. The ‘mean estimate’ drawdown is the average of the maximum predicted drawdown from all of the sensitivity runs, while the ‘worst case’ drawdown is the maximum predicted drawdown in any of the sensitivity runs.

Table 9-2 >2m Drawdown at Groundwater Works – Dendrobium and Cumulative

Case		No. of water supply works affected > 2 m		
		Dendrobium (whole mine)	Cumulative	Historical mining only
'Base case'		**0**	**165**	**145**
Sensitivity	'Best-case'	0		
	Median estimate	0		
	Mean estimate	2		
	'Worst-case'	**5**		

Note: 'Water supply' works are defined in **Section 8.4.4.**

E:\DENDROBIUM\Model\GWModel\Processing\BoreDrawdown\DND\BomGWExplorerBores_Join_Mesh4v2_Layer&DDNCalcv3.xlsx

The number of bores predicted to be affected cumulatively, and by historical and future mining, are presented in **Table 9-2** for comparison. Of the bores predicted to be affected by Dendrobium as a whole (**Table 9-2**), the following outlines the registered purpose:

- Mean estimate drawdown – 2 'water supply works in total: 1 is for irrigation and 1 for water supply. However, under the 'base case' model scenario both of these water supply works are predicted to experience greater than 2 m drawdown due to historic and/or cumulative mining that is not associated with Dendrobium (**Appendix L**) (i.e. they are included in the 165 water supply works predicted to be cumulatively affected by as per **Table 9-2**).
- Worst case estimate –5 'water supply works in total: 3 are for irrigation, 1 for water supply and 1 for stock and domestic use. However, under the 'base case' model scenario all 5 of these water supply works are predicted to experience greater than 2 m drawdown due to historic and/or cumulative mining that is not associated with Dendrobium (**Appendix L**) (i.e. they are included in the 165 water supply works predicted to be cumulatively affected by as per **Table 9-2**). For context, the sensitivity run with the greatest number of bores with drawdown >2 m is DND4v64, which simulates a higher Kh. This run predicts drawdown in excess of the 2 m threshold at 4 (of the 5) bores.

Appendix L lists the model results for each of the 'water supply' works in the model domain.

9.4 LOSS FROM RESERVOIRS

The suite of sensitivity scenarios were processed to extract estimates of predicted losses from reservoirs.

9.4.1 CORDEAUX RESERVOIR

Figure 9-4 shows that the model predicts a maximum loss of <= 0.35 ML/d for 8 of the 11 runs in the suite, including the base case and run with basal shears (**Table 9-1**). The ninth run (4v68) with the broad-scale increase in Sy predicts a maximum loss of almost 0.8 ML/d (during Area 2) and then a subsequent maximum of 0.2 ML/d during Area 6. One of the two runs with higher Kv predicts a maximum loss of 0.6 ML/d.

The last of the 11 model runs (4v64 – **Table 9-1**) with the broad-scale increase in Kh (base case Kh x 5) predicts a maximum loss of almost 1.15 ML/d for a period of about 8 years from 2045.

The average of the predicted maximum loss for all the runs in the suite is 0.38 ML/d, and the median is 0.3 ML/d.

9.4.2 AVON RESERVOIR

Figure 9-5 shows that the model predicts a maximum loss of <= 0.6 ML/d for 8 of the 11 runs in the suite, including the base case (peak 0.48 ML/d) and the run with basal shears (0.58 ML/d). The two runs with higher Kv (base case Kv x 5 and x 10) predict maximum losses of 0.73 and 0.84 ML/d respectively.

The last run (4v64 – see **Table 9-1**) with the broad-scale increase in Kh (base case Kh x 5) predicts a maximum loss of almost 1.5 ML/d.

Based on the suite of runs, the average of the predicted maximum loss is 0.58 ML/d, and the median is 0.49 ML/d.

9.4.3 NEPEAN RESERVOIR

A figure or hydrograph has not been prepared for simulated losses from Nepean Reservoir; however, all model runs indicate losses of less than 0.06 ML/d, averaging 0.02 ML/d.

9.4.4 SUMMARY

The likely maximum losses for each reservoir are reported in **Table 9-3**, and are based on the average result for the available sensitivity runs and the base case run. The single result that produces significantly higher reservoir losses is one of the three runs that had relatively poor calibration to inflow (**Section 9.1**), suggesting that that such high losses are unlikely. However, it is recommended that monitoring and testing take this into account (**Section 11.2**) to confirm whether modelled hydraulic conductivities are representative of field results.

Table 9-3 Predicted maximum loss from reservoirs (ML/d)

MINE AREA	L. CORDEAUX	L. AVON	L. NEPEAN
Dendrobium (including Areas 5 + 6)	0.38	0.58	0.02
Predicted to occur in	2048-2050	2043-2048	2045-2050
Inferred incremental loss due to Areas 5 + 6	0.12	0.2	0.01

As noted previously the inferred losses due to Areas 1-3B for the Avon (approximately 0.2 ML/d) are similar to those predicted in HGEO (2018e), SCT (2018a) and HS (2018), which were predicted via different modelling methods, as summarised in HGEO (2018e).

- HGEO (2018e) reported a range of 0.03 to 0.53 ML/d/km of shore length or the equivalent of 0.07 to 1.3 ML/d for Area 3B to the end of Longwall 18;
- SCT (2018a) reported a range of 0.01 to 1 ML/d/km, equivalent to 0.02 to 1.6 ML/d for Area 3B to the end of Longwall 18.
- HS (2018) reported a loss of 0.26 ML/d for Area 3B to the end of Longwall 18.

10 GROUNDWATER MONITORING AND QUALITY INDICATORS

The protection of groundwater resources in NSW against degradation and pollution is primarily governed through the *Protection of the Environment Operations Act, 1997* (POEO Act) which makes it an offence to pollute groundwater. Key NSW Government policies adopt the concept of Water Quality Objectives (WQOs) for the management and protection of groundwater quality.

Water quality objectives are specific water quality targets (numerical concentration limits) agreed between stakeholders that become the indicators of management performance. The Australian and New Zealand guidelines for fresh and marine water quality (ANZECC, 2000) provides a framework for developing WQOs and defining management trigger levels for the protection of environmental values. They are not intended to be applied directly as regulatory criteria, but a factor to be considered by stakeholders when making decisions affecting the future of a water resource.

The ANZECC guidelines apply to the quality of surface water and of groundwater since the environmental values which they protect relate to above-ground uses (e.g. irrigation, drinking water, farm animal or fish production and maintenance of aquatic ecosystems). Therefore, groundwater should be managed in such a way that when it comes to the surface, whether from natural seepages or from bores, it would not cause the established water quality objectives for these waters to be exceeded, nor compromise their designated environmental values.

In the project area, shallow groundwater (<150 m depth) discharges at the surface via baseflow and seeps in creeks and reservoirs, and via evapotranspiration. Groundwater quality therefore has an influence on the quality of surface water and its environmental values, particularly under low-flow conditions in gaining streams. However, it is noted also that groundwater quality is naturally variable and, in upland areas, can be of considerably poorer quality (higher in salinity and trace metal concentrations) than surface water into which it discharges. Therefore, management trigger levels should be based on local groundwater reference data, in preference to default surface water protection guidelines (as recommended in the ANZECC guidelines).

Monitoring approaches also differ as a function of different access opportunities and flow timeframes between surface water and groundwater. For example, surface water flow is rapidly concentrated into channels whereby spatially representative samples can be obtained (for example) at downstream weirs and rockpools. On the other hand, groundwater samples are collected at discrete sites (monitoring bores) which may not be representative of groundwater across the site. Some changes in groundwater quality may only be apparent when (and if) it manifests as seeps and baseflow in creeks.

Finally, it is important to consider underground aquatic ecosystems and their fauna (stygofauna). Further information on the lifecycles and environmental requirements of the relevant communities are available in the ecology/biodiversity assessment (Niche, 2019).

Groundwater quality objectives and management trigger levels for this Project consider the above discussion, and are based on the following key principles:

- an activity should not result in a substantial change over the natural background groundwater quality (NSW Groundwater Quality Protection Policy), therefore providing protection for the existing and future environmental values; and
- any change in the groundwater quality should not lower the beneficial use category of the groundwater source beyond 40 m from the activity (NSW AI Policy; porous and fractured rock water sources).

Groundwater quality objectives are presented in **Table 10-1**. Groundwater quality indicators and management trigger levels would be developed for selected locations using baseline data as recommended in the ANZECC (2000) guidelines (e.g. 80th and 20th percentiles). 'Running median' values would be used to define whether an exceedance has occurred as these reduce the number of 'false alarms' caused by a single spike. This is consistent with the approach recommended in Section 7.4.4 of the ANZECC (2000) guidelines.

Table 10-1 Groundwater quality objectives and proposed management triggers for Areas 5 & 6

ENVIRONMENTAL VALUES	PROTECTION REQUIREMENTS	POTENTIAL FACTORS	INDICATORS	MANAGEMENT TRIGGER LEVEL	EXCEEDANCE CRITERIA
Connected with surface water systems that: ▪ support aquatic ecosystems of high conservation value; and ▪ are within a drinking water catchment. ▪ Stygofauna communities	▪ An activity should not result in a substantial change over the natural background groundwater quality (NSW Groundwater Quality Protection Policy) ▪ Any change in the groundwater quality should not lower the beneficial use category of the groundwater source beyond 40m from the activity (NSW AI Policy)	▪ Fracturing of porous sandstone leading to increased mineral dissolution and increased salinity and trace metal concentrations. ▪ Surface fracturing and groundwater level changes may result in oxidation of sulphide minerals; acidification of groundwater and increase in Fe, Mn and trace metals. ▪ Chemical and fuel spills at the surface or underground.	Electrical Conductivity (EC)	80^{th} percentile of the baseline* EC at selected locations.	Median of 6 most recent field observations exceeds the management trigger level.
			pH	$>80^{th}$ or $<20^{th}$ percentile of the baseline* pH at selected location.	Median of 6 most recent field observations exceeds the management trigger level.

* Baseline ideally consists of the most recent 24 monthly field observations.

11 CONCLUSIONS

A new, upgraded numerical groundwater model has been developed and calibrated for the Project. The model improves on elements from previous modelling (Coffey, 2012b; HS 2014a, 2016a, 2018).

The upgraded model uses the MODFLOW-USG software code with variable cell sizes and orientation to simulate drawdown in more detail around mine workings and watercourses, and in less detail via more widely spaced model cells in areas away from Dendrobium.

The model uses 'Stacked Drains' to simulate the connected fracture zone. The 'Stacked Drains' are now more rigorously calculated than in previous modelling at Dendrobium and rely on inputs from FLAC2D geotechnical modelling (SCT, 2017 and 2018b).

This model has been assessed for calibration using a very large dataset of 40,000 observations of groundwater levels from more than 600 bore and piezometer locations. The model has also been calibrated for mine inflow in each mine area as well as the total inflow and corresponding groundwater levels, as well as constraining the model to field testing of permeability while incorporating the accepted and conceptually appropriate relationship between hydraulic conductivity with depth.

Rainfall recharge input to the groundwater model has also been improved compared to previous modelling. Previous model recharge by HS was based and calibrated against various estimates from analysis of field data and literature. That modelling has now been compared against BoM's AWRA-L long-term average estimates of recharge and runoff – the two models compare favourably with one another, adding confidence to this key input.

The calibrated model provides suitable and improved capability for assessing groundwater drawdown and inflow at Dendrobium. The model has subsequently been used to simulate the effects of the proposed development of Dendrobium Area 5 (approximately 18.2 sq.km of longwalls) and Area 6 (4.7 sq.km); the associated roadways and link to the Cordeaux Colliery, as well as other approved future longwalls in Areas 3A-3C. Development and extraction of Areas 5 and 6 are proposed to occur between 2023 and 2049.

The following results were obtained from the groundwater modelling, including the simulation and sensitivity runs:

- The model matches historical inflow to the Dendrobium Mine with reasonable accuracy for total mine inflow and the pattern of inflow over time to individual areas.
- Dendrobium Mine inflows or groundwater capture ('take') from the surrounding geological sequence is predicted to be in the range 21 to 26 ML/d, with most of this inflow derived from Area 5 which has a quite high width-to-depth ratio (W/D) indicating cracking to the ground surface. However, the inflow predicted is considered to be conservative.
- Based on the above, groundwater take is predicted to peak at about 7,600-9,500 ML/yr. This predicted inflow is a significant increase compared to historical inflows at Dendrobium but nevertheless appears consistent given the relationship between longwall area and inflow recorded in previous areas and having a similar high W/H ratios.
- In the case of the Avon Reservoir, the simulated leakage from the reservoir due to the development of the whole of Dendrobium, including Areas 5 and 6 is predicted to be approximately 0.48 ML/d based on the base case model. The range in maximum losses predicted by the suite of sensitivity runs is 0.07-1.49 ML/d. The average and the peak rate of loss for 10 of the 11 model runs is less than 0.8 ML/d for the whole of Dendrobium. The incremental rate of loss due to Area 5 is predicted to be about 0.36 ML/d.

- Leakage loss from Cordeaux Reservoir is predicted to be approximately 0.29 ML/d (base case model), with a range 0.04-1.15 ML/d (mean of 0.38 ML/d) from the all the sensitivity models. The incremental effect of Area 6 is predicted to be about 0.1 ML/d.
- Leakage from Nepean Reservoir is predicted to be approximately 0.02 ML/d.
- Incidental stream flow losses (due to baseflow capture and stream bed cracking) has been estimated using the groundwater model and tabulated as required in **Table 8-4** (broad-scale) and in **Table 8-5** (specific watercourses). The predicted 'take' from watercourses is up to 2,782-3,340 ML/yr from the whole of Dendrobium Mine, including Areas 5 and 6. The incremental take due to mining in Areas 5 and 6 is predicted to be up to about 1,632-1,938 ML/yr (**Table 8-4**).
- Modelling suggests that groundwater drawdown is unlikely to exceed AI Policy minimal impact criterion at any water supply works (i.e. no bores were predicted to be affected by the base case run or by the majority or the suite of sensitivity runs. The most extreme sensitivity run suggested exceedance of 2 m drawdown due to mining at Dendrobium drawdown at up to 5 water supply works (**Appendix L**) out of 309 registered 'water supply' works. However, under the 'base case' model scenario these water supply works are predicted to experience greater than 2 m drawdown due to historic and/or cumulative mining that is not associated with Dendrobium.
- After mining, groundwater levels are likely to equilibrate over decades or longer. In Area 5, modelling suggests that groundwater levels in the deeper units may recover to greater pressures than in shallower strata, leading to the possibility of an upward gradient. This may result in poorer quality water from the coal measures upwelling in the goaf and fractured zones, with the potential to reduce the quality of water in the shallower strata, however, there would be significant dilution of any water from the deeper units that upwardly migrates from surrounding groundwater in the shallower units, as well as from surface water runoff. The modelling suggests that upward gradient of water from the deeper units is less likely in Area 6, where a downward gradient is predicted in the long term.
- The nearest High Priority Groundwater Dependent Ecosystems (GDE), as defined in the relevant WSP are along O'Hares Creek and the Macquarie Rivulet Estuary. O'Hares Creek catchment is approximately 14 km northeast of Dendrobium Area 6, and Macquarie Rivulet is about 16 km south of Dendrobium. No drawdown effects will occur at these locations as a result of mining at Dendrobium.

11.1 AQUIFER INTERFERENCE POLICY ASSESSMENT

Assessment of the Aquifer Interference (AI) Policy is summarised in **Table 11-1**.

Table 11-1 Summary of AI Policy Assessment – Fractured and Porous Rock

Aquifer	Sydney Basin Porous Rock (Nepean Sandstone and Sydney Basin – South Groundwater Sources)
Category	Highly Productive (Nepean Sandstone) and Less Productive (Sydney Basin – South)
Level 1 Minimal Impact Consideration	**Assessment**
Water Table Less than or equal to a 10% cumulative variation in the water table, allowing for typical climatic "post-water sharing plan" variations, 40 m from any: - high priority groundwater dependent ecosystem; or - high priority culturally significant site; listed in the schedule of the relevant water sharing plan. OR a maximum of a 2 m water table decline cumulatively at any water supply work.	The relevant Water Sharing Plan is the 'Greater Metropolitan Groundwater Sources' (dated 1 October 2011). There are no High Priority Groundwater Dependent Ecosystems (GDEs) listed in this WSP within 14 km of Dendrobium, including Areas 5 and 6. Hence there are no known groundwater-related risks to such sites due to activity at Dendrobium. There are no Culturally Significant Sites in the Study Area listed in the WSP. Hence there are no known risks of mine development to such sites. There is a very low risk of drawdown in excess of the water supply work drawdown criterion at any 'water supply works' within the Permo-Triassic or shallow strata due to mining at Dendrobium. **Level 1 minimal impact consideration classification.** (*see discussion in Sections 8.4.4 and 9.3.2 regarding the cumulative drawdown effects associated with other mining operations).*
Water pressure A cumulative pressure head decline of not more than a 2m decline, at any water supply work.	The base case model suggests that no water supply works would be affected by drawdown from Dendrobium. The suite of sensitivity runs also suggest that the number 'water supply' works to be affected by operations at Dendrobium is likely to be zero, with sensitivity runs indicating that up to 5 would be affected >2 m (noting these water supply works are predicted to experience greater than 2 m drawdown due to historic and/or cumulative mining that is not associated with Dendrobium). **Level 1 minimal impact consideration classification.**
Water quality	Mining-induced changes to the hydraulic properties and depressurisation of the strata in the Dendrobium Mine area may result in mixing of potentially chemically different groundwater between overlying and underlying units. However, it is considered unlikely that this will result in changes to the beneficial uses of groundwater in the Permo-Triassic rock units. The risk of water quality impacts decreases with distance from the mine footprint. **Level 1 minimal impact consideration classification.**

11.2 RECOMMENDATIONS

11.2.1 MONITORING AND DATA GATHERING

A review of groundwater monitoring infrastructure, covering available data, scheduled installations and other planned monitoring bores/piezometers should be conducted to ensure adequate spatial coverage of monitoring around Areas 5 and 6 that meets IEPMC's (2018) recommended 2- or 4-year baseline requirement (depending on the type and importance of the monitoring site). That is for Area 5 additional monitoring should generally be installed by 2019-21 and by 2038-40 for Area 6.

Surface water monitoring should include monitoring at sites around Areas 5 and 6 that have been discussed with HS, but also include a site on Donalds Castle Creek located downstream of Area 5.

Groundwater and surface water monitoring needs to be carried out with the aim of meeting the needs of the water quality objectives outlined in **Section 10**.

HS recommends that multiple sites between the mine areas and the reservoirs are tested via packer and NMR permeability testing, focusing on the hydraulic conductivity of the Hawkesbury Sandstone, Bald Hill Claystone and upper Bulgo Sandstone. As is being done around Area 3B, this should include multiple pre-mining test sites, followed by packer testing in the post-mining environment.

At least one round of surface water flow observations should be conducted to determine flow conditions (using the qualitative “no flow”/”trickle”/”flowing” methodology used by Illawarra Coal) along watercourses flowing above and near to longwalls in Areas 5 and 6 particularly during the current (2018) dry period to establish the flow conditions and whether these tributaries flow under such dry conditions or have some persistent baseflow. Watercourses around Area 3C should also be included. This would provide a valuable ‘drought baseline’ dataset.

HS recommends that Dendrobium’s extensive programme of water level monitoring, in both ‘deep’ and ‘shallow’ (swamp) groundwater systems, be continued in areas of recent, approved and proposed mining.

Owners of groundwater works (bores) predicted to be affected by Dendrobium (**Section 9.3.2**), based on the sensitivity models, should be contacted, and the condition of the bores truthed to confirm depths/screen intervals and their usage. Subject to monitoring data during mining indicating that greater than 2 m drawdown attributable to the Dendrobium Mine, make good arrangements should be established, such as deepening of the bore.

As discussed with Illawarra Coal, the programme of packer (Kh) and core (Kv) testing should continue at new drillholes, as well as packer testing at selected sites re-drilled above longwalls. The requirement for this testing may decline somewhat with the advances in the downhole Nuclear Magnetic Resonance (NMR) technology being trialled at Dendrobium. This has shown promise in terms of its ability to replicate packer test results as well as its ability to provide continuous, fine scale measurement. With respect to Kv measurements, focus should be on the strata from the Hawkesbury Sandstone down to the Scarborough Sandstone.

The recent practice of pre- and post-mining permeability testing above longwalls should be continued for Areas 5 and 6, should they be approved.

HS recommended that Illawarra Coal’s records of hydraulic conductivity and porosity be collated into a single database covering all operations (i.e. Dendrobium, BSO), as well as any other data collected historically. This process is on-going, and has facilitated analysis, including comparison of pre- and post-mining strata properties. This process should continue.

A tracer testing programme is being planned by Illawarra Coal. The recently installed bores S2335-S2338 (also referred to as WC21-1/4) at tributary WC21 (SCT, 2016) provide useful infrastructure for testing the path or fate of surface water leaking from watercourses and potentially entering goaf via fracture networks. HS recommends that a tracer test be conducted, first at WC21-3 /WC21-4, which are located above Longwall 10. Monitoring for tracers should be conducted at three or four downstream locations, including Wongawilli Creek, and in the underground mine.

Based on modelling and water quality ‘finger-printing’, the groundwater entering the mine is calculated to be made up of a small amount of modern water, which can include town supply and surface water. Discussion with site staff indicates that upward flow through floor strata is a significant component of groundwater inflow, possibly particularly when there has been significant floor heave. It is recommended that some sampling of waters known to be entering the workings through the floor (i.e. at the point of entry if possible) are included in the water finger-printing monitoring and analysis. Sampling could be conducted from an underground bore or a sump cut into the floor. Analysis would include chemical composition (as per **Figure 4-17**, **Figure 4-18**), and possibly tritium (age), although the former is likely to be the more useful.

11.2.2 MODELLING

This study is focussed on effects and impacts associated with Areas 5 and 6, based on calibration to mining and hydrological data from 2005-2018.

The groundwater modelling should be reviewed periodically to assess the on-going ability of the model to simulate or replicate groundwater levels and inflows as the mine progresses. The model should be verified again in approximately 2021, after more groundwater data has been gathered in Areas 5 and 6.

The current understanding of geological structure is documented in PSM (2019). As the level of knowledge is improved or developed, i.e. if further structural features are identified within Areas 5 and 6 (or elsewhere) that have the potential to act as significant conduits or barriers to groundwater flow, then these should be included in a revised version of the groundwater model.

As per recommendations by the IEPMC (2018), the groundwater model will be updated with new data and assumptions as necessary.

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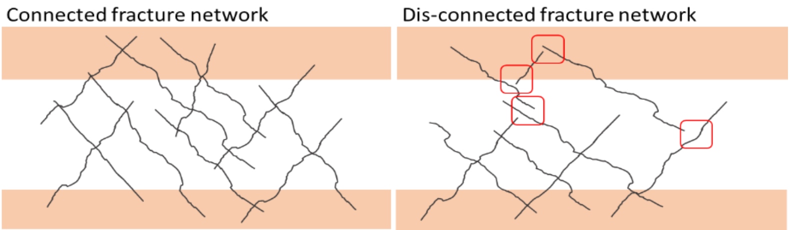
13 GLOSSARY

AWRA-L	Australian Water Resource Assessment – Landscape model (rainfall-runoff model)
BoM	Bureau of Meteorology
DoI Water	Department of Industry – Crown Lands and Water Division
DPE	NSW Department of Planning and Environment
DSC	Dams Safety Committee
EPA	NSW Environment Protection Authority
ICEFT	Illawarra Coal Environmental Field Team
IEPMC	Independent Expert Panel for Mining in the Catchment (advising DPE)
mAHD	metres above Australian Height Datum (effectively elevation as metres above sea level)
mBG	metres below ground
ML/d	megalitres per day
Primary hydraulic conductivity (permeability)	The ease with which water (a fluid) can flow though pore spaces. Pore spaces are also referred to as primary porosity.
Secondary hydraulic conductivity (permeability)	The ease with which water (a fluid) can flow through secondary porosity, which includes joints, cavities and fractures. Rocks like limestone and granite may be very permeable if they have been jointed by weathering or fractured by earth movements (natural or mining-induced).
Connective cracking (fracturing)	Fractures and other secondary porosity (natural joints, separated bedding planes) that are in hydraulic connection with one another can form a network that connects two areas. This may cause, for example, direct flow between a shallow aquifer and underlying underground mine workings via that connected secondary permeability.
Caved Zone	The zone immediately above the extracted seam (longwall panel). This zone is filled by large blocks resulting from roof collapse. This zone is dewatered during mining and would subsequently be flooded once mining ceases and groundwater levels recover. (https://www.environment.gov.au/system/files/resources/8a22c56a-3c83-4812-aa2f-9d0bc40ac718/files/monitoring-management-subsidence-induced-longwall-coal-mining-activity.pdf)
Fractured Zone	This zone lies directly above the caved zone where extensive connected fracturing results in large increases in permeability and porosity. The lower part of the fractured zone has more vertical/sub-vertical fracturing, resulting in connected fracturing. The degree of vertical fracturing decreases with height above the mined seam, reducing the degree of vertical connection.



Surface Fracturing	Surface fracturing or surface cracking is caused by subsidence above longwalls. Sagging and compression of strata at or near the surface, as well as upsidence, can cause the rock to crack. In the base of watercourses or swamps, this can result in water loss via infiltration into the groundwater system, and may cause other disturbance (e.g. erosion of swamps).
Recharge	Recharge is the process where water enters a groundwater body (aquifer). Typically 'recharge' is used to refer to rainfall or infiltration recharge, but could occur via leakage from rivers, lakes, or from pumping wells or some other process. Recharge could also occur as a result of flow from another groundwater body, so 'connection' could result in recharge.
Baseflow	Groundwater discharge to a watercourse (or surface waterbody, e.g. lake). Difficult to measure, so must be inferred or estimated by a number of techniques.
Groundwater-surface water interaction	An overarching description of all processes whereby water moves between surface water (e.g. rivers, creeks, lakes) and groundwater (usually shallow aquifers). This usually refers to baseflow discharge and leakage from stream/lake to aquifer, but could also include rainfall recharge, evapotranspiration.
Upland Swamp	Coastal Upland Swamps are an ecological community in the Sydney Basin bioregion associated with periodically waterlogged soils on Hawkesbury Sandstone plateaus, generally where mean rainfall exceeds 950 mm/yr. (http://www.environment.nsw.gov.au/threatenedSpeciesApp/profile.aspx?id=20261) These are similar to Temperate Highland Peat Swamps, which are typically located >600 mAHD.

FIGURES

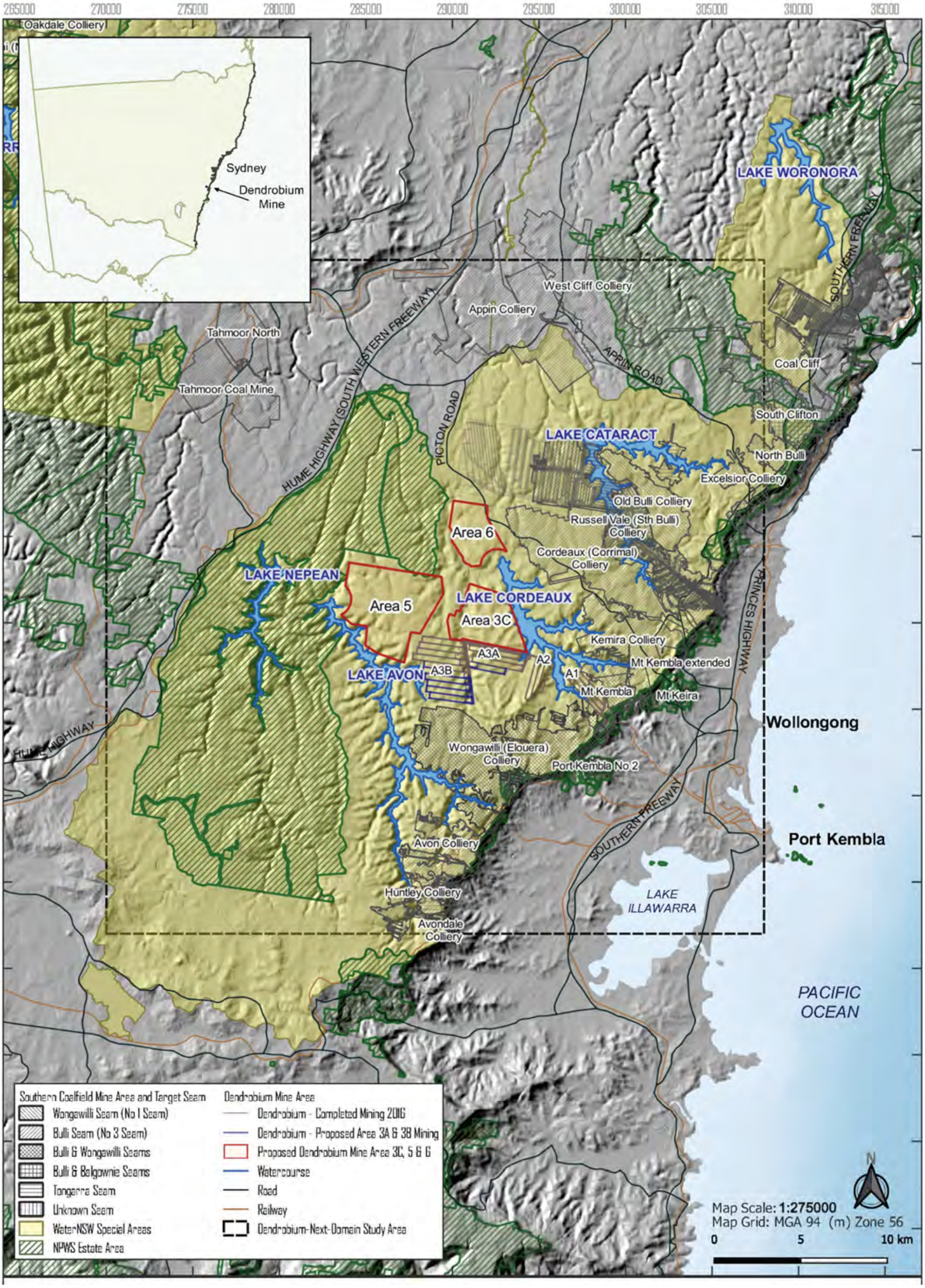


Figure 1-1 Project Location and Regional Setting

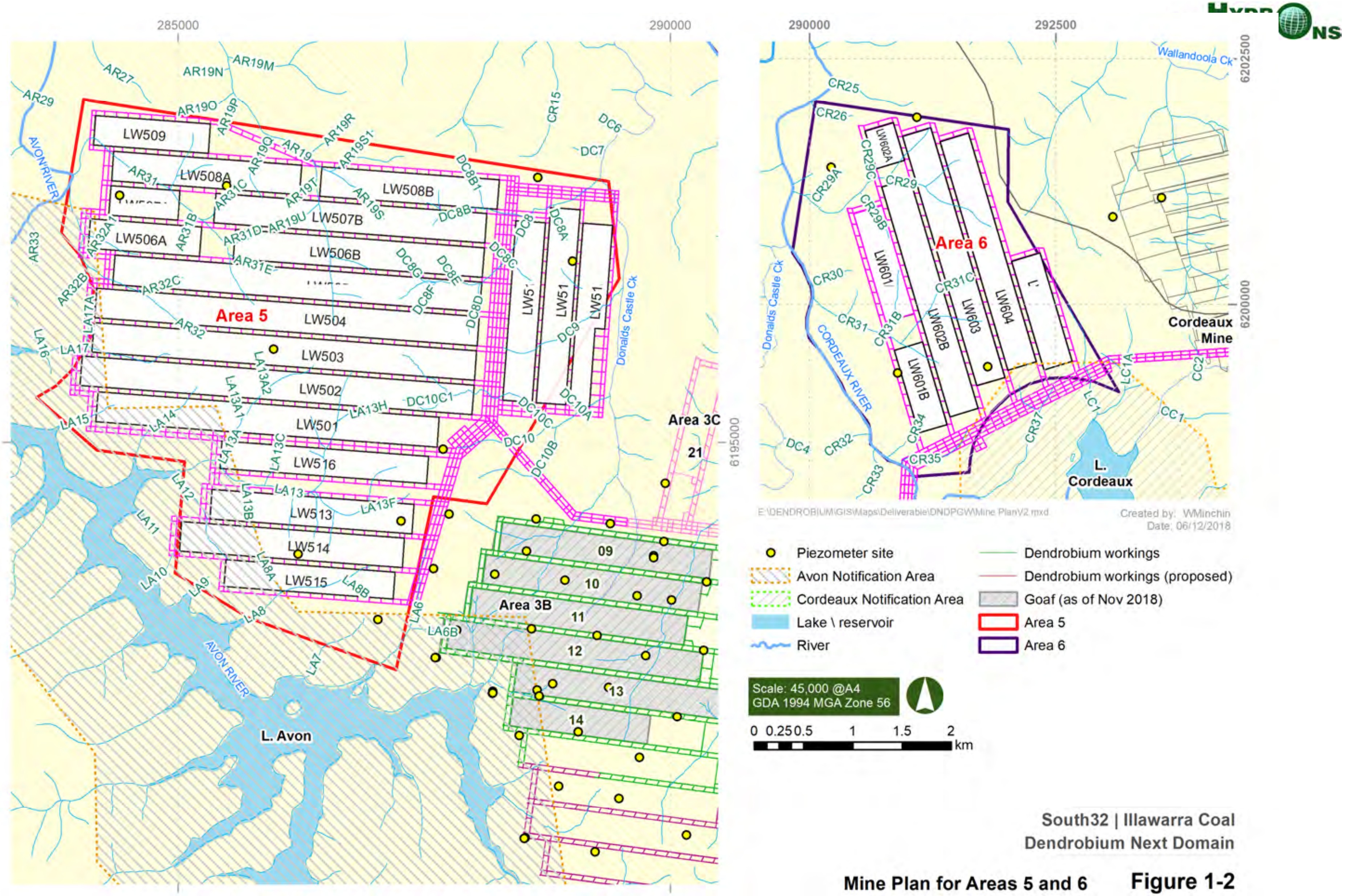


Figure 1-2 Proposed Mine Plan for Dendrobium Areas 5 and 6

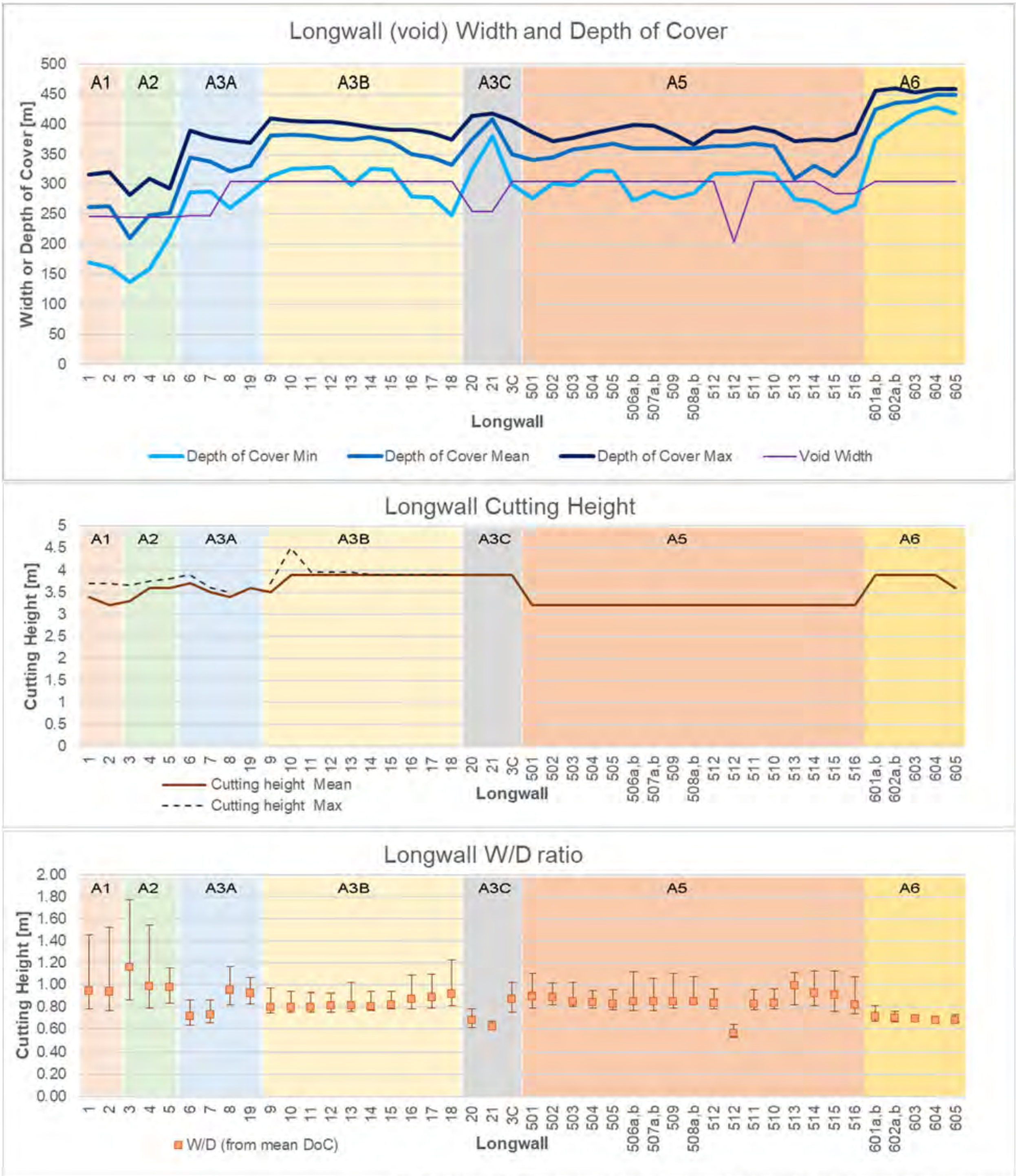


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Figure 1-3 Variation in Longwall Geometry and Depth of Cover at Dendrobium

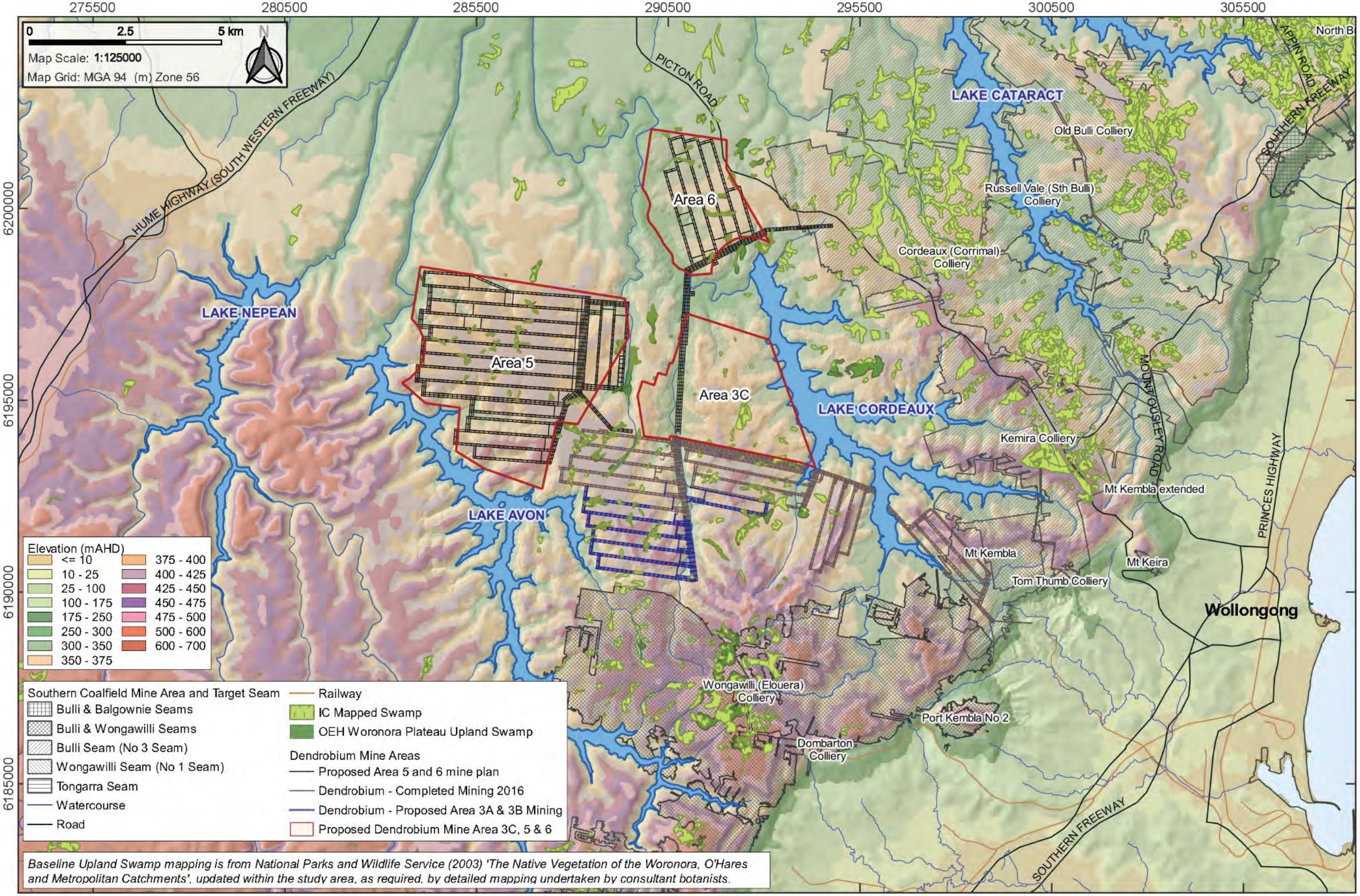

Figure 2-1 Topographic Setting

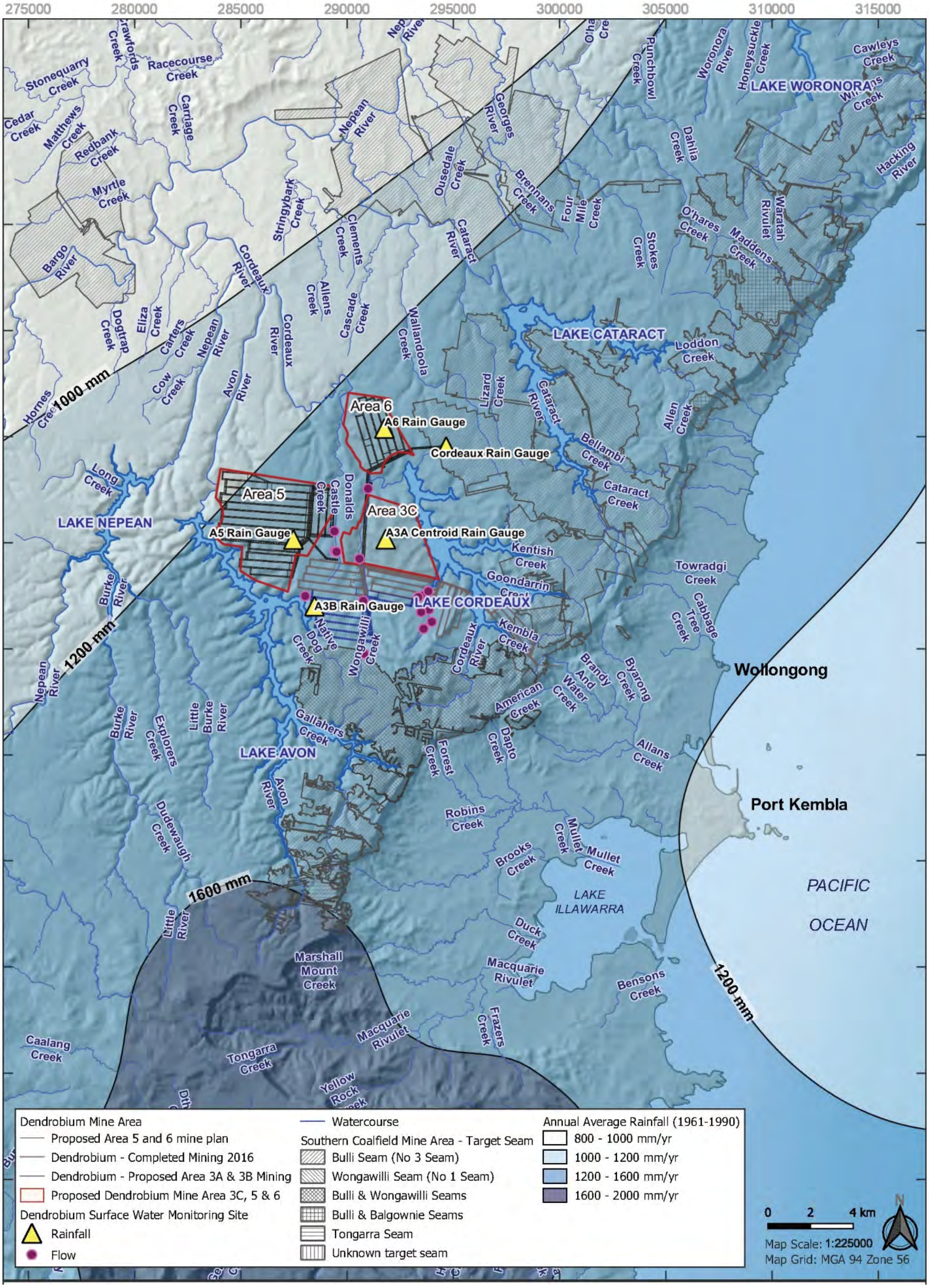

Figure 2-2 Mean Rainfall and Regional Drainage

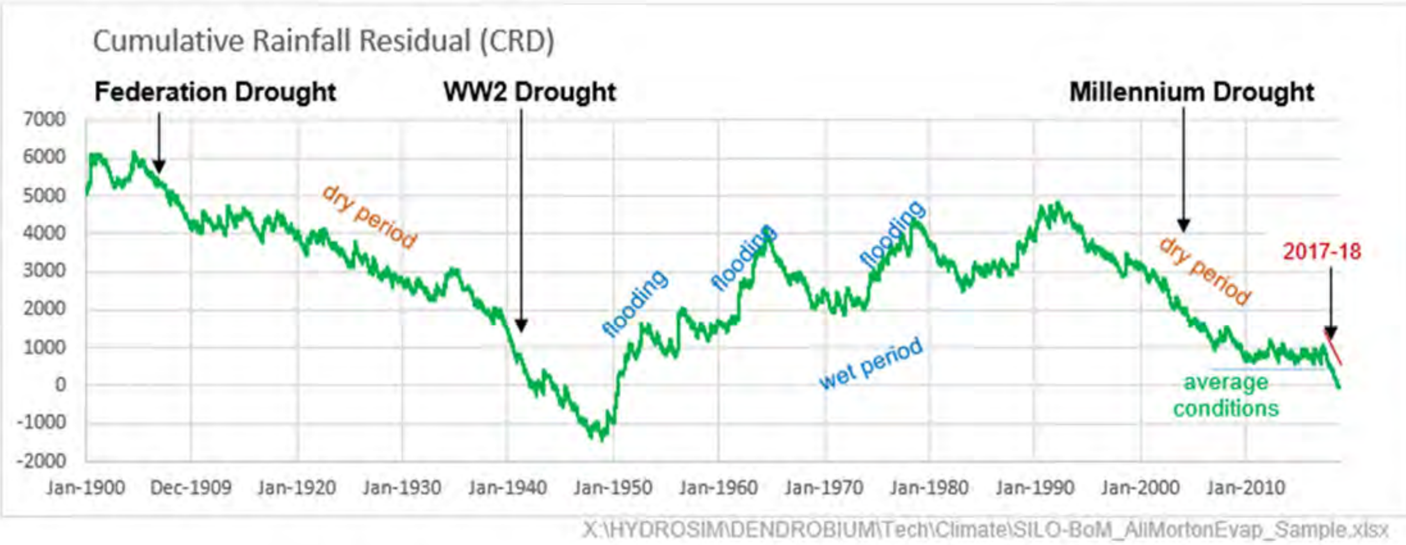

Figure 2-3 Historical Trends in Rainfall at Dendrobium (SILO data)

