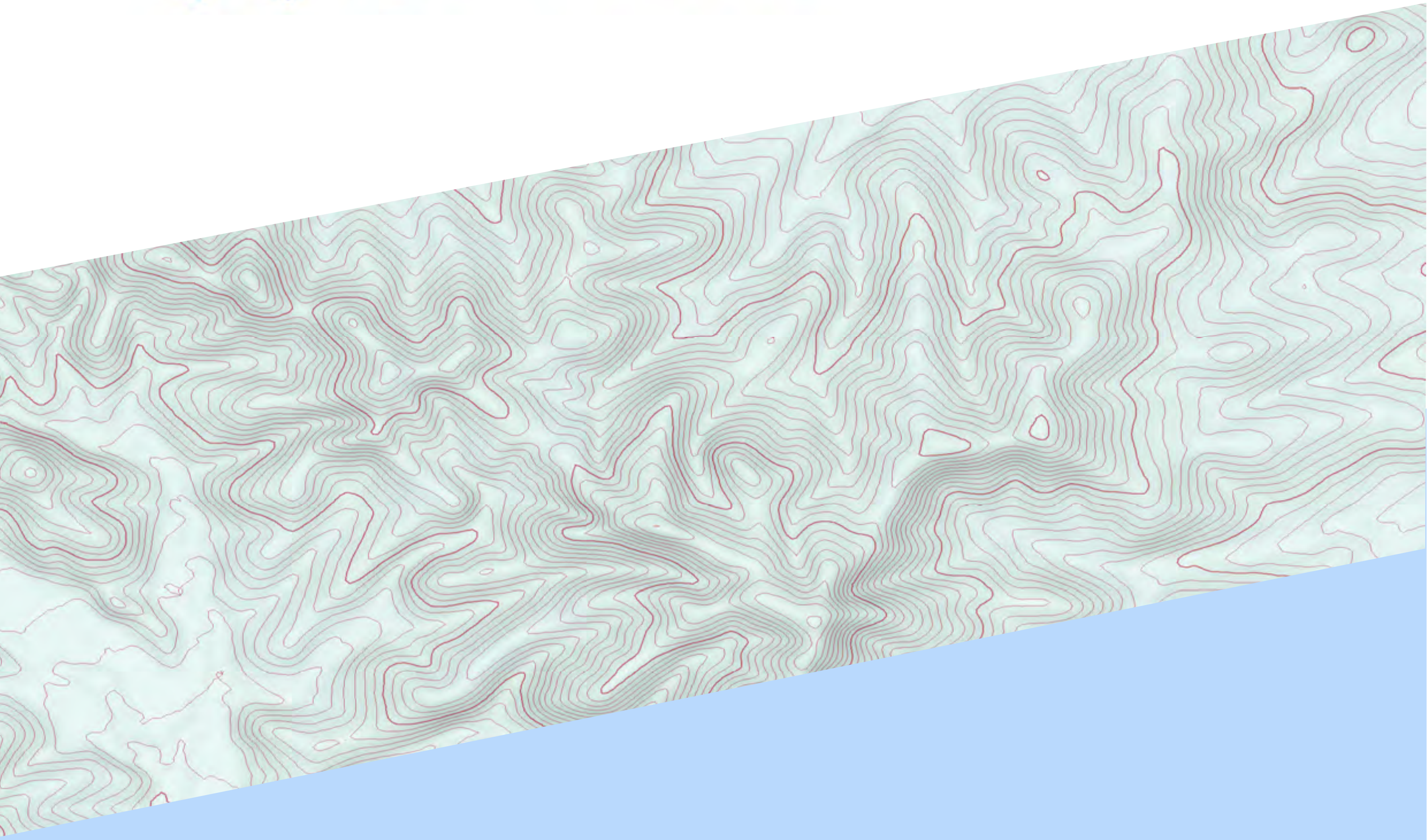

South32 Illawarra Metallurgical Coal

Dendrobium Area 3A:
Longwall 19A Groundwater Assessment

September 2022

DOCUMENT REGISTER

Rev/Issue	Date	Comments
A	28 June 2022	Draft for comment
B	06 Sept 2022	Revised following IMC comments and added Exec Summary
C	07 Sept 2022	Revised following final comments

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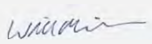
Function	Staff	Signature	Date
Authors	Will Minchin		07/09/2022
Approved	Will Minchin		

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ABBREVIATIONS

Abbreviation/Term	Meaning
BCS	Biodiversity Conservation and Science Directorate (formerly Biodiversity and Conservation Division [BCD]) and Office of Environment and Heritage [OEH])
BoM	Bureau of Meteorology
DPE	NSW Department of Planning and Environment
EPA	NSW Environment Protection Authority
IAPUM	Independent Advisory Panel for Underground Mining (advising DPIE, succeeding IEPMC)
IMC	Illawarra Metallurgical Coal
IMCEFT	Illawarra Metallurgical Coal Environmental Field Team
IEPMC	Independent Expert Panel for Mining in the Catchment (advising DPIE)
IESC	Independent Expert Scientific Committee (advising Federal and state governments)
IMC	Illawarra Metallurgical Coal
mAHD	metres above Australian Height Datum (effectively elevation as metres above sea level)
mBG	metres below ground
ML/d	megalitres per day
Q50	Median (50^{th} percentile) flow at a gauge for a specified period
WaterNSW	Bulk water supply and source protection authority for Greater Sydney

EXECUTIVE SUMMARY

South32 Illawarra Metallurgical Coal (IMC) engaged Watershed HydroGeo Pty Ltd to undertake this Groundwater Assessment to inform IMC's application for SMP approval for the Dendrobium Mine Area 3A Longwall 19A. This longwall would be the fifth longwall in Area 3A, and is proposed to be extracted in mid-2023 to early-2024.

This assessment builds upon previously completed work for the Dendrobium Mine and includes a conceptual model of the impacts of this longwall, both in the operational and post-closure phases. Numerical flow modelling and consideration of likely water quality effects on groundwater and connected surface waters are presented, along with recommendations for monitoring.

This study included data review and conceptualisation, incorporating reviews of:

- geotechnical and geological data and IMC's geological model;
- a significant database of pre-mining and post-mining hydraulic properties from packer testing and other methods;
- hydrological data related to groundwater:
  - groundwater levels;
  - groundwater inflow;
  - groundwater chemistry;
  - groundwater recharge; as well as
- surface water flow and water quality.

The main environmental risk pathway associated with longwall mining is subsidence and the associated fracturing and deformation of strata above and adjacent to longwall panels. Fracturing causes changes to hydraulic properties, mainly to hydraulic conductivity or permeability. This fracturing can cause connected fracturing or disconnected fracturing. Depending on the geometry of the longwall panel and depth of cover, this can potentially provide direct flow pathways from the surface to deeper fracture networks and the mine workings. Additionally, near-surface strata above longwall panels are very likely to be affected by tensile cracking ('surface cracking'), while deformation of strata outside the longwalls can also increase permeability, although this latter effect is not consistent.

A site-specific conceptual model is presented for fracturing above longwalls at Dendrobium, based on multiple lines of evidence, including IMC's recent and significant investigative drilling and borehole logging program. The need for this site-specific model was a recommendation of the Independent Advisory Panel for Underground Mining (IAPUM). The fracture model and the general height of fracturing assessment presented in this report have been Peer Reviewed by Professor Bruce Hebblewhite, albeit as part of a separate study (the Dendrobium Area 5 EIS; (Watershed HydroGeo, 2022)).

Longwall 19A targets an area of similar depth of cover to recent Area 3B and Area 3A longwalls, with the same longwall geometry as Longwalls 8 and 19 in Area 3A (and most Area 3B panels). These mining parameters imply a similar height and degree of subsidence to recent mining areas. This finding is made irrespective of the method or empirical model used to assess height of fracturing.

Longwall 19A is relatively distant from WaterNSW's water supply reservoirs (Cordeaux and Avon). The nearest hydrological receptors are SC10 (a tributary of Sandy Creek) to the east and Wongawilli Creek to the west. These watercourses typically pass within 75-200 m and 400-550 m of the longwall respectively. A number of minor tributaries, including WC13, WC14, SC10A and SC10B, pass above or adjacent to Longwall 19A. Swamp Den15A is located close to the eastern end of Longwall 19A, while other Upland Swamps are also nearby (Den43 and Den48).

The numerical groundwater model has been modified from previous assessments to incorporate findings from IMC's over-goaf and Avon shoreline drilling programs and the site-specific model of subsidence fracturing, as well as improved methods for simulating surface water and groundwater-surface water interaction. The model incorporates recharge estimates derived from a soil moisture model calibrated against independent estimates of recharge from literature and from the Bureau of Meteorology modelling, and model parameters for hydraulic conductivity are constrained by the significant database compiled for this site and for neighbouring mines.

The numerical model is calibrated against transient groundwater levels, historical records of mine inflow, and, in an advance on the previous application, calibration against historical surface water flow reductions as determined from field data. This last point addresses comments by the Independent Planning Commission (IPC) and other agencies regarding the reliability of previous forecasts of the effect on water resources.

The modelling indicates that the peak groundwater inflow to Longwall 19A would be approximately 1.2 ML/day (ML/d) and would contribute to a peak groundwater inflow of approximately 12 ML/d in combination with inflow to other parts of Dendrobium Mine. The predicted peak groundwater 'take' to Dendrobium Mine (inclusive of Longwall 19A) of approximately 4,400 ML/year (ML/yr) is less than the groundwater entitlement already held by IMC for the *Nepean Sandstone Groundwater Source* (Management Zone 2) that Dendrobium Mine (and Area 3A) are located within.

As a result of longwall extraction, groundwater drawdown will occur in strata above and around Area 3A longwalls. Reductions in surface water flow will occur, especially in areas affected by surface cracking. Groundwater drawdown caused by the dewatering and subsidence will be similar to drawdown observed in other parts of Dendrobium, with pressures declining 200-300 metres (m) in the Wongawilli Coal seam and adjacent strata, drawdowns of 50-100 m in the Bulgo Sandstone, and in the order of tens of metres or less in the Hawkesbury Sandstone. The nature of fracturing and deformation in the Hawkesbury Sandstone aquifer above Area 3A longwalls means that groundwater drawdown will likely be temporary, i.e. will recover, or partially recover over years to decades.

As has been observed at Area 3A and 3B, following initial groundwater drawdown, recovery of groundwater waters within and then through near-surface fracture networks can cause discharge of poorer quality groundwater. Elevated concentrations of metals, such as iron, manganese, zinc and aluminium, are likely in groundwater and locally in watercourses, with concentrations declining with distance away from longwall areas, and for some of these species, this effect probably temporary. The potential for impacts to long-term surface water quality as a result of groundwater recovery and upward migration groundwater from deep strata is very low.

An assessment of the Aquifer Interference Policy minimal harm considerations indicates that no High Priority Groundwater Dependent Ecosystems (GDEs) would be affected by drawdown from Longwall 19A, which is consistent with the large distance to such features. No registered 'water supply' bores are predicted to experience more than 2 m of drawdown due to this longwall. This is due to the distance between the longwall (and the mine in general) and registered bores.

Significantly, Longwall 19A is located least 1,500 m from the Cordeaux Reservoir Full Supply Level, and 3,000 m from the Avon Reservoir Full Supply Level. Numerical modelling predicts that losses from the reservoir, caused by drawdown would be <0.01 ML/d (i.e. negligible). The maximum loss due to Dendrobium Mine is predicted to be up to 0.3 ML/d, which is within prescribed threshold of 1 ML/d.

Given the distance, there is negligible risk of Longwall 19A causing further deformation of strata between the longwall panel and the reservoir. Incremental losses, due to the longwall, from Avon Reservoir, which are more distant than Cordeaux, would be negligible.

Losses of surface water flow are related to the proximity and footprint of longwalls to watercourses, and also to the prevailing weather/flow conditions, i.e. losses are greater in wet periods, however while they are lower in dry periods, they constitute a greater fraction of the prevailing flow in a watercourse. Dendrobium Mine's total predicted effect to a maximum of approximately 3 ML/d (1090 ML/yr) in average rainfall years, but up to approximately 4.2 ML/d (1530 ML/yr) in wet years. Longwall 19A's incremental effect on this total would be negligible, however this longwall would cause localised effects (including cracking) on minor tributaries WC13 and WC14, SC10A and SC10B, with groundwater drawdown leading to reductions in baseflow in SC10 and the nearby reach of Wongawilli Creek.