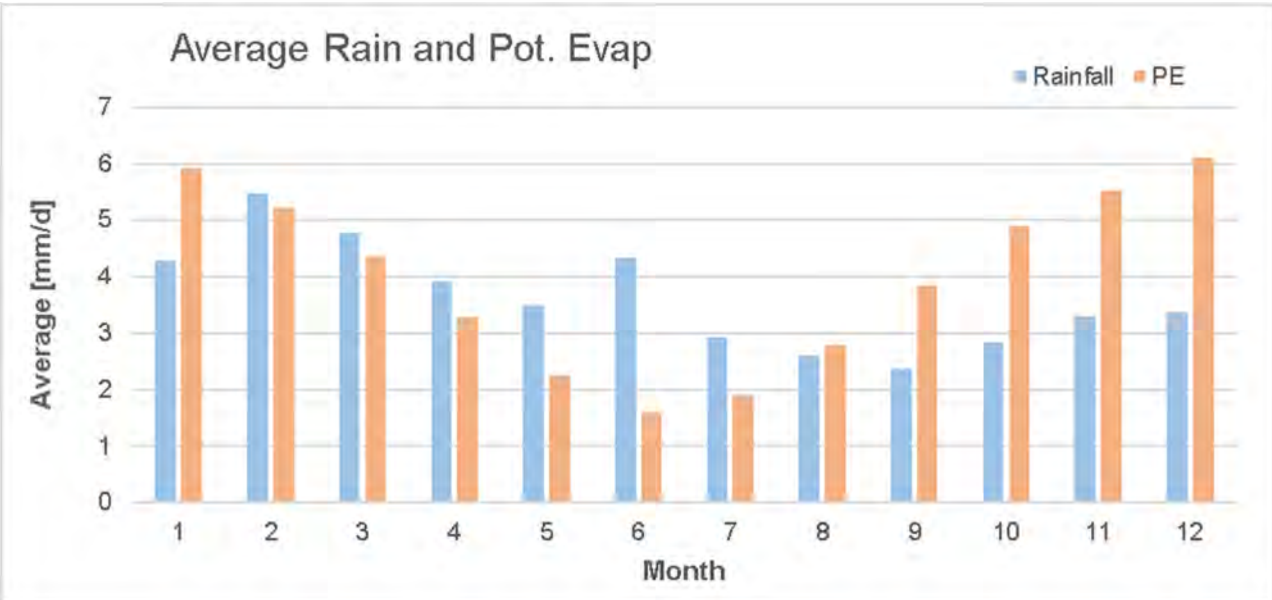

Figure 2-4 Comparison of Average Rainfall and Potential Evaporation

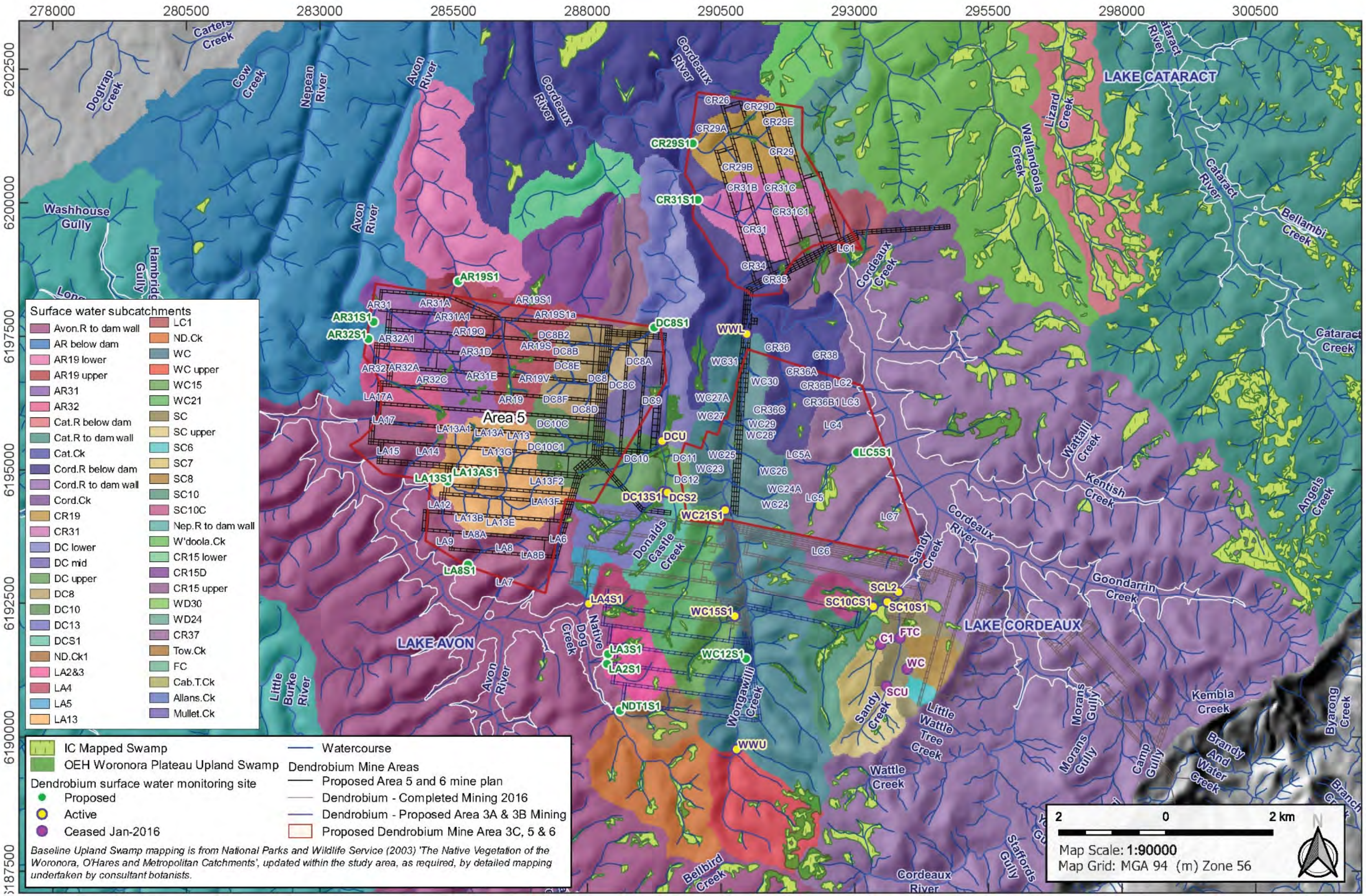

Figure 2-5 Detail of Hydrology at Dendrobium

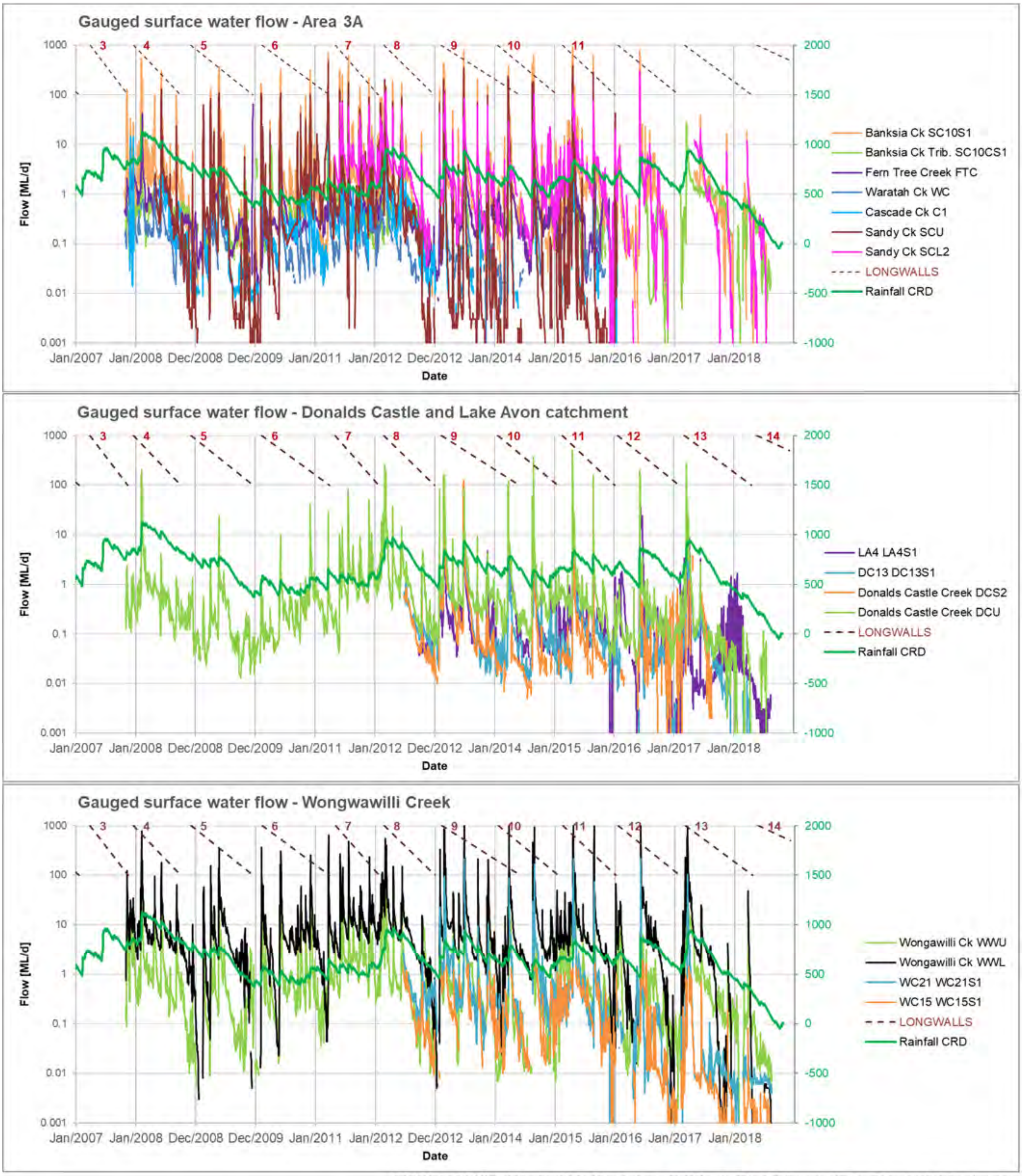

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Figure 2-6 Summary of Surface Water Flow at Dendrobium

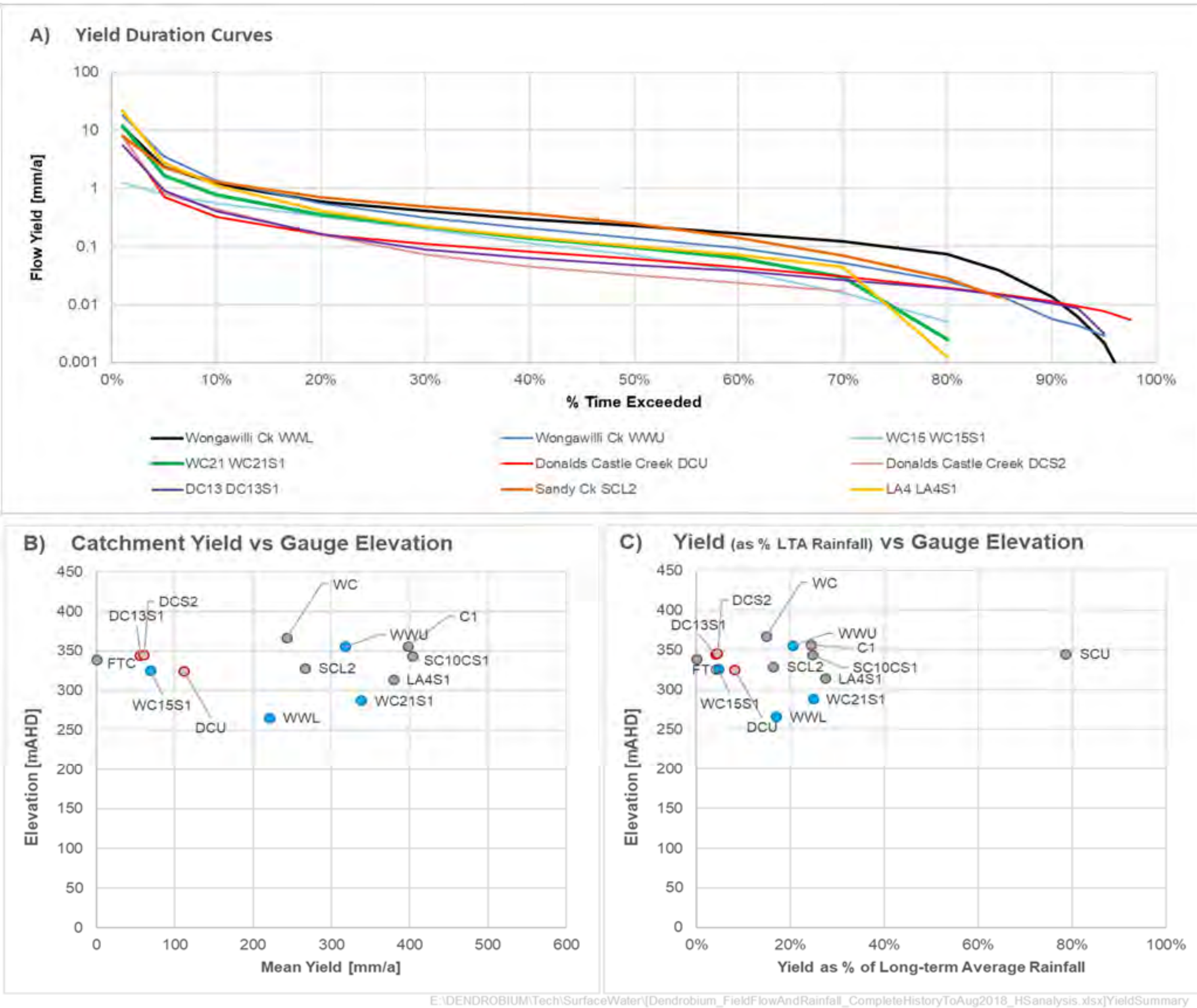
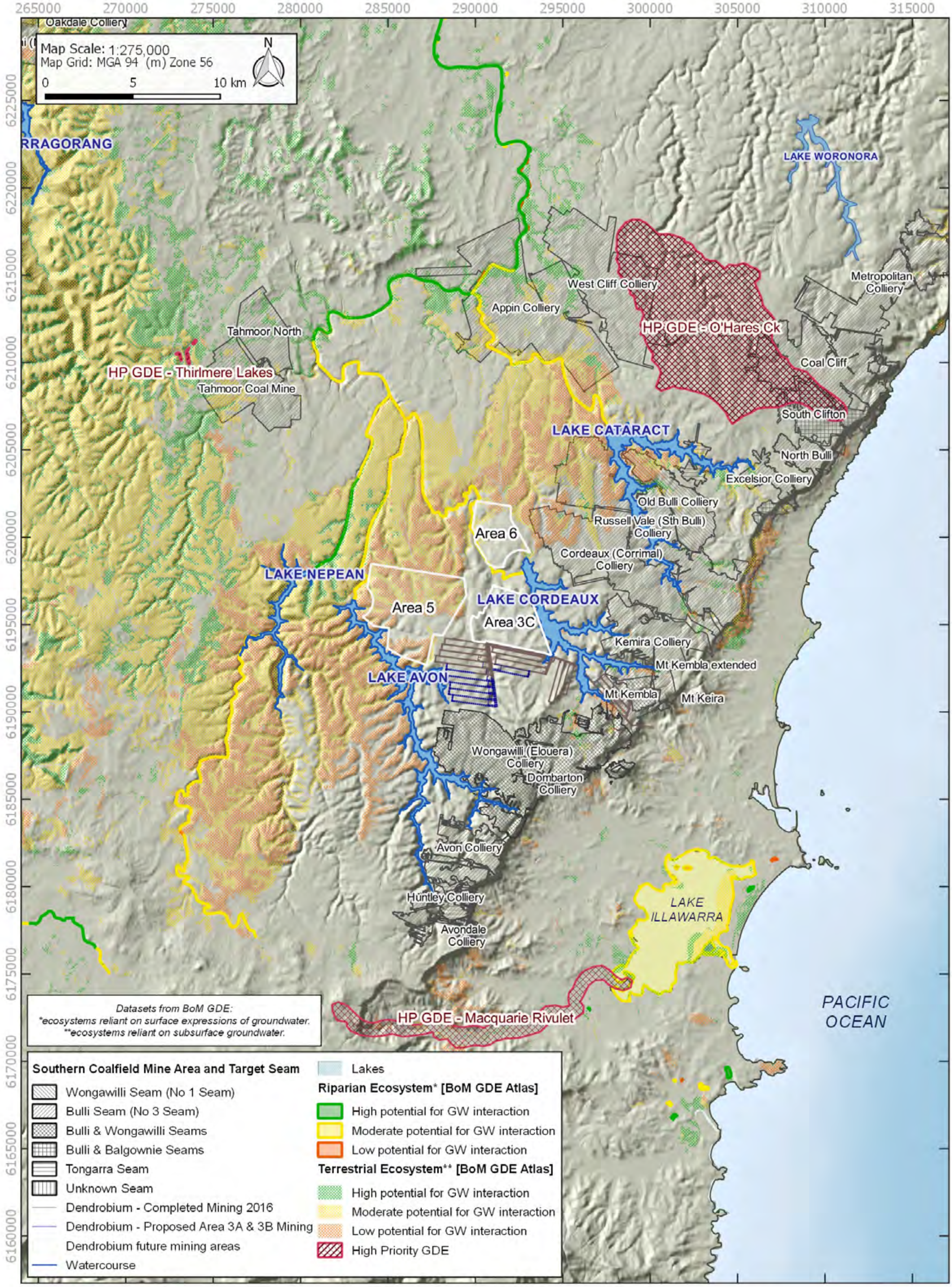


Figure 2-7 Summary of Flow and Yield at Dendrobium



HYDROSIMULATIONS

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Dendrobium Mine

Plan for the Future: Coal for Steelmaking

Groundwater Dependent Ecosystem (GDE) mapping

Figure 2.8

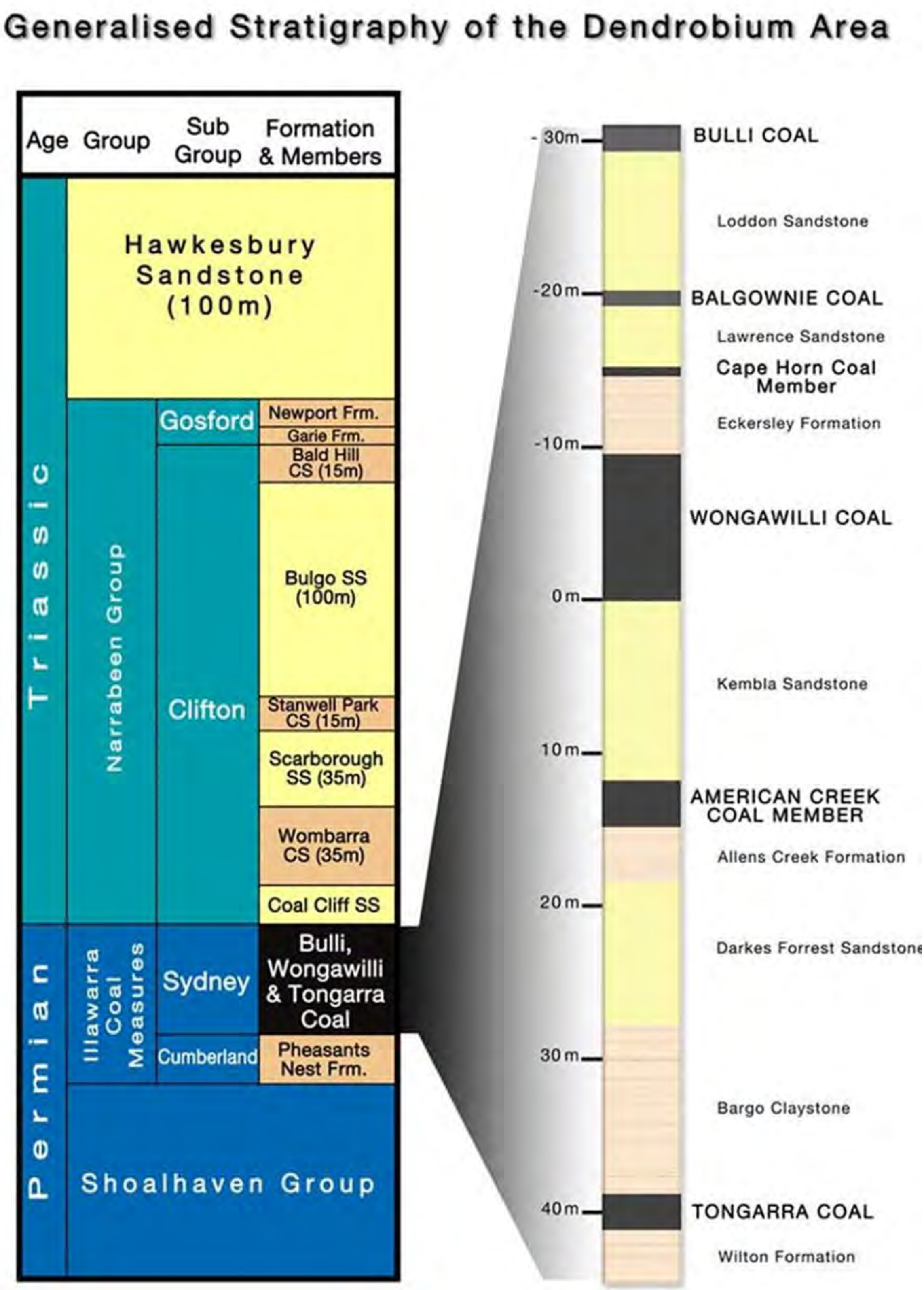
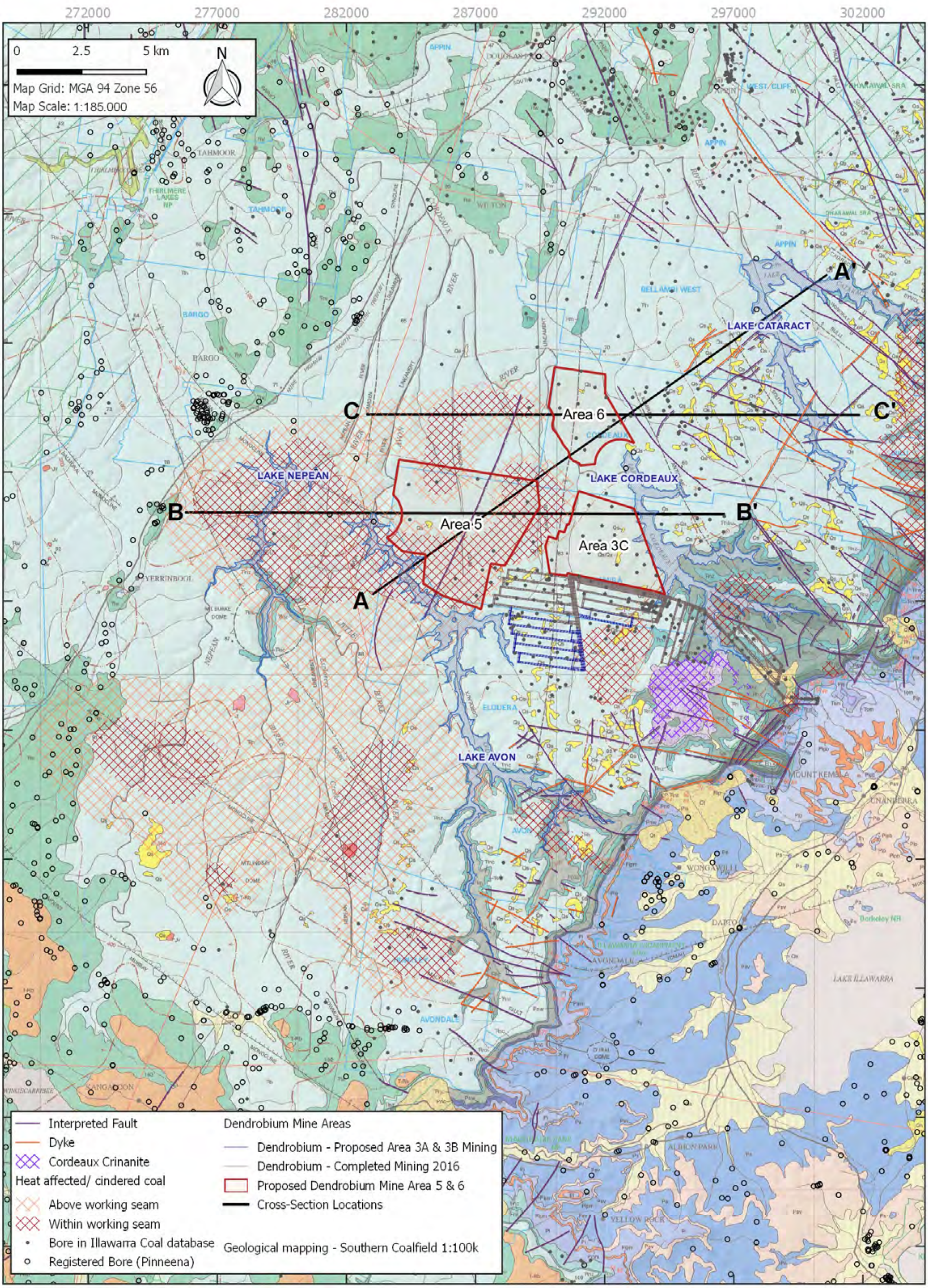


Figure 3-1 Stratigraphic Framework at Dendrobium



HYDROSIMULATIONS

Dendrobium Mine

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Outcrop Geology

Figure 3.2

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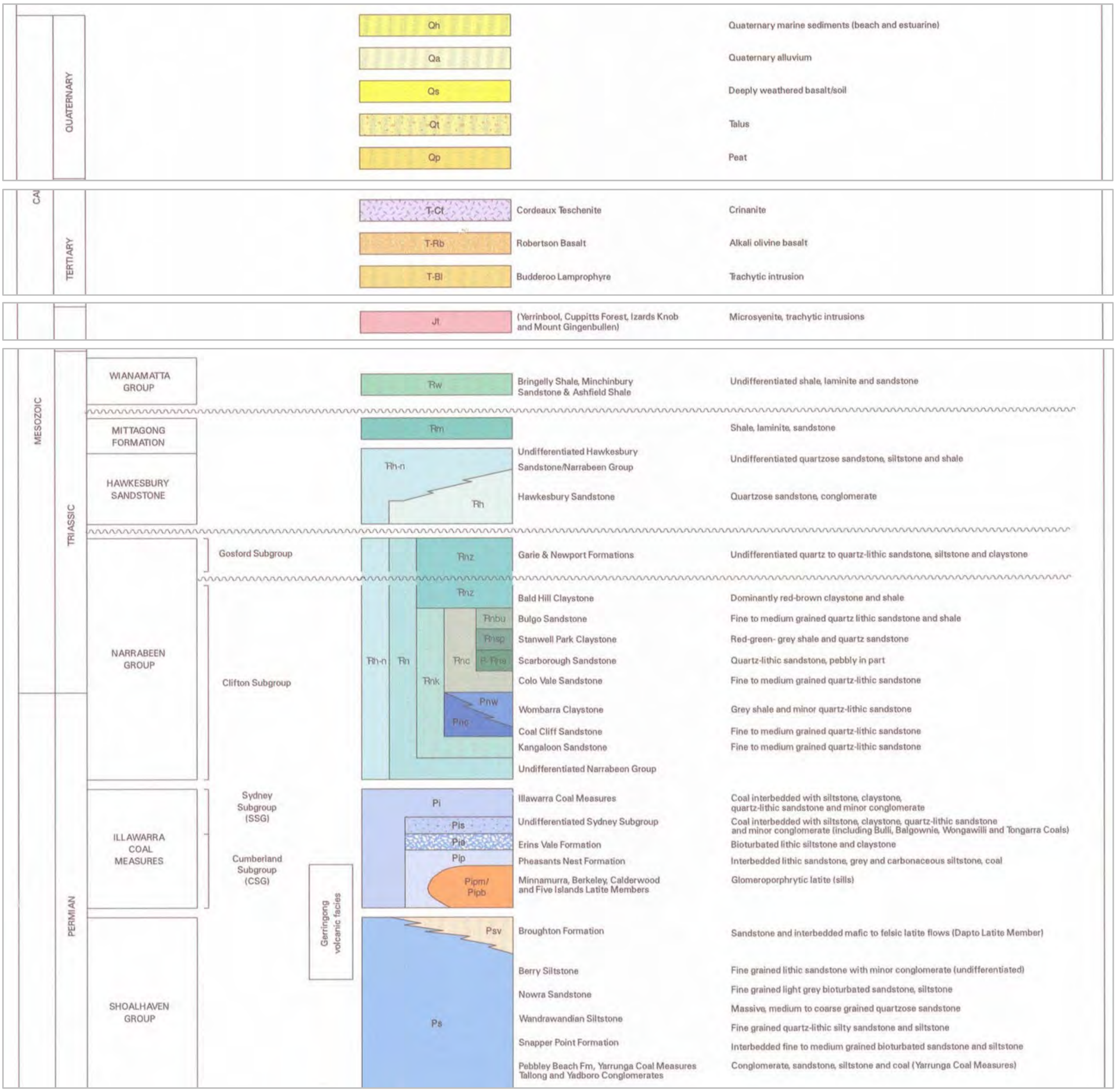

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Figure 3-3 Key to Southern Coalfield Geological Map (Moffitt, 1999)

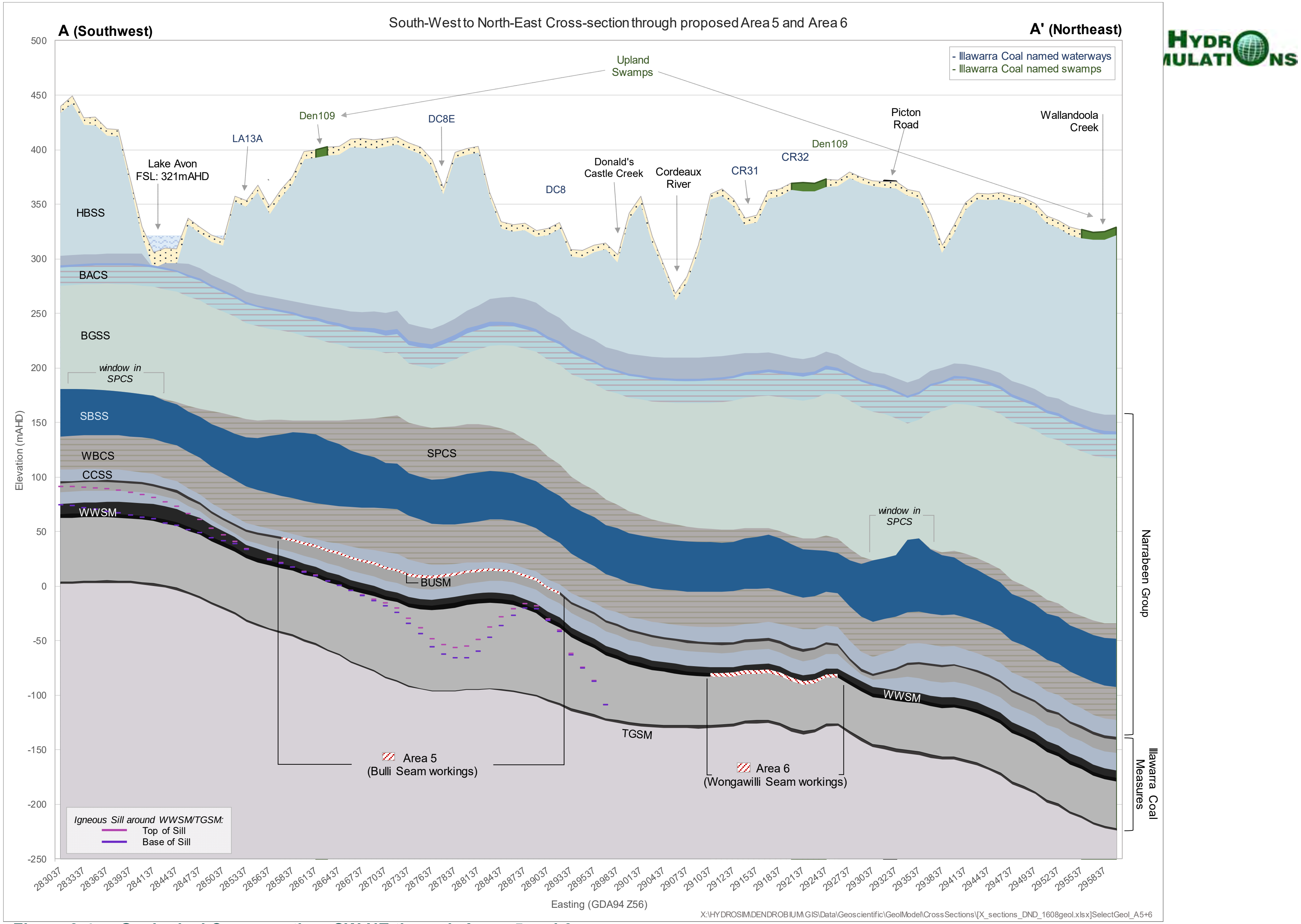


Figure 3-4 Geological Cross-section: SW-NE through Areas 5 and 6

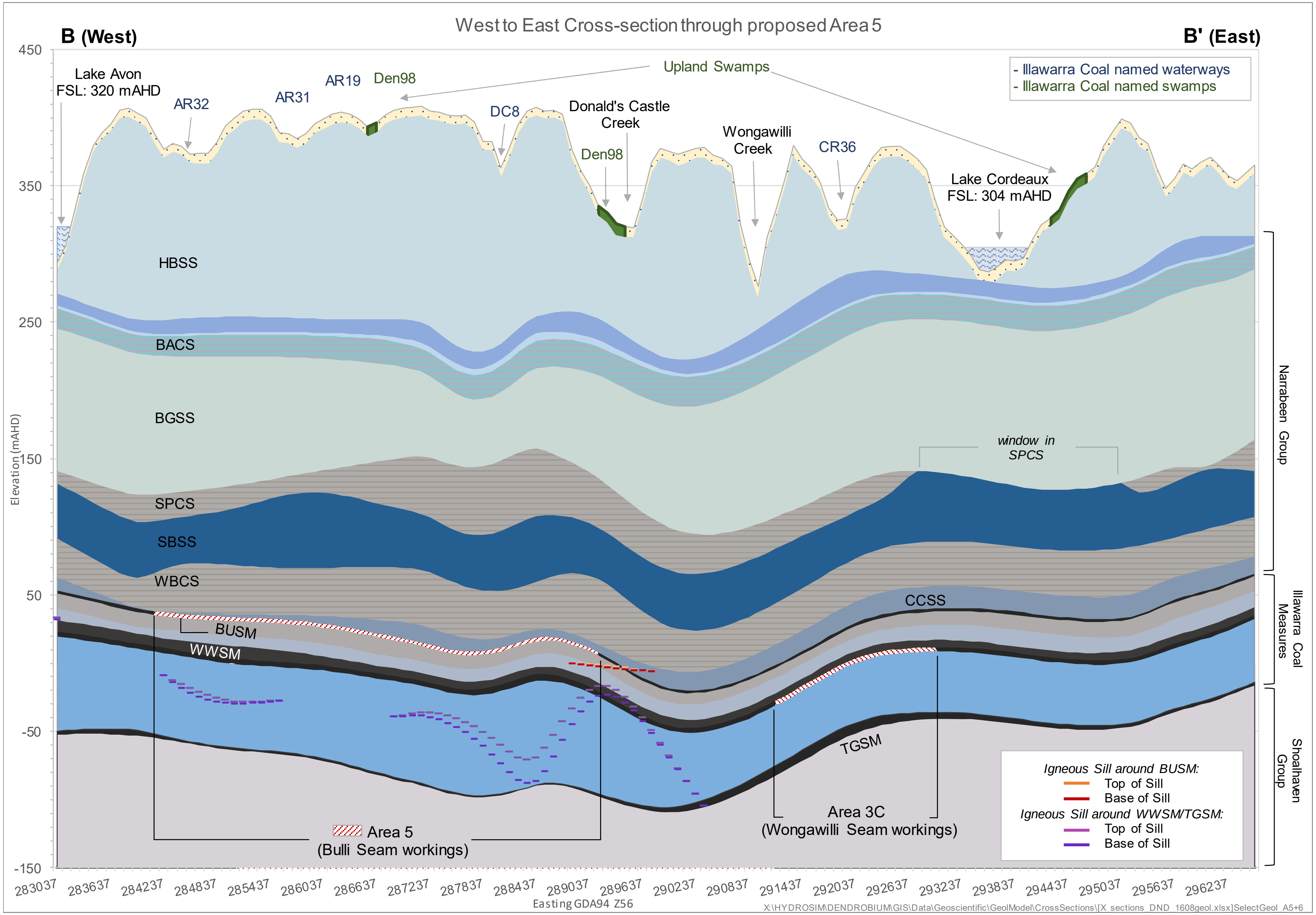


Figure 3-5 Geological Cross-section: West-East through Area 5

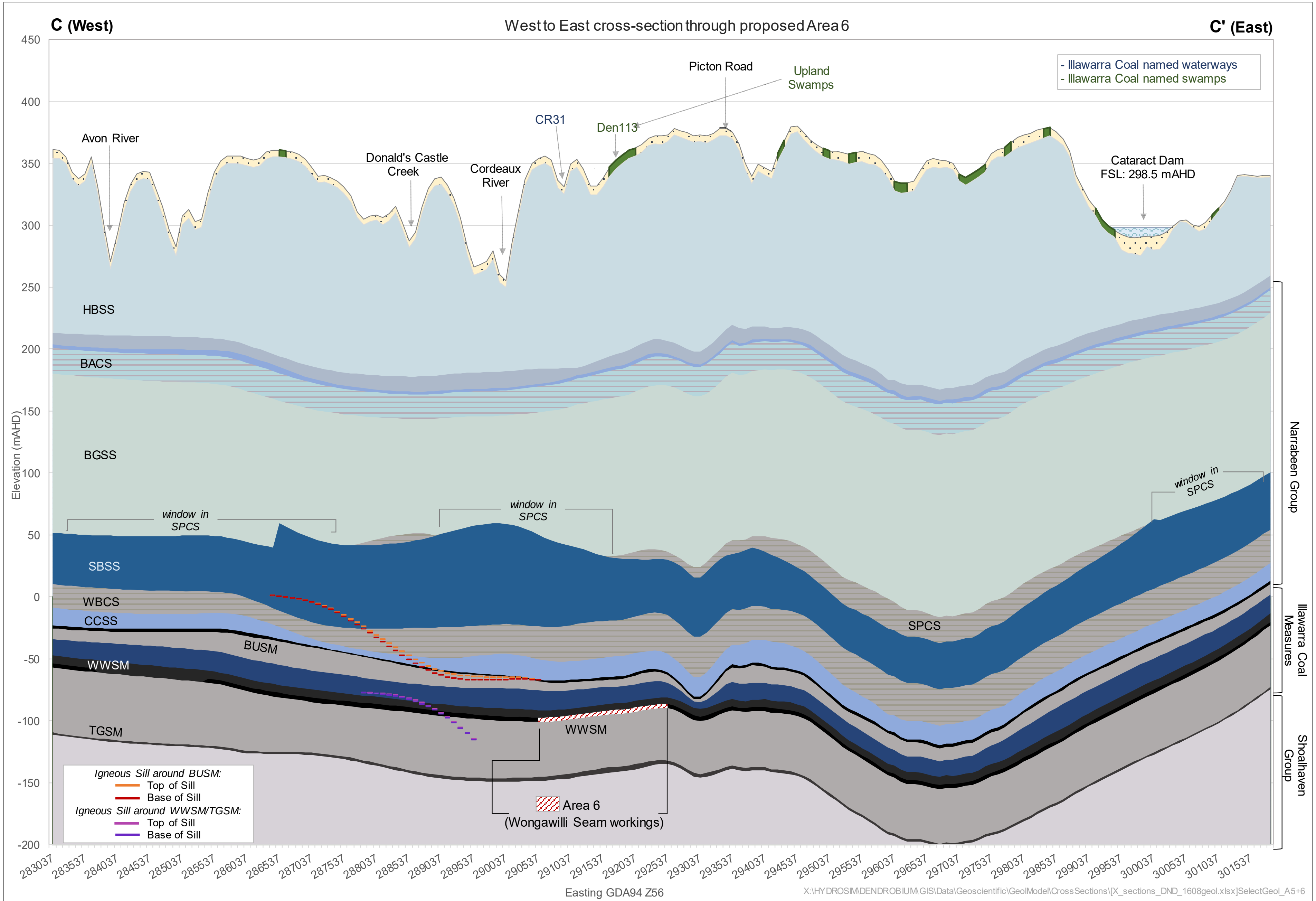
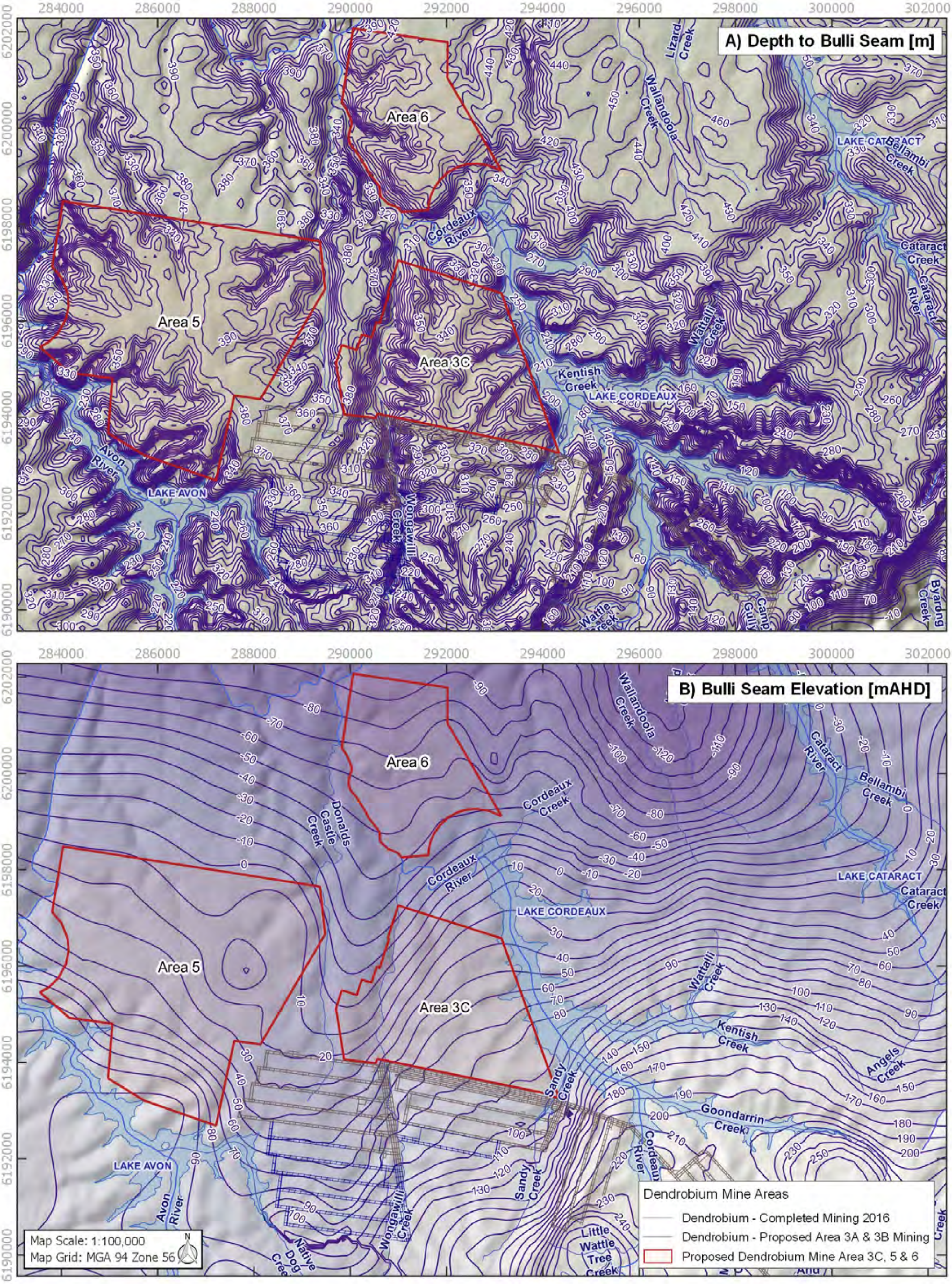