The modelling includes simulations of groundwater responses to post-closure management measures (installation of bulkheads) recommended by SLR (2022). The modelling suggests that the mining of Longwall 19A would have a negligible incremental effect on the volume of this discharge water from the mine portals following closure. Similarly, water quality or chemistry of the mine discharge is not considered to be altered due to the mining of Longwall 19A.

The potential for groundwater recovery in the long-term after mine closure in the presence of vertically-connected fracturing to act as a pathway for the upward migration of poor quality groundwater from the coal measures or other deep strata has been assessed as very minor. The flushing of shallower fracture networks (noted above) is more likely to cause water quality effects within the Special Area and would occur in a shorter timeframe after mining (as has been observed in watercourses SC10C and SC10, above Area 3A). However, the magnitude of these effects would not affect WaterNSW's ability to meet the standards stated in raw water supply agreements.

The numerical model relied on in this study has been the subject of Peer Review by Brian Barnett (Jacobs), as part of the Area 5 EIS, rather than specifically for this SMP.

IMC already operates a significant hydrological monitoring network in Area 3A, with many monitoring bores in the Triassic and Permian aged strata, shallow piezometers in Upland Swamps, and surface water flow and water quality monitoring sites. This assessment provides some recommendations for further groundwater and surface water monitoring in the event that SMP approval is obtained.

1 Introduction

Illawarra Metallurgical Coal (IMC), a subsidiary of South32, extract primarily coking coal at Dendrobium Mine in the Southern Coalfield of NSW. The mine is located approximately 70 km southwest of Sydney and 12 km west of Wollongong. **Figure 1-1** shows the location of Dendrobium Mine, and illustrates that the mine extends from the Illawarra Escarpment to the west under the Metropolitan Special Area (water supply catchment) managed by WaterNSW.

IMC extract coal from the Wongawilli Seam by longwall mining and since 2005 have extracted 18 longwalls at Dendrobium from Areas 1, 2, 3A and the recently completed Area 3B domain.

IMC is seeking Department of Planning and Environment (DPE) approval to extract proposed Longwall 19A within Area 3A. IMC is required to prepare a Subsidence Management Plan (SMP) outlining the potential impacts that may occur to environmental and water supply features of significance within and near to Longwall 19A (Section 1.5). Watershed HydroGeo ("WatershedHG") was engaged by IMC to prepare an assessment of groundwater-related impacts to inform the SMP application.

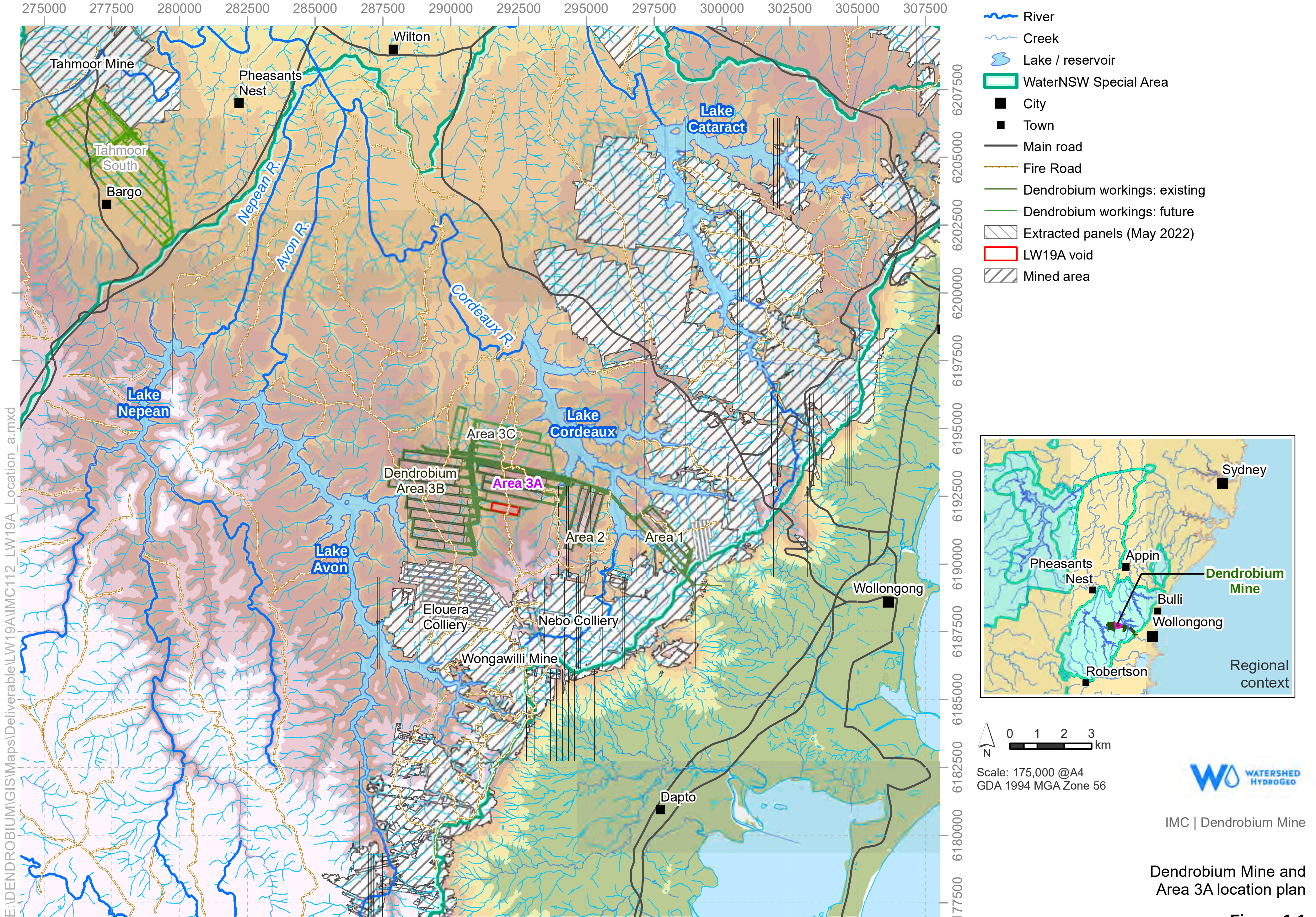
This assessment is provided to meet the requirements of the Dendrobium Development Consent, Condition 7(e), Schedule 3. This current document has been updated with recent data (e.g. investigation of geological structures, groundwater levels and inflow data, surface water losses) and with an updated conceptual model.

1.1 Dendrobium Mine: historical operations

IMC has carried out longwall mining at Dendrobium Mine since 2005 (**Table 1-1**). **Figure 1-2** shows the location of the Dendrobium mining areas including longwalls, location of watercourses and water supply reservoirs. In order of when they were mined, and also from east to west (moving inland from the escarpment):

- Area 1: Longwalls 1 and 2 extracted between 2005 and 2007.
- Area 2: Longwalls 3, 4, and 5 completed between 2007 and 2009.
- Area 3A: Longwalls 6, 7 and 8 extracted between 2010 and 2012. Longwall 19 has SMP approval and commenced 20 June 2022.
- Area 3B: Ten longwalls (Longwalls 9, 10, 11, 12, 13, 14, 15, 16, 17 and 18) completed between 2012 and 2022.

All historical and proposed extraction in Areas 1, 2, 3A, 3B and 3C is from the Wongawilli Coal seam. Longwall dimensions, being panel or void widths and seam cutting heights increased from Area 1 to Area 3B (**Table 1-1**). Maximum cutting heights were approximately 3.7 m in Area 1, and up to 3.9 m in Areas 2 and 3A. Area 3B longwalls up to Longwall 13 had maximum cutting heights between 3.95 and 4.5 m. SMP approvals required that Longwalls 14 to 18 must have a maximum cutting height of no more than 3.9 m.



WATERSHED HYDROGEO

IMC | Dendrobium Mine

Dendrobium Mine and Area 3A location plan

Figure 1-1

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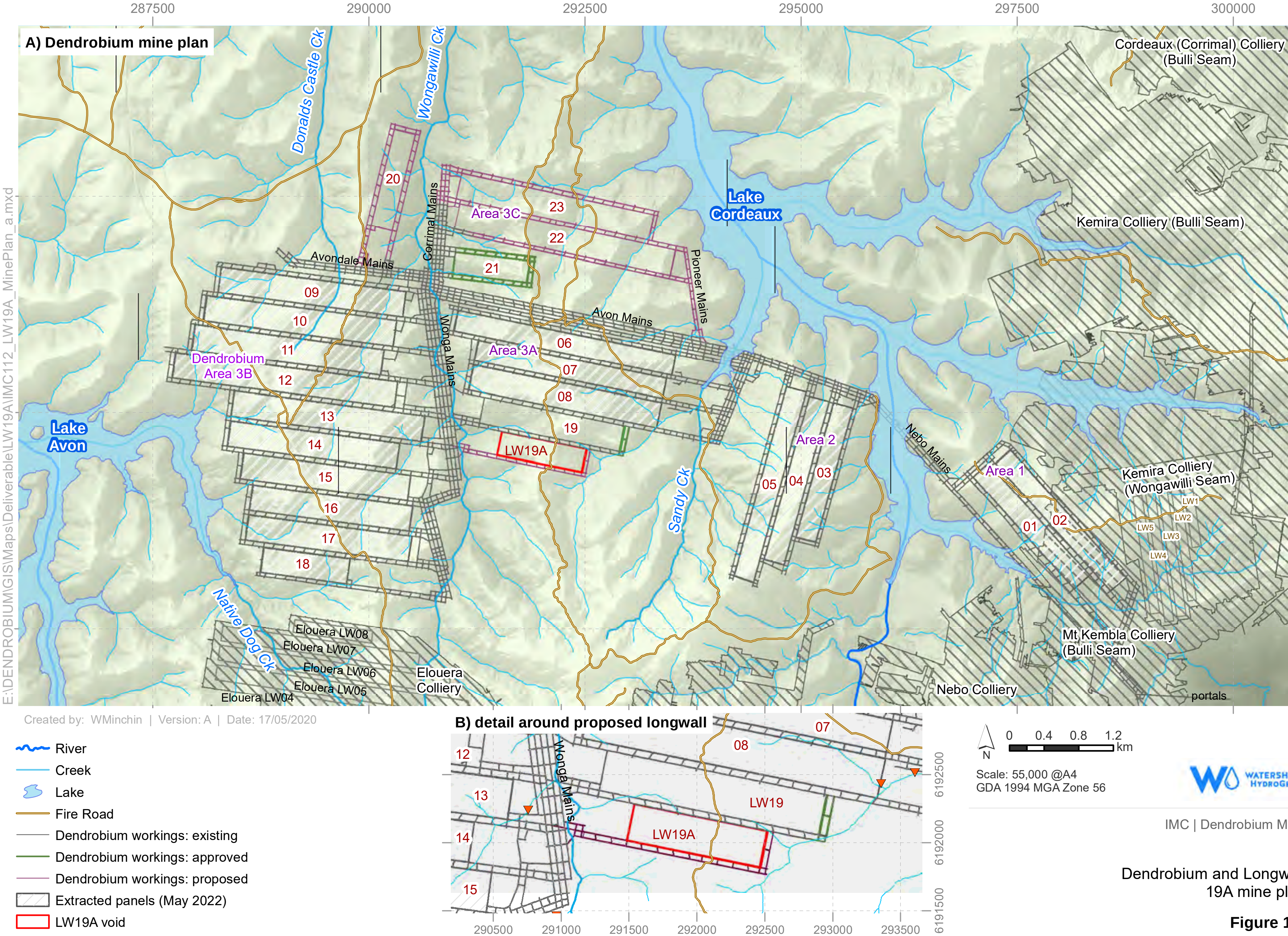

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River
Creek
Lake
Fire Road
Dendrobium workings: existing
Dendrobium workings: approved
Dendrobium workings: proposed
Extracted panels (May 2022)
LW19A void
Mined area

N
0 0.4 0.8 1.2 km

Scale: 55,000 @A4
GDA 1994 MGA Zone 56

WATERSHED HYDROGEO

IMC | Dendrobium Mine

Dendrobium and Longwall 19A mine plan

Figure 1-2

Table 1-1 Historical and Proposed Longwall Dates and Dimensions

Mine Domain	Long-wall	Status	Date		Days	Panel Length [m]	Width [m]		Cutting height [m]		Depth of Cover [m]		
			Start	End			Panel	Void	Mean	Max	Min	Mean	Max
1	1	Historical	30/03/2005	15/12/2005	261	1750	237	247	3.2	3.7	170	262	316
1	2	Historical	09/02/2006	22/01/2007	348	2000	237	247	3.24	3.70	162	264	320
2	3	Historical	30/03/2007	22/11/2007	238	1560	235	245	3.34	3.66	138	211	282
2	4	Historical	17/12/2007	30/09/2008	289	1950	235	245	3.65	3.75	159	249	310
2	5	Historical	04/12/2008	18/12/2009	380	2300	235	245	3.57	3.80	213	252	293
3A	6	Historical	09/02/2010	28/03/2011	413	2610	238.5	248.5	3.7	3.90	287	345	389
3A	7	Historical	04/05/2011	23/01/2012	265	2220	238.5	248.5	3.46	3.60	288	338	379
3A	8	Historical	24/02/2012	29/12/2012	310	2220	295	305	3.38	3.50	261	321	373
3B	9	Historical	09/02/2013	02/06/2014	479	2150	295	305	3.45	3.70	314	381	409
3B	10	Historical	20/01/2014	20/01/2015	366	2200	295	305	3.93	4.50	325	383	406
3B	11	Historical	18/02/2015	05/01/2016	322	2190	295	305	3.86	3.95	327	381	404
3B	12	Historical	22/01/2016	31/01/2017	377	2590	295	305	3.93	3.95	329	376	404
3B	13	Historical	04/03/2017	19/04/2018	411	2210	295	305	3.86	3.95	299	375	400
3B	14	Historical	22/05/2018	26/02/2019	223	1980	295	305	3.89	3.90	325	378	395
3B	15	Historical	08/04/2019	22/01/2020	243	1963	295	305	3.89	3.90	324	370	390
3B	16	Historical	20/02/2020	04/11/2020	244	1874	295	305	3.89	3.90	280	350	390
3B	17	Historical	12/12/2020	13/10/2021	305	2014	295	305		3.9	279	345	385
3B	18	Historical	02/12/2021	17/05/2022	166	1018	295	305		3.9	300	332	370
3A	19	Approved	20/06/2022	*Jan-2023	220	1500	295	305	~3.7 likely	3.9	287	331	369
3C	21	Approved	*Feb-2023	*Jun-2023	100	872	245	256	~3.7	3.9	310	340	382
3A	19A	Proposed	*Jul-2023	*Feb-2024	230	994	295	305	~3.9	3.9	290	320	350
3C	22	Approval sought	*May-2024	*Apr-2026	700	2561	295	305		3.9	305	345	380
3C	23	Approval sought	*Jun-2026	*May-2027	300	2283	295	305		3.9	290	340	395
3C	20	Proposed	*Jun-2027	*Dec-2027	183	1154	245	256		3.9	338	340	405

Dimensions are all in metres [m]. * proposed start and end dates.

1.2 Dendrobium Mine: approved and proposed mining

Proposed longwall extraction within Area 3A and 3C (**Figure 1-2**) that is relevant to this SMP application are outlined in the following sections.

1.2.1 Area 3A (Longwall 19)

Longwall 19 is planned to be 305 m wide (**Table 1-1**) consistent with Longwall 8 and all longwalls in Area 3B. Cutting heights would be similar to recent panels, with a maximum of 3.9 m as stipulated in the conditions of approval for Area 3B Longwalls 14 to 18 and Area 3A Longwall 19.

The likely effects of this longwall on the groundwater system were described in SLR (2020a). SMP approval for this panel was provided by DPE in March 2021, although it was shortened by 100 m at its eastern (commencing) end.

1.2.2 Area 3C (Longwalls 20 to 23)

Longwalls 20 and 21 are proposed to be 256 m wide (**Table 1-1**) and are narrower than Area 3B panels. Cutting heights would be similar to recent panels, with a maximum of 3.9 m in accordance with Schedule 3, Condition 5 of the SMP Approval for Area 3C.

The potential effects of these longwalls on the groundwater system were described in HydroSimulations (HS) (2019c). Longwall 21 has been granted SMP approval by DPE, while further groundwater modelling and assessment was requested by DPE prior to further consideration of Longwall 20.

IMC has sought SMP approval for Longwalls 22 and 23. **Figure 1-2** shows the location of these panels. They are distant from WaterNSW's reservoirs, being at least 1.5 km from Lake Cordeaux and 2.9 km from Lake Avon and are therefore outside of Dams Safety NSW Notification Areas.

Cutting heights for Longwalls 22 and 23 would be similar to recent panels, with a maximum of 3.9 m in accordance with Schedule 3, Condition 5 of the SMP Approval for Area 3C.

1.2.3 Area 3A (Longwall 19A)

Longwall 19A is proposed to be 305 m wide (**Table 1-1**) consistent with Longwalls 8 and 19 (Area 3A), and longwalls in Area 3B. Maximum cutting height would be 3.9 m as per recent longwalls. As shown in MSEC's (2022) Subsidence Assessment, the thickness of the Wongawilli Seam is currently mapped as 3.4-3.65 m, being thinner at the eastern end and thicker at the western end of the panel. The assessment and modelling in this study relies on a cutting height of 3.9 m, which is therefore likely to be an overestimate compared to the cutting height in reality, and so conservative with respect to fracturing and deformation.

This longwall is outside the Dam Safety reservoir Notification Areas, being located 1.5 km or more from Cordeaux Reservoir and more than 3 km from Avon Reservoir.

There are no historical workings overlying Longwall 19A. Longwall 19A would be 2.4 km northeast of old workings at Elouera Colliery and a similar distance north of Nebo Colliery workings (Section 1.3).

1.3 Mining in the Southern Coalfield

There is a long history of coal mining in the Southern Coalfield, especially along the escarpment to the north-east, east and south of Dendrobium (**Figure 1-1**). Historical and contemporary workings in the Wongawilli Coal seam are located to the south at Elouera and Nebo (merged as part of 'Wongawilli

Mine'), and to the east at Kemira. The Bulli Coal seam has been mined at Mt Kembla, partially overlying and east of Dendrobium Area 1.

1.4 Framework for water management

Water use in NSW is managed by the Department of Planning, Industry and Environment-Water (DPE-Water) and Natural Resources Access Regulator (NRAR) and regulated via Water Sharing Plans (WSP). Surface water in the area around Dendrobium is managed under the *Greater Metropolitan Region Unregulated River Water Sources WSP* (DPI Water, 2016).

Dendrobium Mine is located within Management Zone 2 of the Nepean Sandstone Groundwater Source of the *Greater Metropolitan Region Groundwater Sources WSP* (NSW Office of Water, 2011). This groundwater source is classified as 'Highly Productive' by DPE-Water.

1.5 Scope of works

This assessment provides information about potential groundwater behaviour in response to longwall extraction and associated subsidence for consideration by DPE in the assessment of the SMP. This assessment focuses on the potential impacts of Longwall 19A on groundwater, watercourses and reservoirs. The cumulative effects of all relevant operations at Dendrobium as well as those from neighbouring operations, in terms of historical and future effects, are considered.

The assessment must meet requirements from a number of sources:

- NSW Aquifer Interference Policy 2012 ('AIP').
- Recommendations for licensing under the *Water Management Act 2000*.
- Estimates of loss from water supply reservoirs for Dams Safety NSW.
- Conditions of Approval set by DPE; and
- Recommendations made by other agencies or advisory groups, including the Independent Advisory Panel for Underground Mining (IAPUM) and its predecessors.

Details of recent Conditions of Approval and SMP requirements are tabulated in Section 1.5.1, including a reference to where these are addressed in this document. Comments and recommendations from advisory panels and other agencies are summarised in Section 1.5.2. Section 1.5.3 outlines the structure of the document as a whole.

As in previous groundwater assessments for Dendrobium Mine, numerical modelling is used here to inform IMC and regulators about the potential effects and impacts that longwall mining has or may have on water features around Dendrobium. Groundwater modelling for Dendrobium was initially completed in 2007 and has advanced, both in terms of complexity and the requirements, through the modelling of Areas 3A, 3B and 3C.

The groundwater model was most recently revised for the *Dendrobium Mine Extension Project EIS* which proposed mining in Area 5 (Watershed HydroGeo, 2022). A slightly updated version of that model, developed by WatershedHG and incorporating recent weather data and mining progression is presented in this report (Section 5).

1.5.1 Assessment requirements

The Dendrobium Development Consent DA 60-03-2001 was granted by the NSW Minister for Planning in 2008. **Table 1-2** outlines the conditions from Schedule 3 of that document that are relevant to groundwater and identifies where in this report they are addressed.

Table 1-2 Development Consent Conditions and requirements relevant to groundwater

Condition		Detail	Where dealt with
Schedule 3			
Watercourse Impact Management			
2	The Applicant shall ensure that underground mining operations do not cause subsidence impacts at Sandy Creek and Wongawilli Creek other than "minor impacts" to the satisfaction of the Secretary.	"Minor Impacts" refer to minor fracturing, gas release, iron staining and minor impacts on water flows, water levels and water quality.	Predictions of surface water losses in watercourses (surface water take) (Section 7.4.6).
3	The Applicant shall ensure the development does not result in reduction (other than negligible reduction) in the quality or quantity of surface water or groundwater inflows to Lake Cordeaux or Lake Avon or surface water inflow to the Cordeaux River at its confluence with Wongawilli Creek, to the satisfaction of the Secretary.		Predictions of relevant effects: ‣ Avon and Cordeaux leakage (Section 7.4.4); ‣ Lake Cordeaux leakage (Section 7.4.4); ‣ loss from watercourses (surface water take) (Section 7.4.6); and ‣ losses from water supply catchments (Sections 7.4.7).
Groundwater Monitoring Program			
13	The SMPs prepared under condition 7 must include a Groundwater Monitoring Program, which must include:	(a) proposals to develop a detailed regional and local groundwater model, with special reference to flows to and from nearby water storages;	Regional model is presented in Sections 5 to 7. Local modelling not relevant to Longwall 19A.
		(b) detailed baseline data to benchmark the natural variation in groundwater levels, yield and quality;	SLR 2020b presents groundwater monitoring plan.
		(c) groundwater impact assessment criteria;	Assessment criteria outlined in Sections 1.4 and 1.5.
		(d) a program to monitor the impact of the development on: ‣ groundwater levels, yield and quality (particularly any potential loss of flow to, or flow from, WaterNSW water storages); ‣ coal seam aquifers and overlying aquifers; and ‣ groundwater springs and seeps.	SLR 2020b presents groundwater modelling plan. Loss from water storages not relevant to Longwall 19A due to the distance between reservoirs and the proposed longwall.
		(d) provide adequate water table contour plots, drawdown plots and pore pressure vertical section plots for predicted and observed conditions;	Modelled groundwater levels and pressures presented in Sections 6.4 and 7.3.
		(e) take into consideration the findings of any independent report on groundwater commissioned by the Department, or advice from the Independent Expert Panel [or similar], and the report required under condition 19(c) of this approval; and	Refer to Section 1.5.2.
		(f) be peer reviewed by a suitably qualified, experienced and independent expert, who is approved by the Secretary.	Dendrobium groundwater model reviewed in 2022 by Brian Barnett (Jacobs).

Additional requirements have been set via the SMP Approval for Area 3A (latest of which dated 11/03/2021). Those relevant to this groundwater assessment are set out in **Table 1-3**.

Table 1-3 Area 3A Longwall 19 SMP requirements relevant to Groundwater Assessments (11/03/2021)

Condition		Detail	Where dealt with
Schedule 3			
General Conditions			
6	The Applicant must not extract the coal seam in Longwall 19 to a height greater than 3.9 metres, subject to approval from the NSW Resources Regulator to extract a greater height for identified mine safety reasons.		A similar maximum cutting height would apply to Longwall 19A (1.2.3).
7	The Applicant must ensure that the installation road for Longwall 19 is set back at least 100 metres to the west from the location shown in Appendix 1 and in accordance with Appendix 2.		The mine plan for Longwall 19 is such that the void is >60 m from the main body of Swamp 15A along tributary SC10 (HGEO, 2022a).
8	Performance Measures	Minor impacts and environmental consequences… to Wongawilli Creek and Sandy Creek, including • *minor* impacts on water flows, water levels and water quality.	Risks to Wongawilli Creek from Longwall 19A are described empirically in Section 4.3. Model predictions of effects on flow described in Section 7.4.6. Water quality effects described in HGEO (2022a).

1.5.2 Summary of independent advice to regulators

IEPMC and IAPUM advice regarding Area 3B and 3C groundwater modelling has been incorporated by DPE into various conditions, as well as considered by WatershedHG in assessment and modelling.