Figure 3-6 Geological Cross-section: West-East through Area 6



HYDROSIMULATIONS

Dendrobium Mine

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Bulli Seam Characteristics

Figure 3.7

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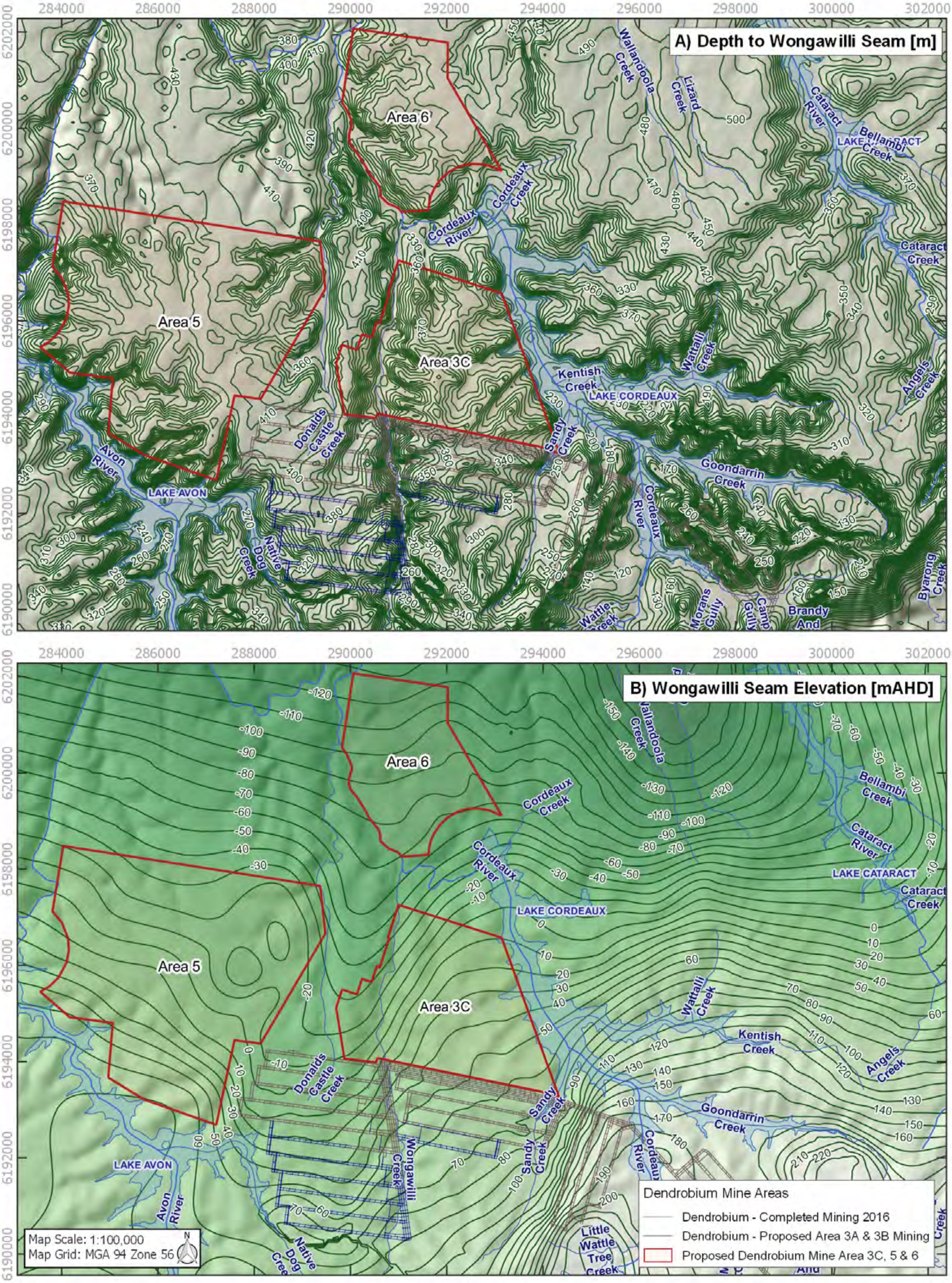

HYDROSIMULATIONS

Dendrobium Mine

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Wongawilli Seam Characteristics

Figure 3.8

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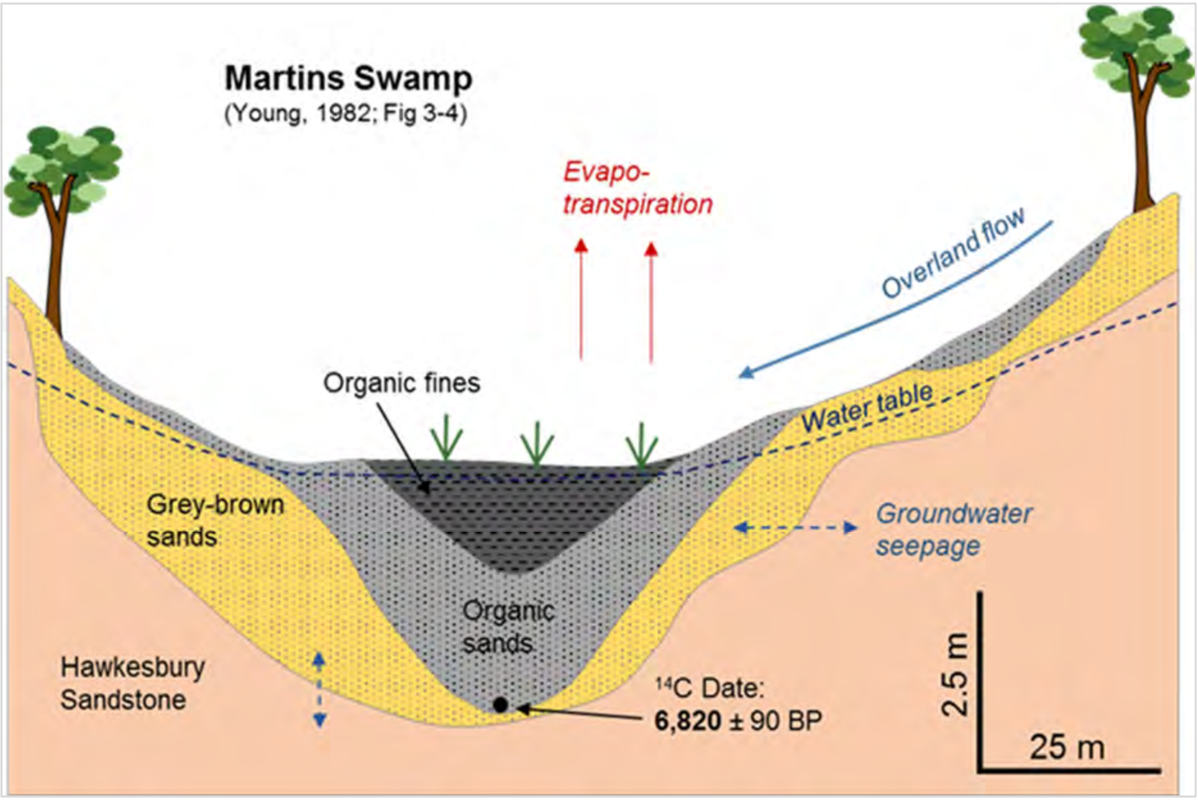
A)



B)

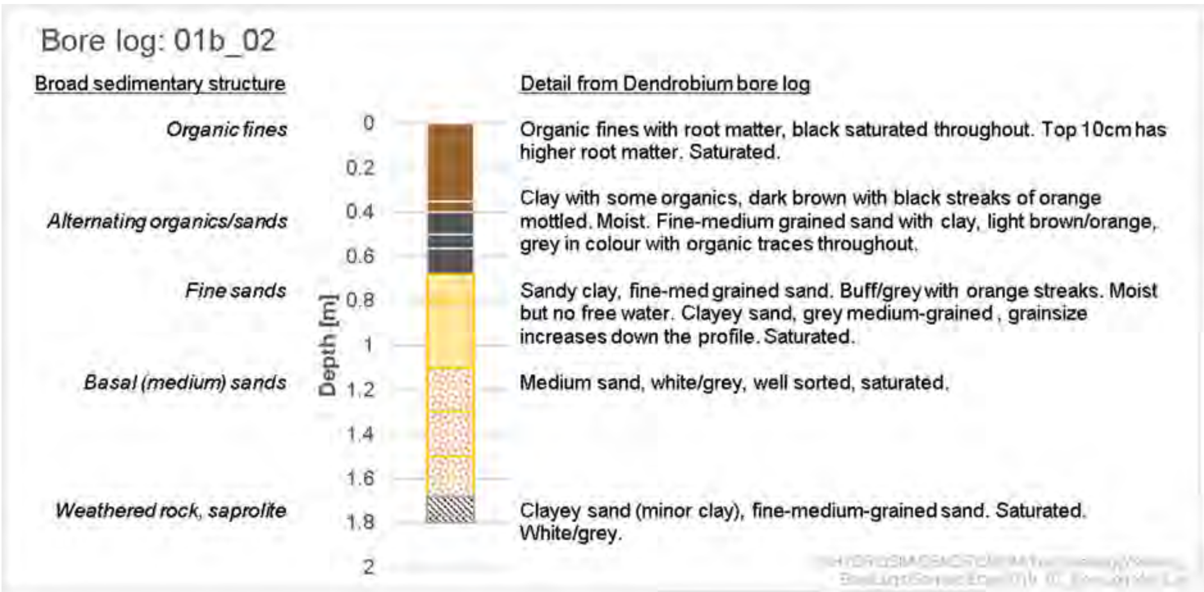
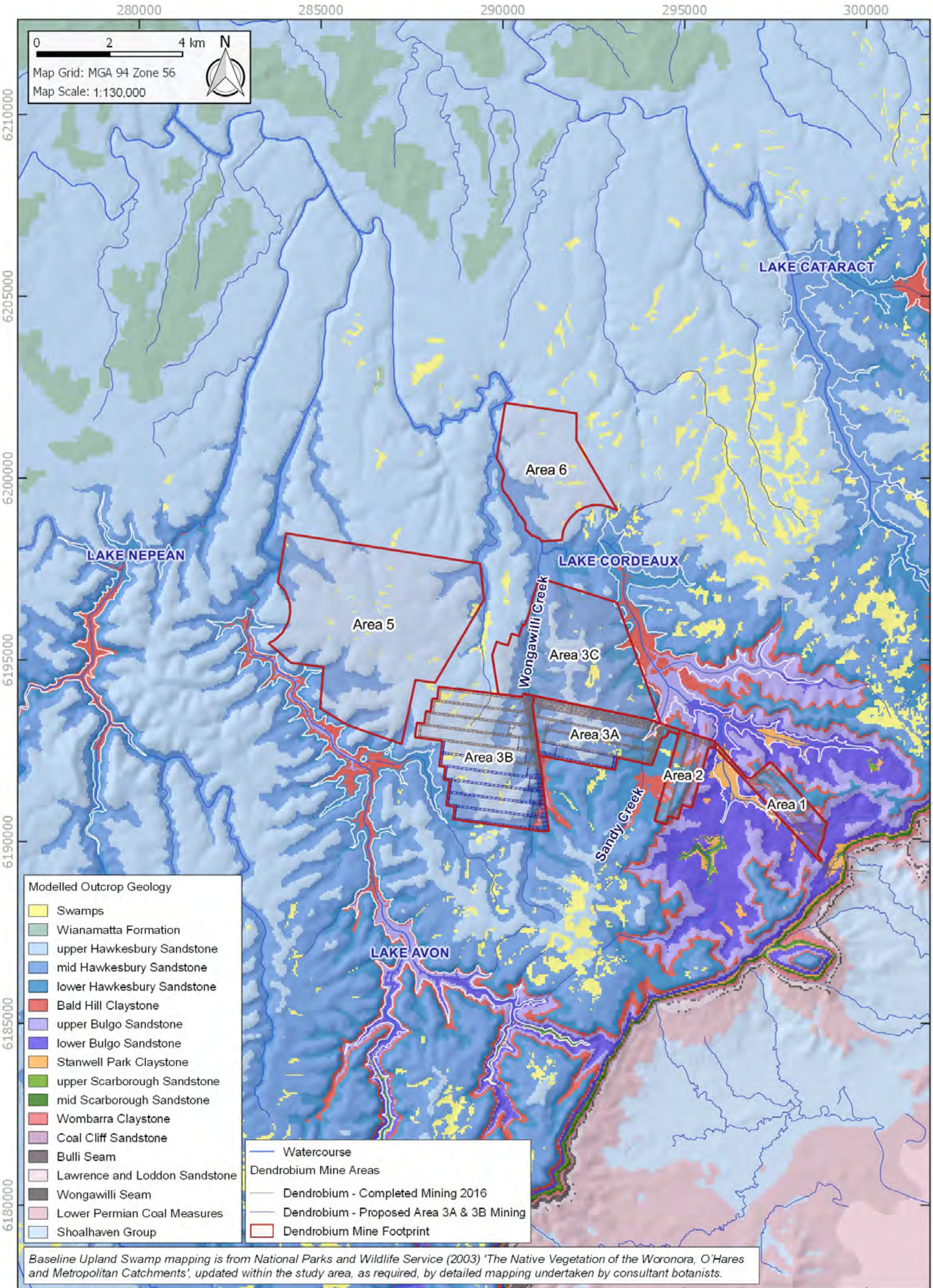


Figure 3-9 Lithological sequence in Upland Swamps



HYDRO SIMULATIONS

Dendrobium Mine

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Geology Model Outcrop

Figure 3.10

X:/HYDROSIM/DENDROBIUM/GIS/Maps/Working/DND_reportFigures/Fig3.10_modelledOutcropGeol.qgs average thickness of 257m (in boreholes Stanley 4, Johndilo 2, and Kay Park 5). Figure 10 shows that the Permian Coal Measures and the Hawkesbury Sandstone contain higher clay contents than the Bulgo Sandstone, which stands out as having less clay.

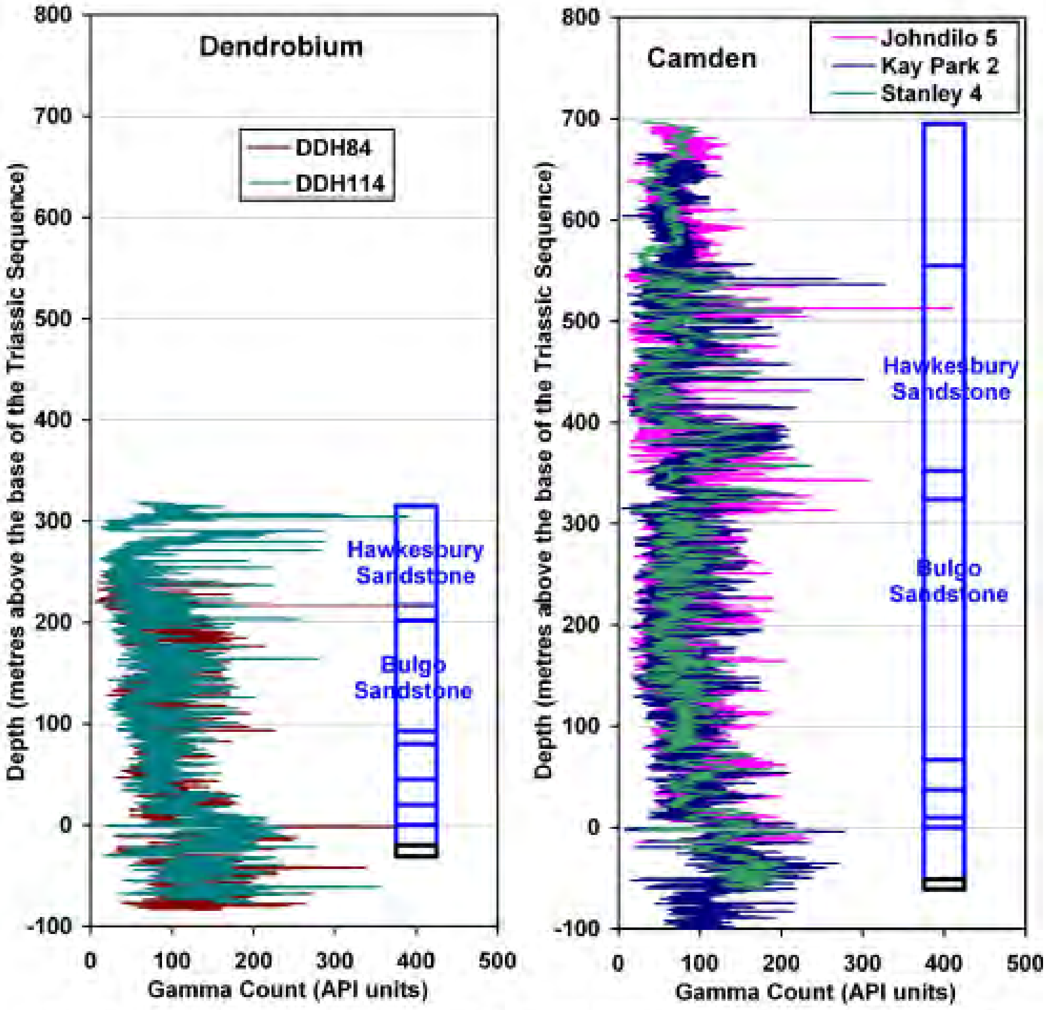

Figure 10. Downhole gamma logs for the bores in the Dendrobium and Camden areas.

Figure 4-1 Downhole gamma logs (from Coffey, 2012a)

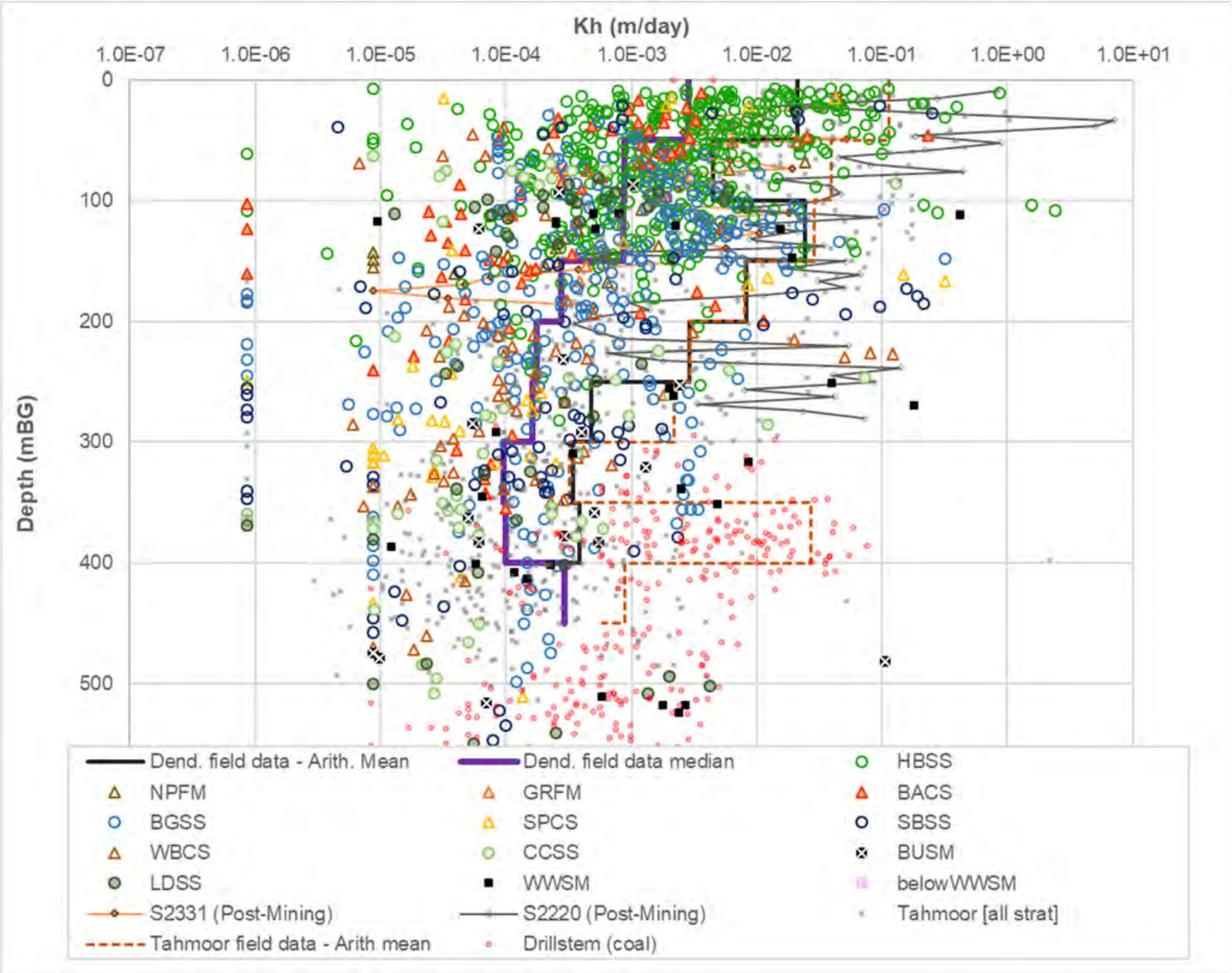

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Figure 4-2 Hydraulic conductivity (Kh) versus test depth

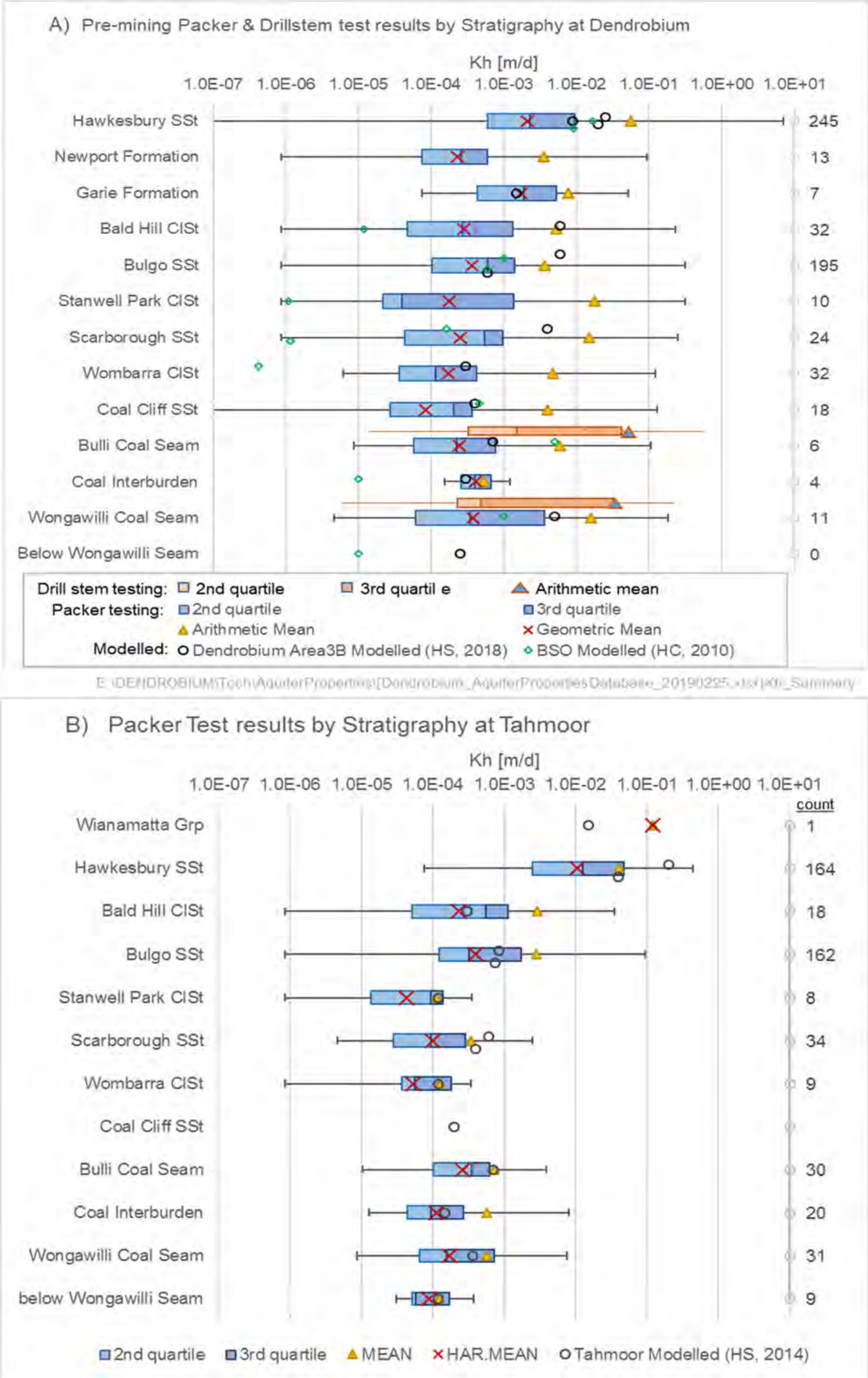


Figure 4-3 Summary of Horizontal Hydraulic Conductivity (Kh) by Stratigraphic unit

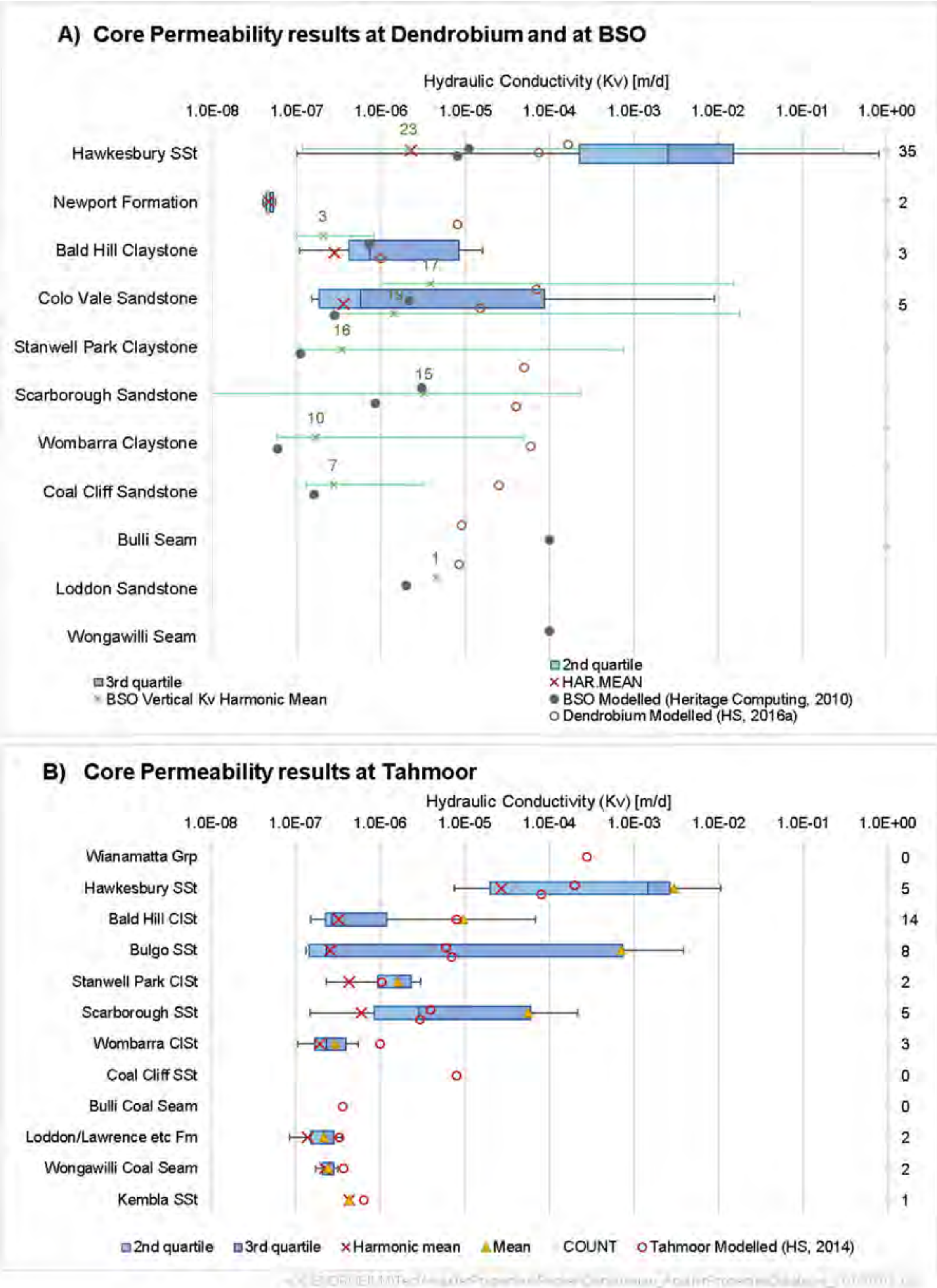


Figure 4-4 Hydraulic conductivity (Kv) from core testing

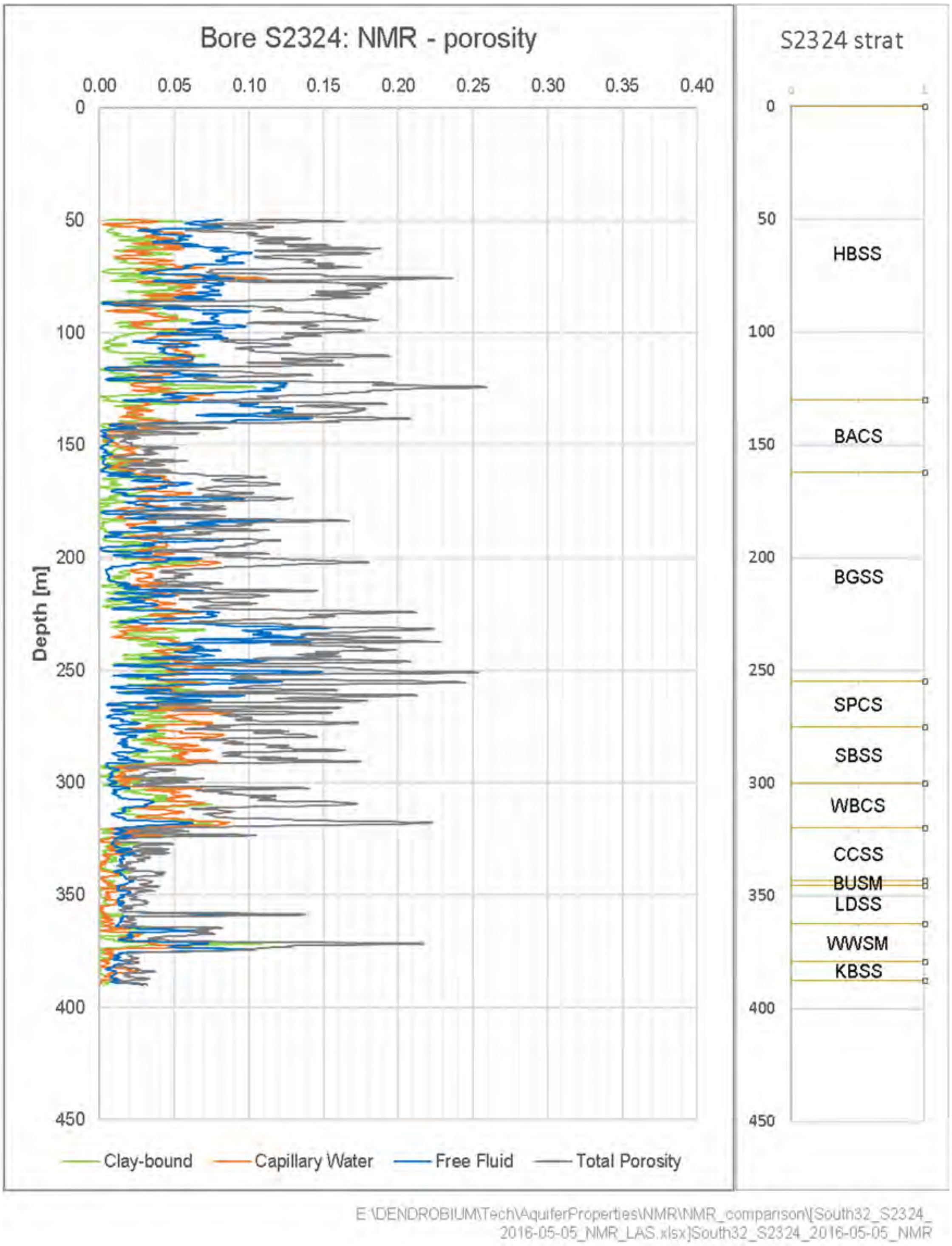


Figure 4-5 NMR porosity in bore S2324

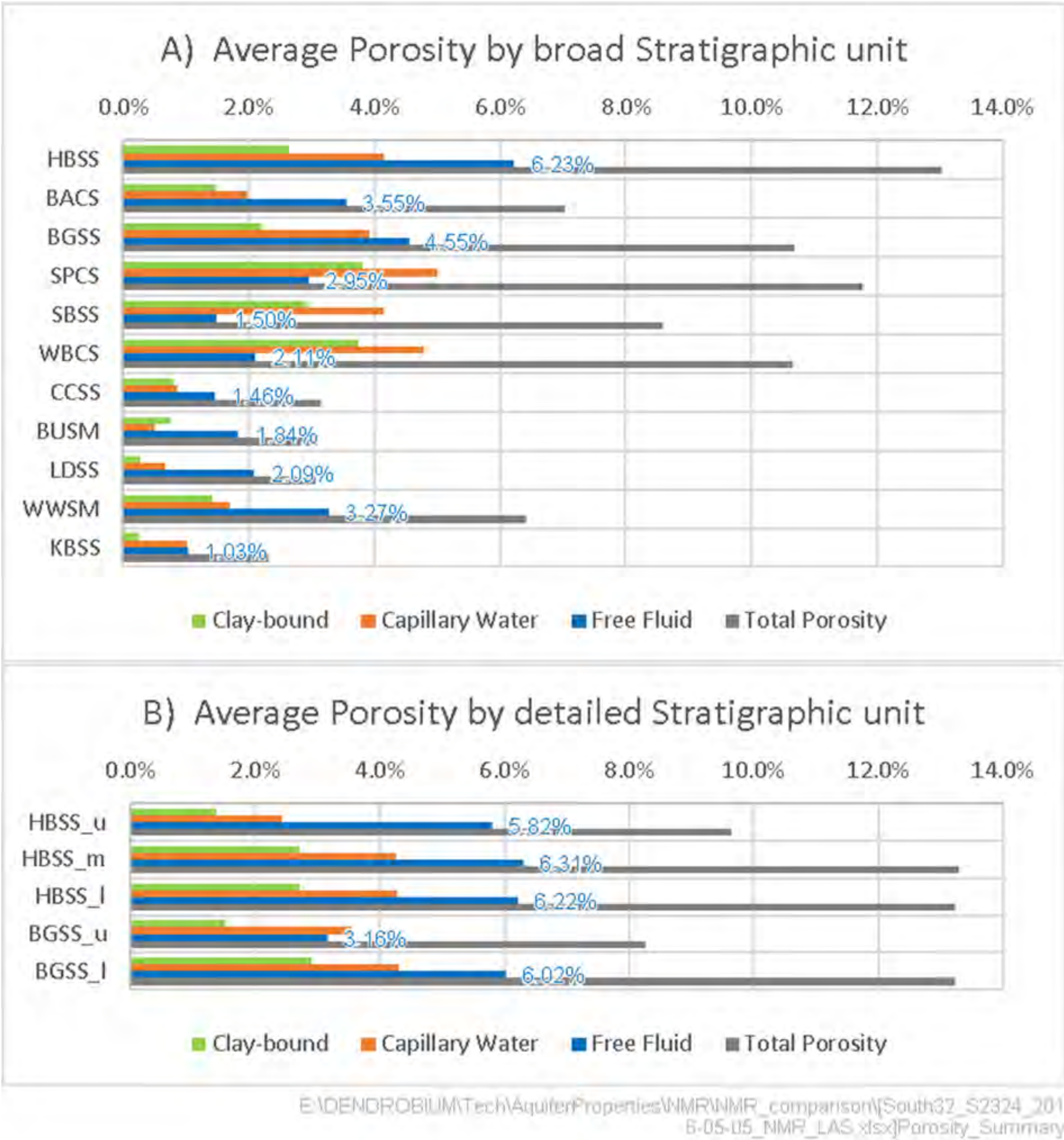


Figure 4-6 Summary of Water Content and Porosity (from NMR) by stratigraphic unit

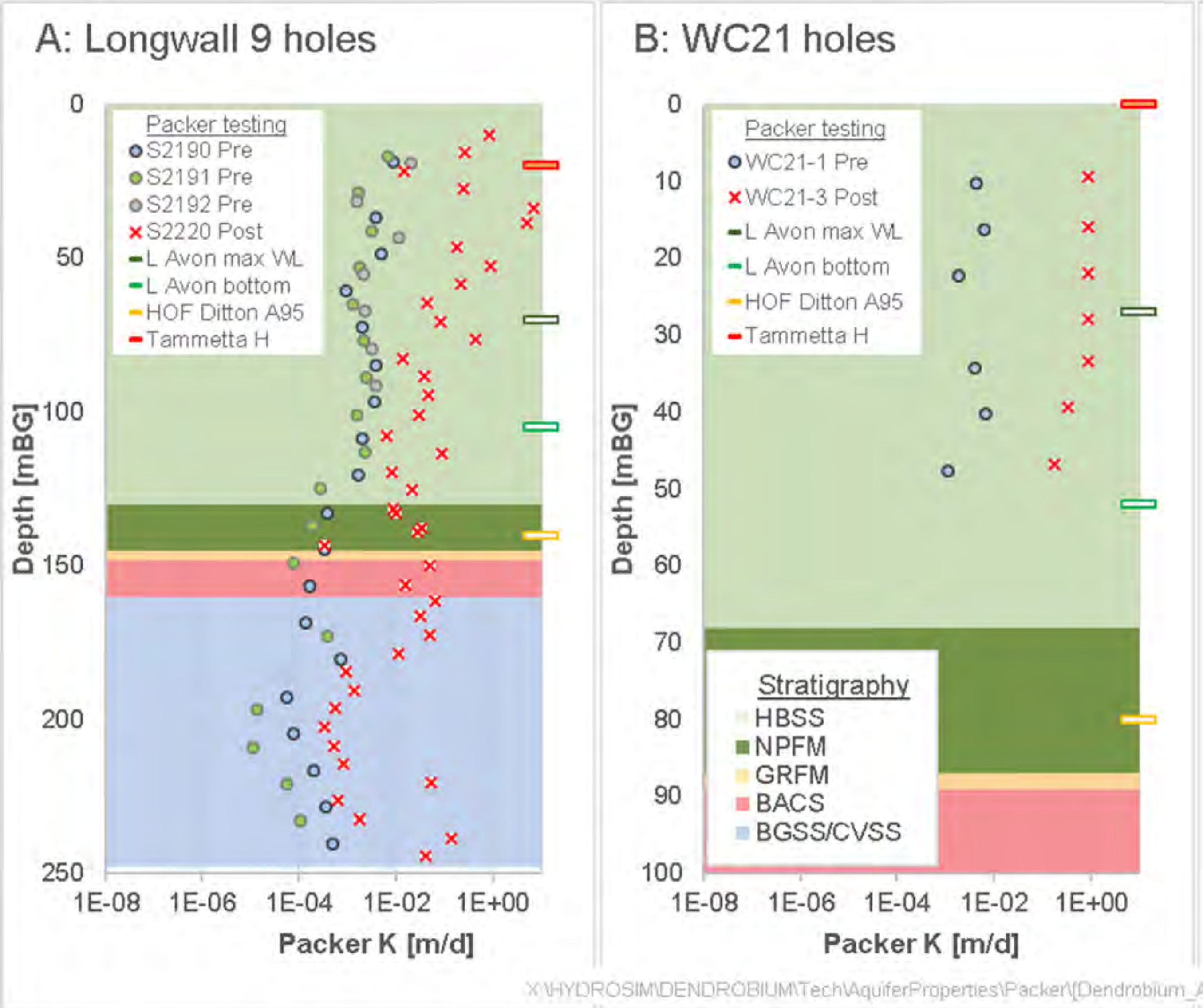


Figure 4-7 Change in Hydraulic Conductivity (Kh) due to mining – above a longwall

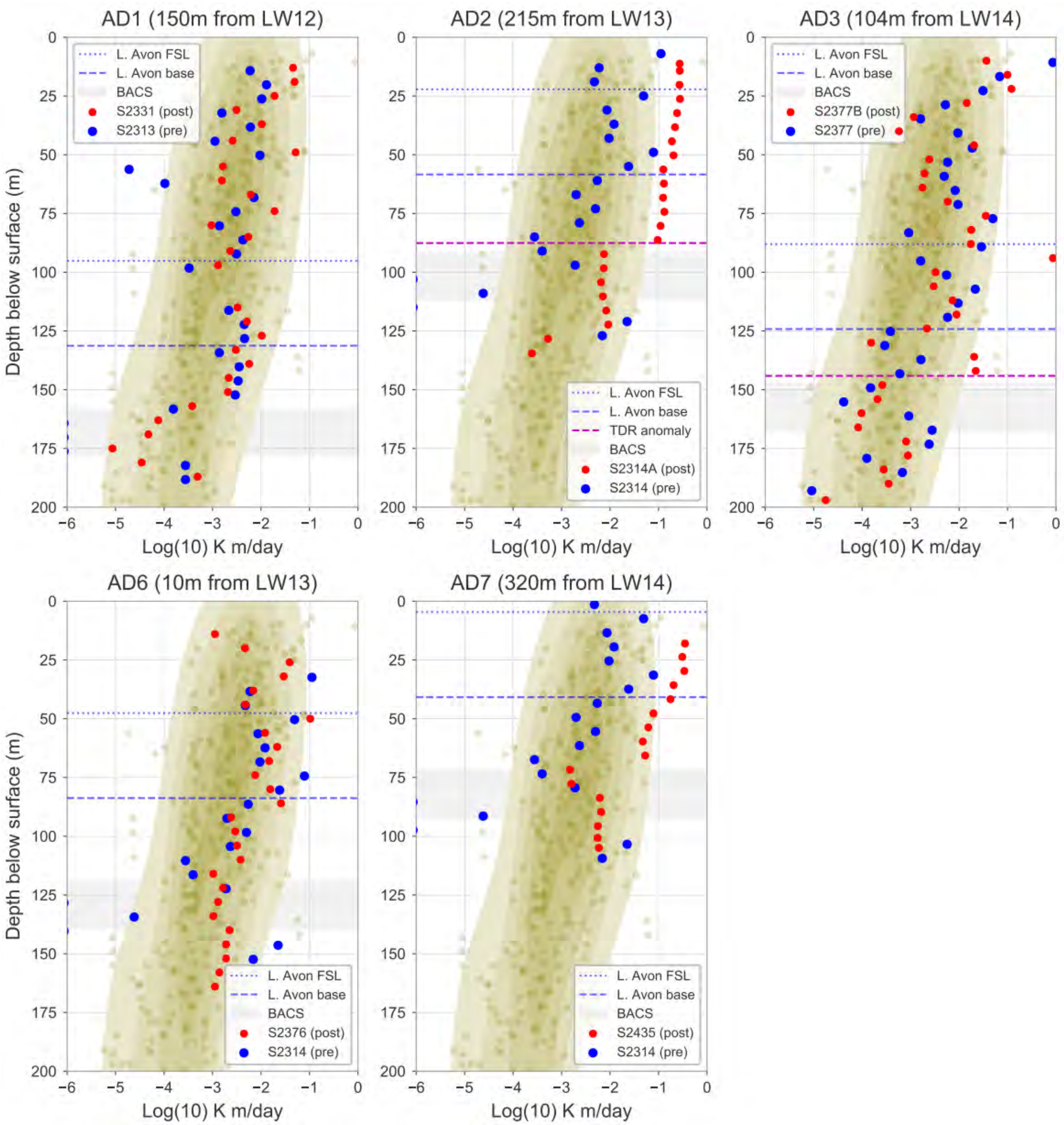


Figure 4-8 Change in hydraulic conductivity (Kh) due to mining – off-goaf areas

(source: HGEO)