In the IEPMC's updated and extended reports (IEPMC, 2019a and 2019b) a number of issues regarding groundwater modelling were raised, as outlined in **Table 1-4**.

Table 1-4 Summary of IEPMC (2019a,b) recommendations

IEPMC recommendation			Response	Reference
p.35	2.3.4	There is a need to consider the ability of geological structures to transmit effects over distance beyond the angle of draw, e.g. as noted at Springvale Mine. WaterNSW (2021) also noted "Inadequate consideration of lineaments impacts" on watercourses, swamps and reservoirs in the Longwall 22-23 SMP assessments.	This effect not yet observed at Dendrobium. To date, impacts at Dendrobium on swamp piezometers have been limited to those within 60 m, and at other shallow piezometers within 120 m of panels ((Watershed HydroGeo, 2019b, 2021b). HGEO (2020i) note that anomalous drawdown responses are not correlated with mapped structures.	Mapped geological structure in Section 2.5.1. Differences between lineaments at Springvale and those at Dendrobium documented in MSEC (2019) and SRK (2020).
p.47	para 3	The Panel foresees that faulting, basal shear planes, lineaments and the potential to unclamp and reactivate fault planes will need to be very carefully considered.	IMC have been investigating the geological structures in Area 3B and exploration and knowledge of structures in Areas 3A and 3C is expanding. Valley closure/basal shears are accounted for in modelling around the deeper valleys near longwalls.	Section 2.5.1 presents discussion of geological structures around Longwall 19A. Modelling of off-goaf effects in Section 5.4.4.
Groundwater impacts at Dendrobium Mine				
p.91	6	Notwithstanding that uncertainty is associated with both the Tammetta and the Ditton height of complete drainage equations, it is recommended to err on the side of caution and defer to the Tammetta equation until field investigations quantify the height of complete drainage AND/OR geomechanical modelling of rock fracturing and fluid flow is utilised.	Further field investigations to understand fracturing and depressurisation above the goaf have been conducted and analysed. These have confirmed that deformation occurs through to the surface. However, recent evidence from independent lines of evidence supports the Ditton Geology model for estimating the extent of vertically connected fracturing Areas 3A and 3B.	Field investigations presented in Sections 2.6 and 3.6. Subsequent model representation of fracturing is presented in Section 5.4.
p.58	s4.3.1	"geomechanical modelling is generally restricted to two dimensions and the results translated into a three-dimensional groundwater flow model for separate (uncoupled) predictive purposes."	This update to the model does not rely on the geomechanical modelling by SCT, which was previously used in HydroSimulations (2019c). This study has concentrated on constraining the model, where possible, using the recently acquired field data.	Field investigations in Sections 2.6 and 3.6. Model representation in Section 5.4.
	8	Groundwater models should: i. continue to be updated ii. be migrated from MODFLOW-SURFACT to MODFLOW-USG only if significant benefits can be demonstrated iii. be underpinned by unified material properties (for common stratigraphic layers) unless differences can be demonstrated to exist through measurements.	i) the model has been updated numerous times, with additional layering, parameters and methods for deformation. ii) Since 2015, MODFLOW-USG-Transport (Section 5.2.1) has become industry-standard software, even being recommended for use by DPE-Water. iii) Differences in material properties may exist between the two sites identified by IEPMC. The parameters of this model rely on the extensive Dendrobium packer test dataset, as well as considering data from other Southern Coalfield sites.	Updates to the model are described in Section 5. Further details on model development and evolution is described through Coffey (2012), HydroSimulations (2014, 2016, 2018, 2019a, 2019b, 2019c), SLR (2020), (Watershed HydroGeo, 2020, 2022) and **Appendix B**.

Surface water impacts at Dendrobium Mine				
p.119	17	ii. installation of weirs and/or flumes at selected sites agreed by WaterNSW and the Dendrobium Mine. ... sites should… include catchments …potentially affected by [future longwalls].	New surface water monitoring sites have been installed.	Section 2.4.1.
	17	iv. additional basal shear monitoring, implemented as a priority between the Avon Dam and LW 14 to 18 before mining commences. The sites should be designed to complement the … strategy (geotechnical and groundwater) at S2313 and S2314.	Aside from S2313 and S2314, new monitoring holes installed between Area 3B and Lake Avon, including S2376, S2377, S2378, S2379, S2435, S2436. Work by HGEO (2019b) and SCT (2017, 2019a) has been reviewed for this assessment.	See network of "Avon monitoring" sites on Figure 3-2. Data from these sites are used to inform scenarios (Section 7.2).

Recommendations and comments have also been received from the IAPUM, who effectively succeed the IEPMC, on Longwall 18, Longwall 19 and Longwall 22 and 23 SMP Groundwater Assessments. A summary of the key comments and responses is presented in **Table 1-5**.

Table 1-5 Summary of IAPUM comments on recent Dendrobium SMPs

IAPUM comment			Response	Reference
LW19-p.23	1	All post mining groundwater rebound data are based on an incorrect conceptual model that is not connected adequately to the expected mine closure plan for the mining complex and cannot therefore be relied on for determination of the long term conditions across the catchment.	The groundwater modelling presented in the recent DMEP EIS (Watershed HydroGeo, 2022) and in this study is consistent with the Closure Concept Plan , including: • extremely high hydraulic conductivity roadways to simulate free drainage; and • model cells at the location of the modulating bulkheads that that simulate material with an average or effective permeability similar to that of undisturbed coal. As a result, simulated long-term groundwater conditions are consistent with the proposed closure methods.	Closure Concept Plan and Sections 4.3 and 5.3.7.
LW22-23 – p.1	1	The Panel is concerned that the long-term groundwater conditions may still not be adequately represented by the modelling outputs.		
LW19-p.24	2	The modelled near surface groundwater conditions appear to produce depths to water that are too small when compared to the available shallow groundwater observations away from the streams and that this affects the estimates of the groundwater recharge above the longwalls. While the result is almost certainly conservative for mine inflows it is likely to produce model results for the near surface hydrology that are not reliable.	Modelled water table elevation along the interfluves (away from creeks) are compared to shallow observations in Appendix F. Not all multi-piezo sites in the Appendix have shallow <10 or <15 m piezometers, but the following sites do: • bores S1830, S1870, S1885, S1930, S1932, S2377, S1969, S2373, each of which show a good representation of water table elevation and depth. • bores S1892, S2194, which have water table at greater depth observed, with the modelled regolith layer frequently de-saturating.	**Appendix F**

LW19-p.24	3	Vertical hydraulic conductivities are based on lower bound estimates from core scale data and could be biasing the assessment deep percolation of water through the different geological formations.	Model vertical hydraulic conductivity (Kv) parameters compare well against harmonic mean of packer test results (Section 3.5.1) and with core testing results, and are similar in magnitude to parameters from elsewhere in the Sydney Basin, e.g. Table 4 of Mackie (2009).	Sections 3.5.1 and 6.2.
LW19-p.24	4	Sensitivity testing is based on large scale changes to regional hydraulic properties, but there is a need to adopt a more targeted approach to sensitivity testing that looks at a wider range of possible conditions so that a clearer assessment of the uncertainties in the model can be made.	Simulation of groundwater levels and drawdown have been improved since the Longwall 19 modelling. The model is shown to be an appropriate tool for estimating surface water losses, and methods to account for sources of uncertainty in those surface water losses have been implemented. Further investigation to improve the model is on-going.	
LW19-p.24	5	The presentation of much of the modelling output is at a spatial and temporal scale that is not appropriate for a reader to investigate specific features of the model results.	Figures (such as those in **Appendix G**) have been zoomed in, and with additional figures (e.g. Figure 7-1) to show more local-scale detail around the longwalls in question.	**Appendix G** and **Figure 7-1**
LW18-p.ii		IAPUM recommend "additional standpipe monitoring bores to be constructed adjacent to vibrating wire piezometers (VWP) to provide validation of VWP sensor data." DPIE-Water made this recommendation originally.	A set of open standpipe piezometers already exists at Dendrobium, and some additional such piezometers will be installed. A study to compare and assess these and VWP results has been commissioned by IMC.	
LW18-p.iii	8	For future mining areas groundwater TARPS and performance measures should be considered.	Recommendations for groundwater TARPs, focussed on two of the primary risk pathways, are presented. These will be reviewed once suitable baseline monitoring data is available.	Section 8.2.1

Recommendations previously incorporated from the DPE-commissioned study into the Height of Connected Fracturing (PSM, 2017) for SMP application groundwater assessments (e.g. (HydroSimulations, 2019; SLR, 2020; Watershed HydroGeo, 2020) have been described in detail in previous assessments. For brevity, this discussion has been removed. Most of those recommendations have been retained for the groundwater model utilised in this assessment, however some, such as those related to seam-to-surface connected fracturing are no longer applicable.

1.5.3 Report structure

The structure of this report is outlined in **Table 1-6**. This report presents a brief description of the relevant environmental features of the site (topography, climate and weather, geological setting) and an update of hydrogeological features and parameters. Further detail of the rainfall, evaporation, topography, geology, as well as detailed descriptions of the conceptual and previous numerical modelling is available from the following reports:

- Coffey, 2012a and 2012b;
- HydroSimulations (HS), 2014;
- HS, 2016a;
- HS, 2016b;
- HS, 2018;
- HS, 2019;
- SLR, 2020; and
- WatershedHG, 2020, 2021 and 2022.

Specific analysis of groundwater and surface water effects are provided in multiple End of Panel reports:

- Groundwater: e.g. HydroSimulations 2012-2016 and HGEO, 2017-2022; and
- Surface Water and Shallow Groundwater, e.g. HGEO, 2017-2022.

A summary of the above work and new field data, analysis and interpretation is presented, as well as changes to groundwater modelling and associated forecasts. A new section has been included (Section 10) that lists the key files/data source relied on in this report.

Table 1-6 Outline of report structure

Section	Title	Contents
1	Introduction	Description of operations and the proposal at the Dendrobium Mine and the scope of work.
2	Data analysis	Describes the environmental context for the area where Dendrobium Mine and the proposed longwall is located.
3	Hydrogeology	A summary and discussion of key facets of the groundwater system, including discussion of relevant points from agency and advisory panel comments.
4	Hydrogeological conceptual model	Summarises the data analysis and the conceptual model developed, which then leads to the design and operation of the numerical model in the following sections.
5	Numerical model development	Describes changes to the groundwater model to meet relevant conditions as well as other modifications.
6	Numerical model history-matching	Outlines the procedure and the results of model history-matching phase of work, focussing on observations and data that are most relevant to the predictions required.
7	Model forecasting	Presents output from the updated model, including predicted groundwater inflow, groundwater level and pressure hydrographs/maps/profiles, and incidental take from surface water features.
8	Conclusions	Summarises the assessment of Longwall 19A and Dendrobium Mine against relevant requirements. Recommendations regarding monitoring.
9	References	List of documents referred to in this report
10	Data Register	List of data sources (e.g. Excel, GIS format) relied upon for mapping, graphics and analysis.

2 Environmental context

The following sections describe the contextual setting and environmental features relevant to the groundwater system (Sections 3 and 4) and numerical modelling (Section 5) of the effects of Dendrobium Mine within that system.

2.1 Land use

Land above or surrounding Dendrobium longwall areas is mainly reserved as part of Sydney's drinking water supply catchments, WaterNSW's 'Special Areas', as shown on **Figure 1-1**. This includes the major reservoirs of the upper Nepean system (Section 2.4.2). These catchment areas are primarily native forest with some areas of swamp vegetation.

Cleared areas or urban areas are restricted to the coastal plain east of Dendrobium (such as the suburbs around Wollongong) or inland (west) of Dendrobium, e.g. Mt Kembla which is 8 km east of Longwall 19A, Yanderra and Bargo which are 15 and 18 km northwest of Longwall 19A, and Wilton which is approximately 17 km north of Longwall 19A.

Mining is present within (under) and outside of the Special Areas, as noted in Section 1.3.

2.2 Topography

Dendrobium Mine is located on the Woronora Plateau above or inland of the Illawarra Escarpment (**Figure 2-1**). The escarpment rises from the coastal plain around Wollongong to elevations greater than 400 mAHD around Dendrobium. On the plateau, topography generally slopes to the north or northwest, toward the centre of the Sydney Basin. The plateau is dissected with the larger valleys incised 50-100 m into the terrain, and these typically host the larger creeks, e.g. Wongawilli Creek, and rivers, e.g. Cordeaux River (Section 2.4), and the reservoirs (Section 2.4.2).