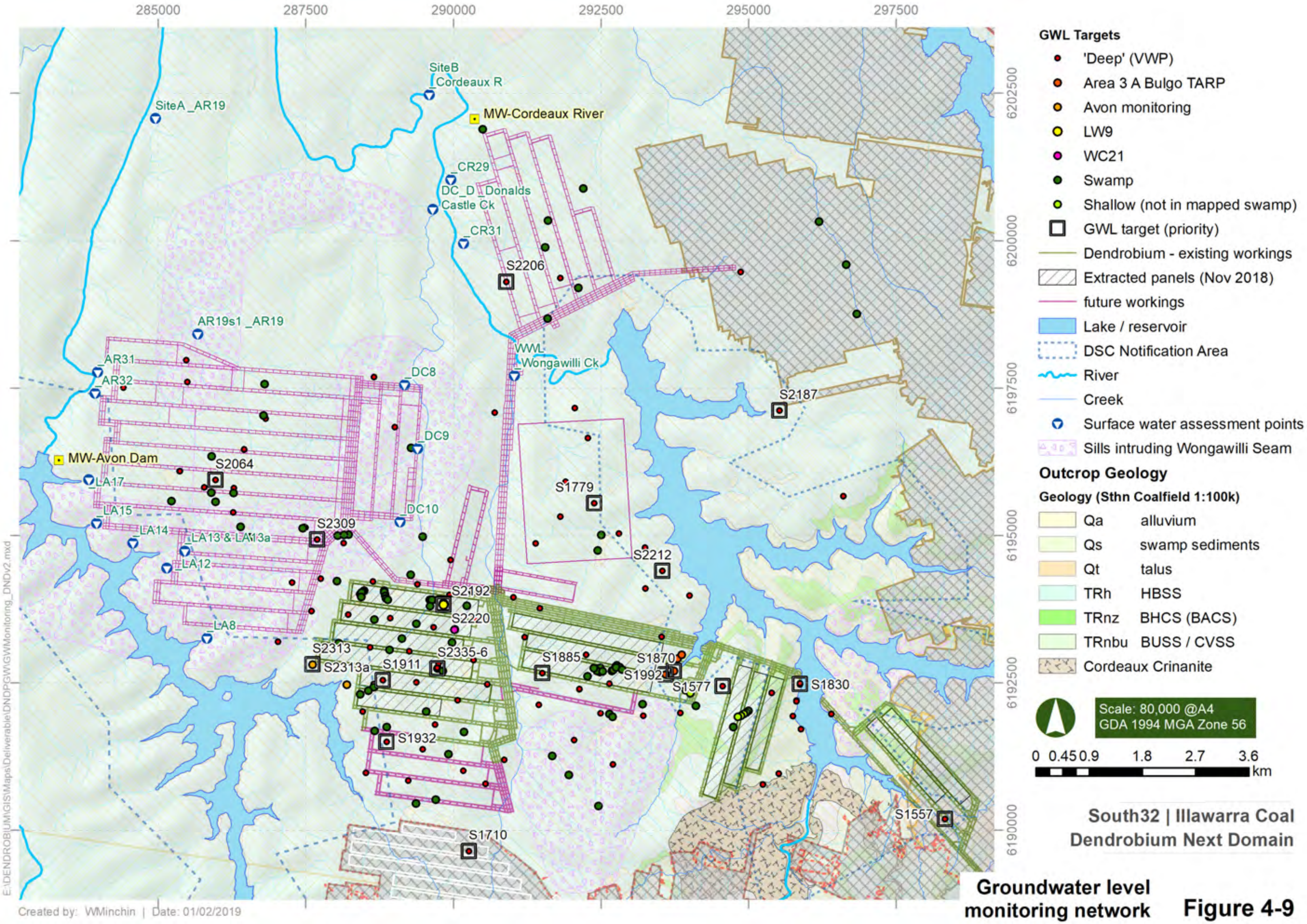
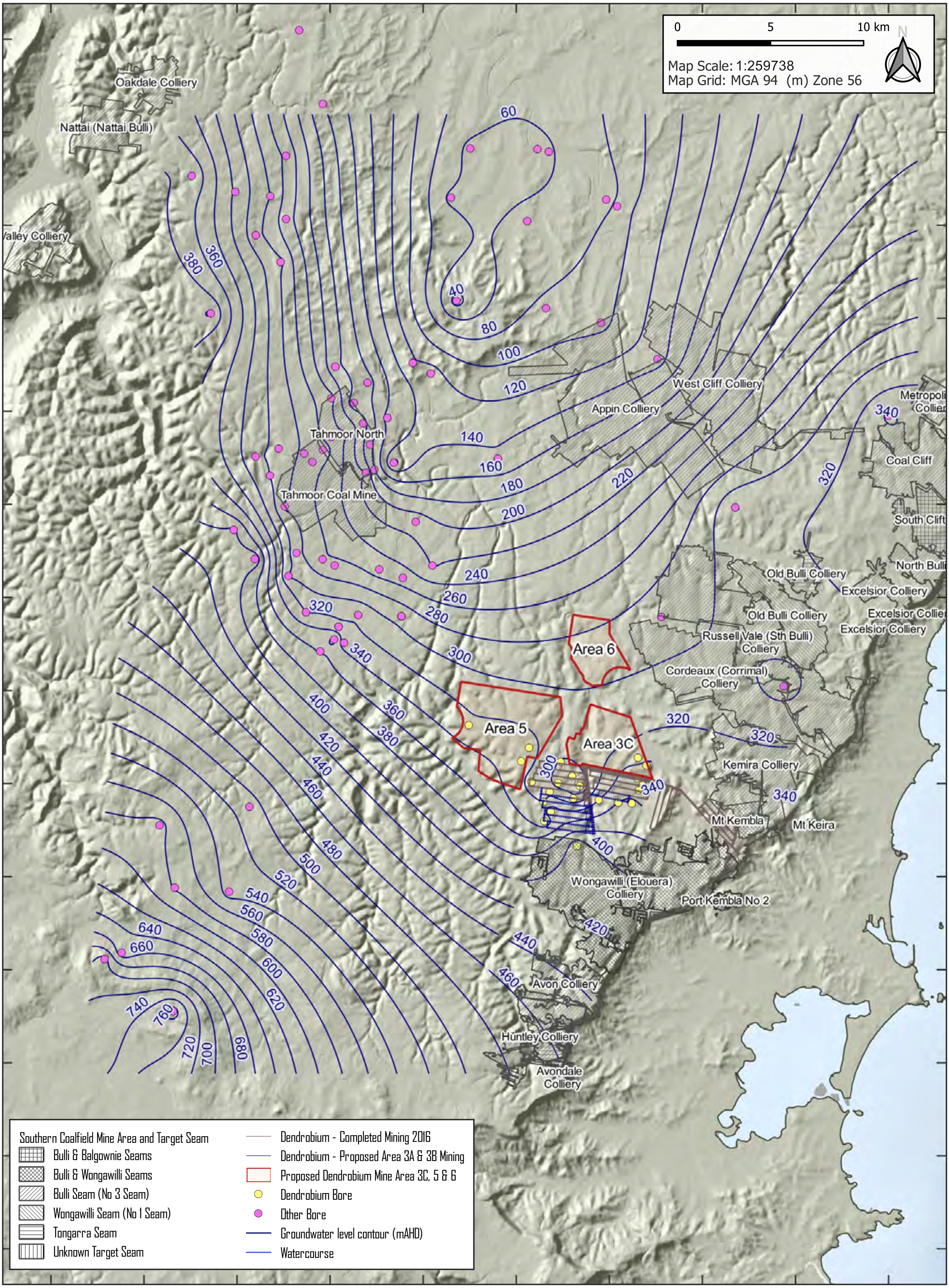


Figure 4-9 Location of groundwater level monitoring sites



HYDRO SIMULATIONS

Dendrobium Mine

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Lower Hawkesbury Sandstone Groundwater Level

Figure 4-10

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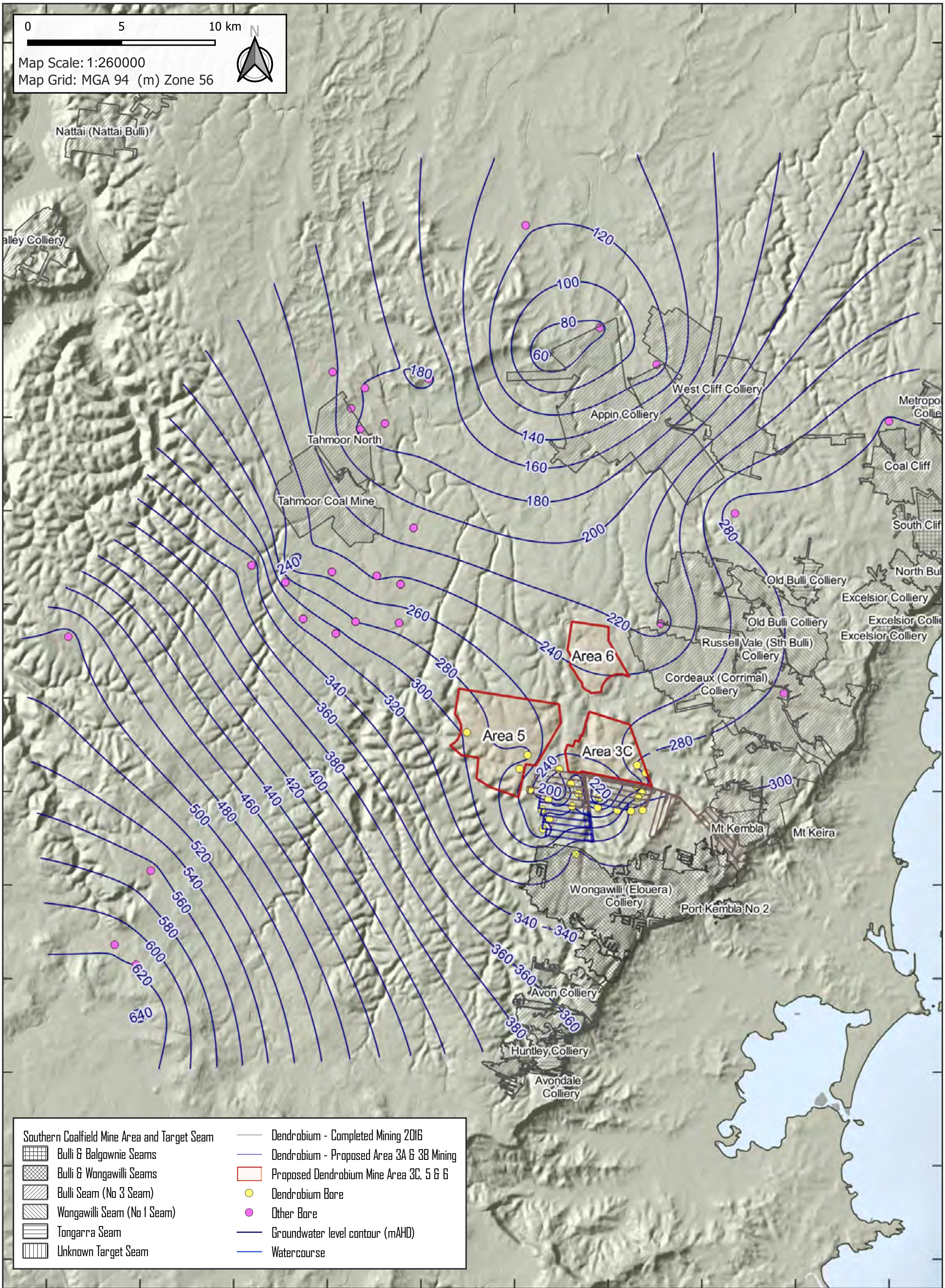

Dendrobium Mine

Plan for the Future: Coal for Steelmaking

Upper Bulgo Sandstone Groundwater Level

Figure 4-11

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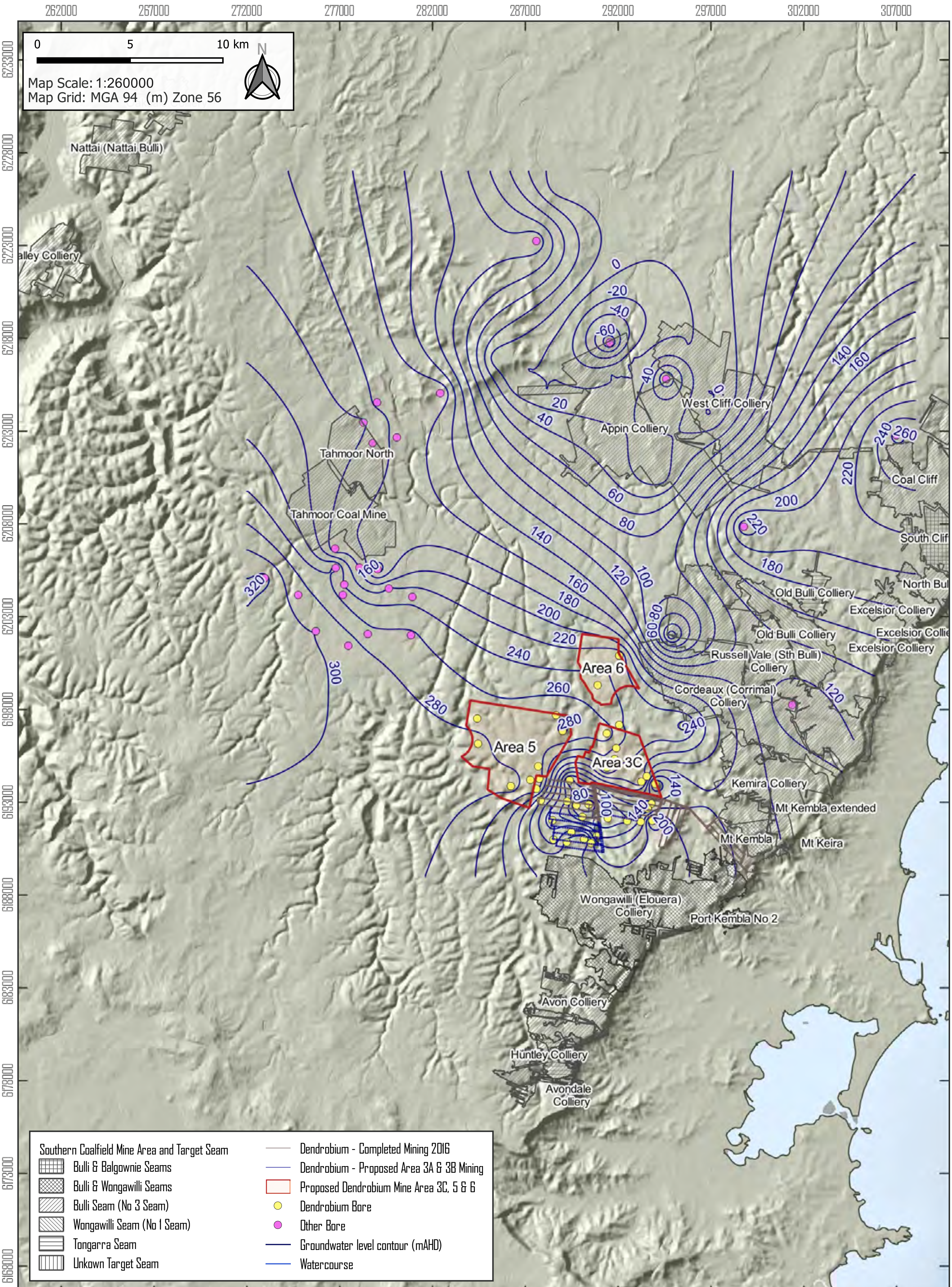

Dendrobium Mine

Plan for the Future: Coal for Steelmaking

Bulli Seam Groundwater Level

Figure 4-12

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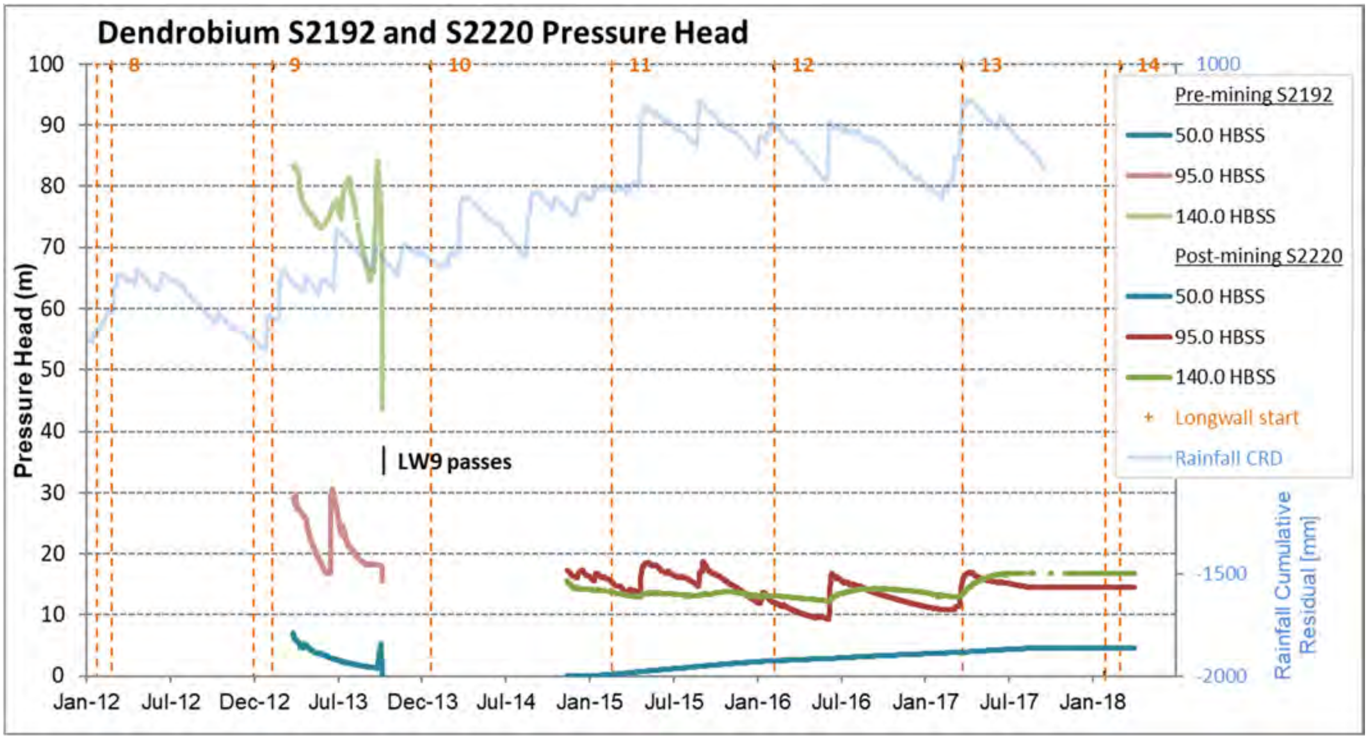
A)



B)

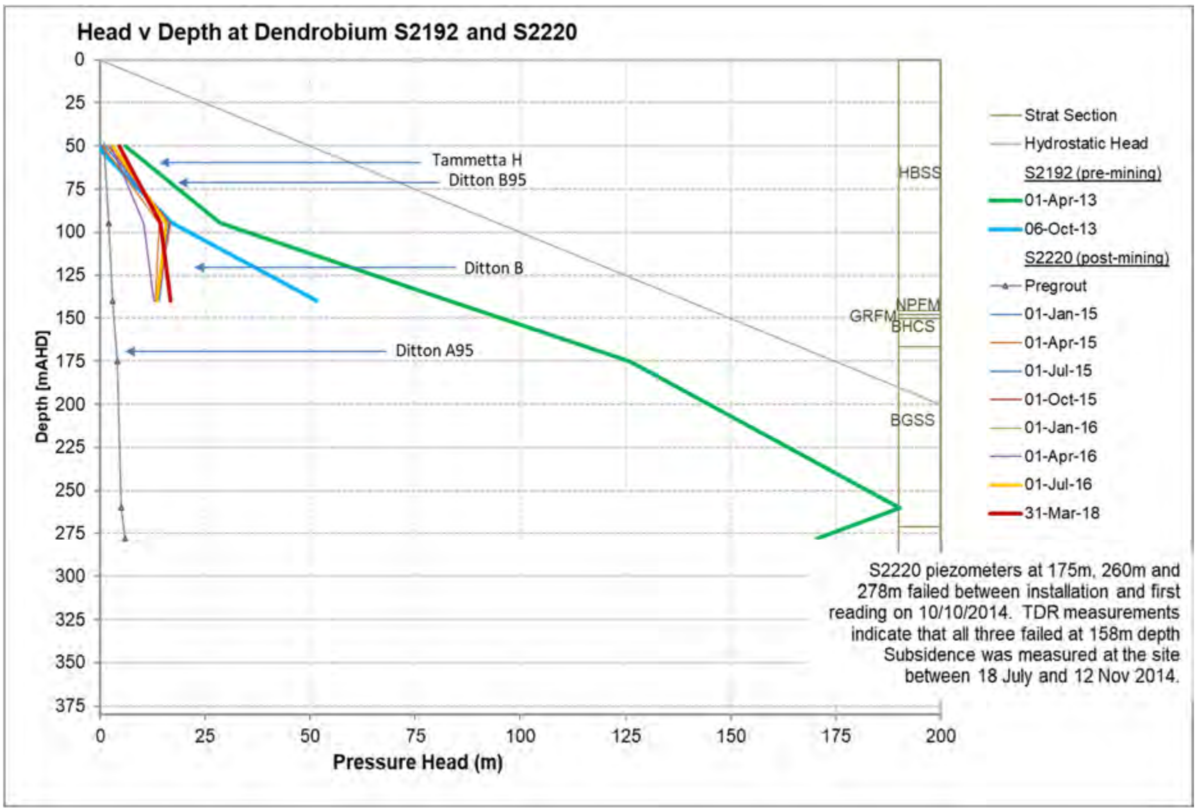


Figure 4-13 Groundwater Levels above Longwall 9: A] Pressure Head; B] Head vs Depth

E:\DENDROBIUM\Tech\Groundwater\GroundwaterLevels\Area 3B\Dend S2220_S2192_late2018.xlsx

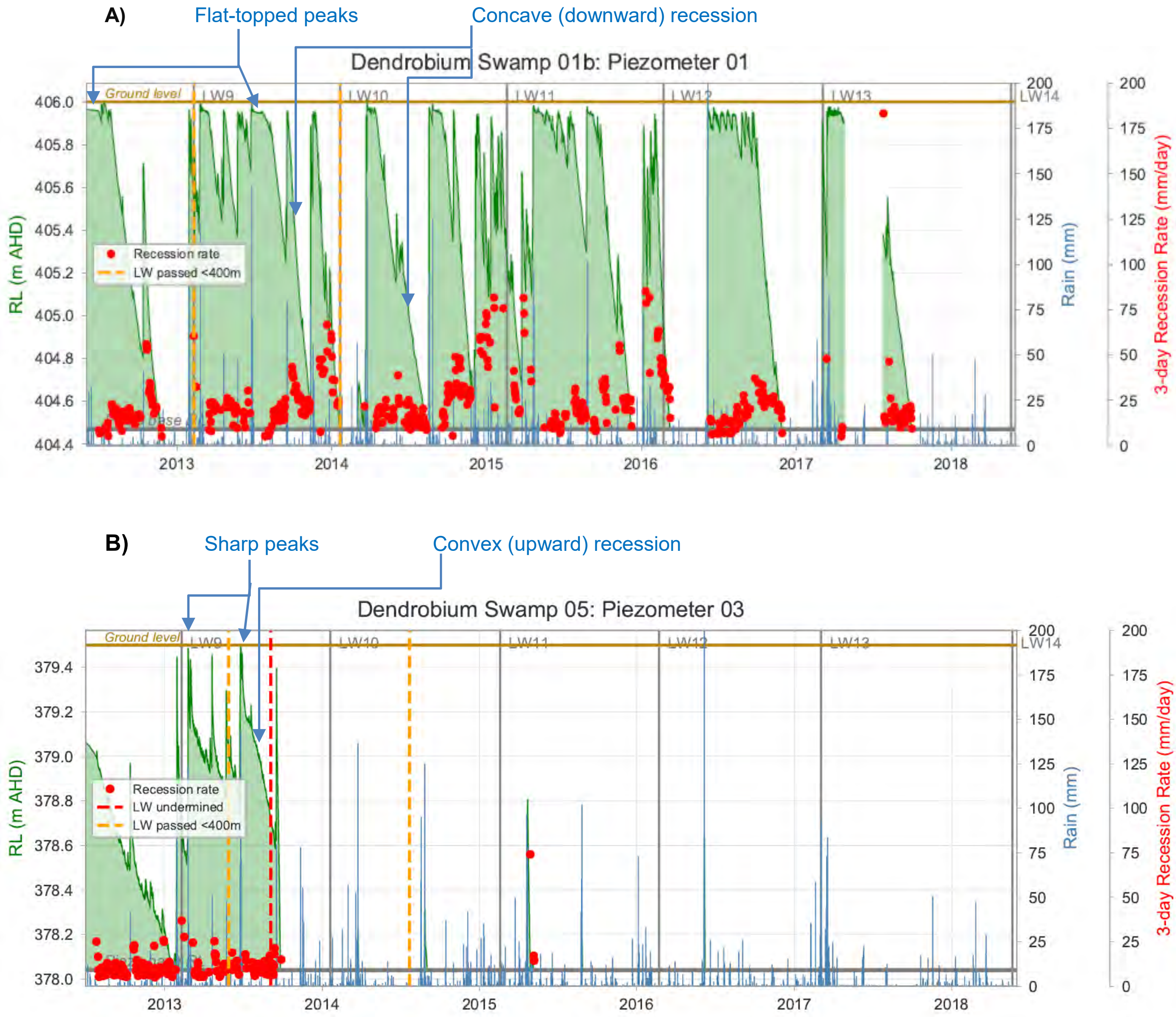


Figure 4-14 Water table hydrographs in Swamps at Dendrobium

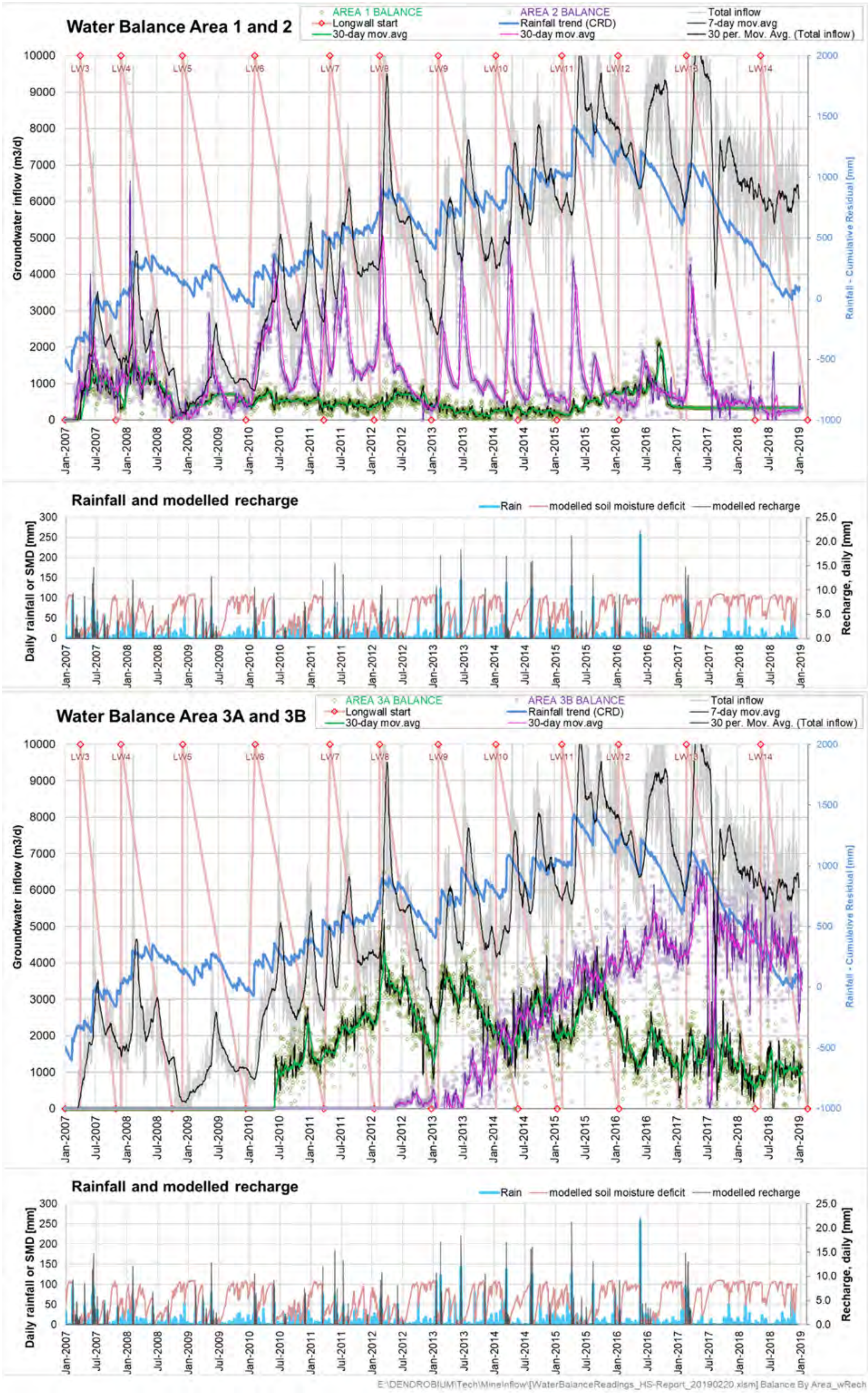


Figure 4-15 Mine Inflow at Dendrobium

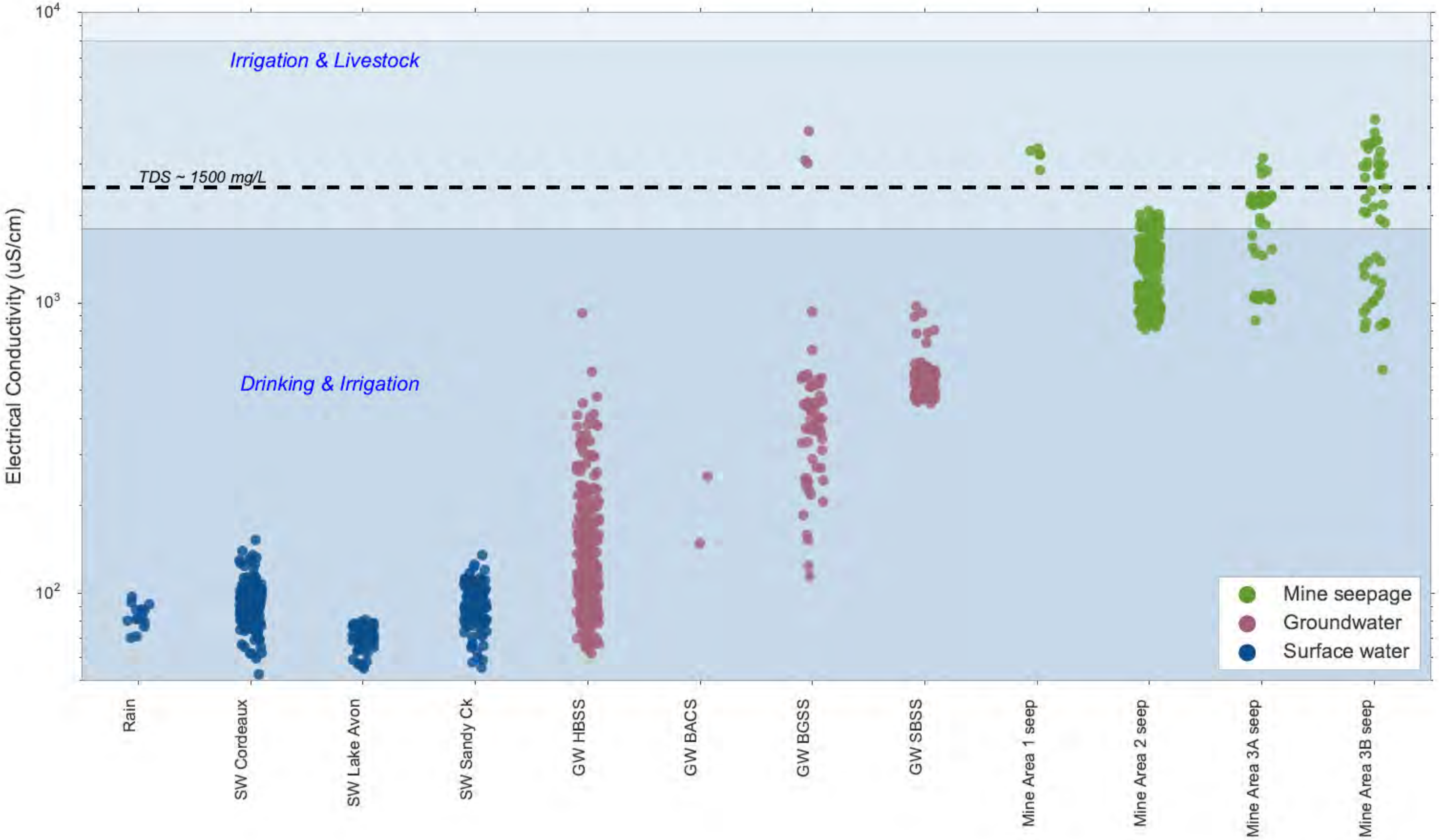


Figure 4-16 Violin plot showing the ranges of EC for various water sources

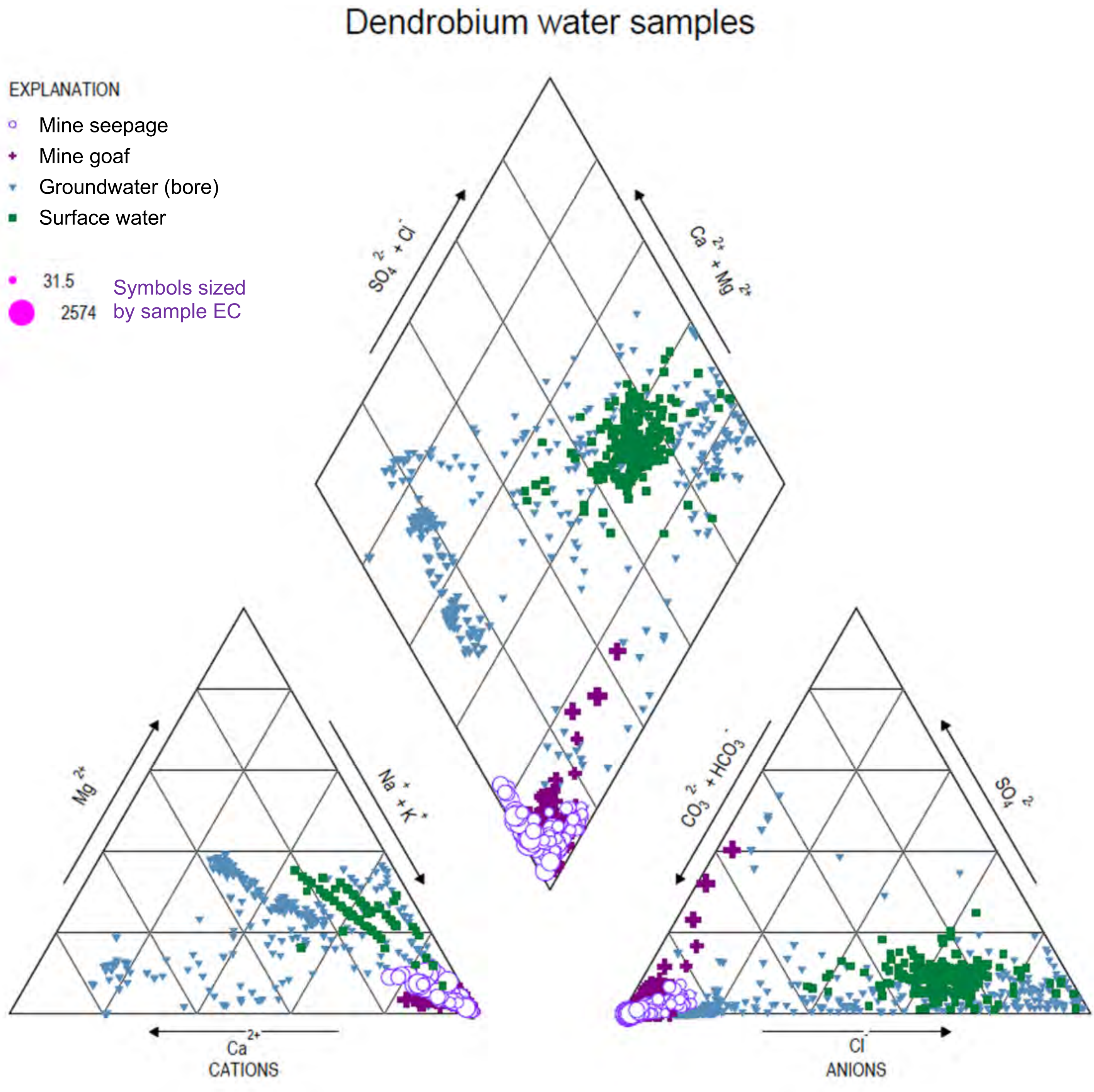


Figure 4-17 Piper plot of major ion composition of all Dendrobium water samples

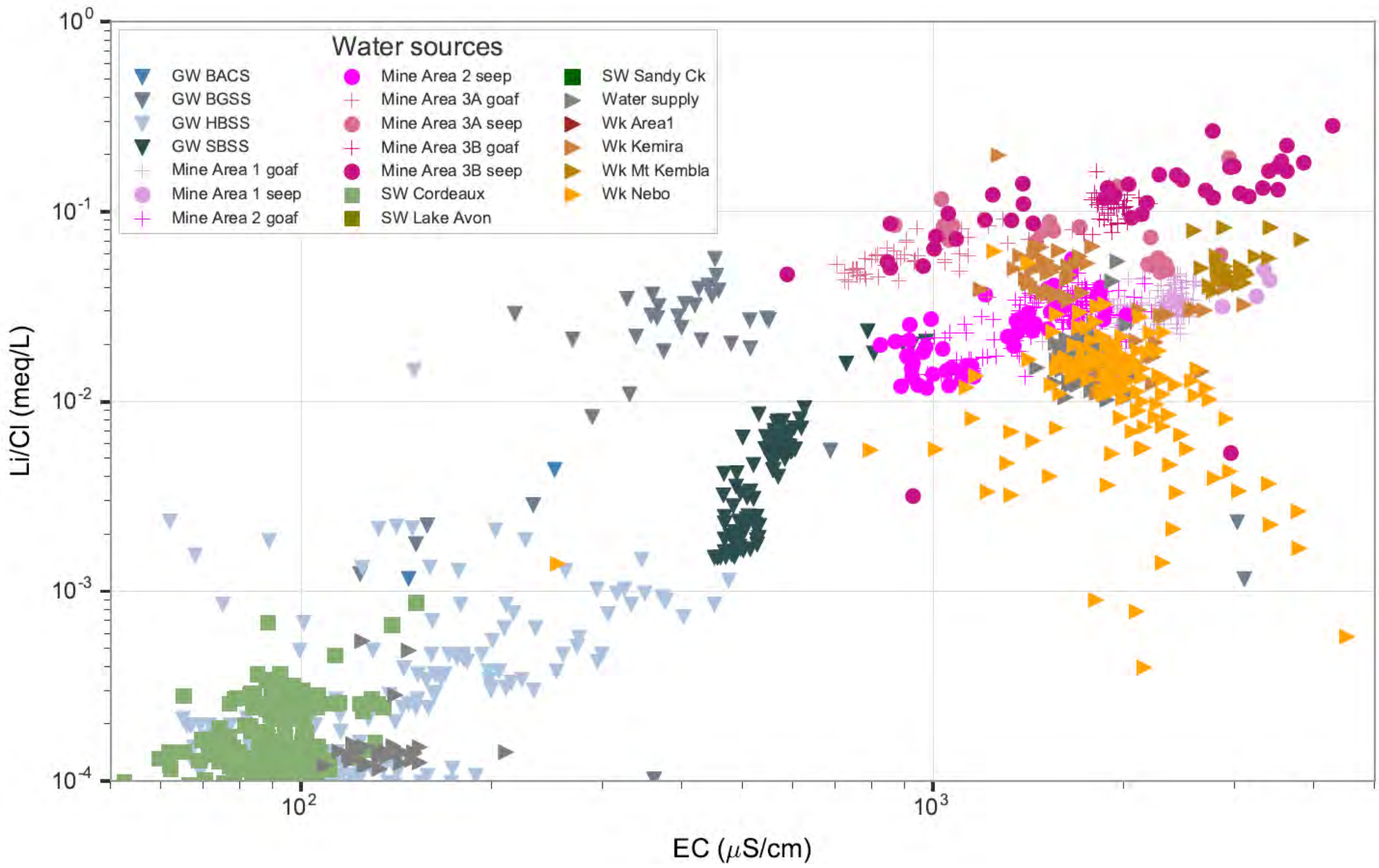


Figure 4-18 Discrimination of water sources using Li/Cl

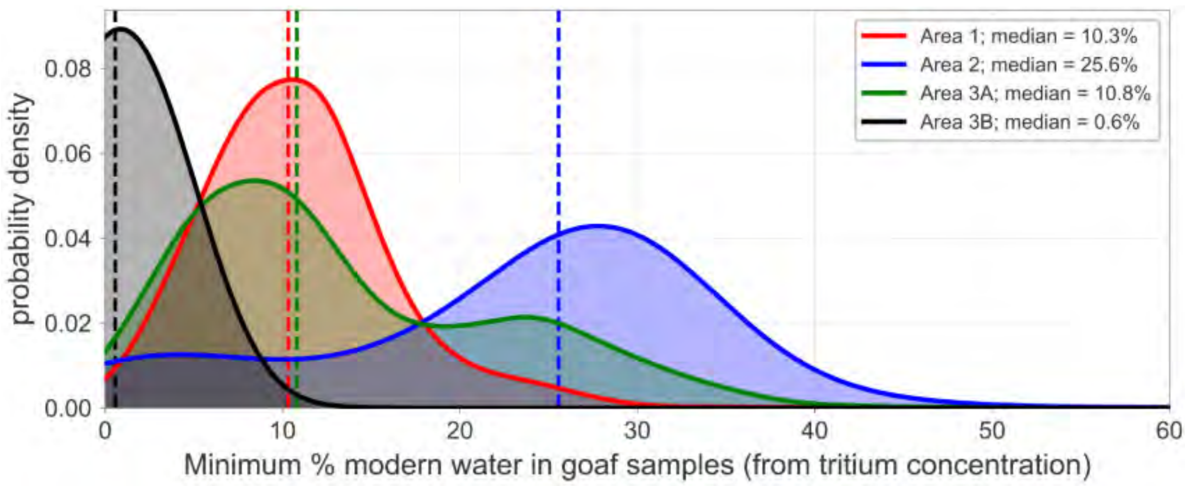
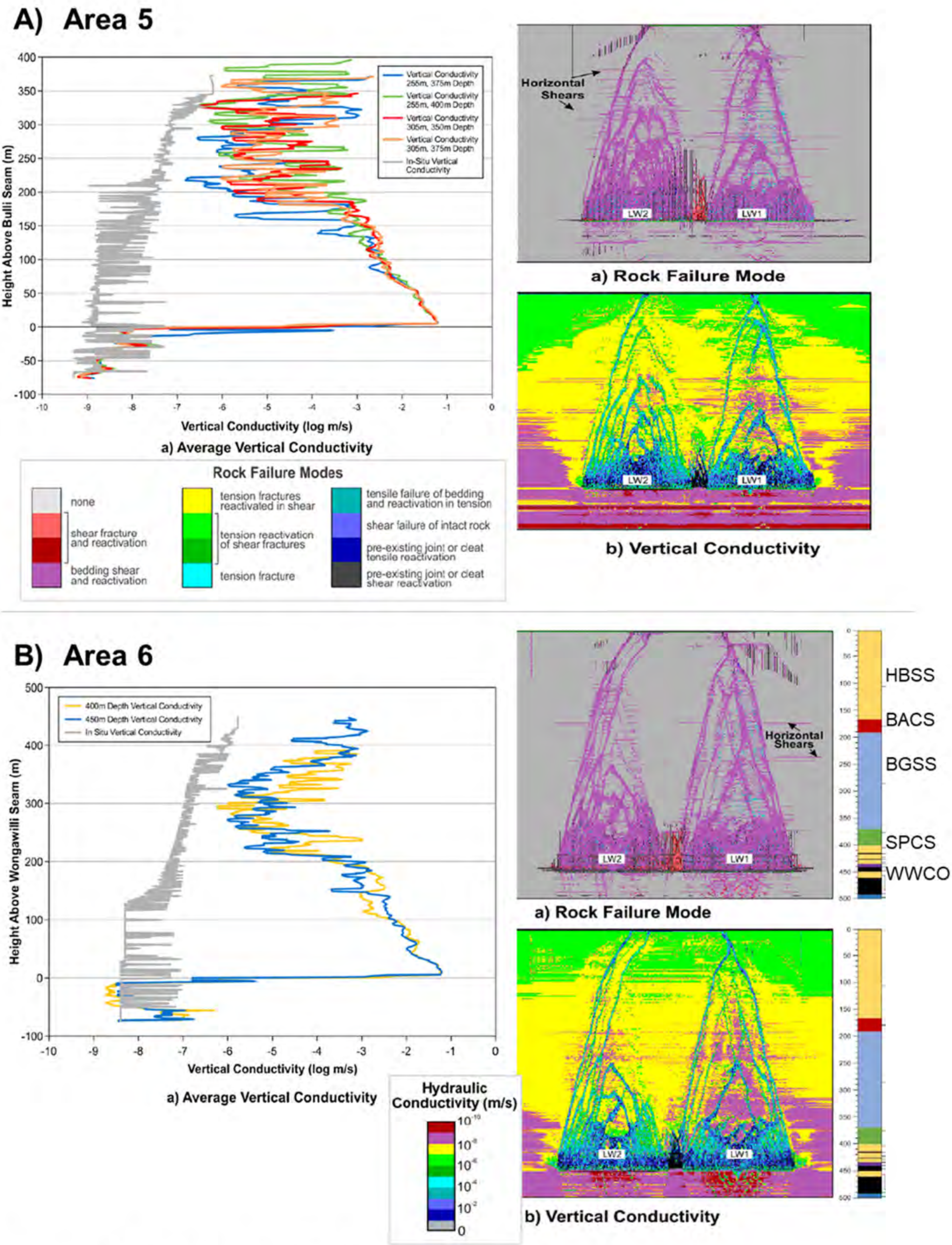


Figure 4-19 Probability distributions of modern water in mine goaf waters

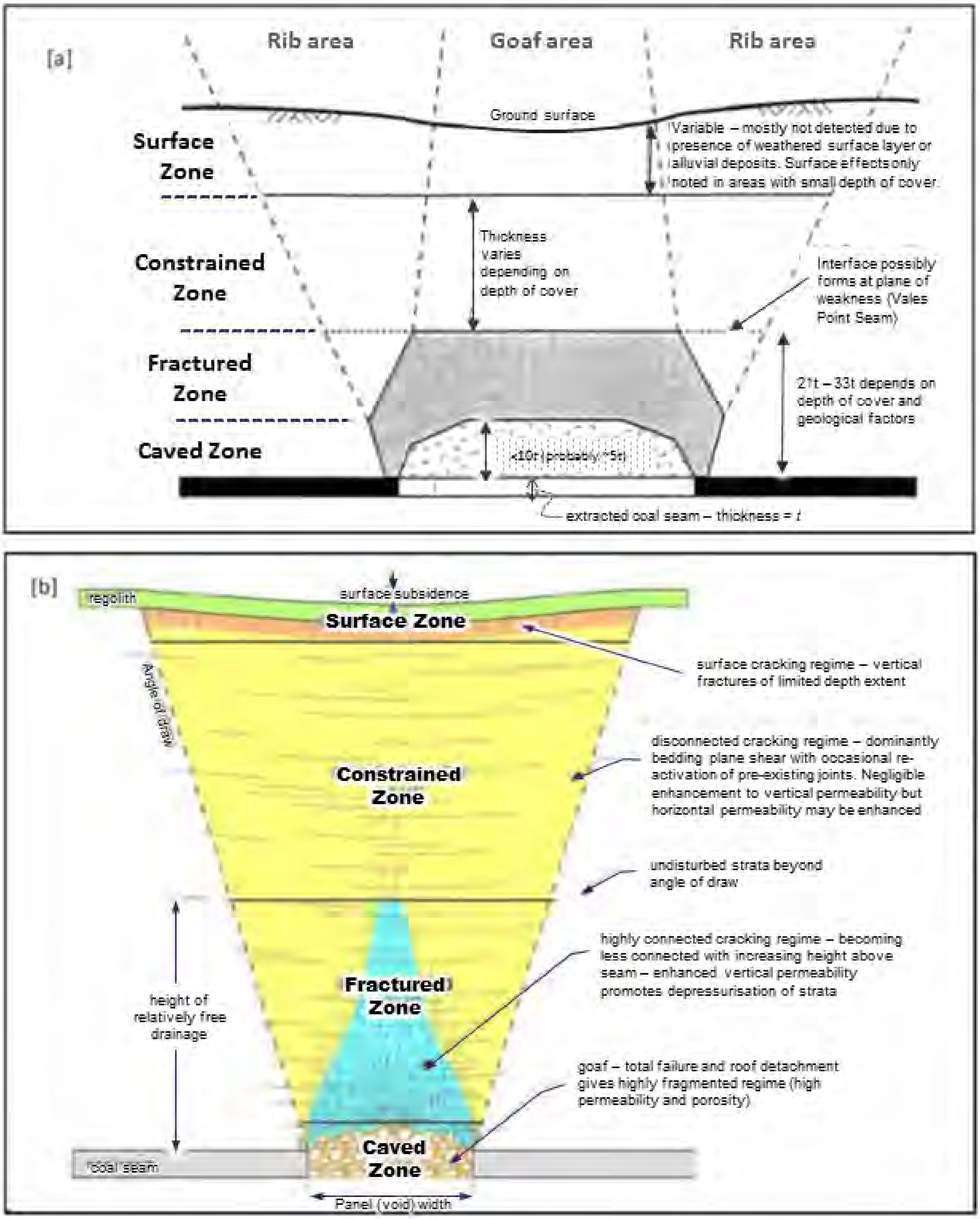
Data used in this analysis (= 12 most recent samples)

	Area_1	Area_2	Area_3A	Area_3B
First data	09/02/2011	08/03/2017	18/01/2012	08/03/2017
Last data	22/01/2014	23/02/2018	18/10/2012	23/02/2018
n (samples)	12	12	12	12



(for more detail, please refer to SCT, 2017 and 2018)

Figure 4-20 Summary of Modelled Fracturing and Deformation (SCT, 2017 and 2018b)



(source Forster & Enever, 1992 and Department of Planning, 2008)

Figure 5-1 General Conceptual Models of Subsidence and Deformation above Longwalls

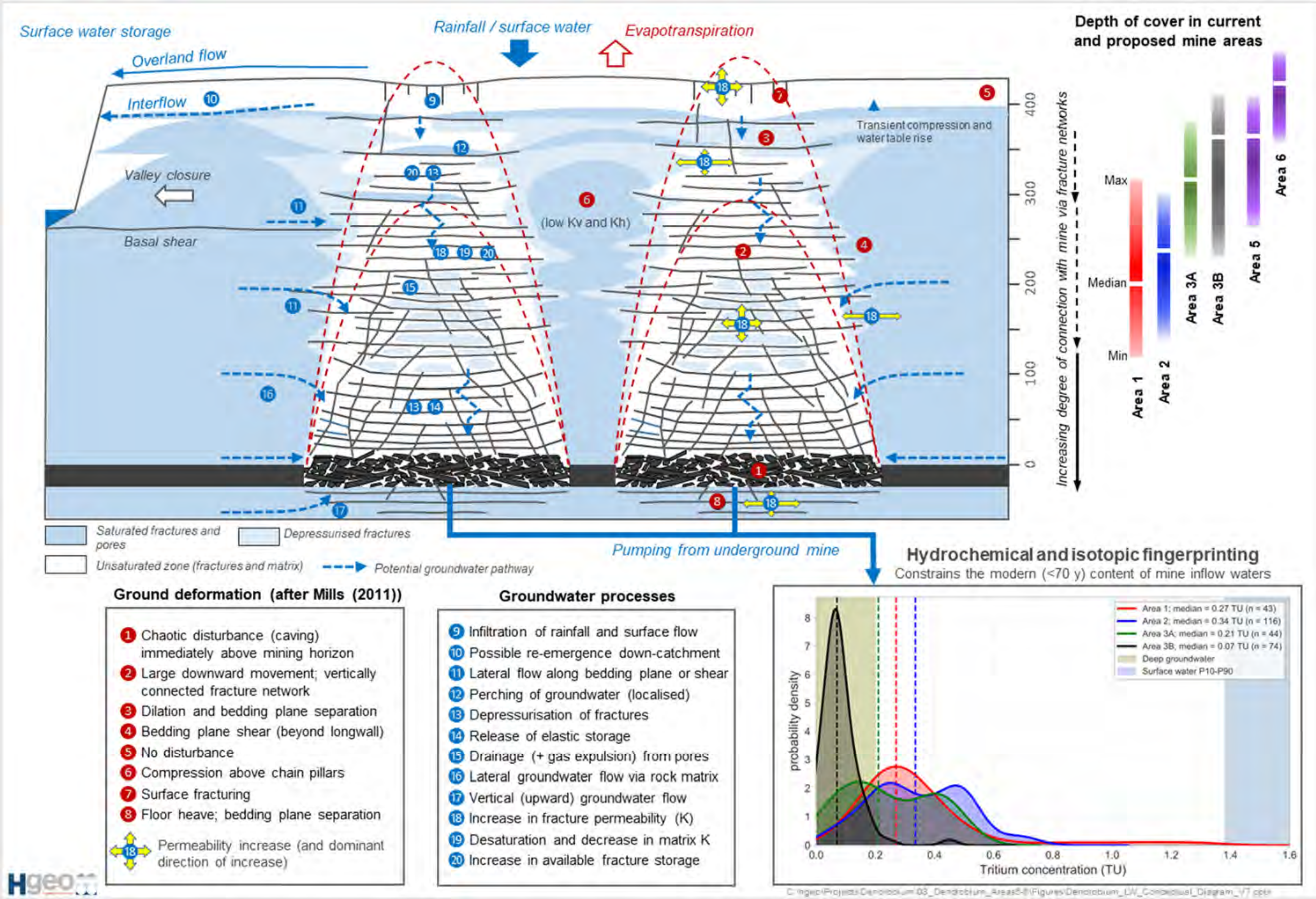


Figure 5-2 Conceptual model: geotechnical and hydrogeological effects of mining at Dendrobium

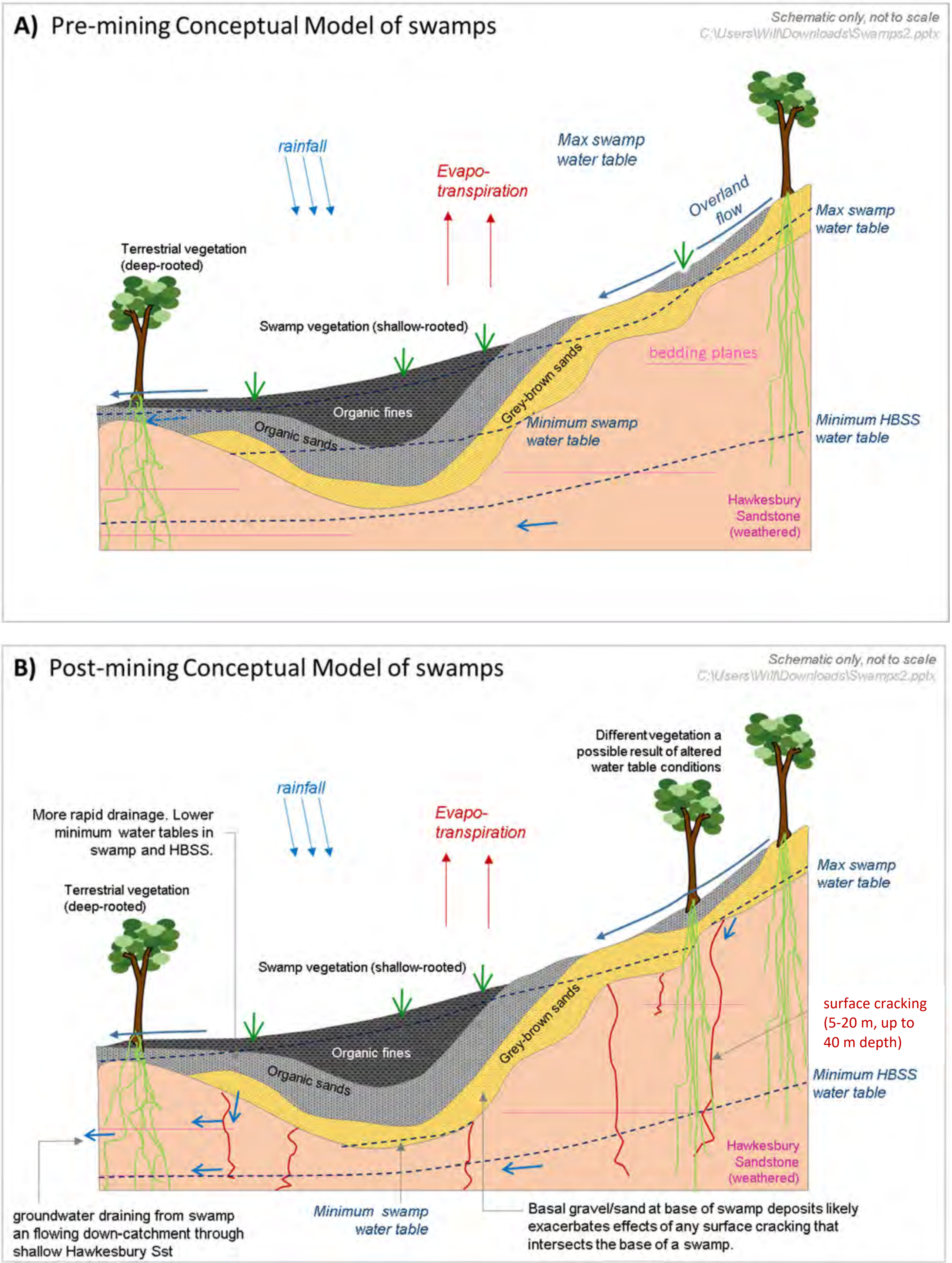
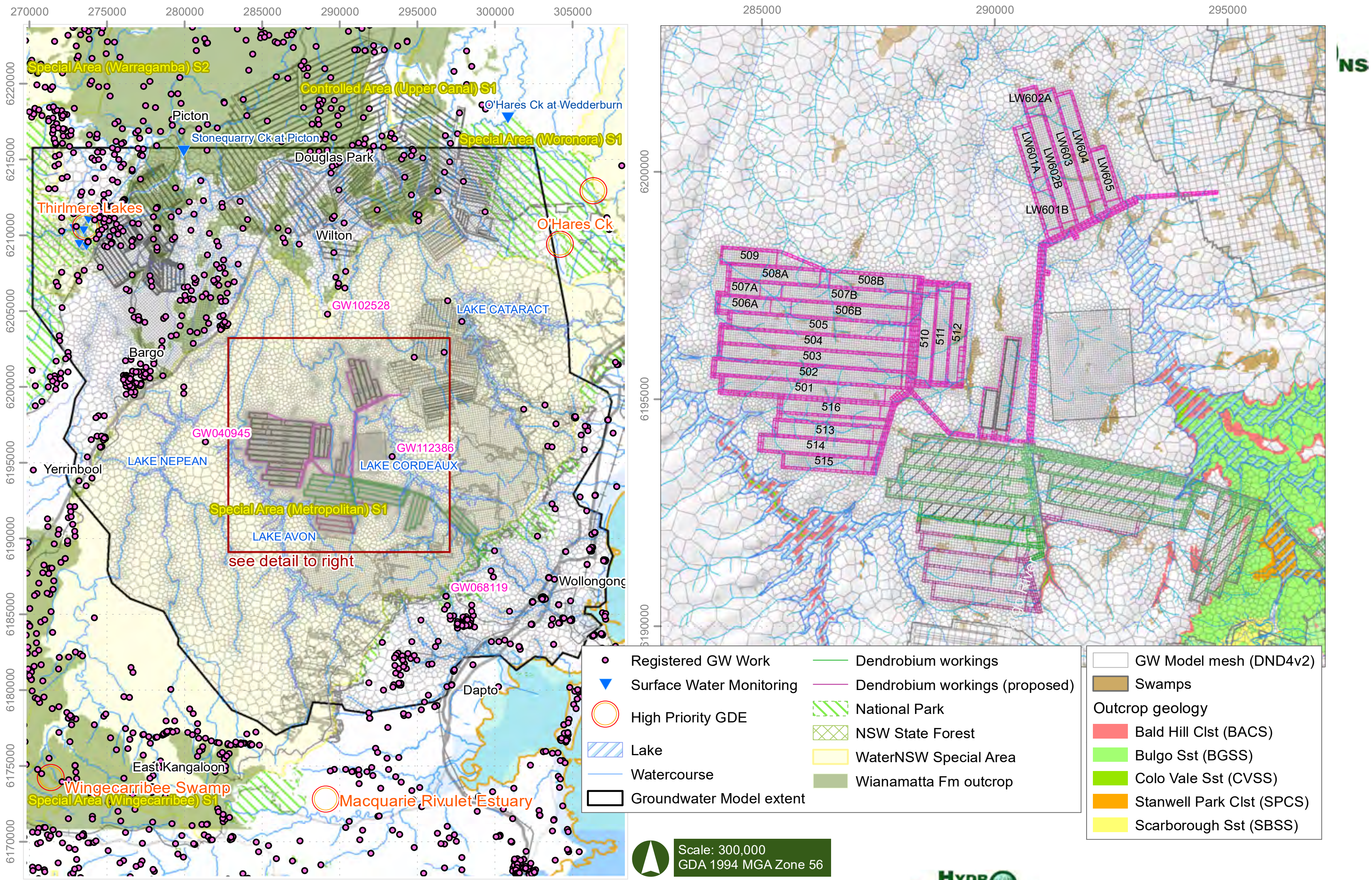


Figure 5-3 Conceptual Model of Upland Swamps



E:\DENDROBIUM\GIS\Maps\Deliverable\DNDPGW\GW ModelExtent_A4L.mxd DrawingNo: IWC-009 | Rev: A | Created by: W.Minchin | Date: 9/05/2018

HydroSimulations

Figure 6-1 Groundwater Model extent and mesh

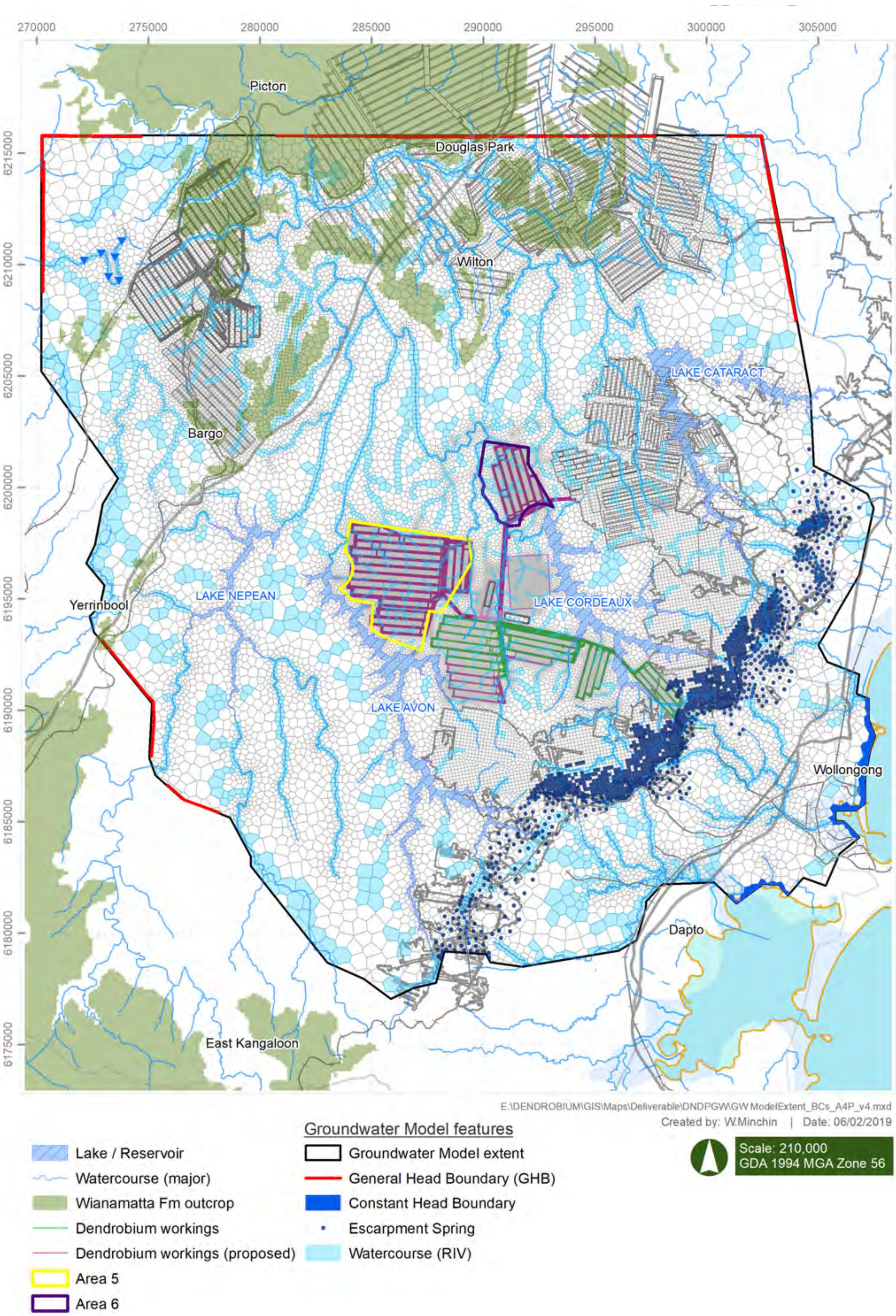


Figure 6-2 Groundwater Model boundary conditions

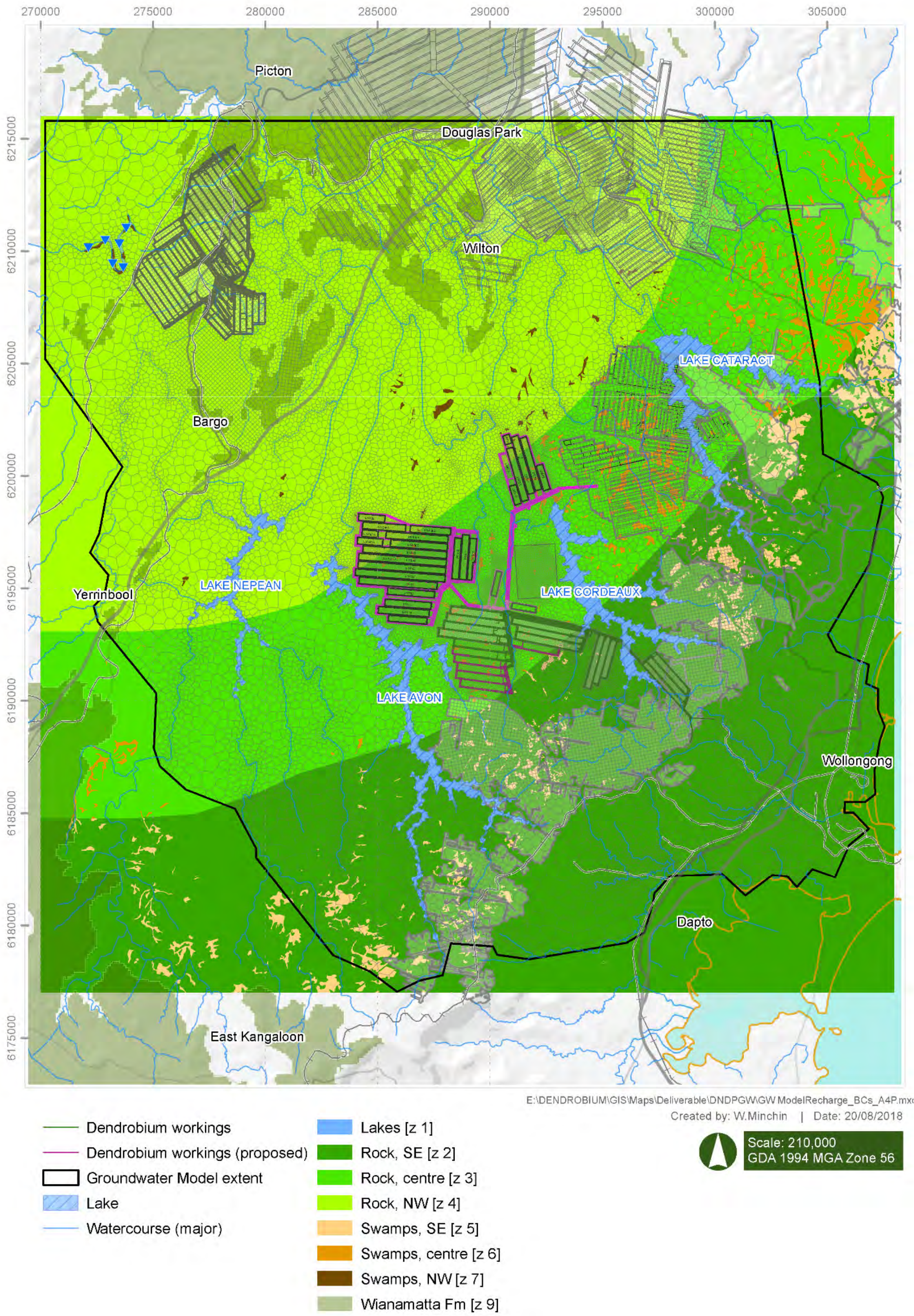


Figure 6-3 Recharge and Evapotranspiration zones

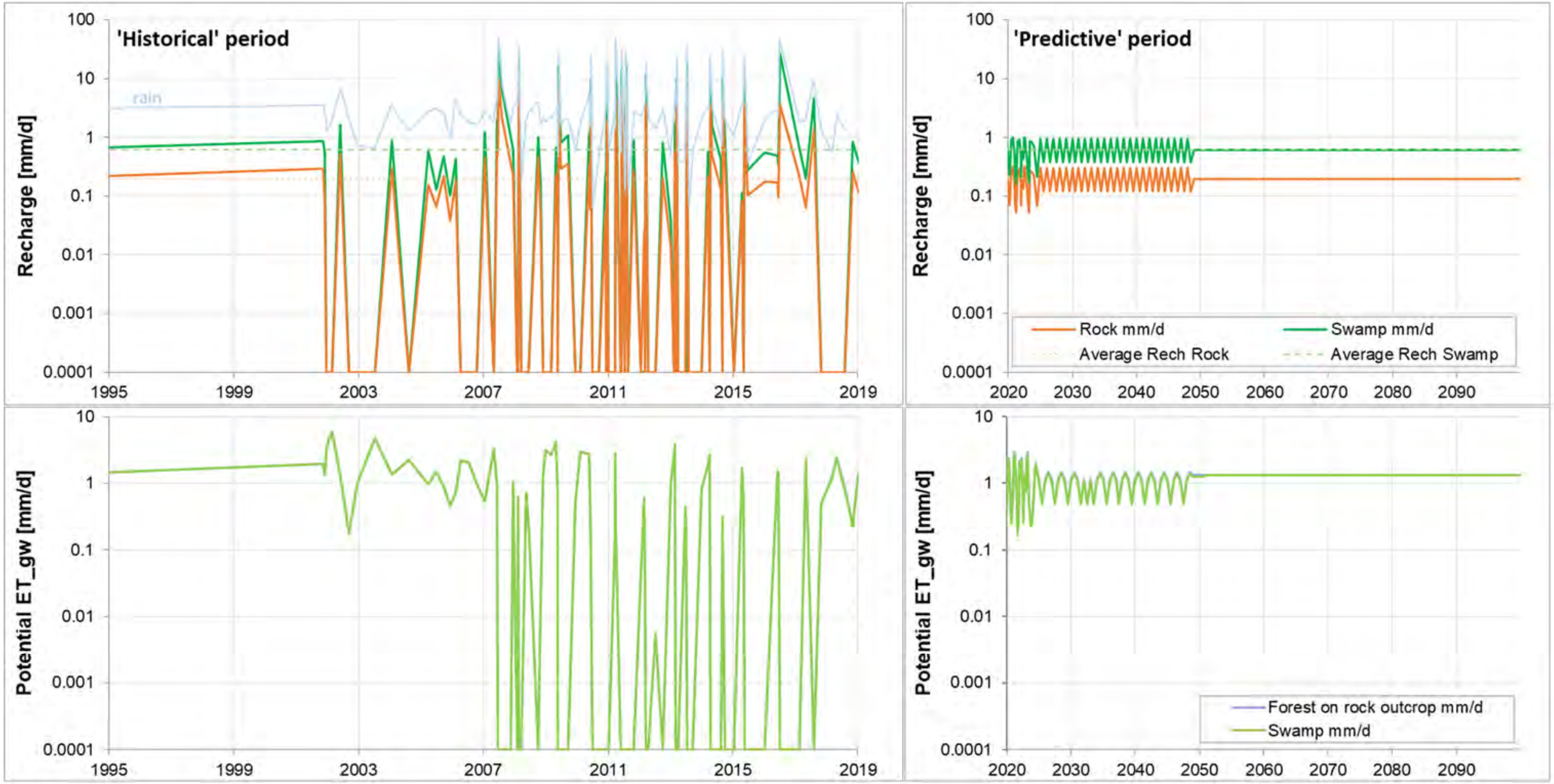
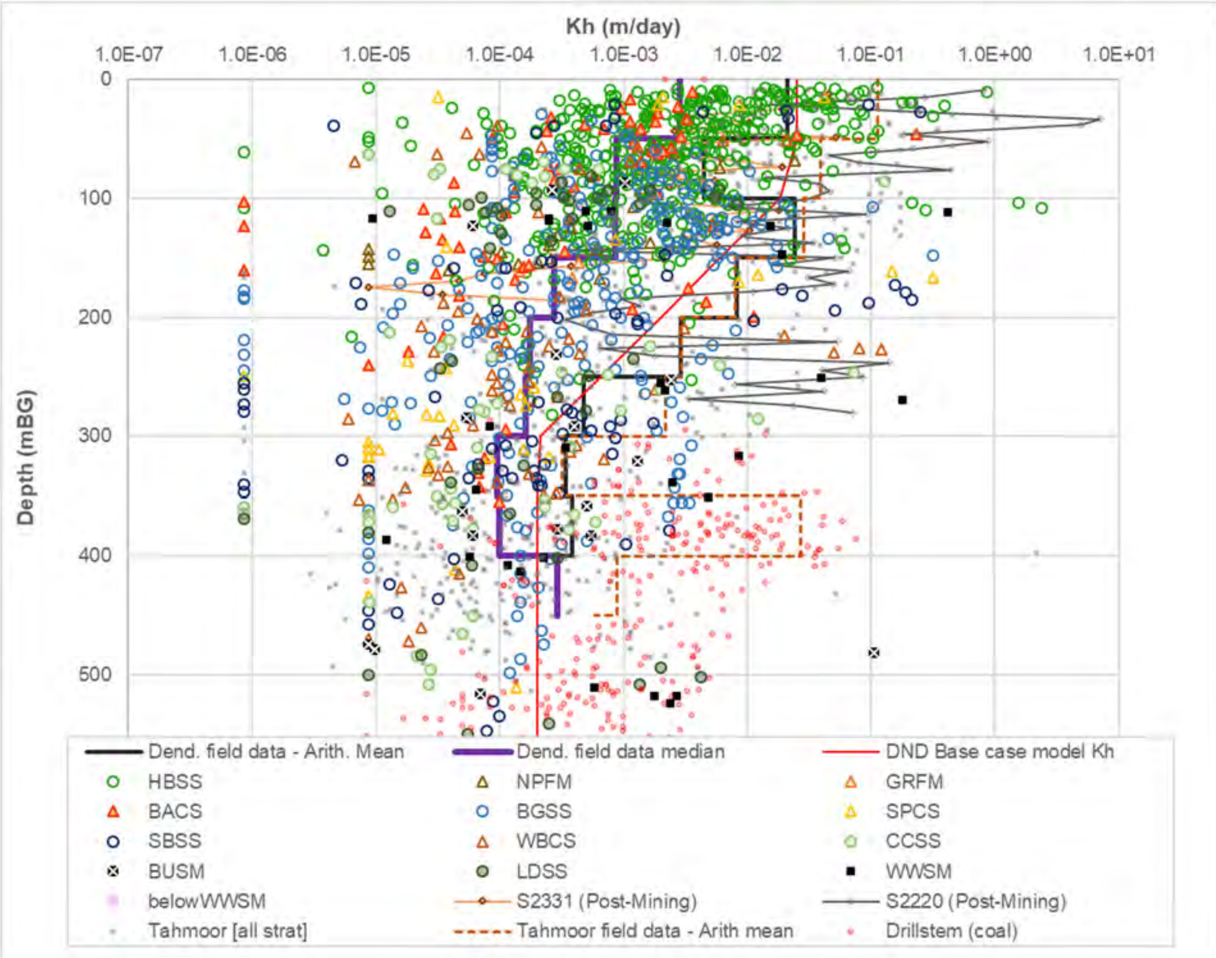


Figure 6-4 **Recharge and ET estimates (by model stress period)**



E:\DENDROBIUM\Tech\AquiferProperties\Packer\Dendrobium_AquiferPropertiesDatabase_20190225.xlsx

Figure 7-1 Comparison of Modelled K-with-Depth and packer test field data

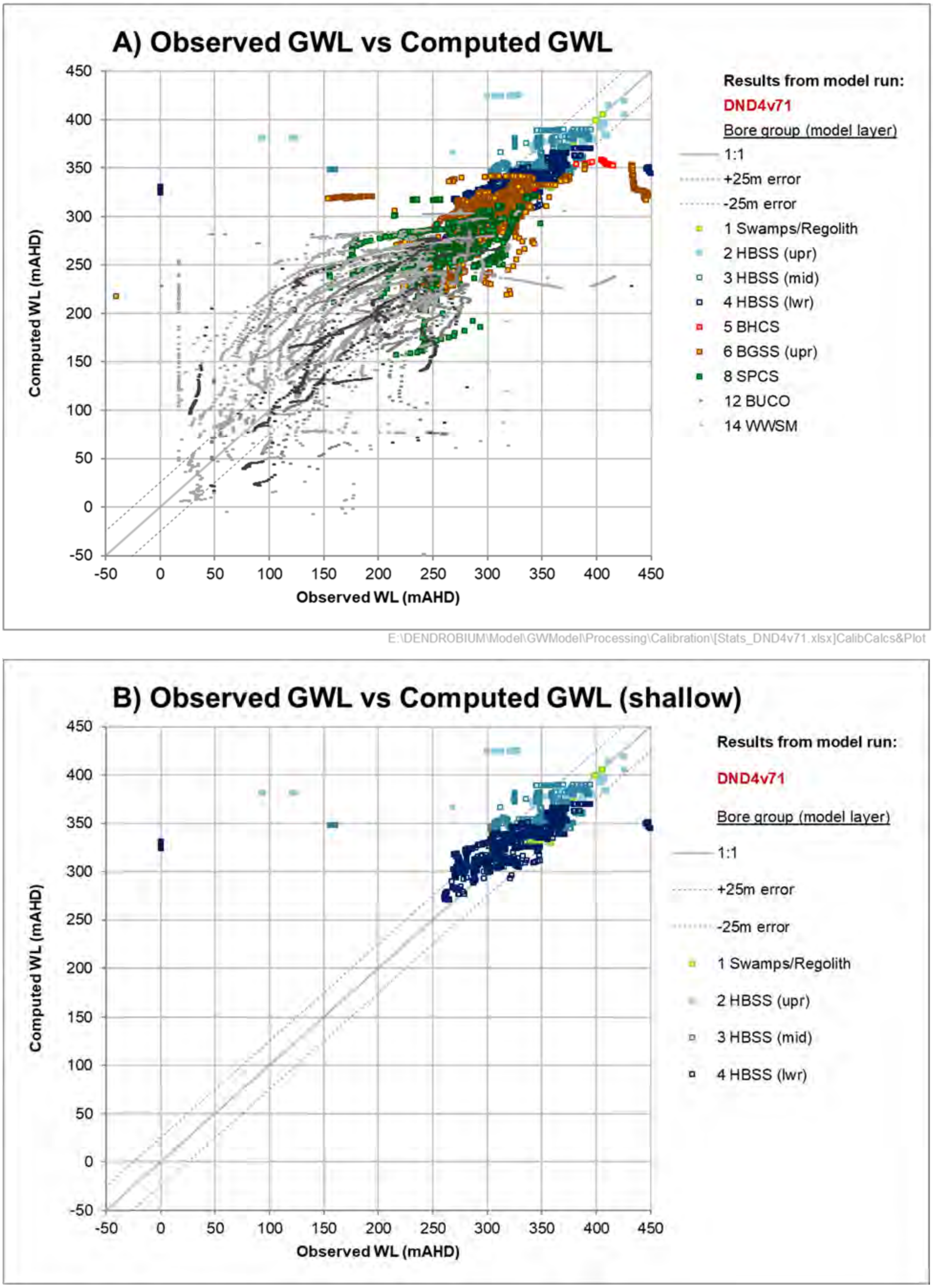


Figure 7-2 Summary of groundwater level calibration

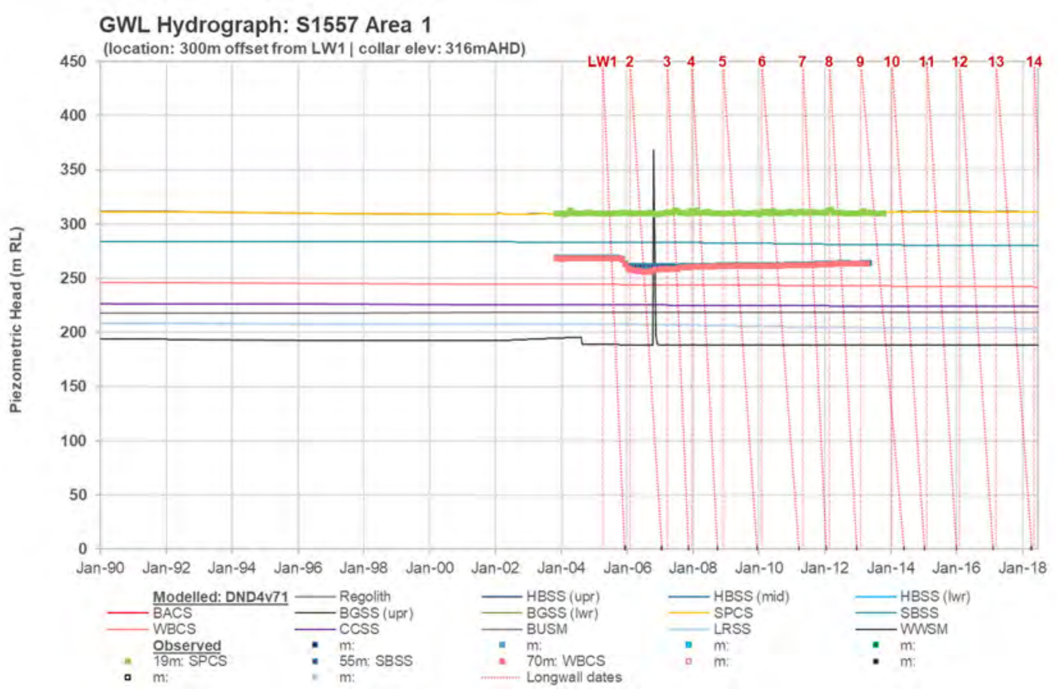


Figure 7-3 Modelled vs observed groundwater level hydrograph – Bore S1557

E:\DENDROBIUM\Model\GWModel\Processing\Calibration\Calibration_Hydrographs_Priority_DND4v71.xlsx

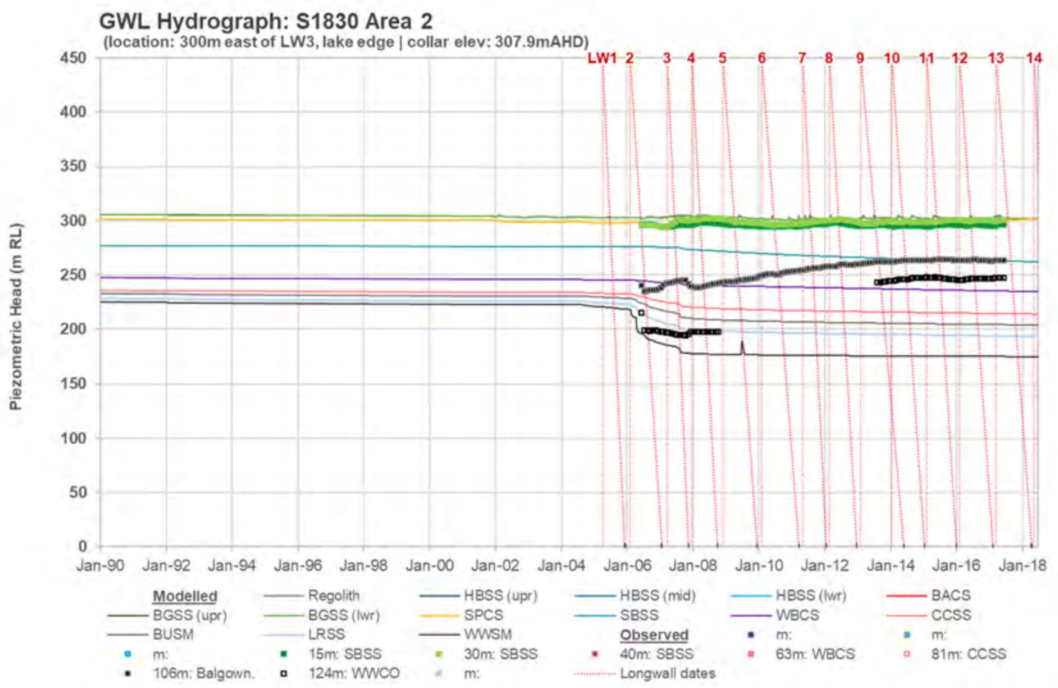


Figure 7-4 Modelled vs observed groundwater level hydrograph – Bore S1830

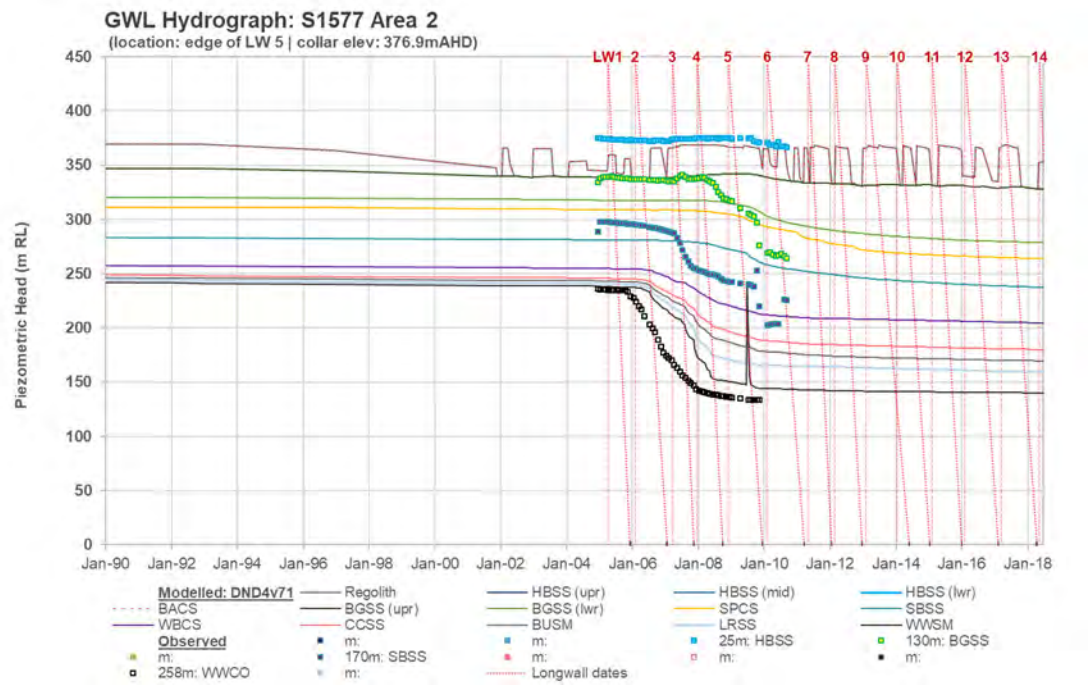


Figure 7-5 Modelled vs observed groundwater level hydrograph – Bore S1577

E:\DENDROBIUM\Model\GWModel\Processing\Calibration\Calibration_Hydrographs_Priority_DND4v71.xlsx

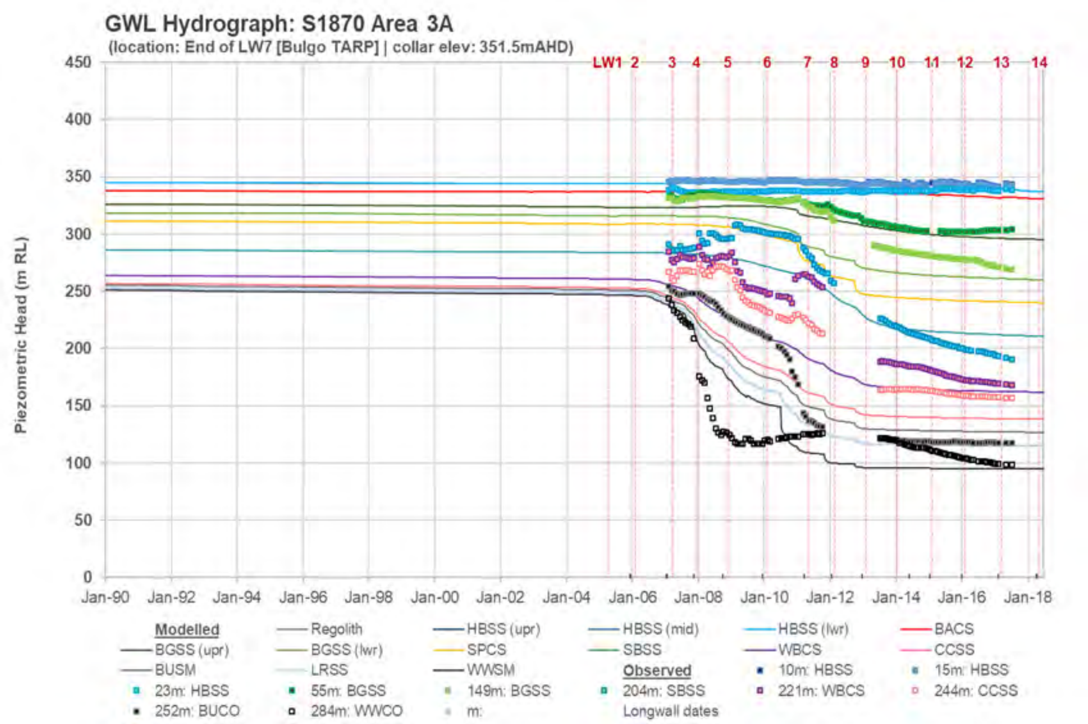


Figure 7-6 Modelled vs observed groundwater level hydrograph – Bore S1870

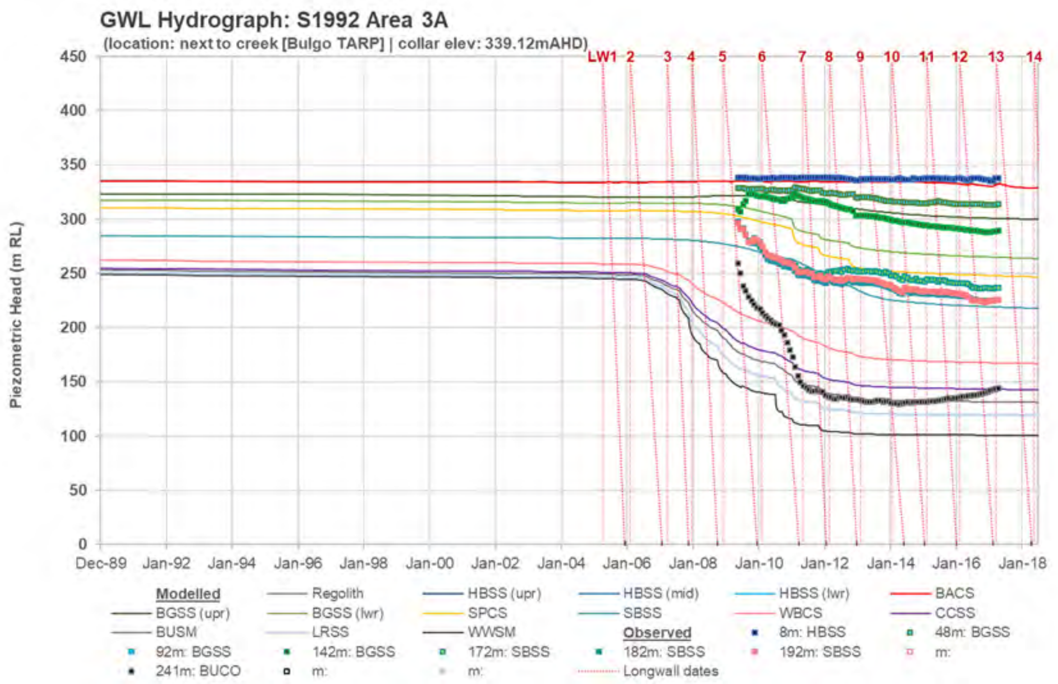


Figure 7-7 Modelled vs observed groundwater level hydrograph – Bore S1992

E:\DENDROBIUM\Model\GWModel\Processing\Calibration\Calibration_Hydrographs_Priority_DND4v71.xlsx