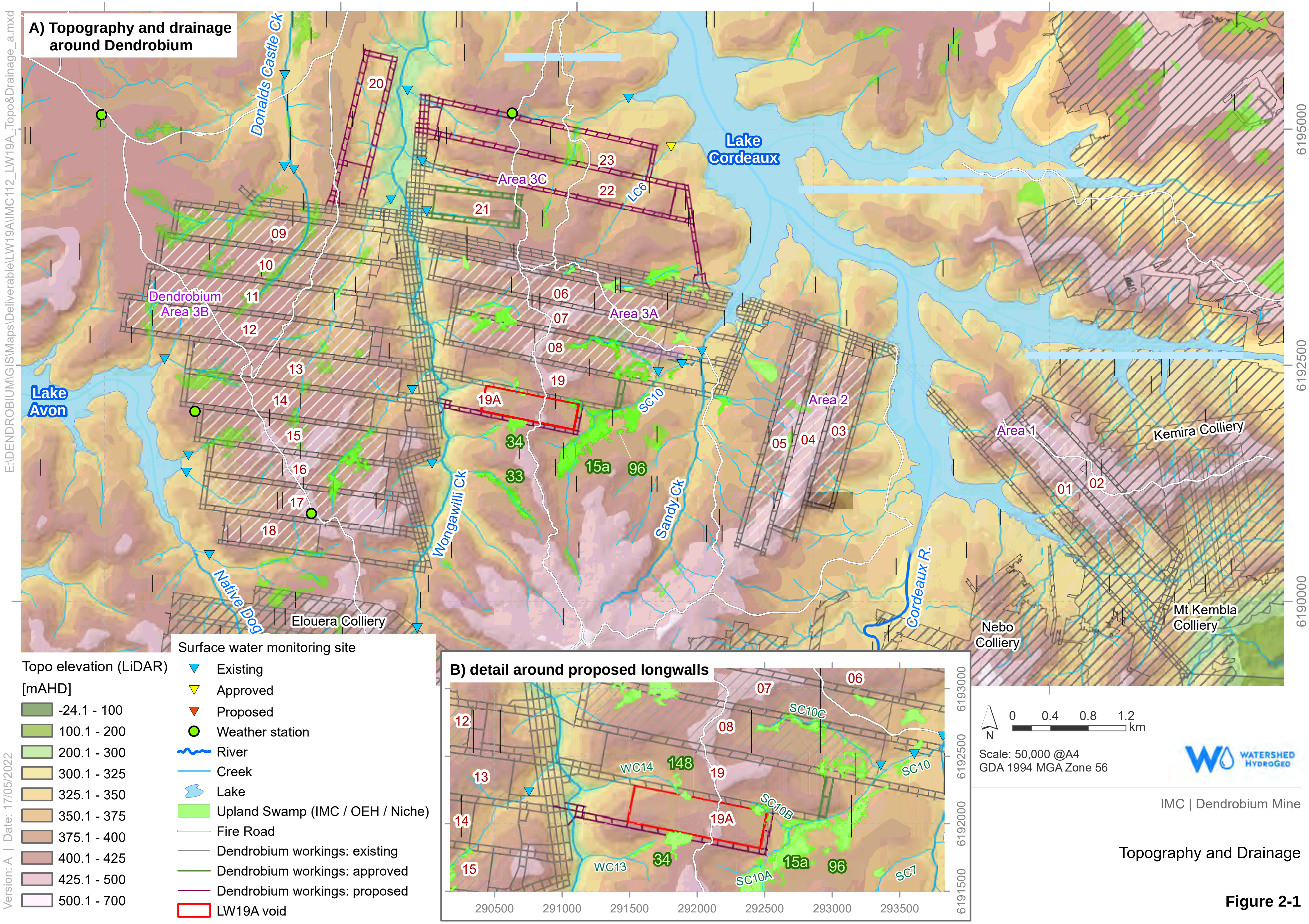
Within the footprint of Longwall 19A, ground elevation ranges between 349 mAHD (northwest corner) to 427 mAHD in the centre of the area, averaging about 390 mAHD. Topography declines to the east of Longwall 19A toward Sandy Creek (flowing north to Cordeaux Reservoir). Topography also declines to the west of Longwall 19A toward Wongawilli Creek.

The reach of Wongawilli Creek closest to Longwall 19A is at an elevation of 287 mAHD (south/upstream end) to 285 mAHD (north/downstream end). The Wongawilli Coal seam is at approximately 55 mAHD at the western end of Longwall 19A, meaning there is 230 m vertical separation (as well as horizontal separation).

2.3 Climate

2.3.1 Rainfall

IMC records daily rainfall at multiple stations around the site, and this is augmented through inspection of long-term averages and records obtained from the Bureau of Meteorology (BoM) and SILO. Average rainfall for the period 1961-1990 was about 1200-1400 mm/yr at Dendrobium. This compares with averages of 980-1090 mm/yr as recorded at the IMC stations for the period 2003-2020.

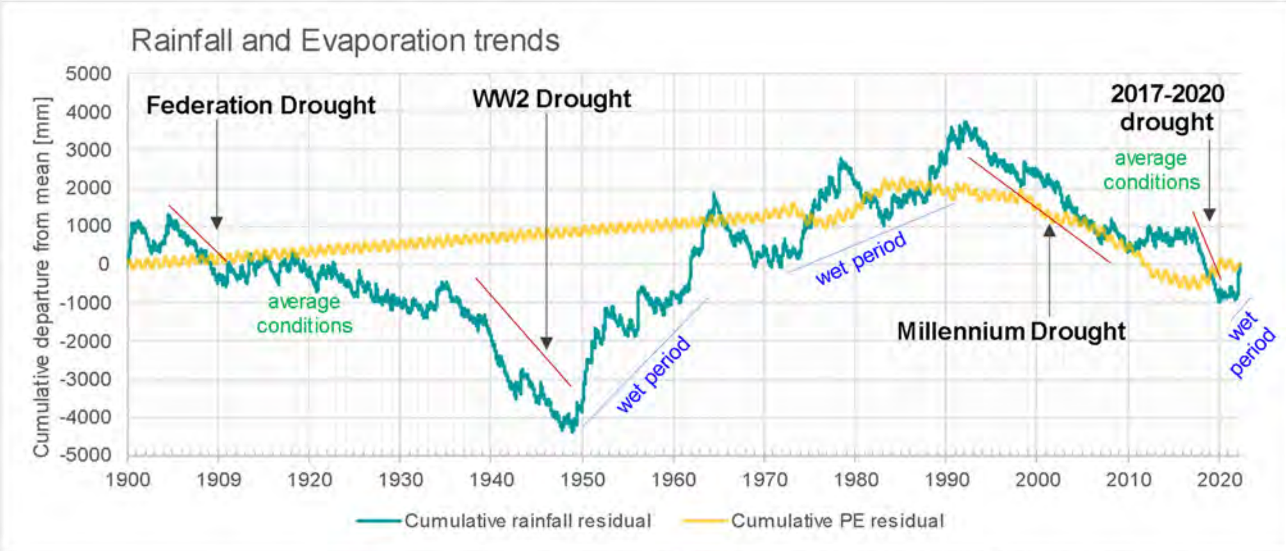


IMC | Dendrobium Mine

Topography and Drainage

Figure 2-1

A) long-term trends in rainfall and evaporation



E:\DENDROBIUM\Tech\Climate\[SILO_&_DEN_&_WaterNSW_Rain&EvapComparison_v4.xlsx]Summary

B) cumulative rainfall by year

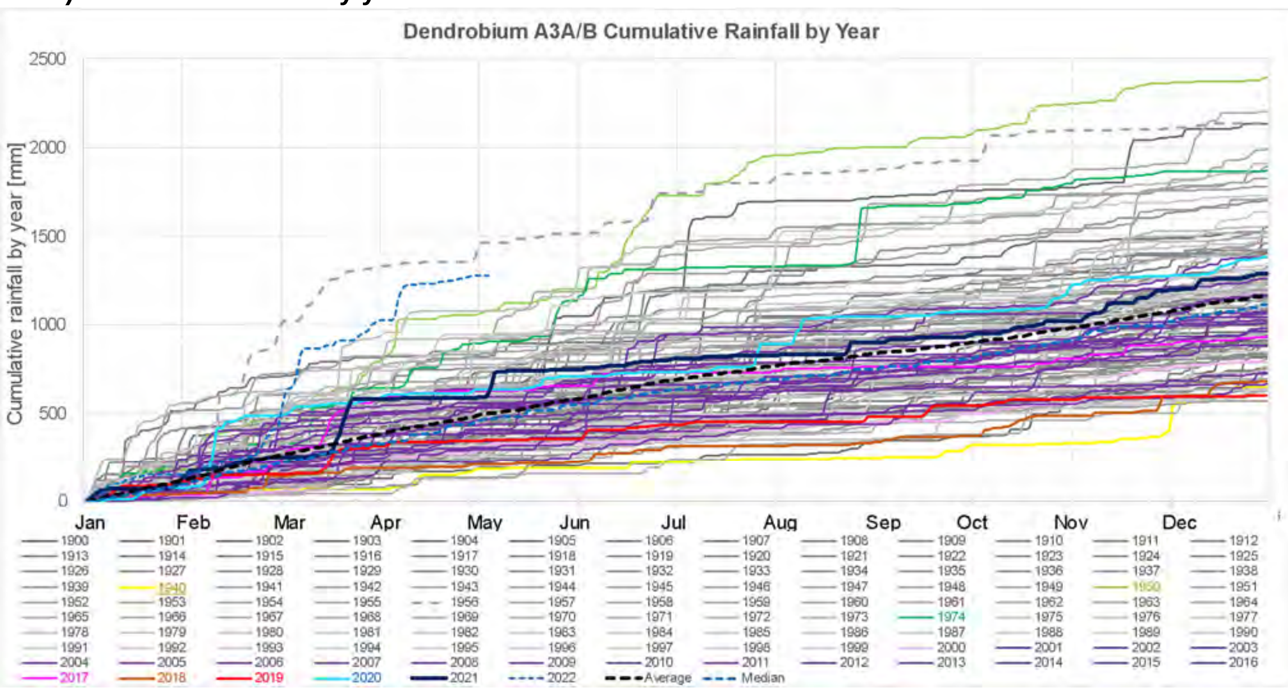


Figure 2-2 Rainfall and evaporation trends

Figure 2-2A shows long-term rainfall trends, as defined by the cumulative rainfall deficit curve. This shows the historical occurrence of wetter than average periods (upward trends) and dry periods (downward trends). **Figure 2-2B** shows cumulative rainfall for each year on record.

The low rainfall totals during the 2-3 years to February 2020 and the slope of the trend curve were indicative of rainfall deficits assessed by BoM as 'severe [rainfall] deficiency]' to 'lowest on record'. Based on the SILO data, 2020 was the 4th wettest year since 2000 (before the start of the Dendrobium Mine) and 9% higher than the average of all years 1900-2021. 2021 rainfall was average, while the first 5 months of 2022 are the wettest start to a year on record. Each of the years 2020, 2021 and 2022 included significant rainfall events, e.g. Feb-2020, Aug-2020, Mar-2021, Apr-2022.

This last point is highlighted on **Figure 2-2B**, which shows that 2022 (to date) is the second wettest year on record (after 1957), and both those years are considerably higher rainfall to May than all other years. Monthly rainfall totals in 2022 include February (250 mm), March (600 mm) and April (267 mm). For context, then annual total for 2019 was 607 mm, essentially the same as the March-2022 total.

2.3.2 Evaporation

Long-term average potential evaporation (PE) is approximately 1430 mm/yr at Dendrobium, and slightly higher at Wollongong on the coast (1520 mm/yr). Actual ET[1] at Dendrobium is approximately 920 mm/yr. During the recent 2017-20 drought, PE was up to 25% higher than is typical, exacerbating the effect of the rainfall deficits (**Figure 2-2A**). PE during 2020-22 (to date) has been slightly below average, reflective of the wetter conditions.

2.4 Drainage and hydrology

Around the Dendrobium Mine most of the local surface runoff is initially captured in the Cordeaux and Avon River catchments. These two catchments are dammed, forming lakes for water supply storage (Section 2.4.2). Regional drainage is to the north-northwest, toward the Nepean River.

The significant watercourses around Area 3A are (**Figure 2-1**):

- Sandy Creek flows north between Areas 2 and 3A toward Cordeaux Reservoir, with tributaries flowing the areas above Longwalls 7, 8, 9 and 19A. The main channel is 1,200 m or more east of the commencing end of Longwall 19A.
- Wongawilli Creek, which flows north from above Elouera Colliery and between Dendrobium Areas 3A and 3B, and then past Area 3C to Cordeaux River. The creek is typically 400-550 m west of Longwall 19A (the thalweg of the creek is 400 m from the finishing end of Longwall 19A, respectively, at its closest point). This is slightly further than Longwall 19 (200-340 m) and Longwall 8 (170-450 m). Recent Area 3B panels are typically 300-600 m from the creek.

Multiple tributaries to these watercourses and to the reservoirs are identified immediately around Longwall 19A (**Figure 2-1**).

Tributary SC10 flows into Sandy Creek to the northeast of Longwalls 19A and 19. At its closest point, SC10 would be 77 m to the east of the commencing end of Longwall 19A, and typically 150-200 m to the east. Minor tributary SC10B flows above the pillars between Longwall 19 and 19A, while tributary SC10A is located 130-180 m to the south of Longwall 19A.

WC13 and WC14 are tributaries to Wongawilli Creek. WC13's channel is mapped as starting 85 m to the south of Longwall 19A. WC14 starts above the northern edge of Longwall 19A, flowing north and then west over Longwall 19. Approximately 10 m of its length is above the void of Longwall 19A, 70 m of its length is above the pillar between Longwalls 19A and 19, and approximately 320 m above Longwall 19.

Waterfall WF54 (on Wongawilli Creek) is located more than 1,700 m to the south of Longwall 19A. Sandy Creek waterfall (SC-WF1) is located 1,400m northeast of Longwall 19A. As a result, neither of these features are likely to be affected by Longwall 19A.

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[1] 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.

2.4.1 Monitoring

IMC has been monitoring stream level and flow around Areas 3A and 3B since late 2007. HGEO (2022a) [in-prep] has more detail on surface water monitoring around Area 3A. Monitoring sites are shown in **Figure 2-1**. Of note are recently installed gauging stations near to Areas 3A and 3C:

- WC20S1 on WC20: was installed 07/12/2021, but no data has yet been collected due to catchment access restrictions (related to wet weather).
- LC5S1 on LC5: commenced monitoring 4/04/2019.
- LC6S1 on LC6: is approved, but not yet installed.

It is important to note with respect to likely effects of Longwalls 19 and 19A, improvements to the gauging site at SC10S1 were commenced in 2021 in advance of Longwall 19 extraction. This included modification of the natural control to allow installation of a half-pipe flume. Subsequent COVID restrictions followed by a period of sustained wet weather (Section 2.3.1) have meant that the upgrade of this site has not been completed, and is unlikely to be completed until after the commencement of Longwall 19, and so may affect the ability to quantify changes in stream flow at this site. This has been communicated to WaterNSW (June 2022).

We note also that there have been issues gathering data at Dendrobium and WaterNSW sites during 2022, with continued wet conditions reducing access and also causing problems with loggers and infrastructure. The reporting here uses the best available data to June 2022.

2.4.2 Reservoirs

Avon and Cordeaux Reservoirs are water supply reservoirs formed by the damming of the upper Avon and Cordeaux Rivers, and form part of the Upper Nepean Scheme, along with Nepean and Cataract Reservoirs, which are located further from Dendrobium. Relevant details are presented in **Table 2-1**. On later charts, and in modelling, historical records of 'stage' (reservoir water level) are used for comparison against groundwater levels.

Table 2-1 Water supply reservoirs near Dendrobium

Reservoir	Area (sq.km)	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 and Bald Hill Claystone

Sources: http://www.waternsw.com.au/supply/visit/. FSL = full supply level. Lake bed bathymetry data from WaterNSW.

FSL is essentially the highest lake stage that the reservoir can fill to before spilling over the dam wall.

At their nearest points (north-eastern corners respectively), Longwall 19A is proposed to be 1,500 m from the Cordeaux Reservoir FSL, and on the other side of four longwalls (three already extracted, plus Longwall 19 which is due for extraction in 2022). Avon Reservoir is on the other side of the Area 3B mining domain and distant from Area 3A, i.e. over 3 km from Longwall 19A.

Surrounding shallow groundwater levels are typically higher in elevation, resulting in groundwater discharging to the lake (HS, 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.

2.5 Geology

The Southern Coalfield is part of the Sydney Basin. Outcrop mapping is based on the Southern Coalfield Regional 1:100,000 Geology Map (Moffitt, 1999) as well as site specific data. 3D mapping of geology is based on IMC's geological model, derived from exploration data and outcrop mapping. IMC geologists have investigated the geological structures within the footprint of proposed Longwall 19A, as described in IMC (2022).

2.5.1 Structural features

Regional structure, as mapped by Moffitt (1999)[2], is presented on **Figure 2-3A**. Tonkin and Timms (2015) reviewed historical data on geological structures in the Southern Coalfield and their role in transmitting groundwater. The review found that >95% (1580/1660) of structures near reservoirs and underground workings were not associated with any groundwater flow, and 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 stress was found to typically close, not open, such structures and reduce the effective hydraulic conductivity. This was based on analysis of dyke and fault systems around Dendrobium.

The dip of the sedimentary strata in this area is predominantly to the north, with some westerly dip toward a regional south-to-north syncline located near Donalds Castle Creek (mapped as plunging to the north through Area 3B, and west of Area 3A).

Structures, typically faults and dykes and lineaments around Dendrobium Mine are mapped and characterised by IMC geologists. Those features around Area 3A are shown on **Figure 2-3B**.

As mining approaches an area, knowledge of local structure and geological conditions improve, however the roadway between Longwalls 19 and 19A has been developed, and a significant amount of inseam drilling has occurred. IMC geologists have provided a summary of structures relevant to Longwall 19A (Illawarra Metallurgical Coal, 2022).

The main structural features around Area 3A shown on **Figure 2-3B** are listed below, based on the information from IMC (2022). Lineaments detected at surface may reveal the presence of faults (IESC, 2021) or dykes. There is little by way of faulting, and more structures are related to the igneous activity that occurred to the south of Area 3A.

As mining approaches an area, knowledge of local structure and geological conditions improve, however the roadway between Longwalls 19 and 19A has been developed, and a significant amount of inseam drilling has occurred. IMC geologists have provided a summary of structures relevant to Longwall 19A (Illawarra Metallurgical Coal, 2022).

The main structural features around Area 3A shown on **Figure 2-3B** are listed below, based on the information from IMC (2022). Lineaments detected at surface may reveal the presence of faults (IESC, 2021) or dykes. There is little by way of faulting, and more structures are related to the igneous activity that occurred to the south of Area 3A.

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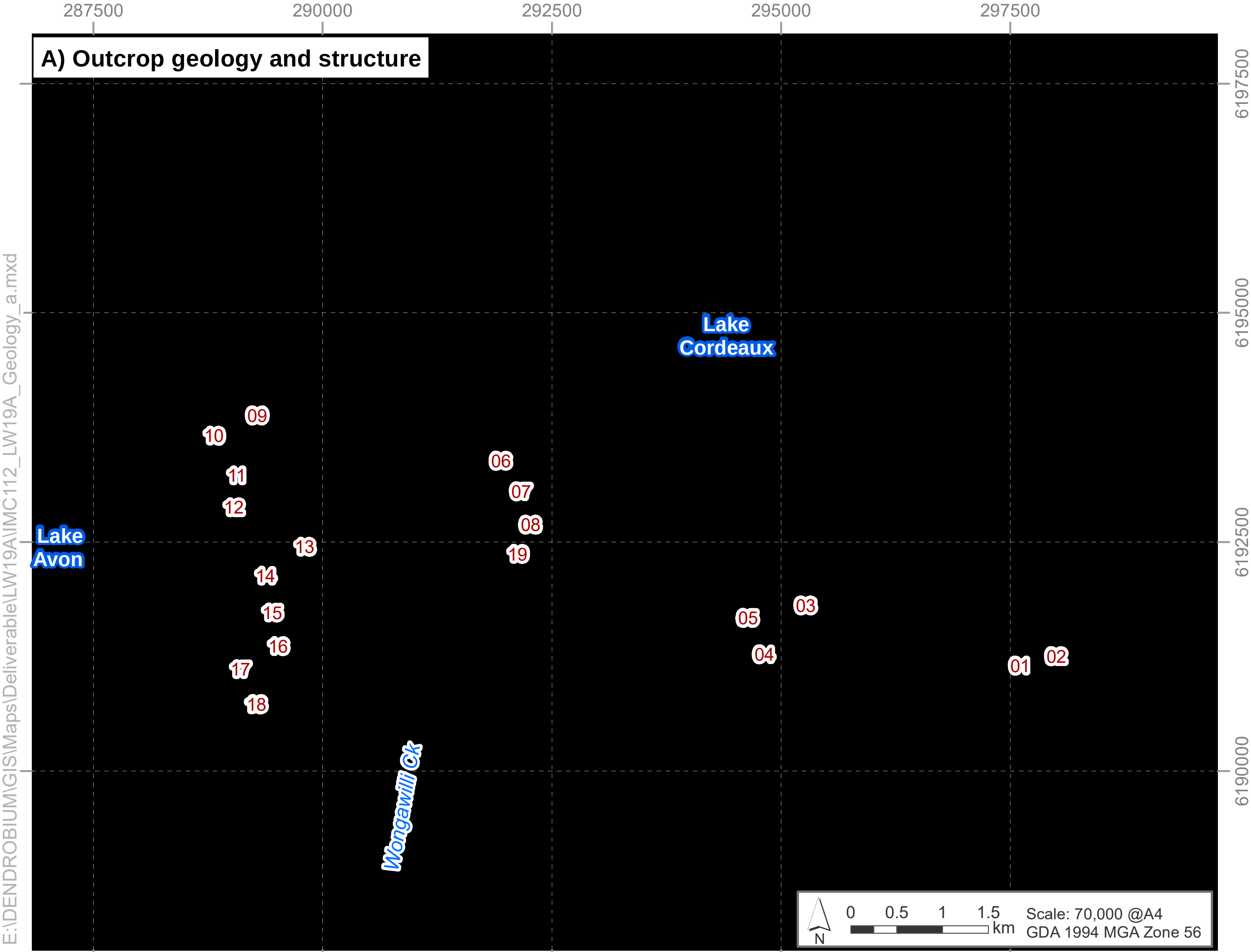
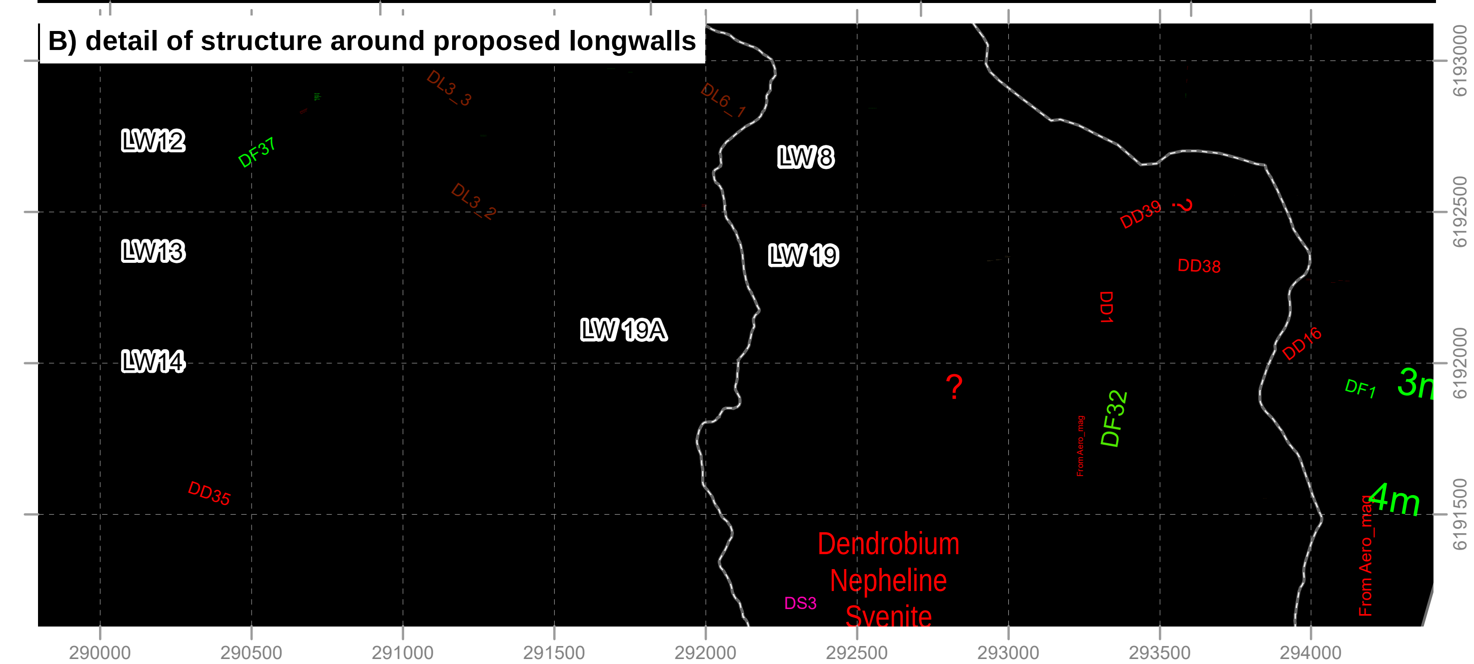
2 If necessary, refer to the original: www.resourcesandenergy.nsw.gov.au/__data/assets/image/0004/352858/Southern_Coalfield_regional_100K_Geology_Map_1st_ed_1999.jpg