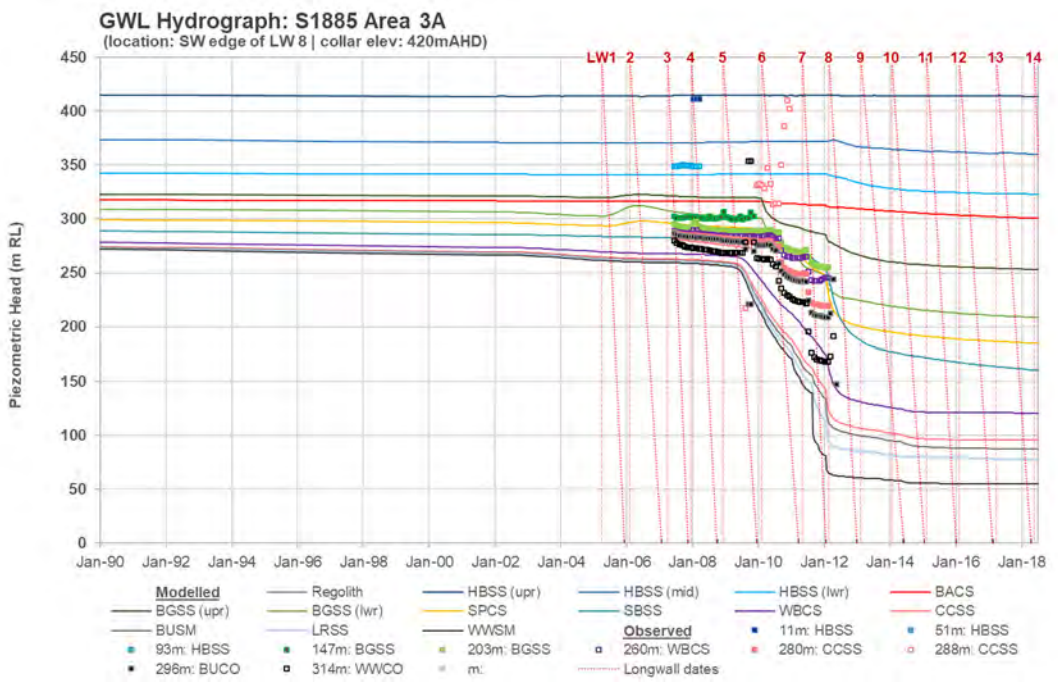


Figure 7-8 Modelled vs observed groundwater level hydrograph – Bore S1885

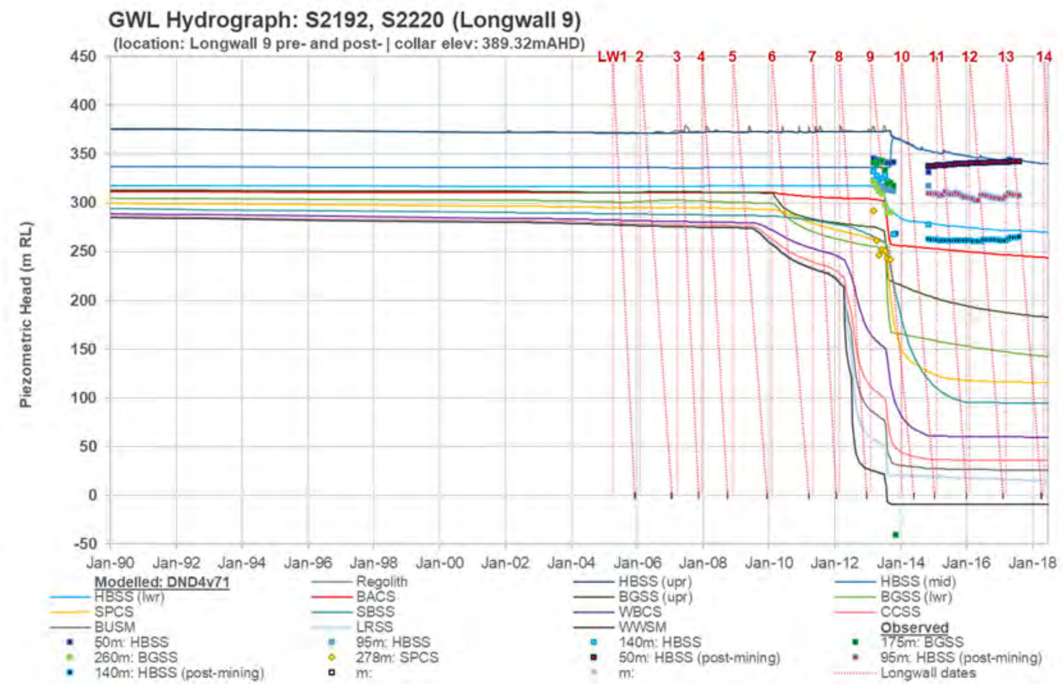


Figure 7-9 Modelled vs observed groundwater level hydrograph – Bore S2192-S2220 (LW9)

E:\DENDROBIUM\Model\GWModel\Processing\Calibration\Calibration_Hydrographs_Priority_DND4v71.xlsx

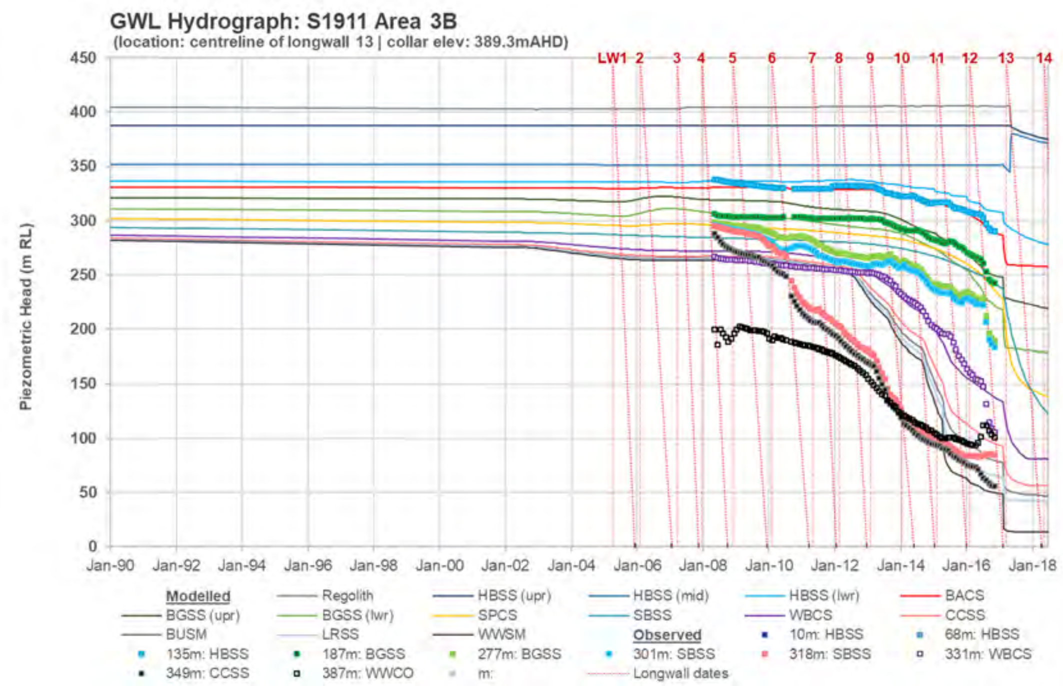


Figure 7-10 Modelled vs observed groundwater level hydrograph – Bore S1911

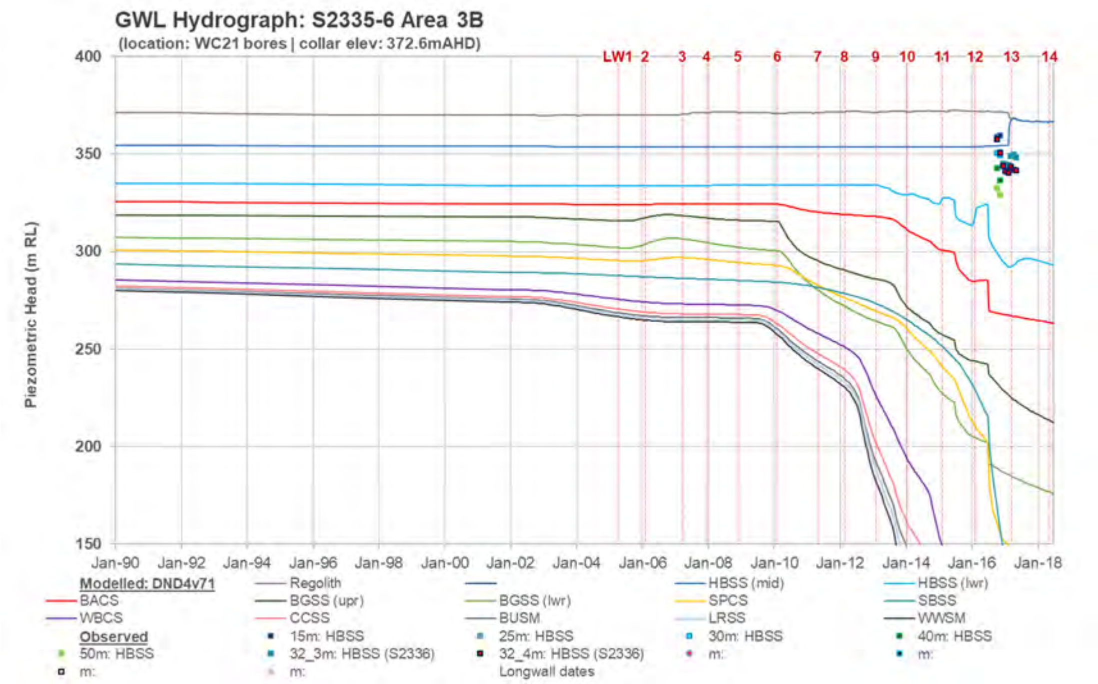


Figure 7-11 Modelled vs observed groundwater level hydrograph – Bore S2335-S2336 (WC21)

E:\DENDROBIUM\Model\GWModel\Processing\Calibration\Calibration_Hydrographs_Priority_DND4v71.xlsx

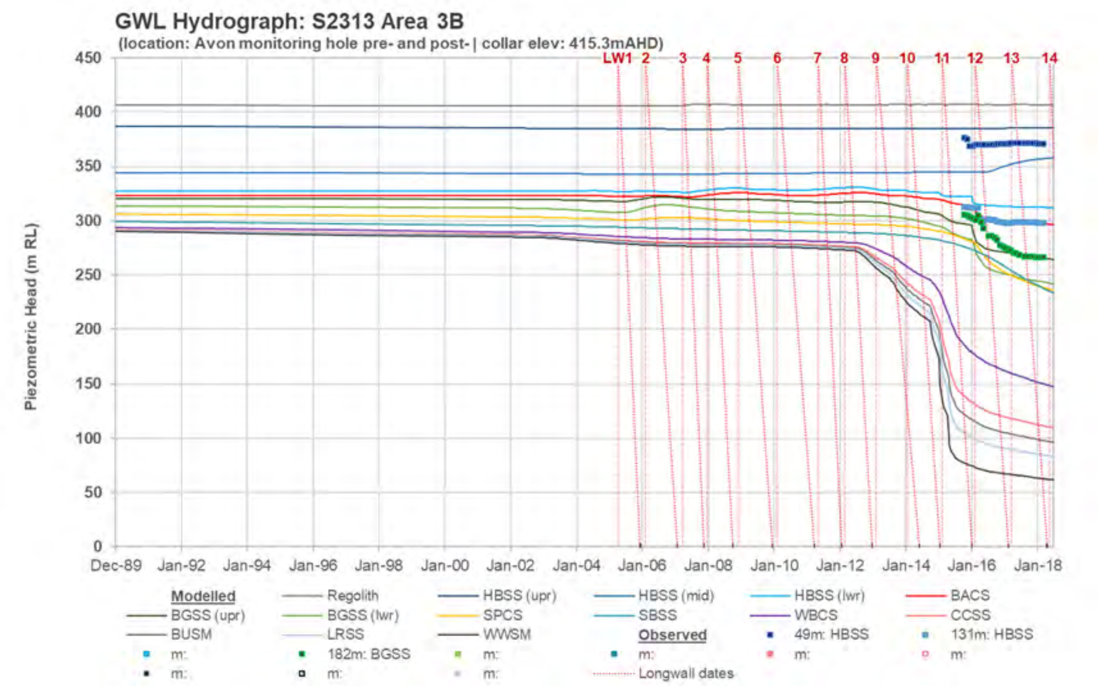


Figure 7-12 Modelled vs observed groundwater level hydrograph – Bore S2313

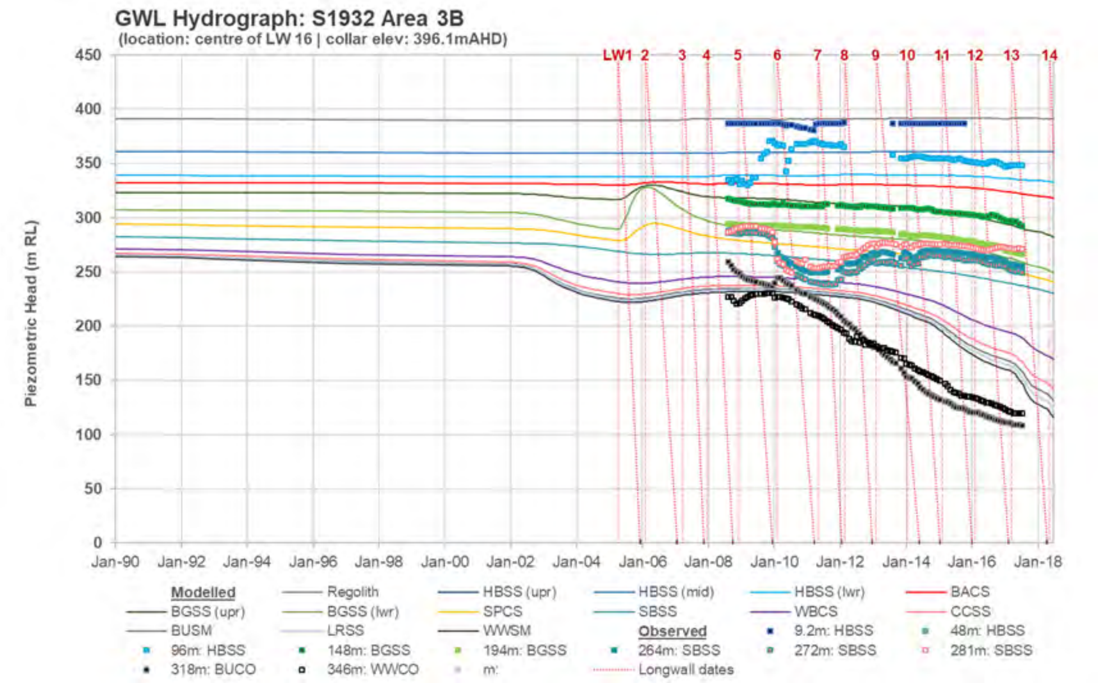


Figure 7-13 Modelled vs observed groundwater level hydrograph – Bore S1932

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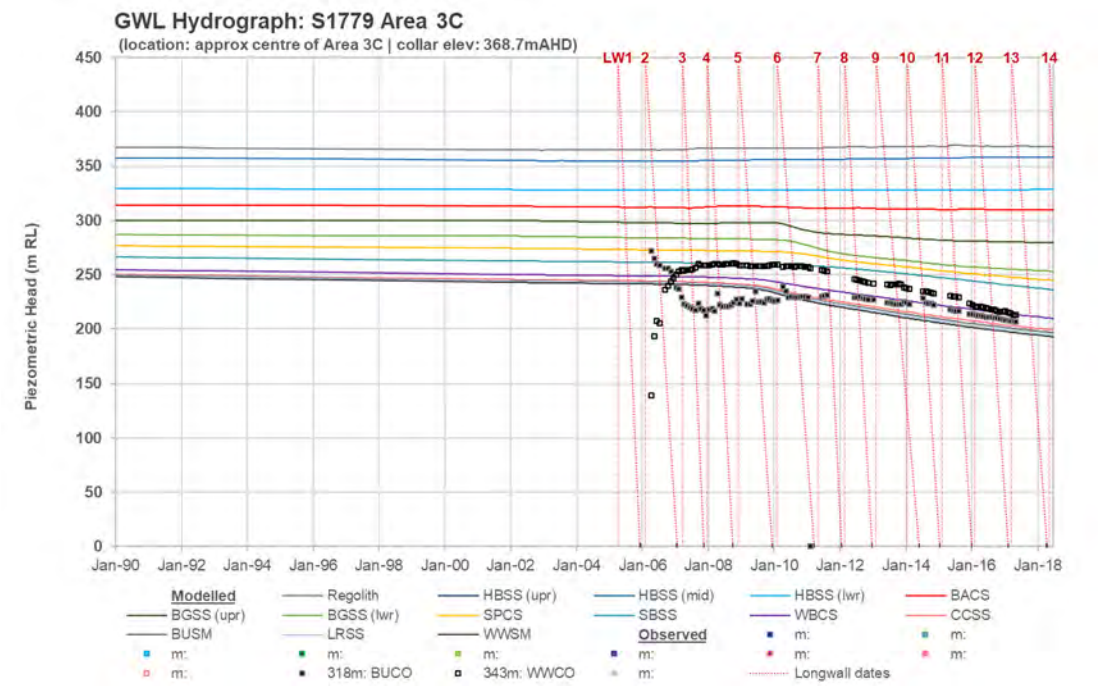

Figure 7-14 Modelled vs observed groundwater level hydrograph – Bore S1779

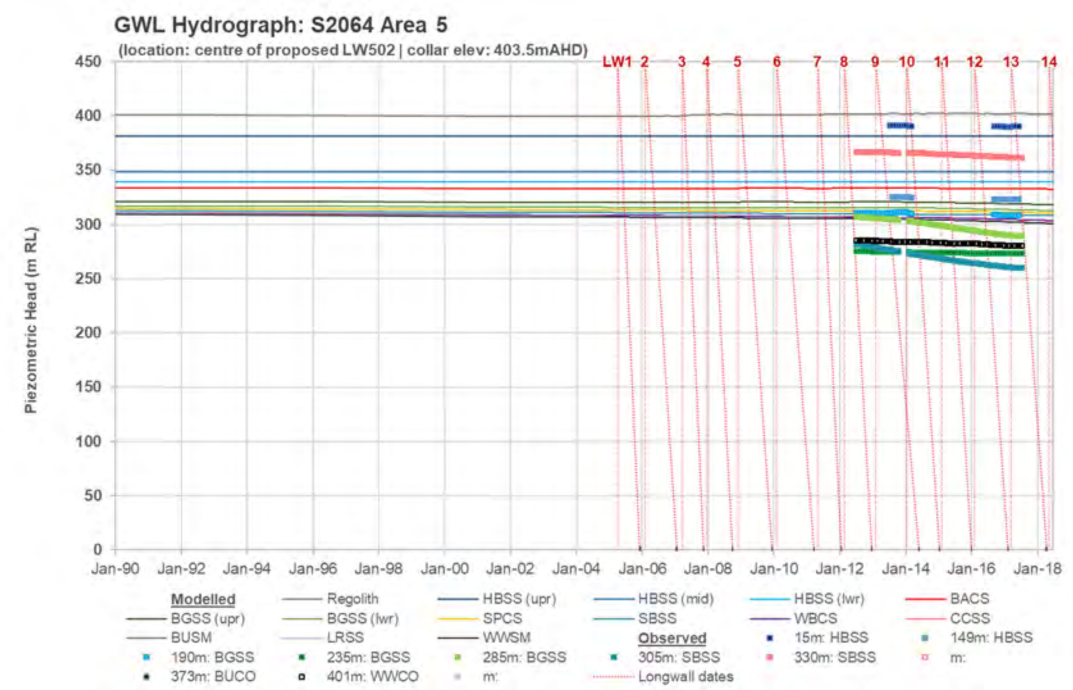

Figure 7-15 Modelled vs observed groundwater level hydrograph – Bore S2064

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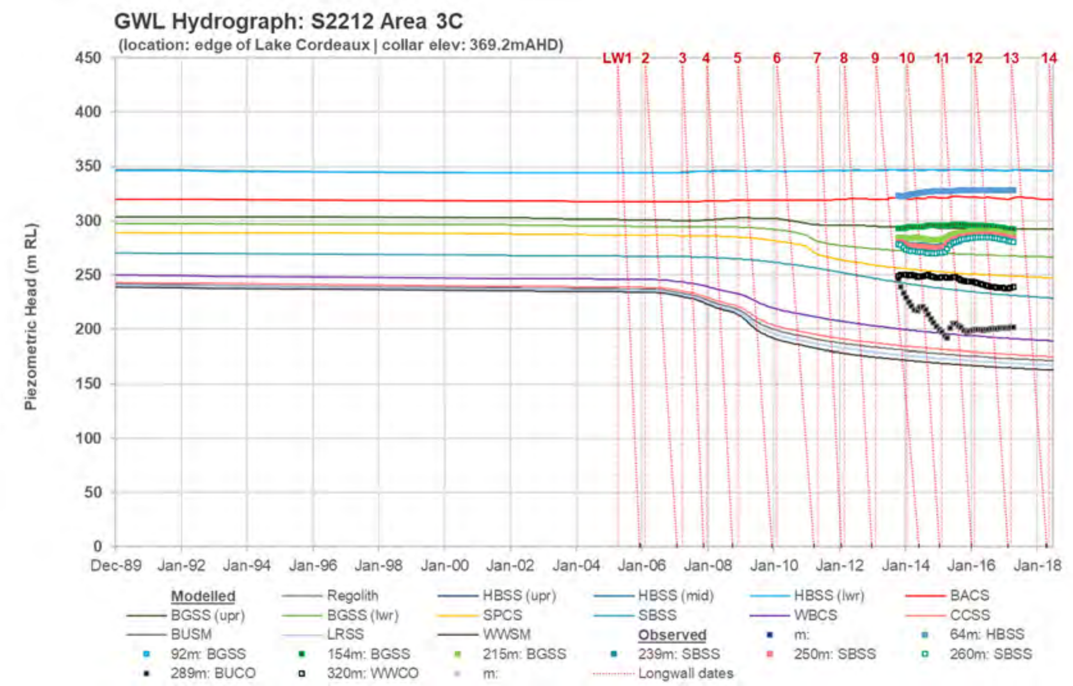

Figure 7-16 Modelled vs observed groundwater level hydrograph – Bore S2212

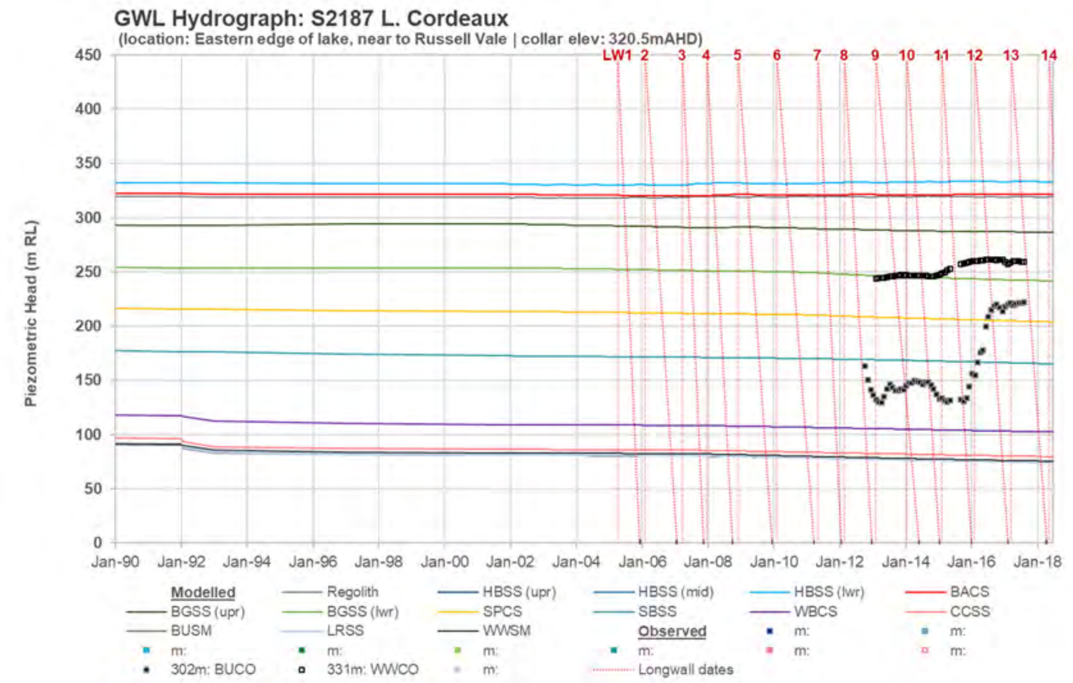

Figure 7-17 Modelled vs observed groundwater level hydrograph – Bore S2187

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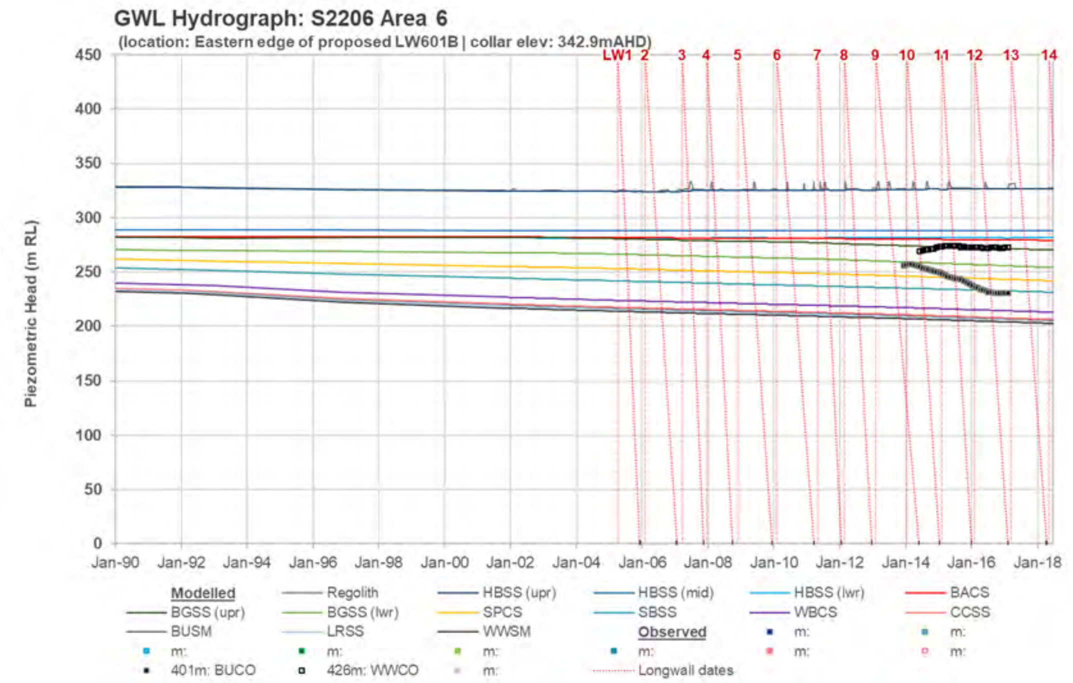

Figure 7-18 Modelled vs observed groundwater level hydrograph – Bore S2206

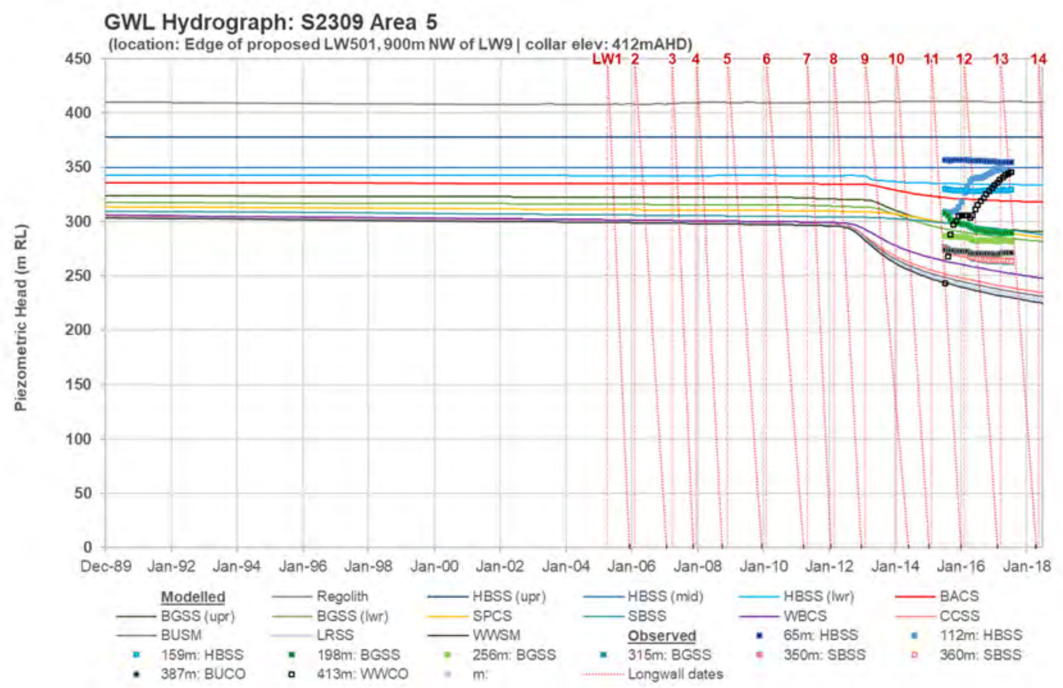

Figure 7-19 Modelled vs observed groundwater level hydrograph – Bore S2309

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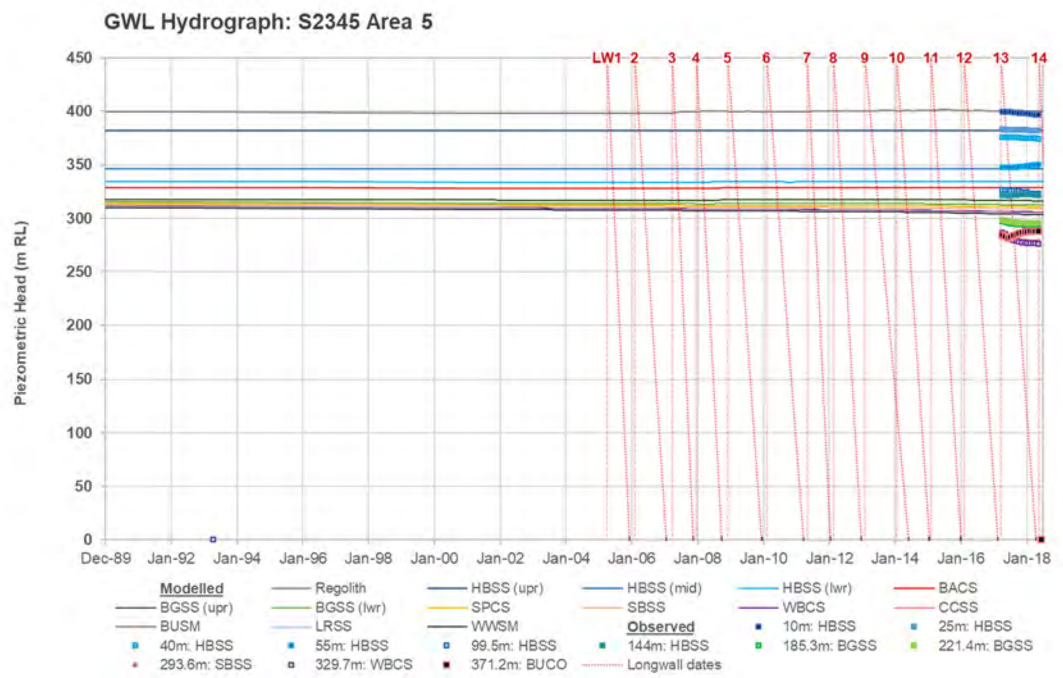

Figure 7-20 Modelled vs observed groundwater level hydrograph – Bore S2345

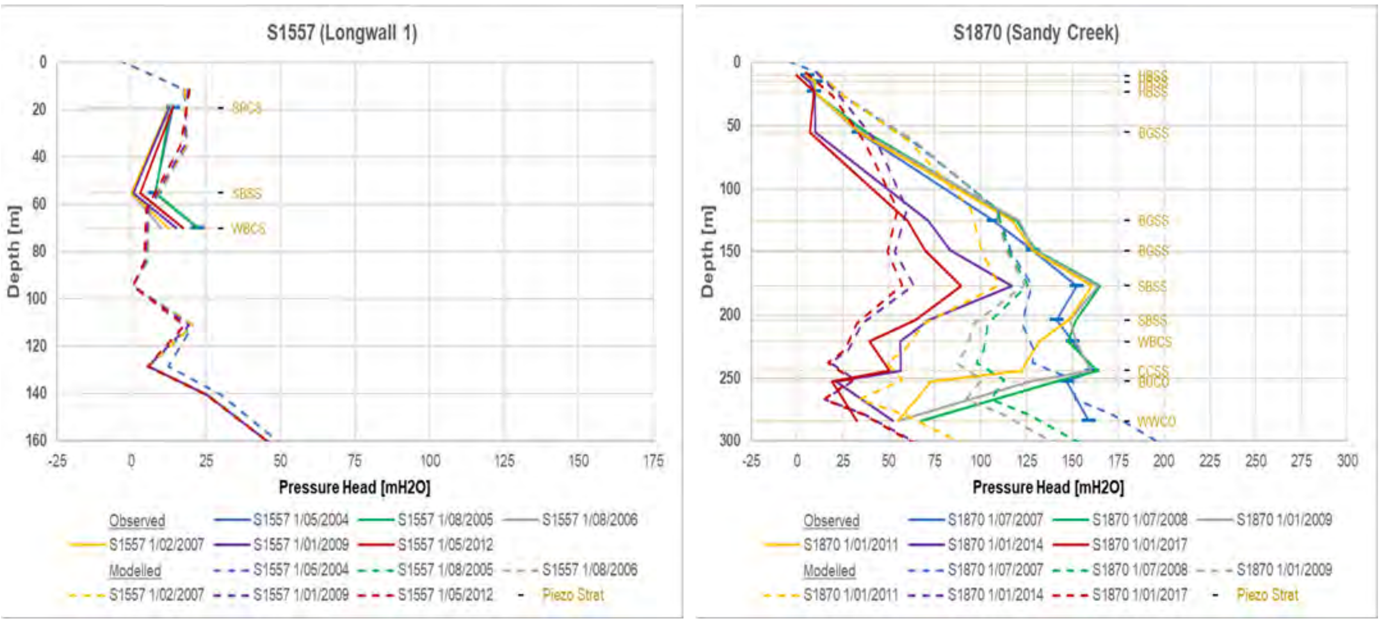

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Figure 7-21 Modelled vs observed vertical pressure profiles – A) Bore S1557 and B) Bore S1870

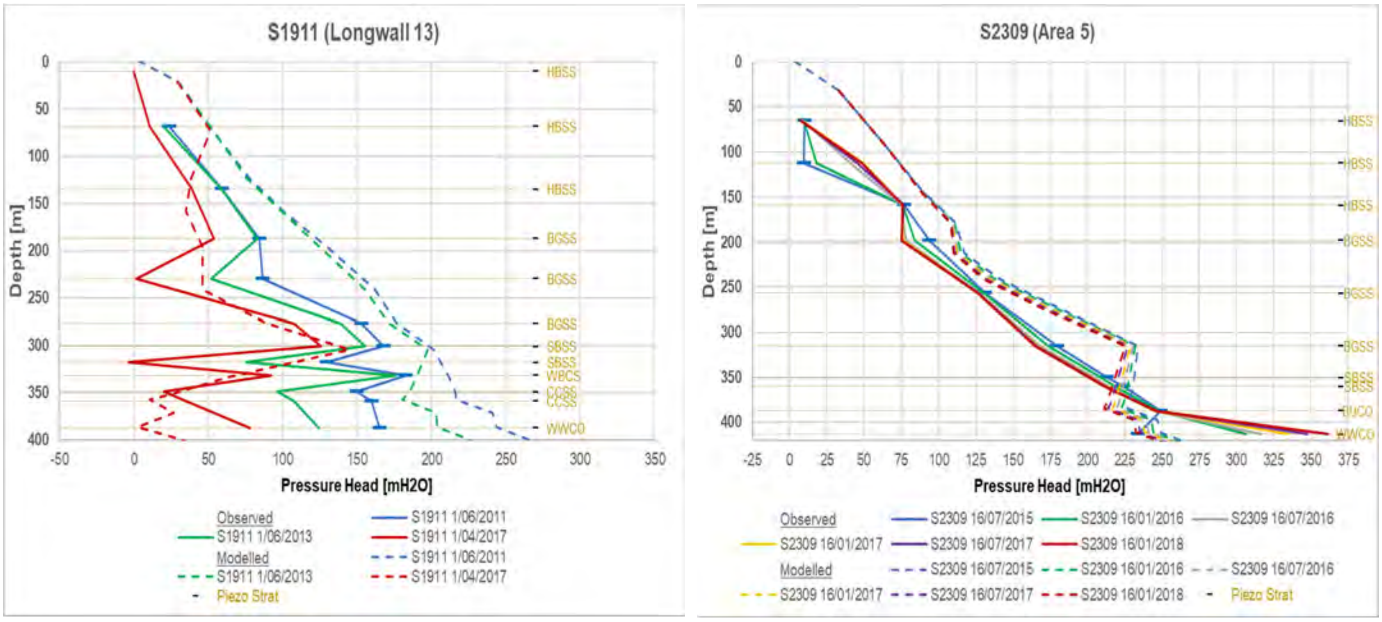

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Figure 7-22 Modelled vs observed vertical pressure profiles – A) Bore S1911 and B) Bore S2309

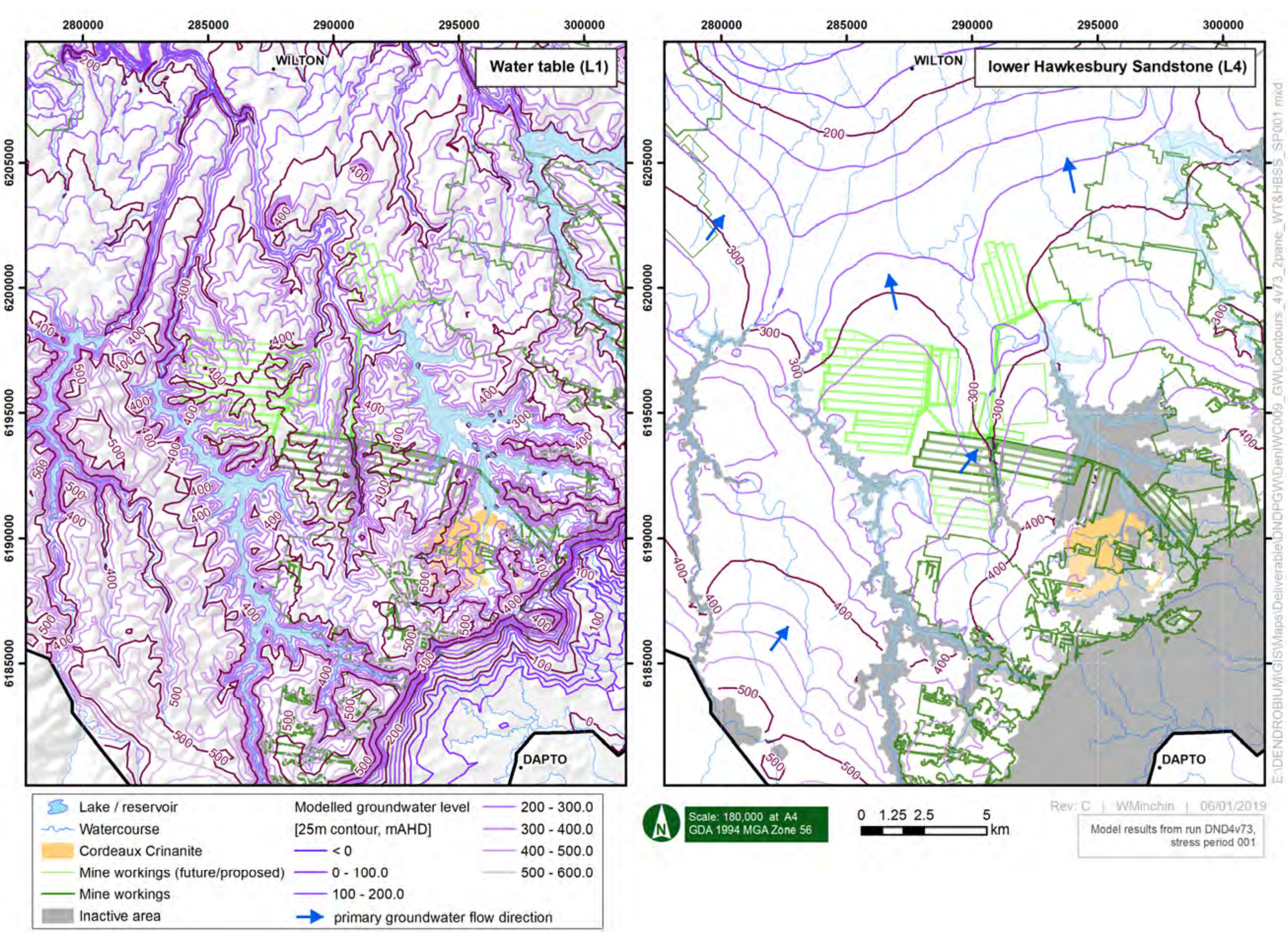


Figure 7-23 Modelled groundwater level contours: model Layers 1 and 4 – pre-mining

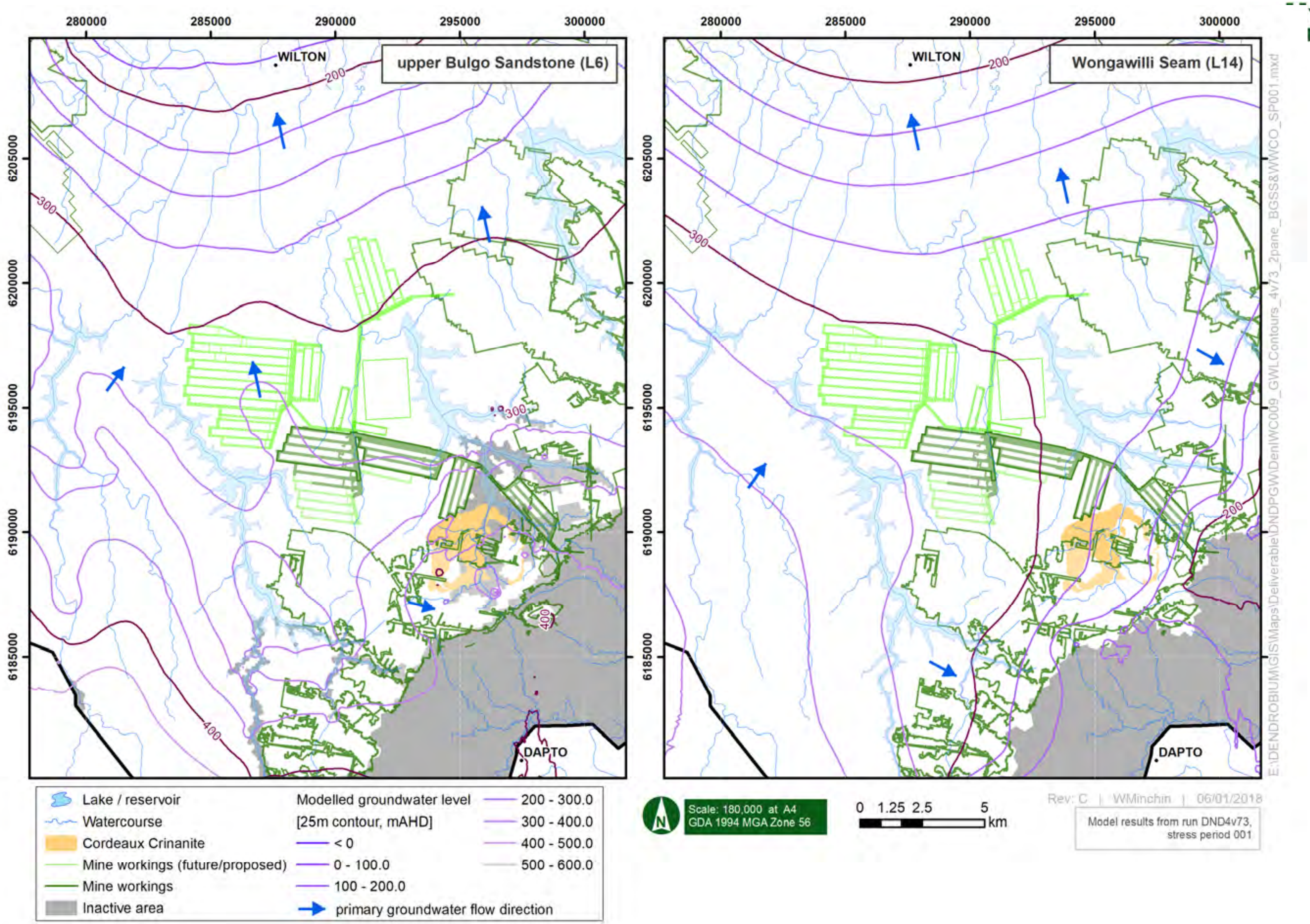


Figure 7-24 Modelled groundwater level contours: model Layers 6 and 14 – pre-mining