Cordeaux Crinanite
Swamp deposit
Wianamatta Fm
HBSS (upper)
HBSS
HBSS (lower)
Bald Hill Claystone
Bulgo Sst (upper)
Bulgo Sst (lower)
Stanwell Park Clst
Scarborough Sst (upper)
Scarborough Sst (lower)
Wombarra Clst
Coalcliff Sst
Bulli Coal
Loddon / Lawrence Sst
Wongawilli Coal
lower Coal Measures
Shoalhaven Group

LW19A void
Southern CF: fault
Southern CF: fold
Southern CF: structure

Geological structure (IMC mapping)
Fault
Dyke
Lineament
Disturbed ground

Created by: WMinchin | Version: A | Date: 07/06/2022

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Geological setting

Figure 2-3

Structures in the vicinity of Longwall 19A are:

- Lineaments:
  - In this southern part of Area 3A there are few lineaments. The only one mapped near Longwall 19A is located approx. 200 m to the west of Longwall 19A.
- Dykes:
  - DD1: running south between Area 2 and 3A, and terminating in the eastern end of Longwall 8. This is 750 m east of Longwall 19A.
  - DD38: trending east-west, passing through Longwall 19, but were not identified in MG19 (roadway to immediate north of Longwall 19A) so are not expected to be present in Longwall 19A.
  - DD39: trending NNE-SSW, passing through Longwalls 8 and 19. As above, this was not detected in MG19, so is not expected to be present in Longwall 19A.
- Faults:
  - "DF32": there is a single fault mapped >850 m to the east of Longwall 19A.

IMC (2022) did not observe anomalous water make or other geological conditions in MG19.

Further discussion of the likely behaviour of these structures in relation to extraction of Longwall 19A is presented in Sections 4.2 and 4.3.

2.5.1.1 Lineaments

SRK (2020) assessed the presence of surface structures, including lineaments, and the role these might play in enhancing subsidence and environmental impacts around mining areas. SRK noted that the conditions at Dendrobium (Southern Coalfield) are different to those in the Western Coalfield (e.g. at Springvale Mine) where lineaments around mining areas enhanced subsidence, leading to the transmission of effects over hundreds of metres or a kilometre from Springvale workings.

SRK's conclusions, based on review of structural and historical subsidence data at Dendrobium, were that "*There is evidence of very minor displacement on discontinuous surface structures immediately above the mined areas*", and more significantly, "*no conclusive evidence … in the data to indicate movement on structures outside the mine areas*". Related to this last point, SRK noted that "*longwall mining activities to date at Dendrobium appear to have had little effect in the reactivation of surface lineaments. Very minor displacement on faults is evident… over Area 3B.*".

Similar behaviour is assumed for the neighbouring Area 3A domain.

2.5.2 Stratigraphy

The stratigraphy of the Southern Coalfield is Permo-Triassic sedimentary rock and is underlain by undifferentiated Carboniferous and Devonian aged sediments. The significant parts of the sequence are summarised in **Table 2-2**. The thicknesses reported are representative only.

The table includes abbreviations for the stratigraphic units which are often used on figures. The whole sequence comprises interlayered sandstone, claystone, siltstone, and, within the Permian strata, coal seams, to significant depth (>400-500 m). Within the Permian coal measures, the main coal seams of economic value are the Bulli and Wongawilli Coal seams. At Dendrobium, the lower part of the Wongawilli Coal is extracted. This 'working section' typically comprises plies from the basal ply ("WW12") up to and including either the "WW2M" or "WW2L" plies.

Table 2-2 Summary of the stratigraphic sequence

<table>
<tr><th>Period</th><th>Group</th><th>Sub-group</th><th colspan="2">Formation</th><th>Description</th><th>Typical thickness (m)</th></tr>
<tr><td colspan="3">Quaternary</td><td colspan="2">“Swamp” deposits</td><td>Sands, silts, organics and peat.</td><td>1-3</td></tr>
<tr><td rowspan="9">Triassic</td><td colspan="4">Hawkesbury Sandstone (HBSS)</td><td>Massive or thickly bedded quartzose sandstone with siltstone, claystone and grey shale lenses up to several metres thick (Bowman, 1974; Moffitt, 1999).</td><td><120</td></tr>
<tr><td rowspan="8">Narrabeen Group</td><td rowspan="2"></td><td colspan="2">Newport Formation (NPFM)</td><td>Fine-grained sandstone (less than 3 m thick) interbedded with light to dark grey, fine-grained sandstones, siltstones and minor claystones (Bowman, 1974).</td><td>10</td></tr>
<tr><td colspan="2">Garie Formation (GRFM)</td><td>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).</td><td>3</td></tr>
<tr><td rowspan="6">Clifton Subgroup</td><td colspan="2">Bald Hill Claystone (BHCS)</td><td>Massive chocolate coloured and cream pelletal claystones and mudstones, and occasional fine-grained channel sand units (Moffitt, 1999).</td><td>12-20</td></tr>
<tr><td rowspan="3">Colo Vale Sandstone (CVSS)</td><td>Bulgo Sandstone (BGSS)</td><td>Thickly bedded sandstone with intercalated siltstone and claystone bands up to 3m thick (Moffitt, 1999).</td><td>95</td></tr>
<tr><td>Stanwell Park Claystone (SPCS)</td><td>Red-green-grey shale and quartz sandstone (Moffitt, 1999; BHP Billiton, 2013).</td><td>20</td></tr>
<tr><td>Scarborough Sandstone (SBSS)</td><td>Quartz-lithic sandstone, pebbly in part (Moffitt, 1999).</td><td>30</td></tr>
<tr><td rowspan="2">Wombarra Formation (WBFM)</td><td>Wombarra Claystone (WBCS)</td><td>Grey shale and minor quartz-lithic sandstone (Moffitt, 1999; BHP Billiton, 2013).</td><td>25</td></tr>
<tr><td>Coal Cliff Sandstone (CCSS)</td><td>Fine to medium grained quartz-lithic sandstone (Moffitt, 1999; BHP Billiton, 2013) suggests CCSS is a sub-unit or facies grading into the Wombarra Formation.</td><td>15</td></tr>
<tr><td rowspan="2">Permian</td><td colspan="4">Illawarra Coal Measures</td><td>Coal interbedded with siltstone, claystone, quartz-lithic sandstone and minor conglomerate (Moffitt, 1999). Includes the Bulli Coal (BUSM/BUCO), Balgownie Coal, Wongawilli seam (WWSM/WWCO) and Tongarra Coal, plus Loddon/Lawrence Ssts (LRSS) and Kembla Sandstone (KBSS).</td><td>200-300</td></tr>
<tr><td colspan="4">Shoalhaven Group</td><td>various sedimentary and igneous units</td><td></td></tr>
</table>

Figure 2-3A shows that around Area 3A, the dominant outcrop type is the Hawkesbury Sandstone (HBSS), with minor occurrences of Quaternary swamp sediments. There are some exposures of underlying Narrabeen Group, specifically the Bald Hill Claystone and Bulgo Sandstone: These occur in the deepest Sandy Creek and Cordeaux Reservoir valleys to the east and northeast. Parts of Wongawilli Creek are similarly incised through the Hawkesbury Sandstone into the Bald Hill Claystone in the reach near to (west of) Longwall 19A

The cross-section (**Figure 2-4**) illustrates the main units and geometry of the sequence around Area 3A. The section shows that the Wongawilli Seam is approximately 290 to 355 m deep through Longwall 19A, being 330-340 m deep at the centre of the panel. Outside of the panel footprint, depth of cover declines to the east and west, mainly associated with variable ground, to 250 m near Wongawilli Creek and to 240 m near Sandy Creek.

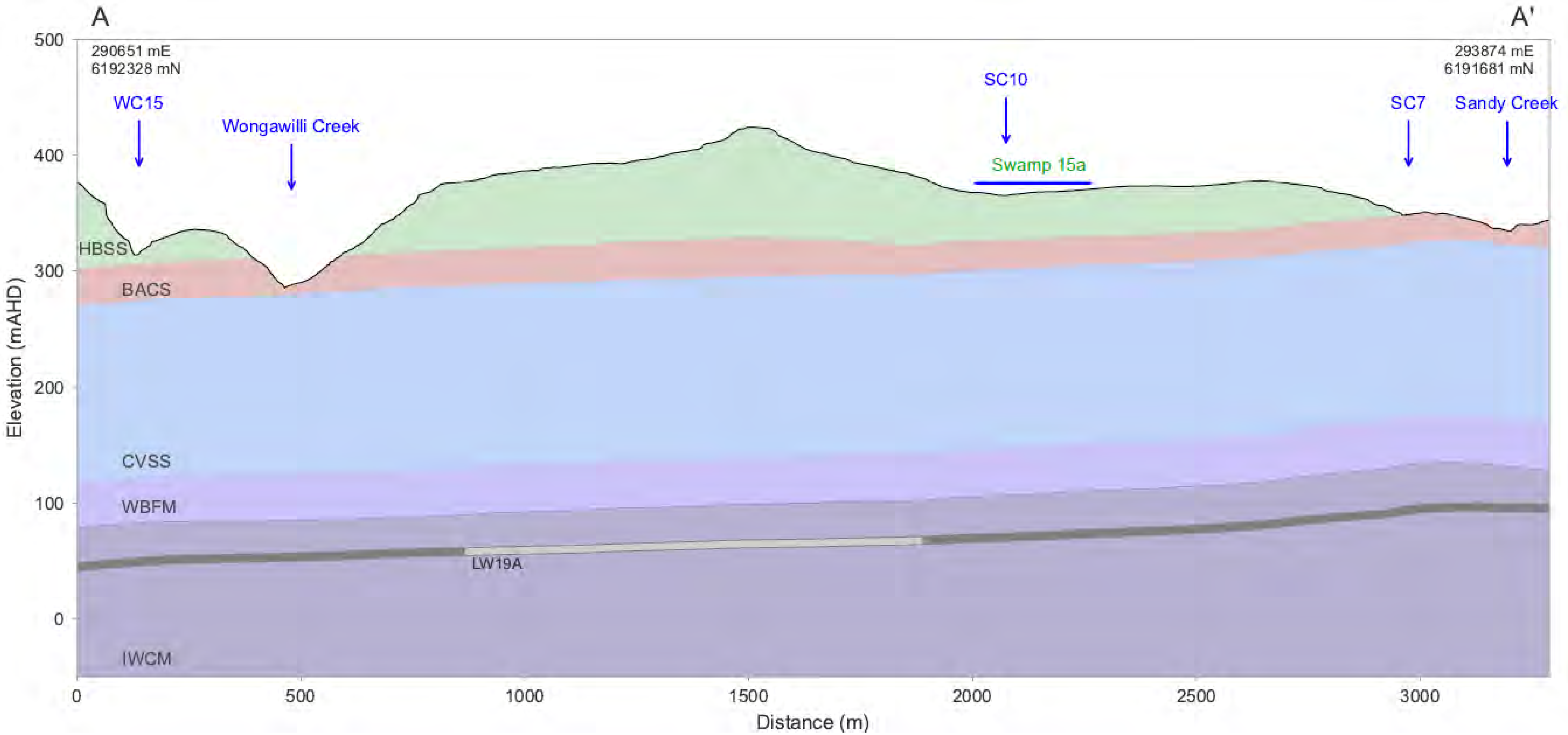

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Figure 2-4 Cross-section through A3A Longwall 19A

2.6 Effects of longwall mining on geological strata

The effect of longwall mining, in terms of the physical changes it causes to geological strata is important context for the subsequent description of hydrogeology. Therefore it is important to outline the broad behaviours prior to more detailed in Section 3.6.