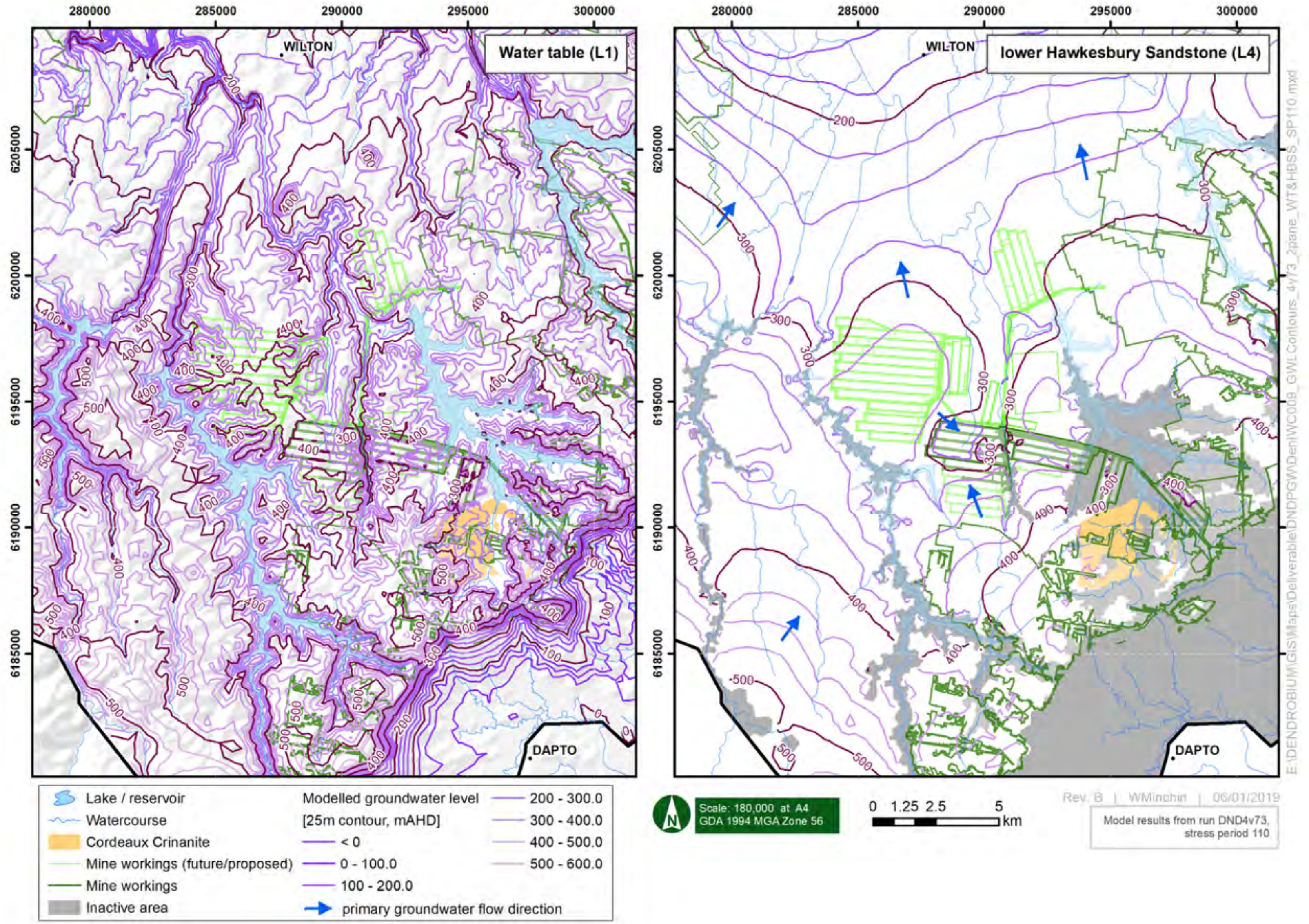


Figure 7-25 Modelled groundwater level contours: model Layers 1 and 4 – mid-2018

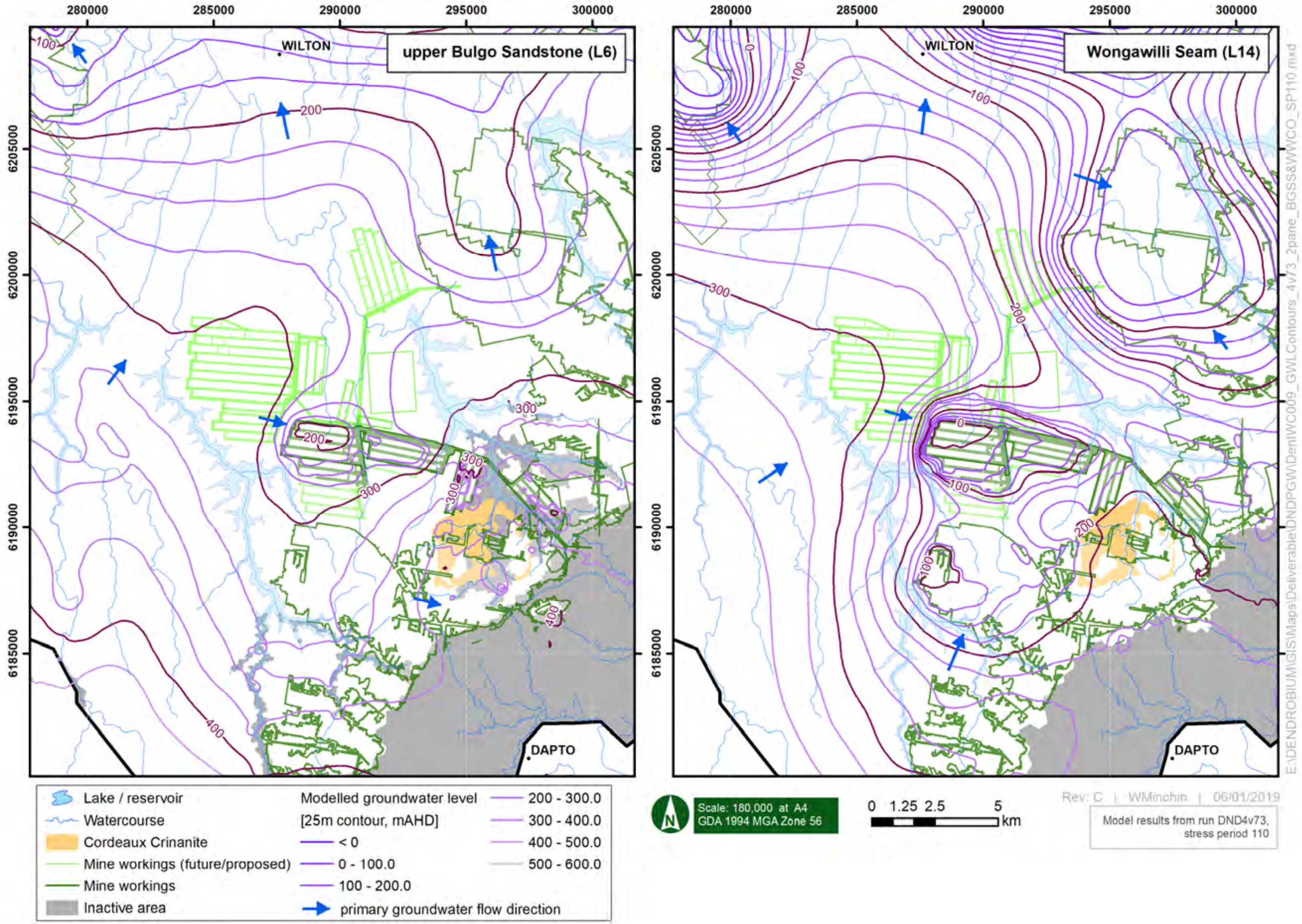


Figure 7-26 Modelled groundwater level contours: model Layers 6 and 14 – mid-2018

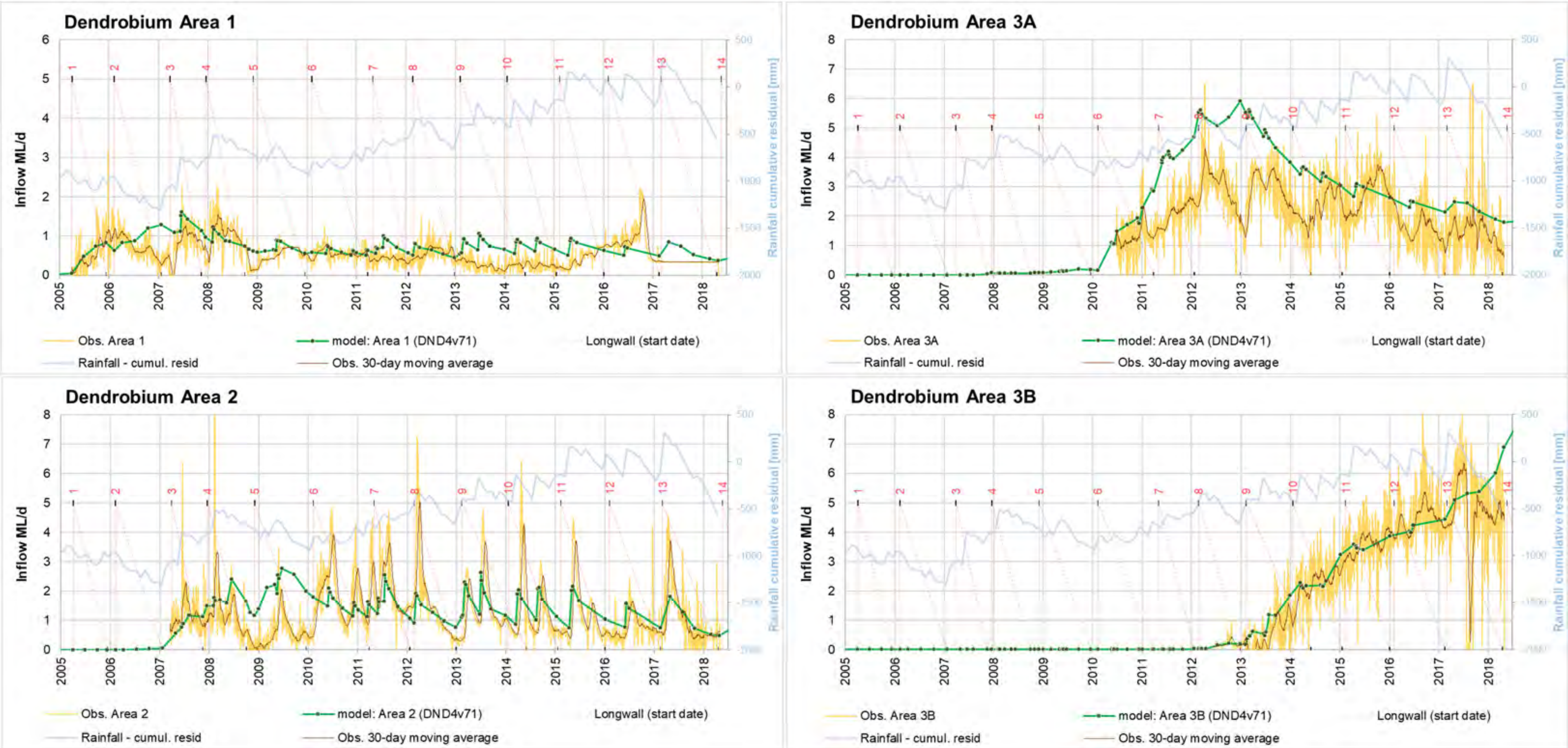
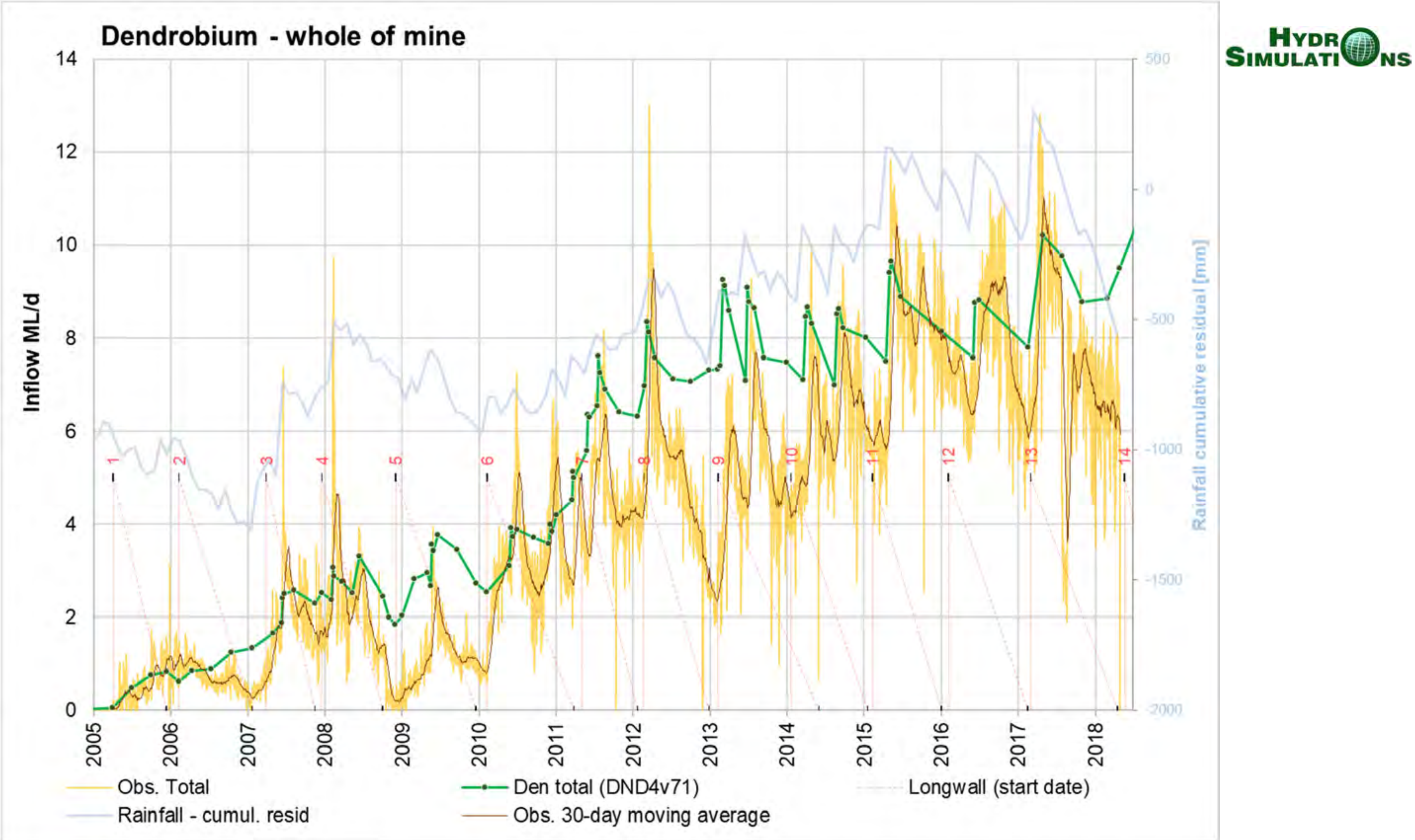


Figure 7-27 Modelled vs observed Mine Inflow by Area



E:\DENDROBIUM\Model\GWModel\Processing\Inflow_Leakage\[MineInflow_Zbud_DND4v71_&_DND4v57.xlsx]Calibration

Figure 7-28 Modelled vs observed Mine Inflow – Dendrobium Mine total

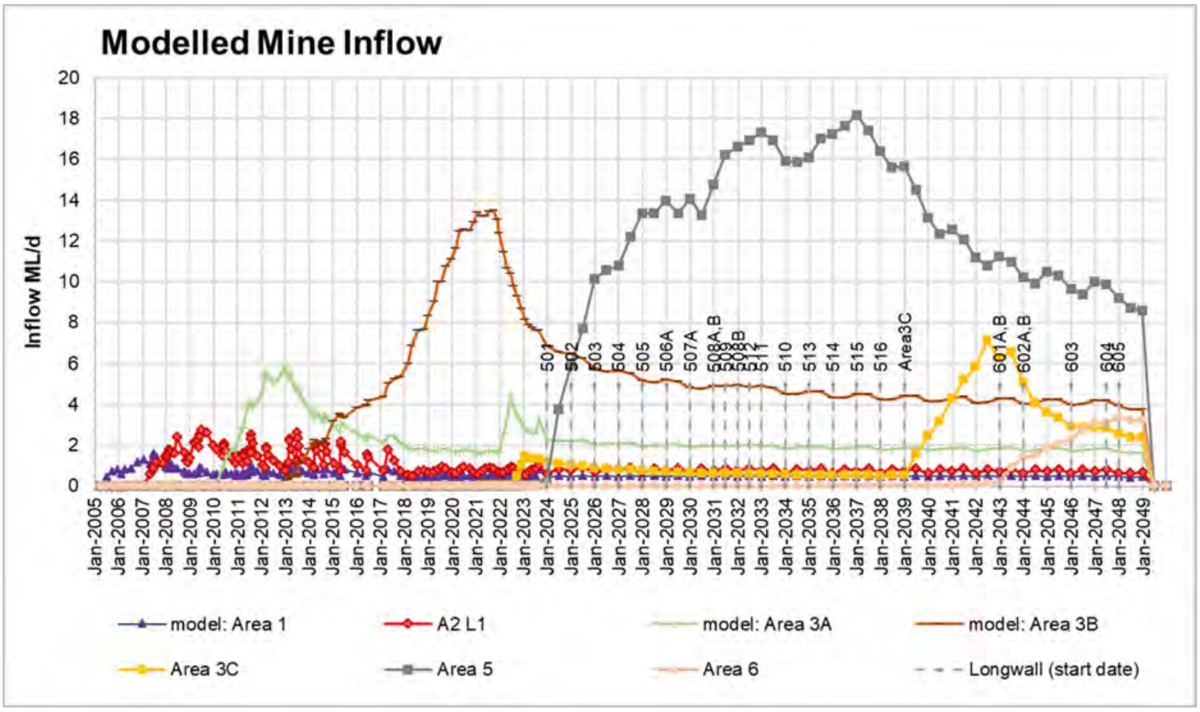


Figure 8-1 Predicted Mine Inflow – by Area

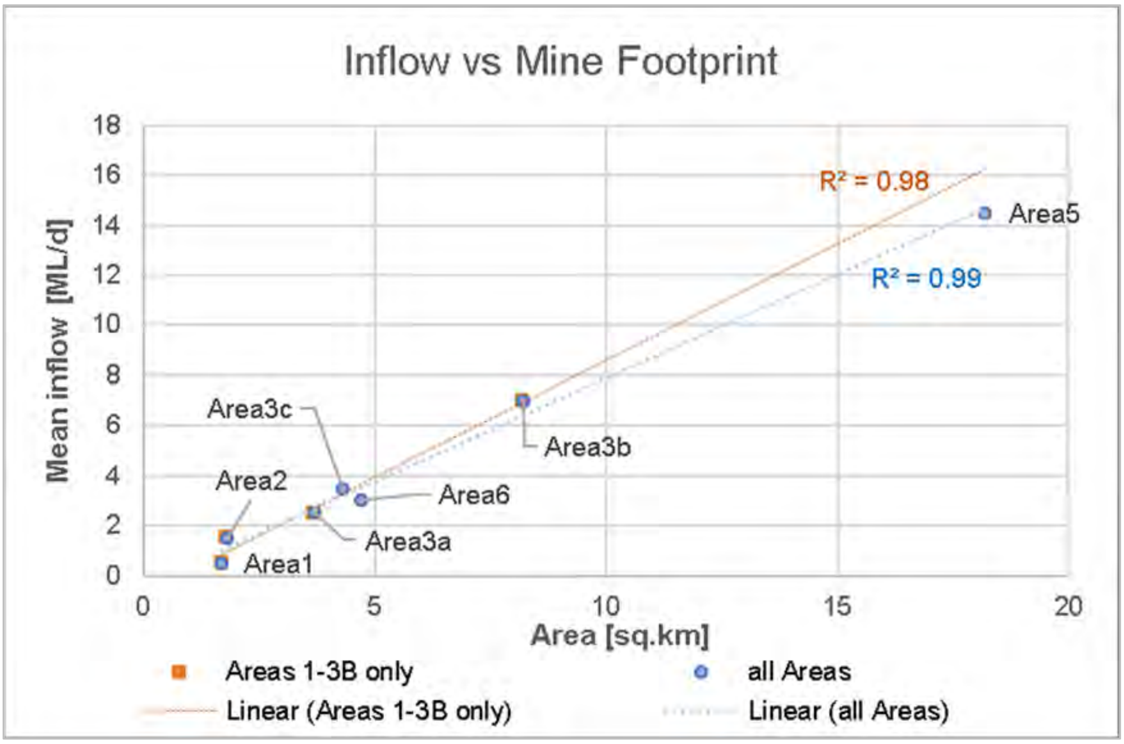


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Figure 8-2 Comparison of observed and predicted inflow and longwall area

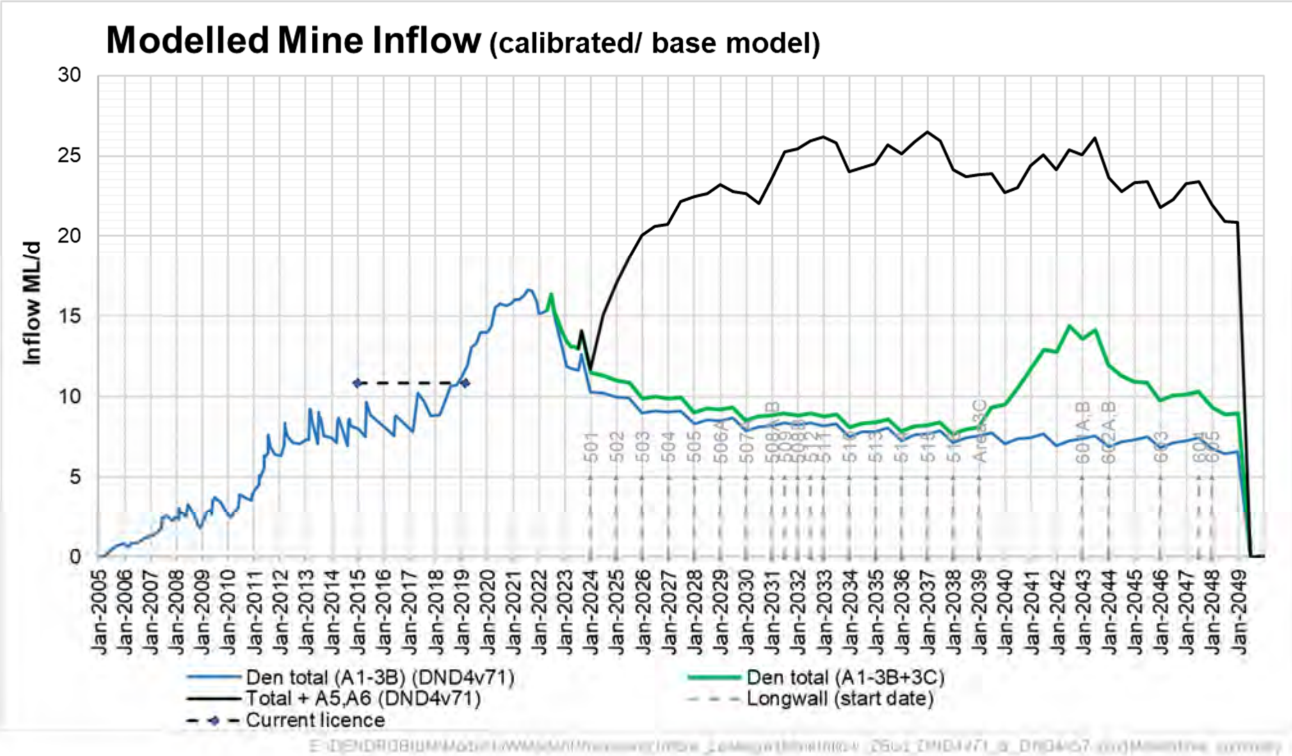
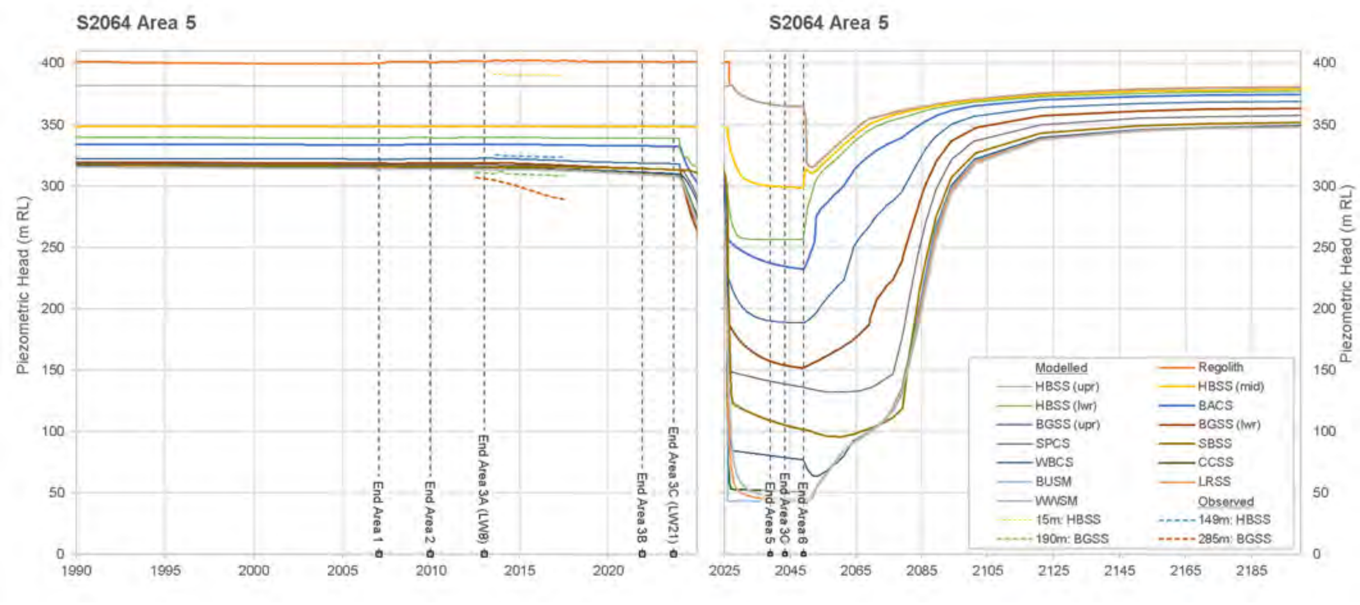


Figure 8-3 Predicted total mine inflow

A)



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B)

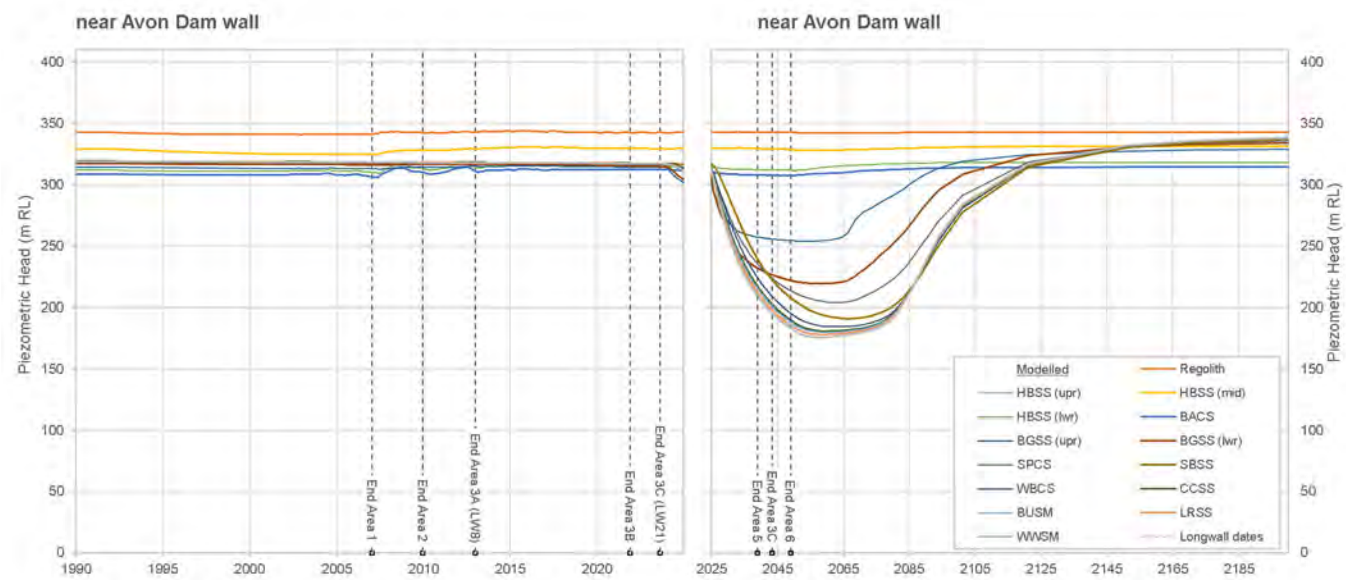
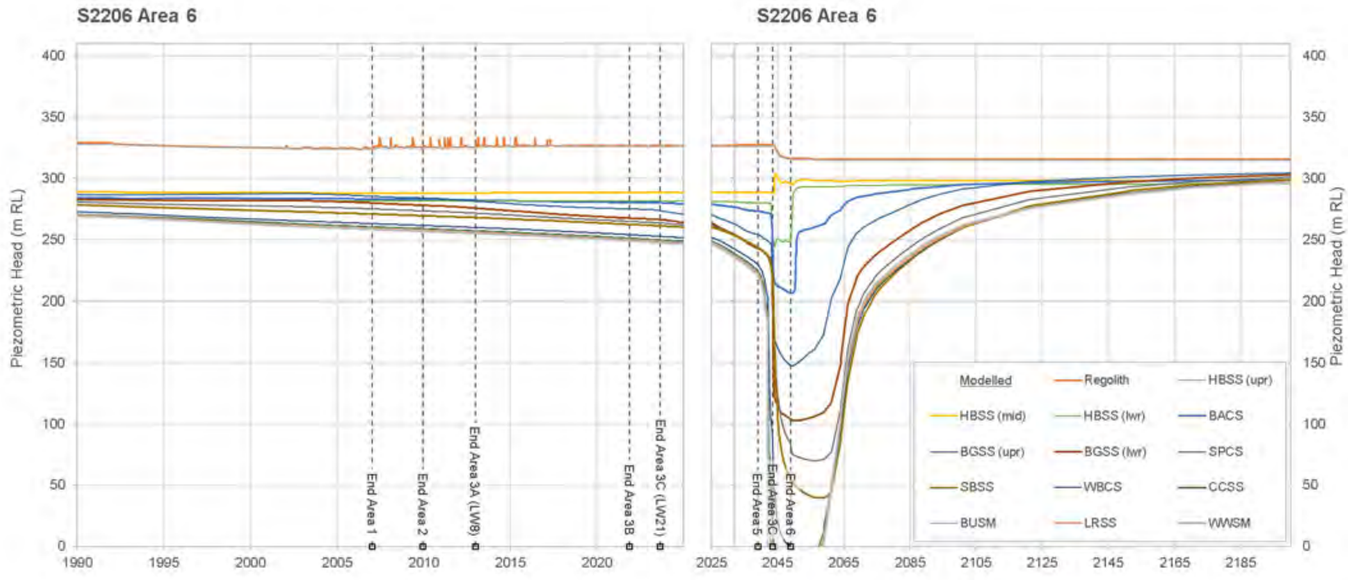


Figure 8-4 Predicted groundwater levels – hydrographs in and near Area 5

A)



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B)

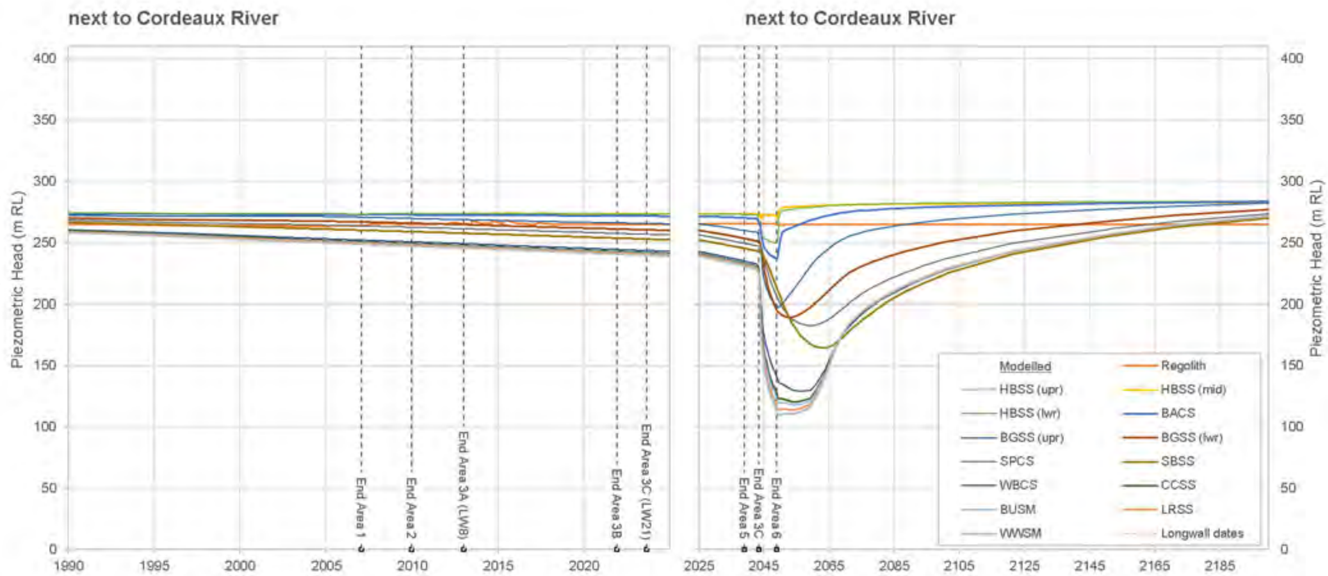


Figure 8-5 Predicted groundwater levels – hydrographs in and near Area 6

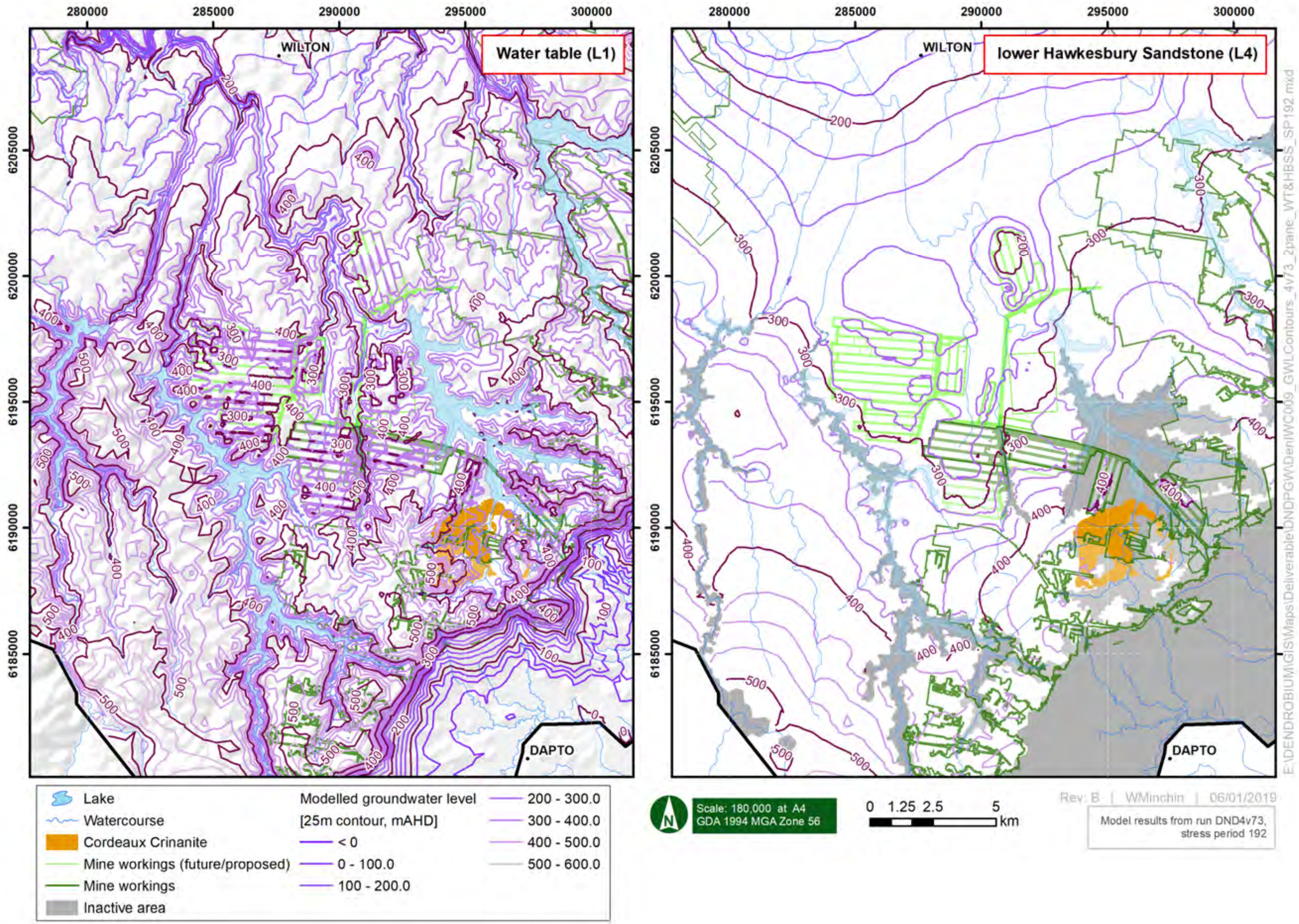


Figure 8-6 Modelled groundwater level contours: model Layers 1 and 4 – 2049

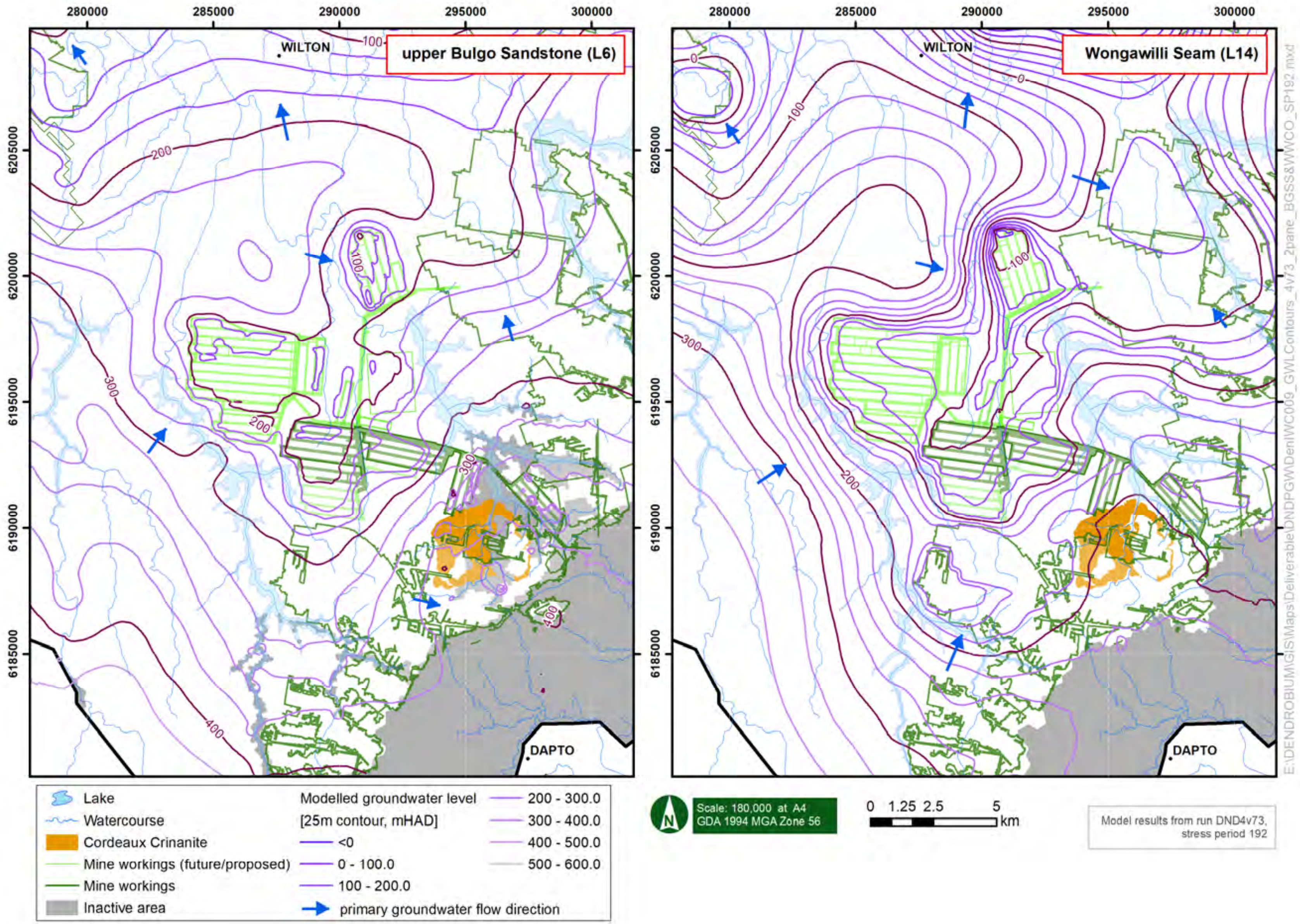


Figure 8-7 Modelled groundwater level contours: model layers 6 and 14 -2049

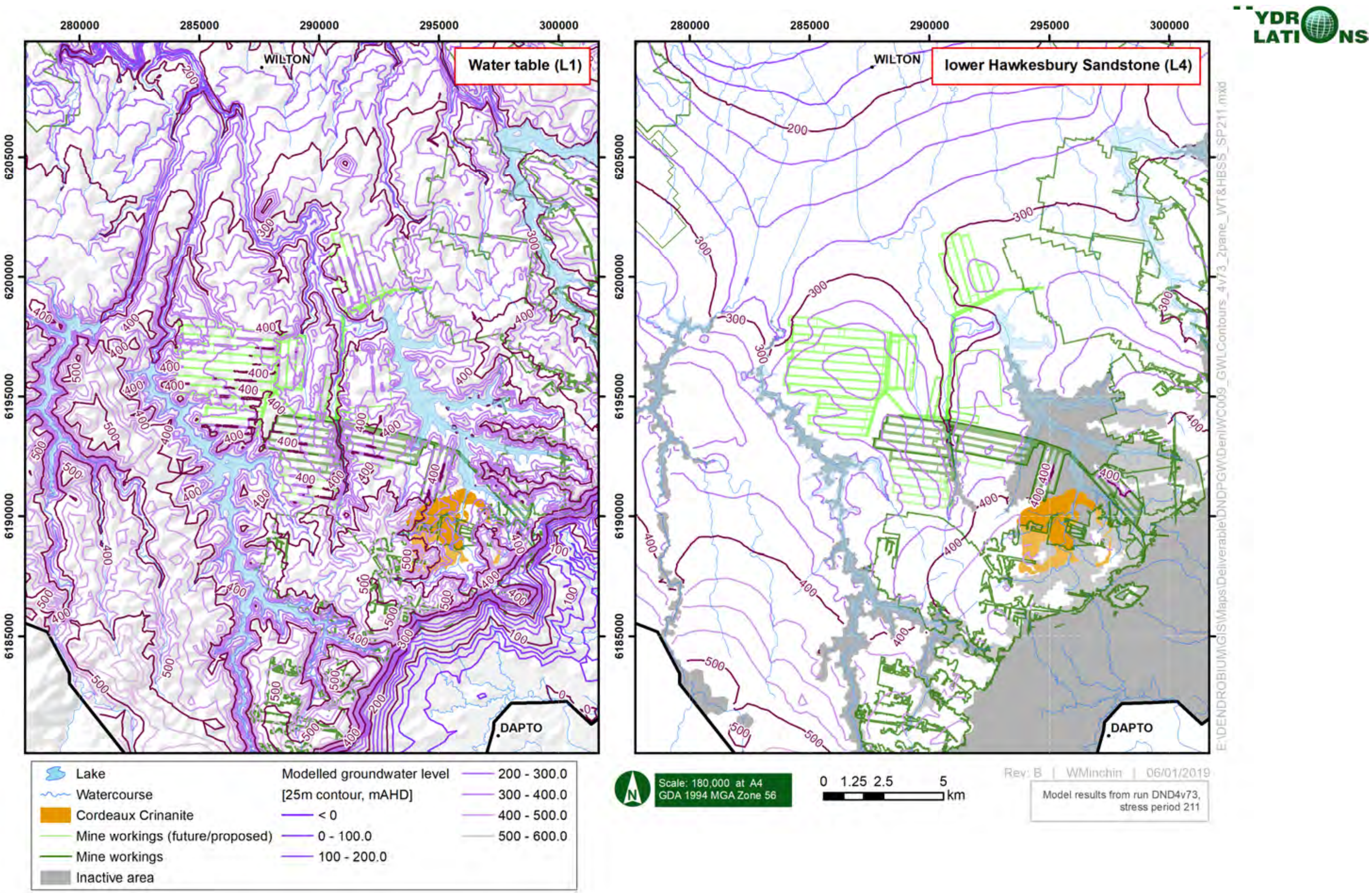


Figure 8-8 Modelled groundwater level contours: model layers 1 and 4 -2200

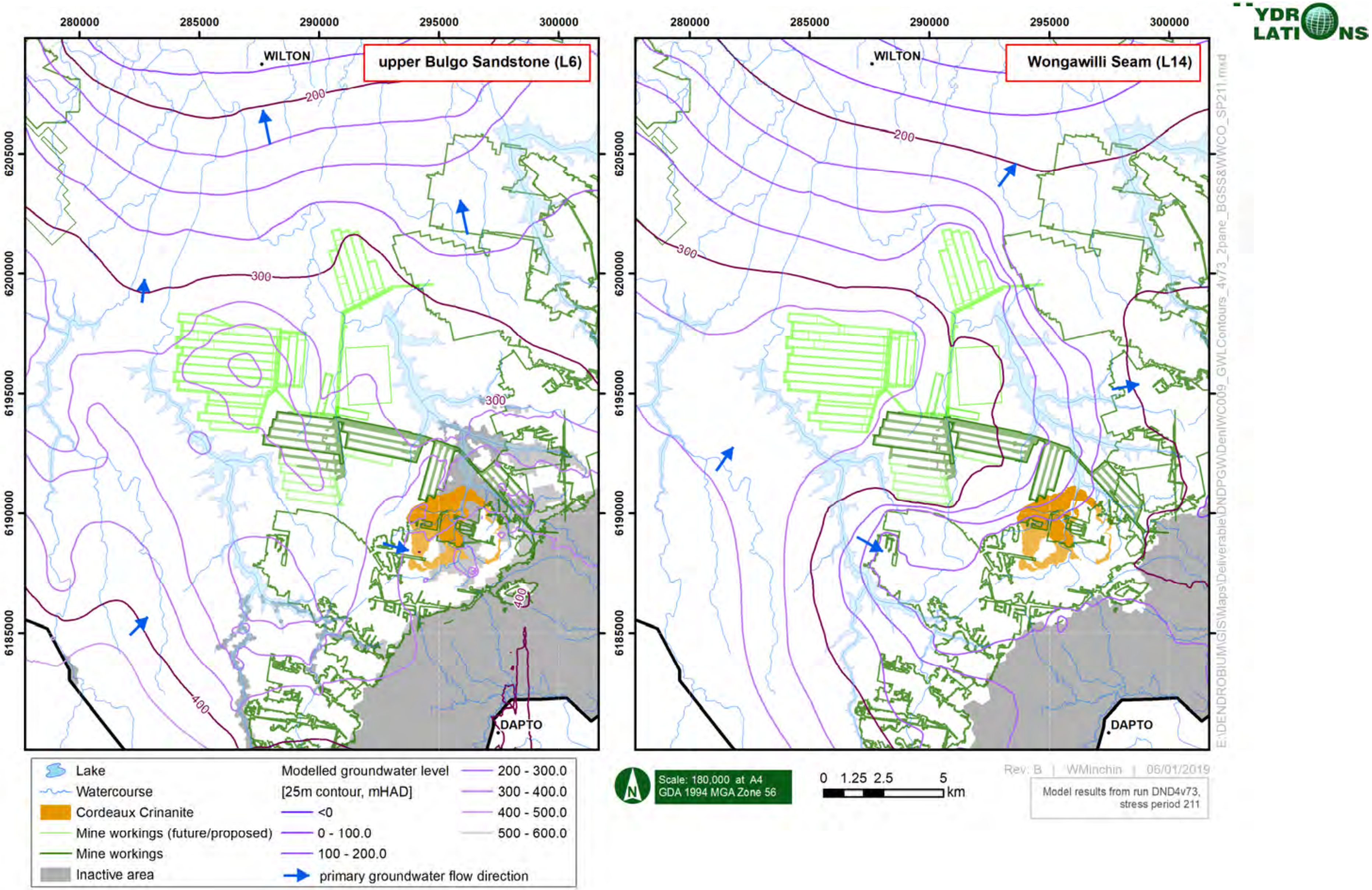


Figure 8-9 Modelled groundwater level contours: model layers 6 and 14 -2200

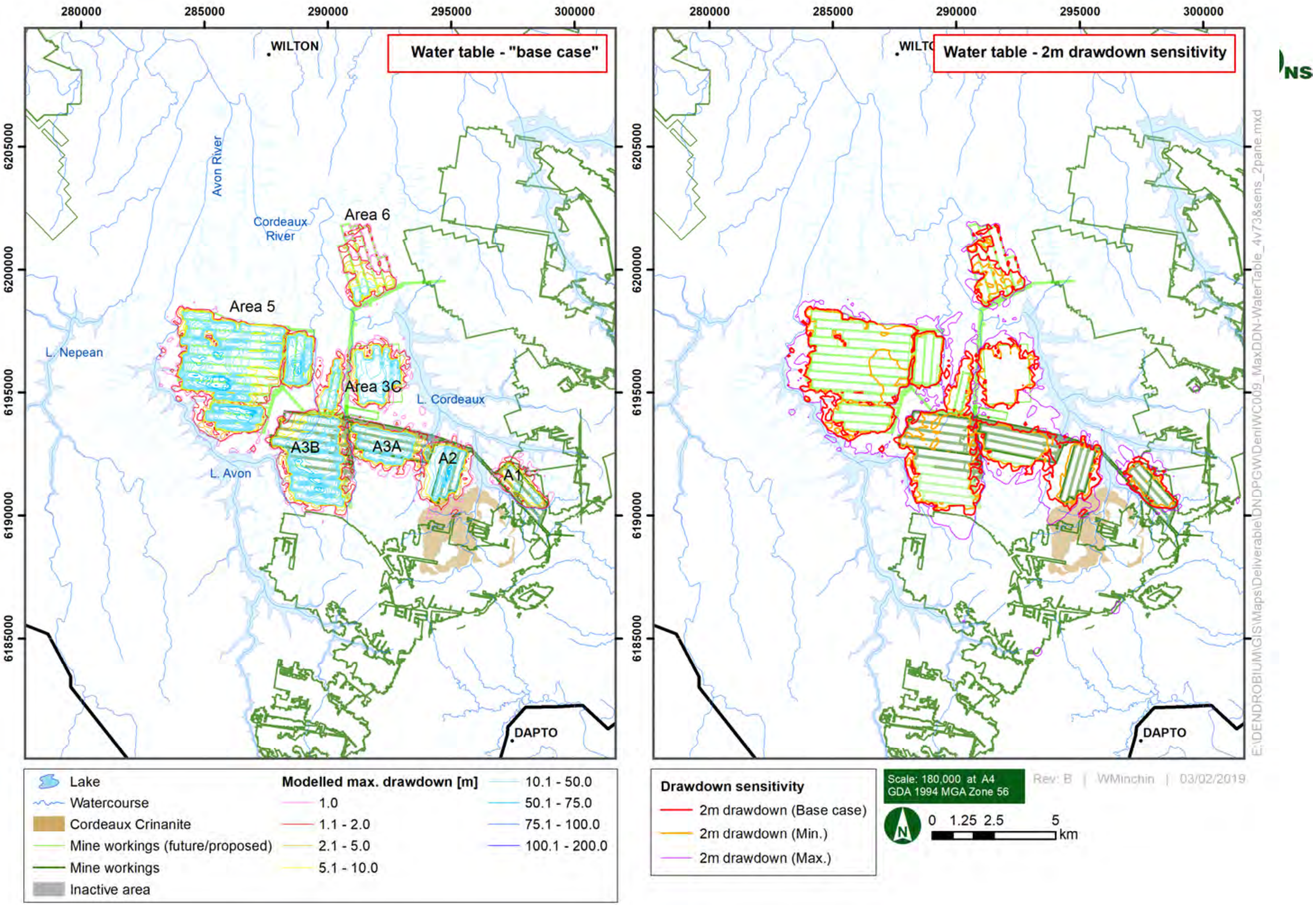


Figure 8-10 Modelled maximum water table drawdown – Dendrobium

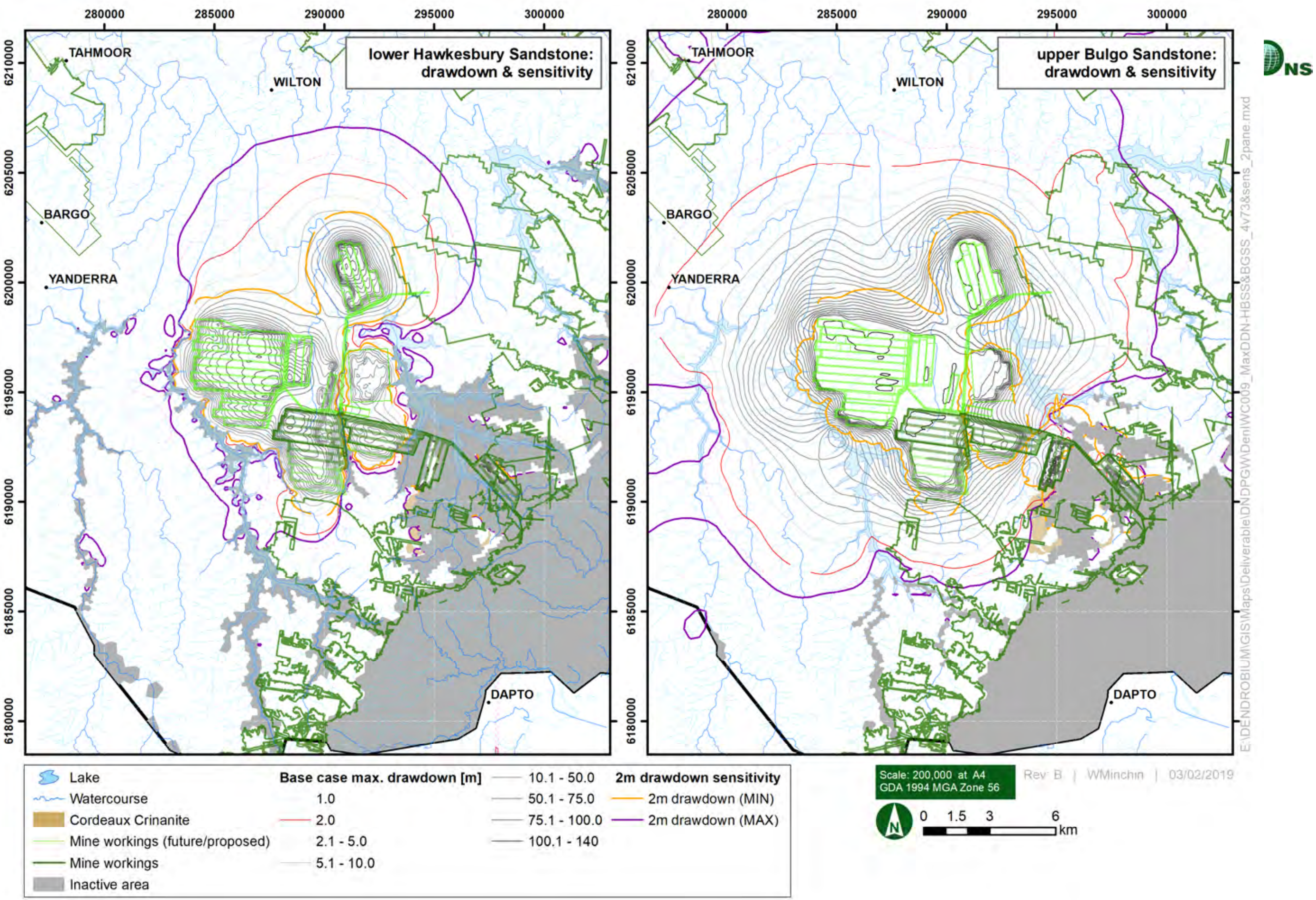


Figure 8-11 Modelled maximum drawdown – Dendrobium: model layers 4 and 6

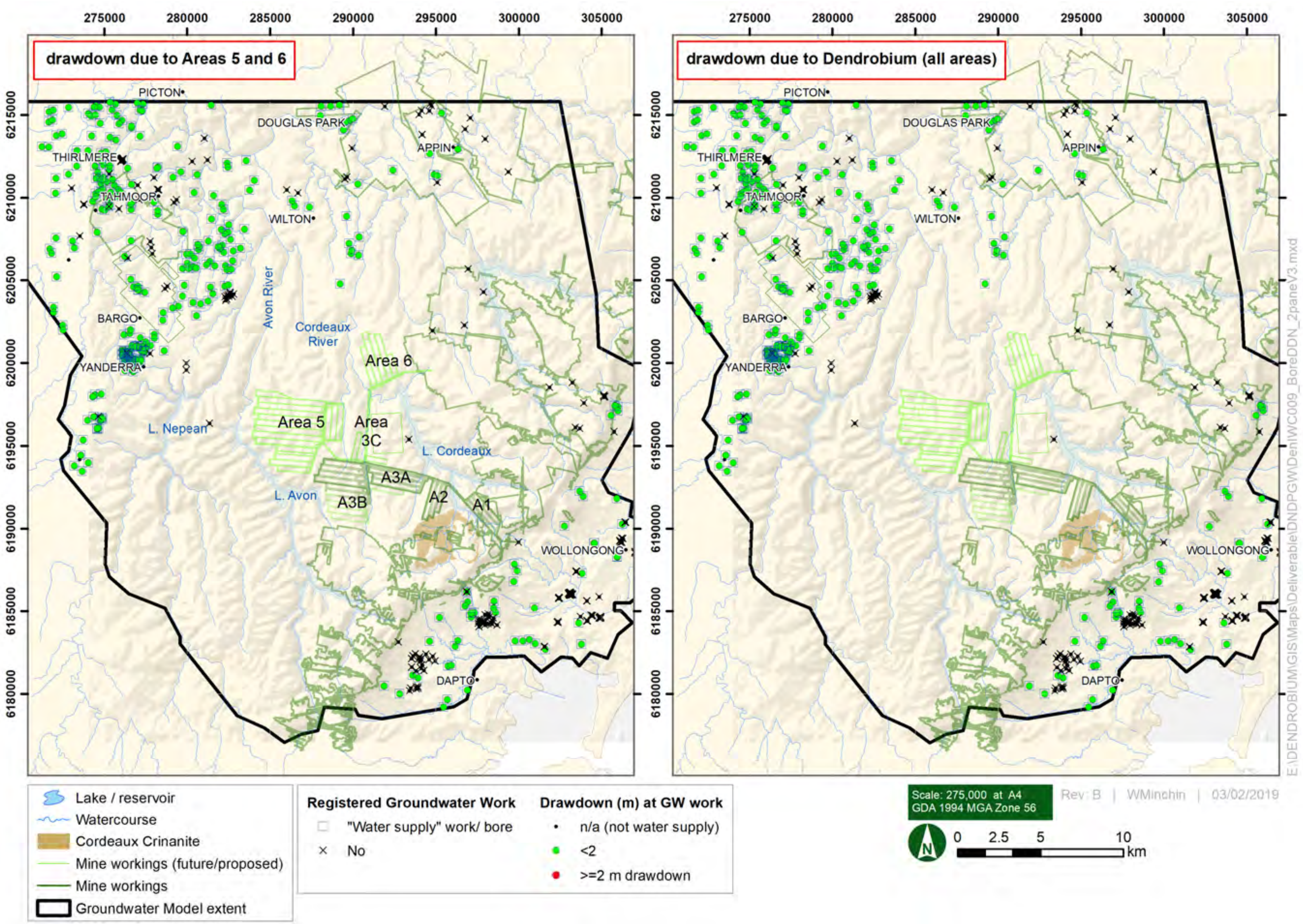
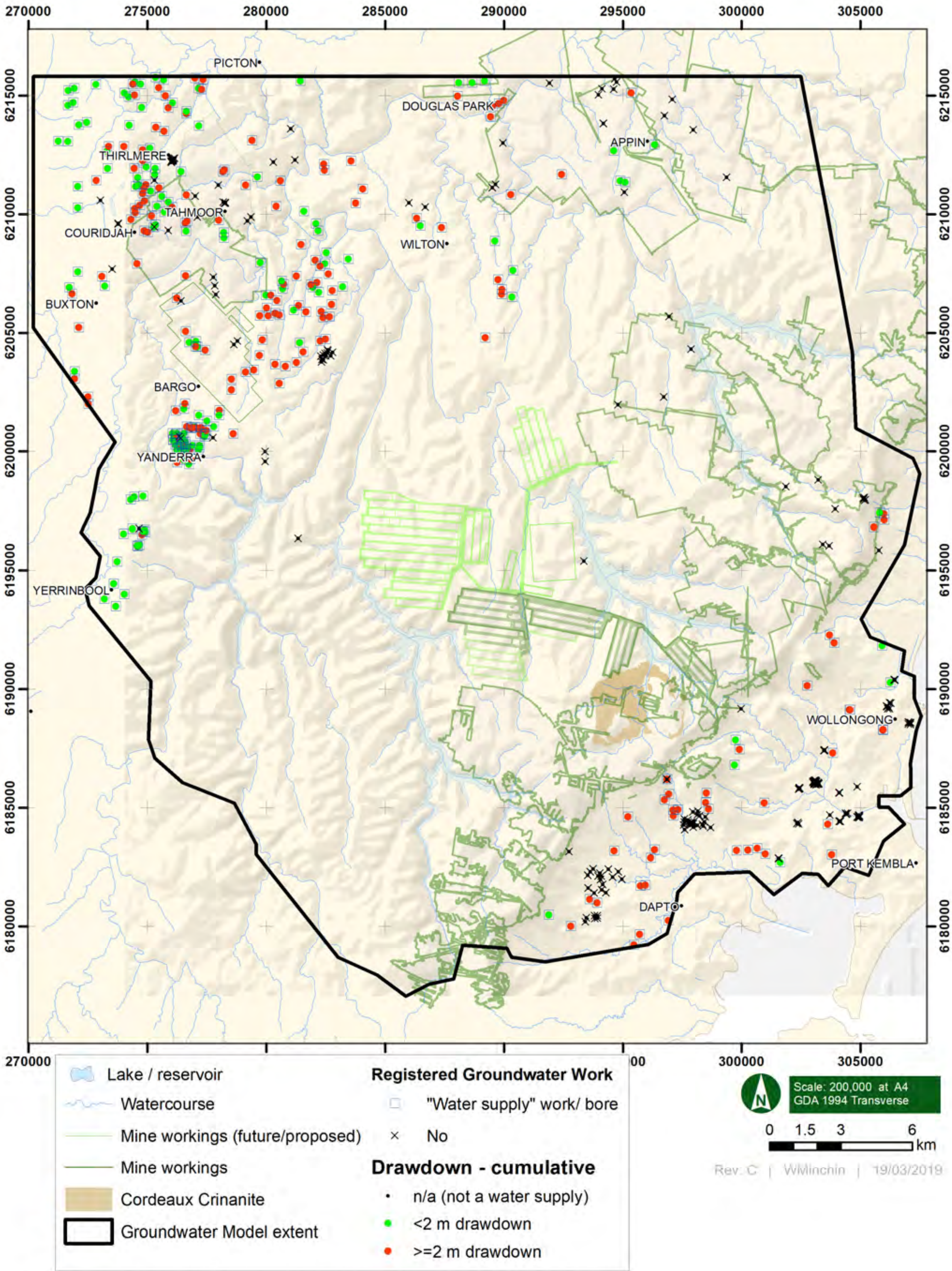


Figure 8-12 Modelled maximum drawdown at Groundwater Works (bores): Dendrobium



E:\DENDROBIUM\GIS\Maps\Deliverable\DNDPGW\DenIWC009_BoreDDN_CUMULv3.mxd

Figure 8-13 Modelled maximum drawdown at registered Groundwater Works: cumulative

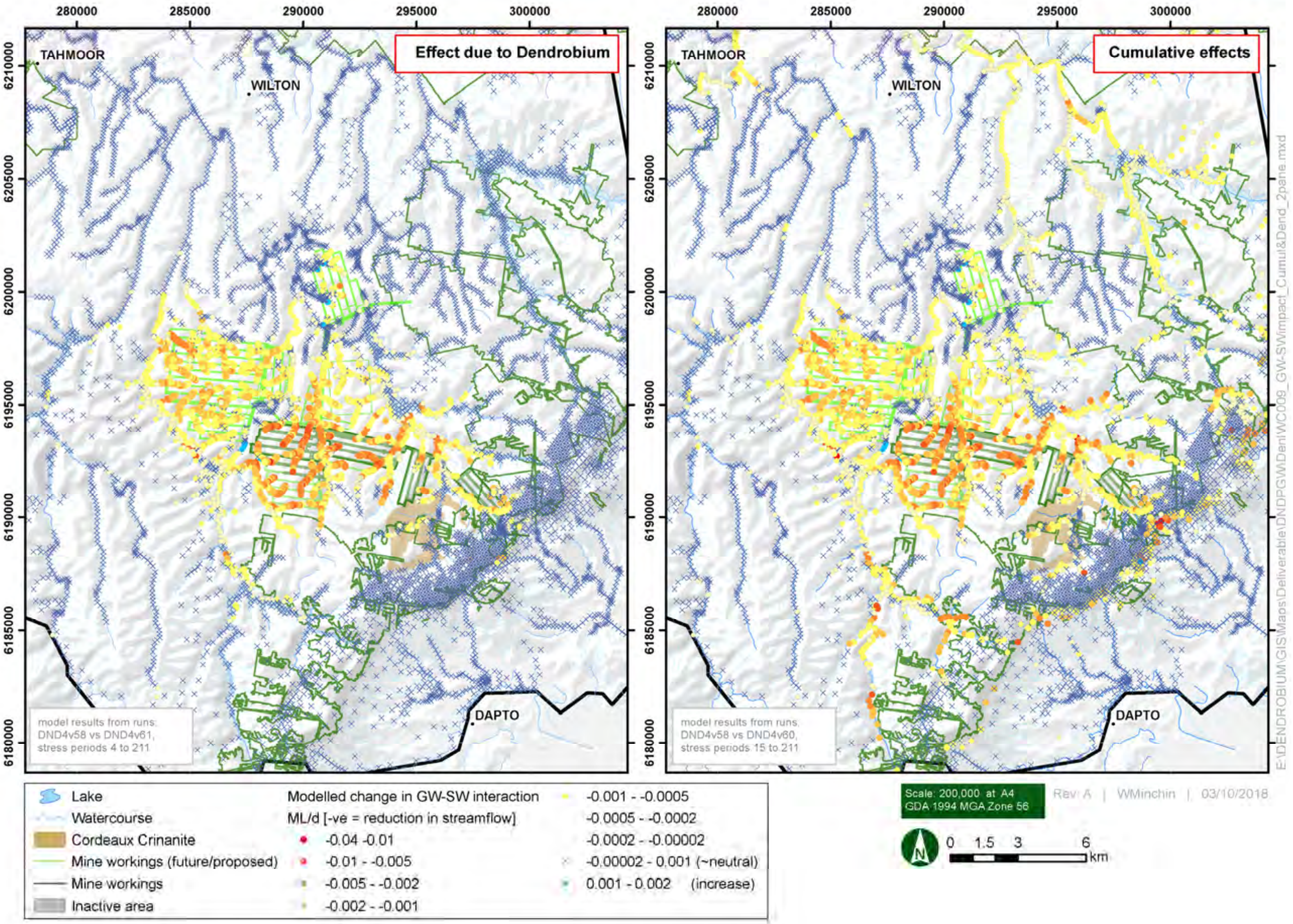
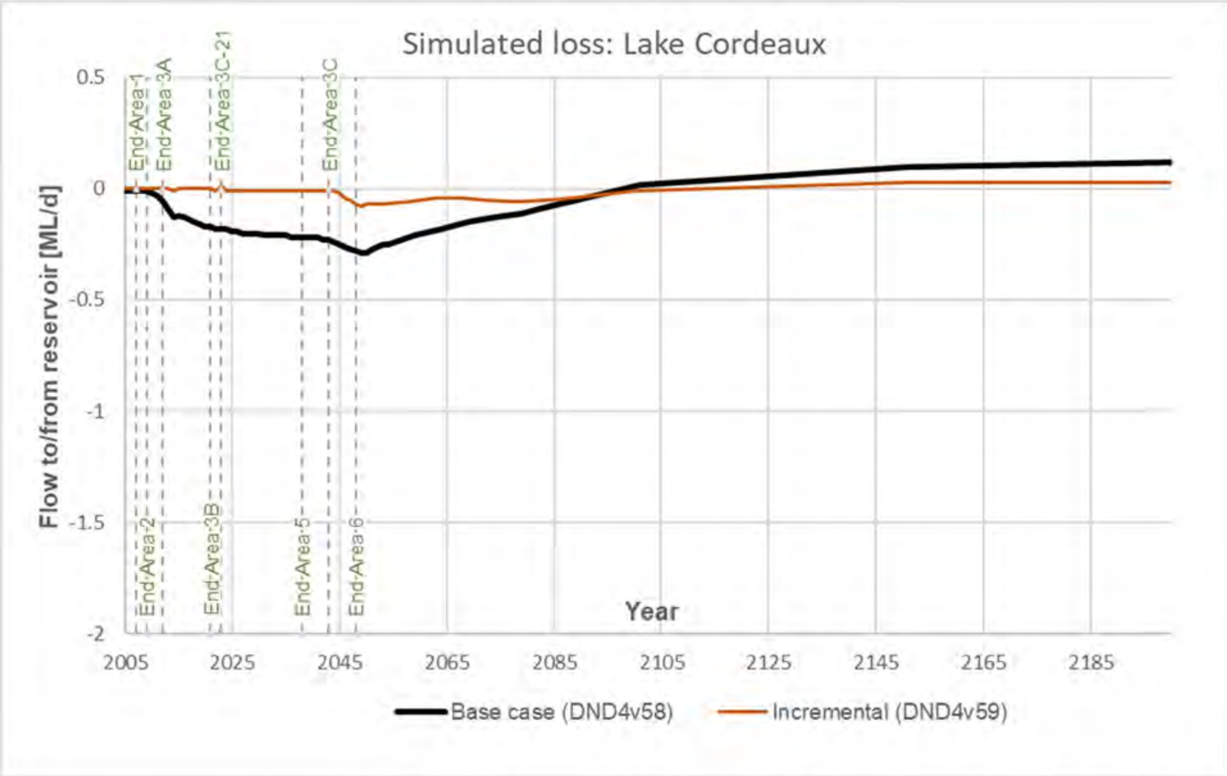


Figure 8-14 Predicted distribution of stream flow depletion



E:\DENDROBIUM\Model\GWModel\Processing\Inflow_Leakage\ReservoirLeakage_Summary_DNDv1.xlsx

Figure 8-15 Predicted loss from Cordeaux Reservoir

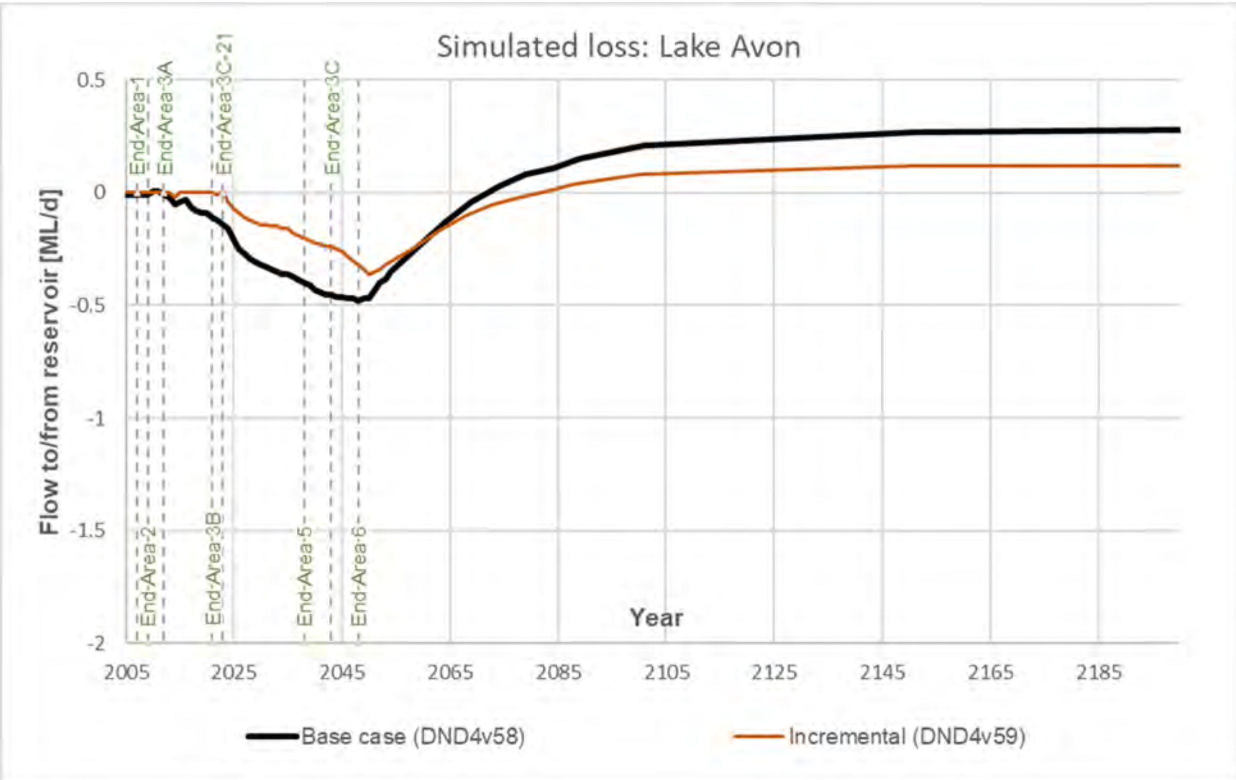
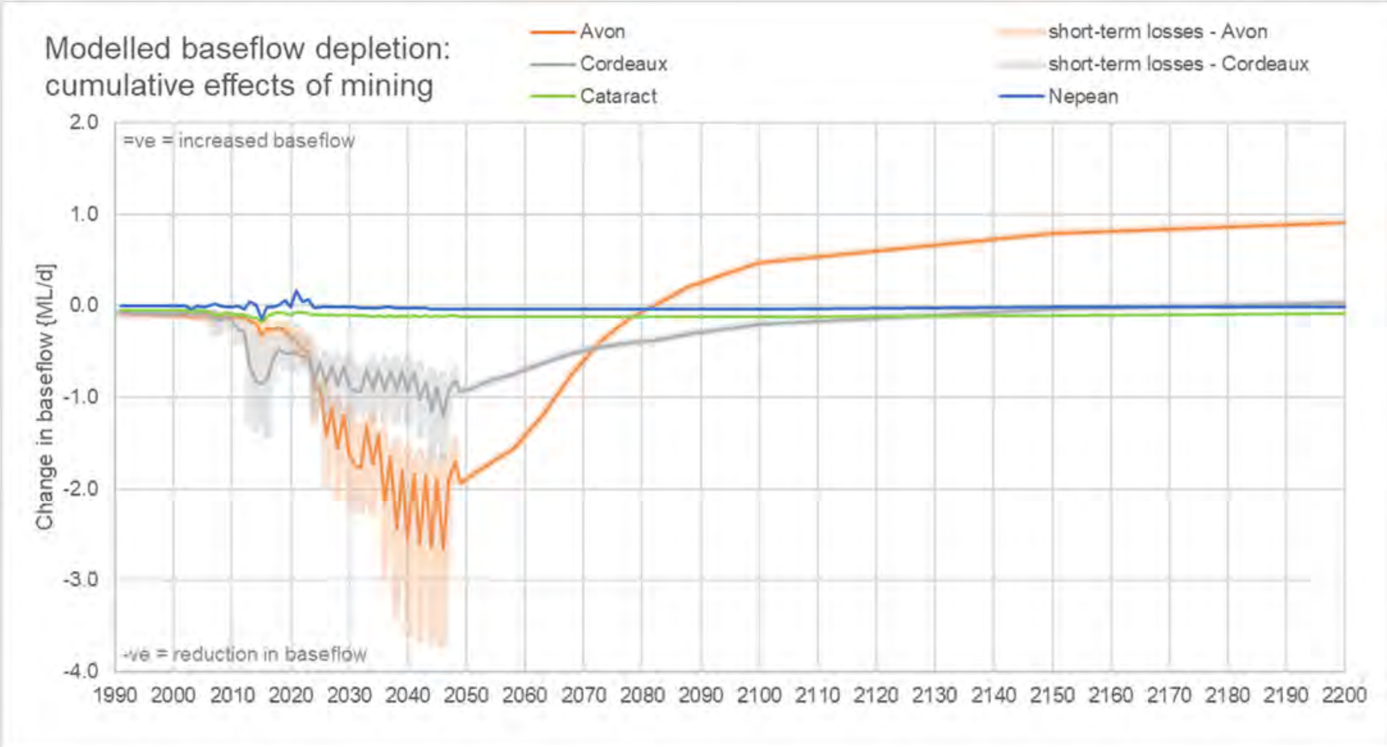


Figure 8-16 Predicted loss from Avon Reservoir



(the catchments are the areas upgradient of the dam wall at each reservoir and within the model domain)

E:\DENDROBIUM\Model\GWModel\Processing\Baseflow\CumulativeLosses_Reservoirs_4v73_v_4v72.xlsx

Figure 8-17 Modelled cumulative losses from catchments to water supply reservoirs

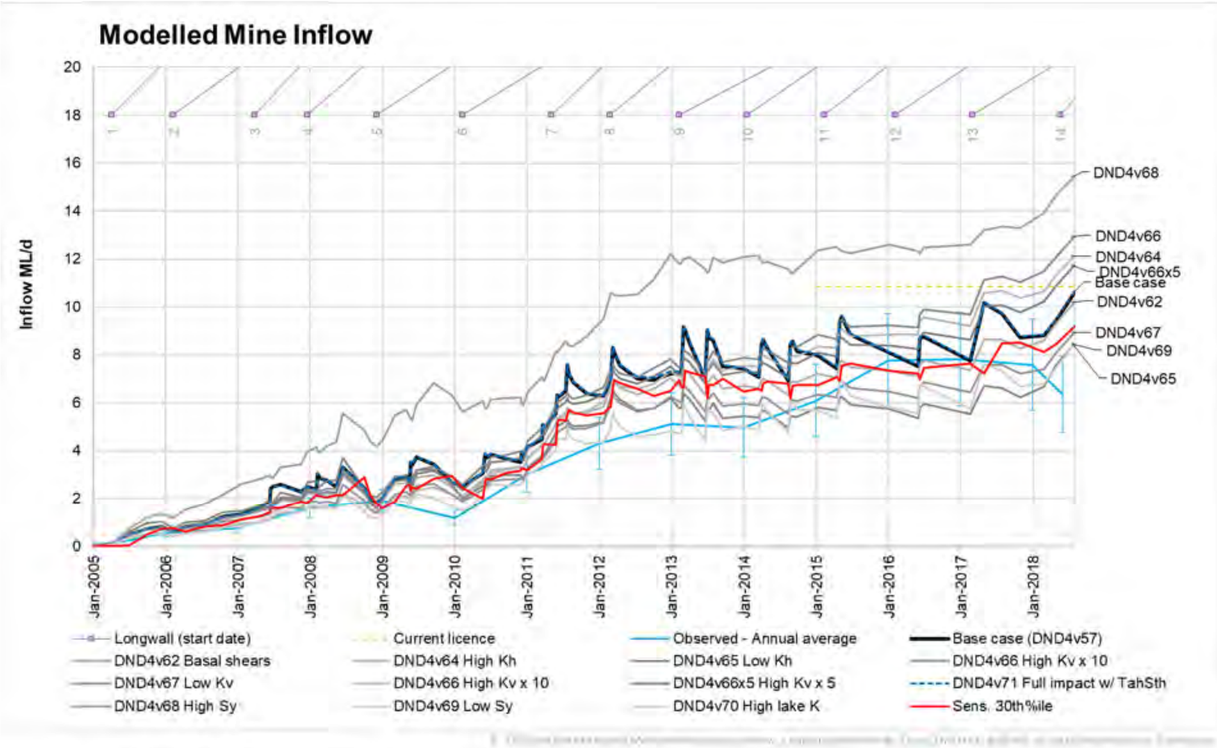


Figure 9-1 Predicted Mine Inflow – assessment of sensitivity runs

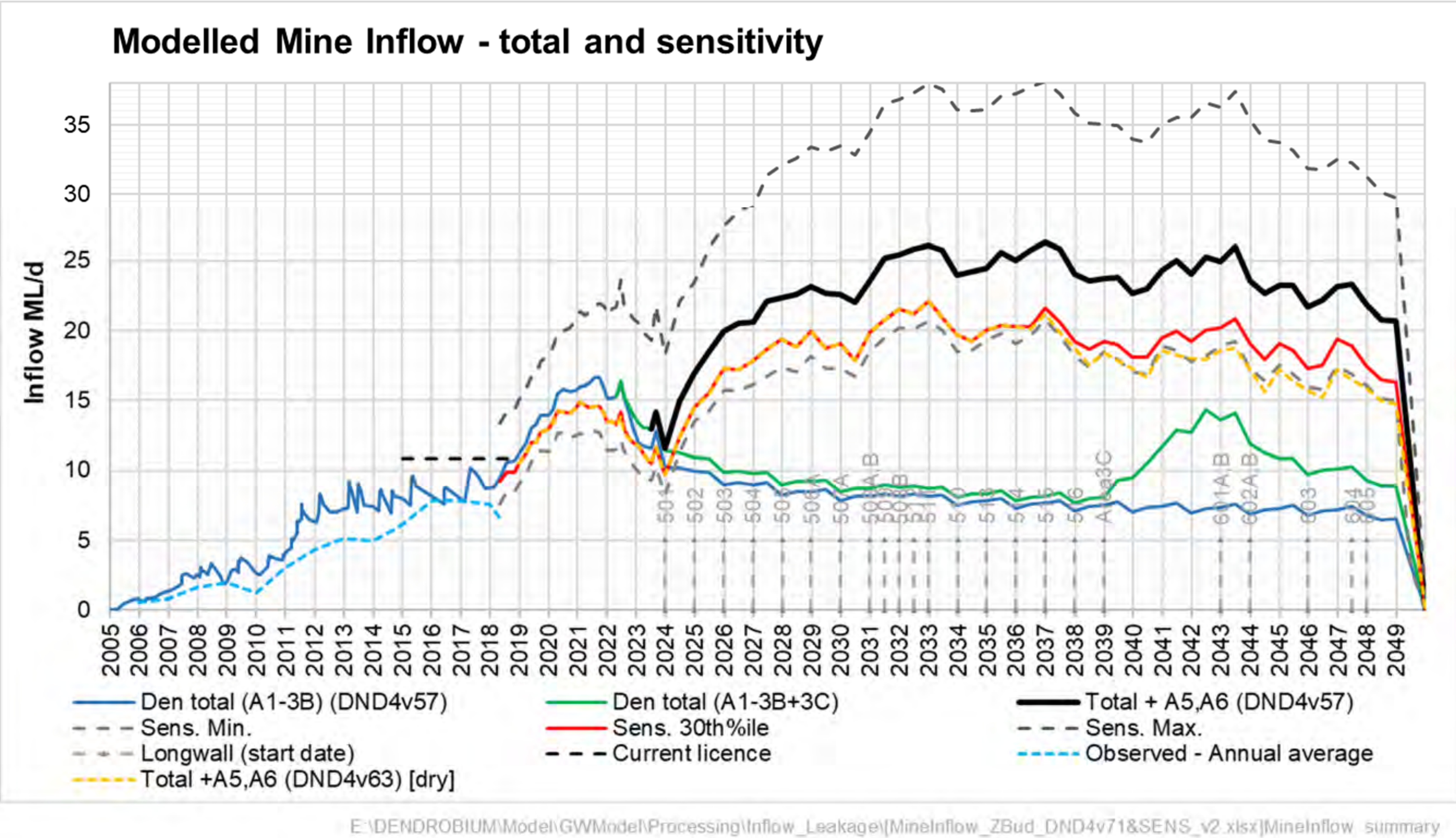


Figure 9-2 Predicted Mine Inflow – Whole of Mine

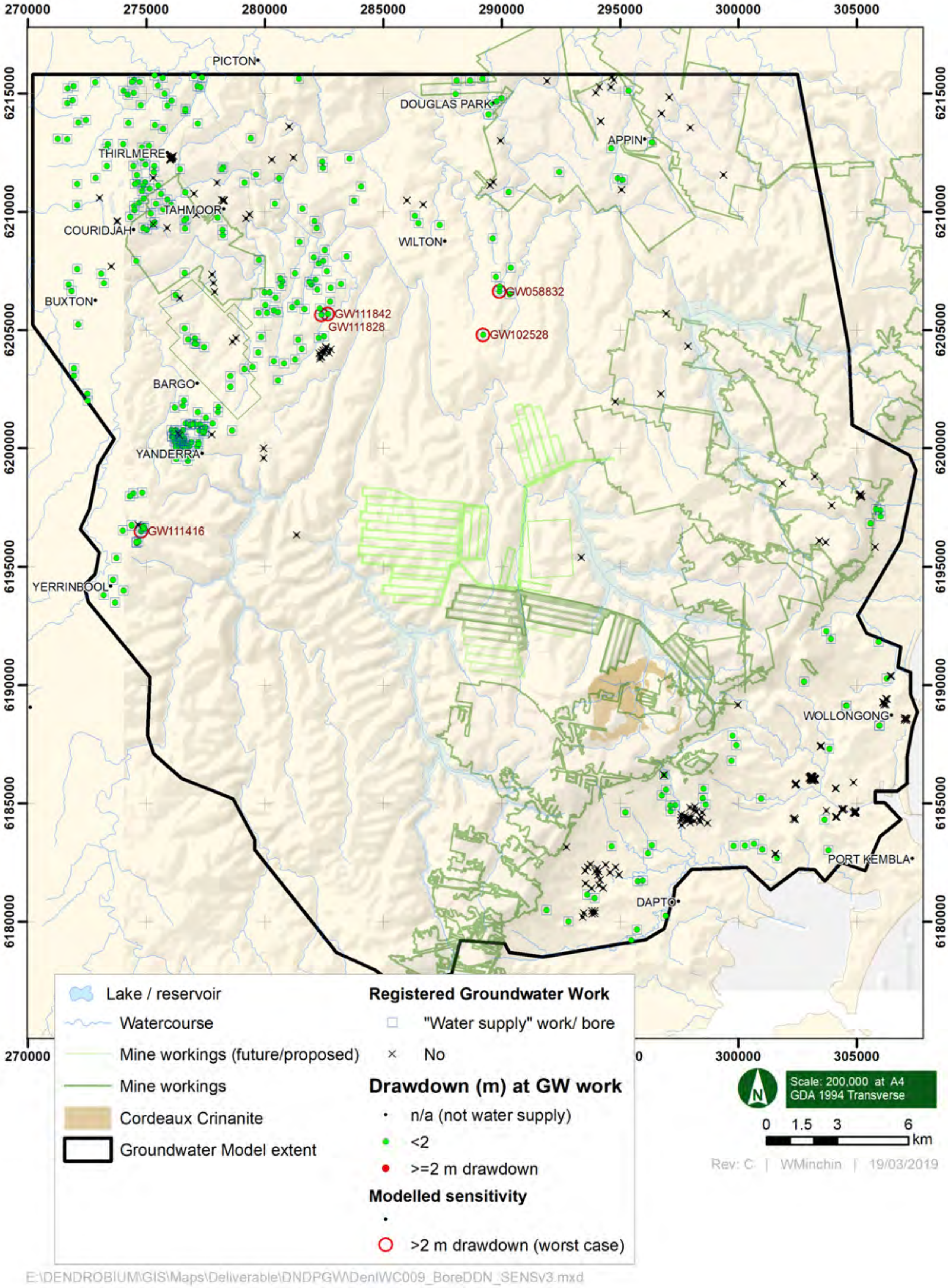
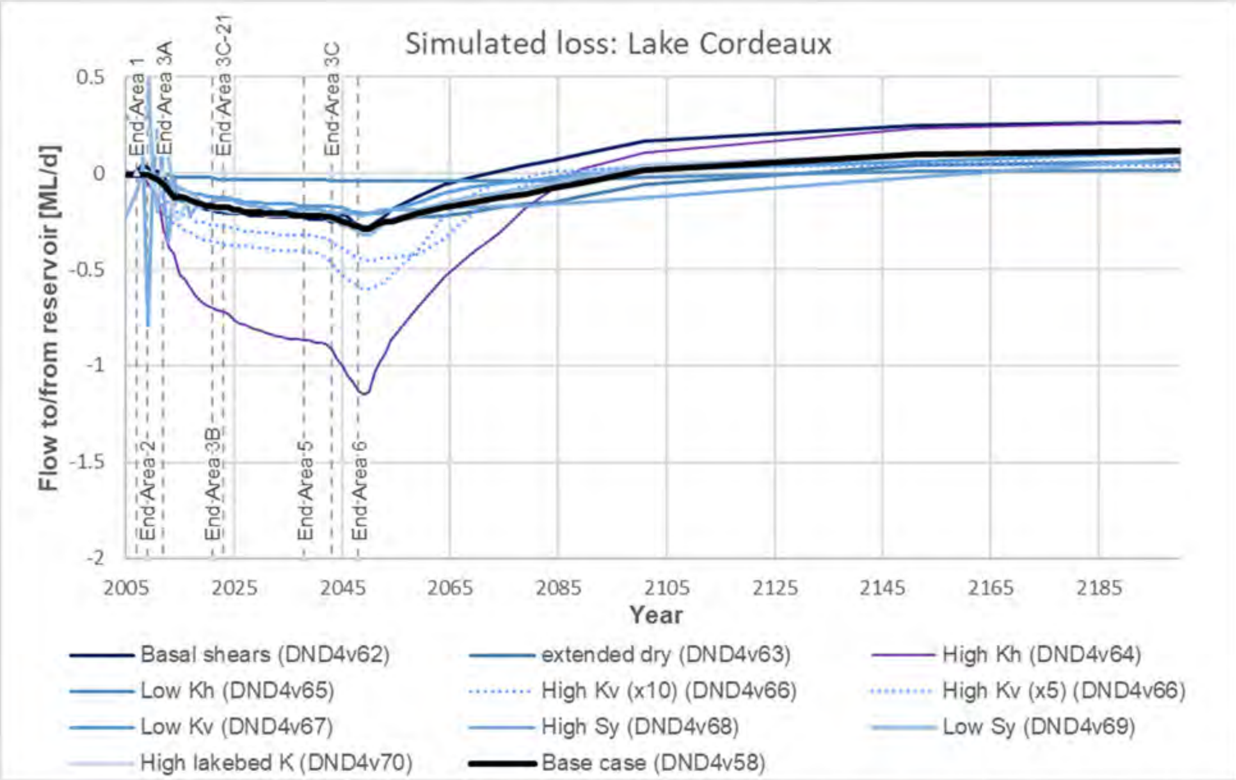


Figure 9-3 Maximum drawdown sensitivity at Groundwater Works due to Dendrobium



E:\DENDROBIUM\Model\GWModel\Processing\Inflow_Leakage\ReservoirLeakage_Summary_DNDv1.xlsx

Figure 9-4 Predicted loss from Cordeaux Reservoir – sensitivity

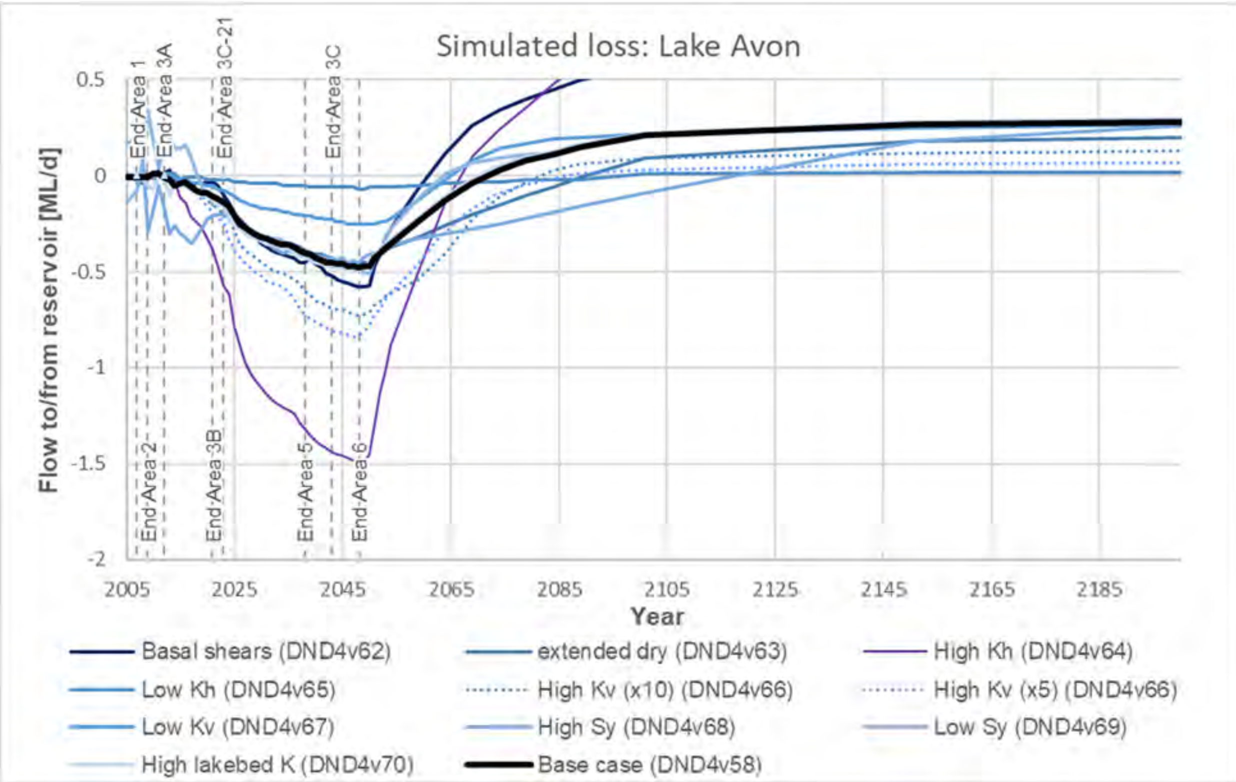


Figure 9-5 Predicted loss from Avon Reservoir – sensitivity