Longwall coal mining 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 patterns of deformation. Specific 'zones' are often used to describe the conceptual model (as on **Figure 2-5**), although as noted by various authors (PSM, 2017; Mackie, 2017) the reality is that there are typically not discrete boundaries between zones, but more a continuum of fracture modes and intensity 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. On **Figure 2-5B**, WatershedHG has made some annotations and edits based on observations at Dendrobium and Tahmoor mines.

Fracturing is most intense and vertically connected immediately above the collapsed longwall (goaf) (the 'caved zone'), and above the mined panel the intensity of fracturing grades upwards through to less fractured strata (Booth, 2002) leading to reducing degrees of 'connection' along fracture networks. Fracturing of the overburden can cause significant changes in aquifer characteristics such as hydraulic conductivity and secondary porosity (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) within this area are therefore important in assessing potential impact of longwall mining on groundwater and surface water systems. Further analysis of specific effects, including the height of deformation and the effects on strata permeability based on recent investigations at Dendrobium (HGEO, 2020f, 2021d), are presented later, in Sections 3.6.1.

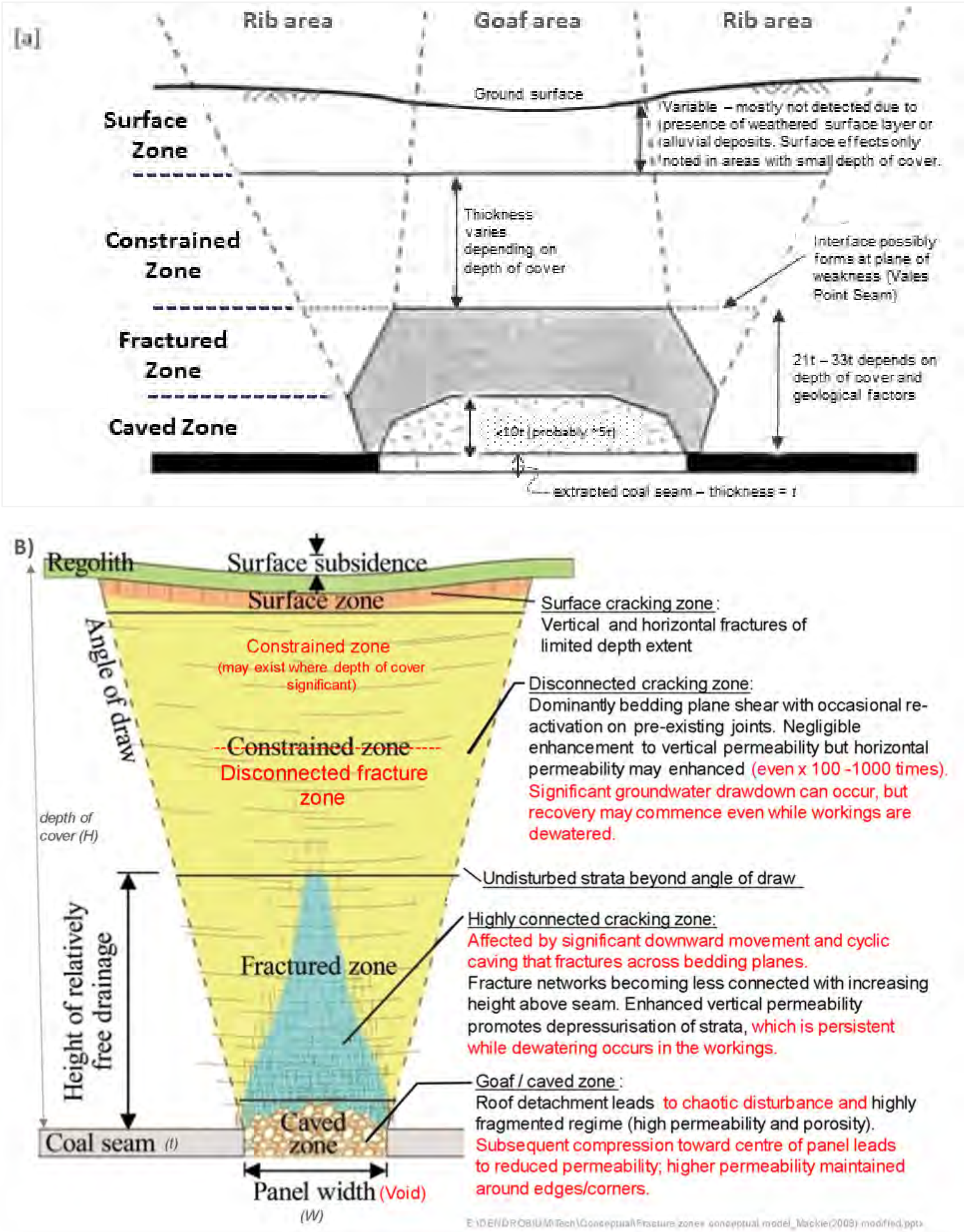
Between the surface zone and the fractured (connected and disconnected) zones, a 'constrained zone' may occur, with minimal disturbance of strata. The longwall geometry at Dendrobium has not allowed for such a zone to occur.

At the surface, subsidence and tension across the subsidence trough combine to cause 'surface cracking'. This is significant with respect to impacts on surface water features, such as watercourses and swamps, that may overlie or be adjacent to longwalls.

A feature of post-mining strata deformation that is not simulated in modelling, but may be important in understanding inflow behaviour is the compression or reconsolidation of heavily disturbed strata within the 'caved zone' (**Figure 2-5**). This concept is described in Zhang *et al*. (2016) and Seedsman (2018). Using gas drainage data, Zhang *et al*. (2016) estimated 40-80% permeability reduction (average 65%) in the caved zone from the initial high permeability that occurred after longwall extraction. This reduction due to reconsolidation occurred over a period of months.

Beneath the mined panel, deformation due to unloading and heaving can occur in the floor strata (Meaney, 1997; Karacan *et al.*, 2011).

Deformation of geological strata may also occur outside the footprint of longwalls. Such effects might occur out to distances of over 1 km, such as at Springvale Mine (Section 2.5.1.1) which is in a different geological and structural setting to Dendrobium. At Dendrobium effects specifically associated with structures are not observed far beyond panels (SRK, 2020). However, valley closure effects, as at Sandy Creek or the Avon Reservoir shoreline, could occur to up to 600 m (Section 3.6.3).



sources: A] (Forster and Enever, 1992) and B] (Mackie/Department of Planning, 2008). red = edits by WatershedHG)

Figure 2-5 General Conceptual Models of Subsidence and Deformation above Longwalls

3 Hydrogeology

The following sections outline the baseline or existing hydrogeological conditions or parameters. Where longwall mining is considered to affect these, a subsection summarises the relevant studies and data analysis and associated findings.

3.1 Groundwater users

The distribution of groundwater bores, as registered in the NSW government database, is shown on **Figure 3-1**. 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/Pheasants Nest and the Southern Highlands respectively. This highlights the lack of population immediately around the Dendrobium mining areas, consistent with the dominant land use (Section 2.1).

The details of the nearest 'water supply works', as per the AIP, are summarised in **Table 3-1** (labelled on **Figure 3-1**).

Table 3-1 Bores (GW works) nearest Dendrobium Mine

GW work ID	Distance from Dendrobium Mine	Distance from Longwall 19A	Description
GW112386	1.9 km north of Area 3A, 0.5 km northeast of Longwall 23.	3.4 km to the N of Longwall 19A	Monitoring bore installed by WaterNSW on western edge of Cordeaux Reservoir.
GW040945	7.2 km WNW of Area 3B	11 km to the W of Longwall 19A	WaterNSW test bore drilled to investigate groundwater supply near Avon Dam.
GW068119 and others	4.5 km south of Areas 1-2	7 km to the SE of Longwall 19A	GW068119 and nearby private bores are located on the coastal plain, and in the lower Permian units (e.g. Shoalhaven Group).
GW102528	10.5 km north of Areas 3B	13 km to the N of Longwall 19A	Domestic/stock bore completed in the Hawkesbury Sandstone, just south of Wilton.

All other Groundwater Works are further from Longwall 19A, and most of them are along the coastal plain, and stratigraphically separated from the coal measures.

3.2 Groundwater Dependent Ecosystems (GDE) and environmental features

3.2.1 High Priority GDEs

The relevant WSPs list a number of High Priority GDEs in this region (**Figure 3-1**). The nearest such feature is the O'Hares Creek catchment, located 18 km north of Longwall 19A. Given the distance involved, these features are therefore not at risk from the extraction of Longwall 19A.

3.2.2 Upland Swamps

Figure 2-1 and **Figure 3-1** show the regional distribution of Upland Swamps around the Southern Coalfield, based on regional mapping by NSW OEH (now BCS) and by IMC in the area around Dendrobium. With reference to these figures, of most relevance to Longwall 19A are:

- Den15A: a large swamp along sections of SC10 and SC10B, mainly to the east of Longwall 19A. A Performance Measure applies to this swamp.
- Den34: a headwater swamp above the mapped extent of tributary WC13, located above the pillars and to the south of Longwall 19A. Niche (2022) indicate that the vegetation in the area

of Den43 above the pillar is not in the Upland Swamp EEC, but the vegetation along WC13 (**Figure 3-1B**).

- Den148: a headwater swamp at the top of tributary WC14. A portion of this feature lies above the Longwall 19A panel, while most of it lies above the MG19 pillars or Longwall 19.

The Surface Water assessment (HGEO, 2022a) [in prep] describes these further.

3.2.3 Other potential groundwater-dependant features

Mapping of potential GDEs from the BOM's GDE Atlas has been reviewed. There are no potential *aquatic* GDEs or potential *terrestrial* GDEs mapped on the GDE Atlas within 3 km of Longwall 19A. However, it is likely that this mapping is incomplete, hence it is not shown on a figure in this report.

BCS advised that alternative mapping should be used; mapping of likely groundwater dependence for possible terrestrial GDEs ("HEVAE" mapping) is provided on **Figure 3-2** (Dabovic *et al.*, 2019).

Within and adjacent to Longwall 19A, areas of green and orange (higher and moderate potential groundwater dependence) occur along SC10 and SC10B (Swamp 15A and associated features), Swamp 34, WC14, and Wongawilli Creek. Areas of orange are also mapped away from the watercourses, in the plateau or ridgeline near the centre of Longwall 19A.

Cross-referencing against swamp and vegetation mapping (Niche, 2022) [Figure 3 of Niche's assessment] indicates that the most of the high-probability features mapped using the HEVAE methodology (Dabovic *et al.*, 2019), correspond to the mapped and ground-truthed Upland Swamp areas (Section 3.2.2).

The exceptions to this are:

- the Upland Swamp vegetation (Banksia Thicket and Tea-tree Thicket) within Swamp Den34 along the upper part of tributary WC13 (i.e. the vegetation is considered Upland Swamp EEC, but the groundwater dependence is apparently low);
- the Mallee Heath vegetation that comprises the main area of Den34, shows high probability of groundwater dependence, but is not considered Upland Swamp EEC.

Swamp 15a is more complex in terms of vegetation composition than the other swamps near Longwall 19A (Niche, 2022).

Based on advice from Niche, the Upland Swamp vegetation communities described in the points above can be sensitive to changes in groundwater level as a result of subsidence and associated fracturing, and are therefore the focus of the ecological impact assessment (Niche, 2022). Recent review of previously affected swamps has indicated that swamp piezometers located at distances up to 60 m from extracted longwalls at Dendrobium are highly likely to exhibit effects of mining on water table behaviour, however no sites beyond 60 m have exhibited such effects (Watershed HydroGeo, 2021b). More discussion on the effects of Longwall 19A on local Upland Swamps is presented in the Surface Water Assessment (HGEO, 2022a).

Niche (2022) conclude that impacts to riparian vegetation associated with the proposal are predicted to be minor in occurrence, being localised if they occurred. Niche advise that previous observed impacts to riparian vegetation (at Waratah Rivulet and Cataract River) were restricted to dieback as a result of methane gas release, from which the vegetation regenerated, and other localised changes.

3.3 Monitoring

Groundwater monitoring locations are described in the following section. Surface water monitoring sites are presented in Section 2.4.1.

3.3.1 Groundwater Monitoring

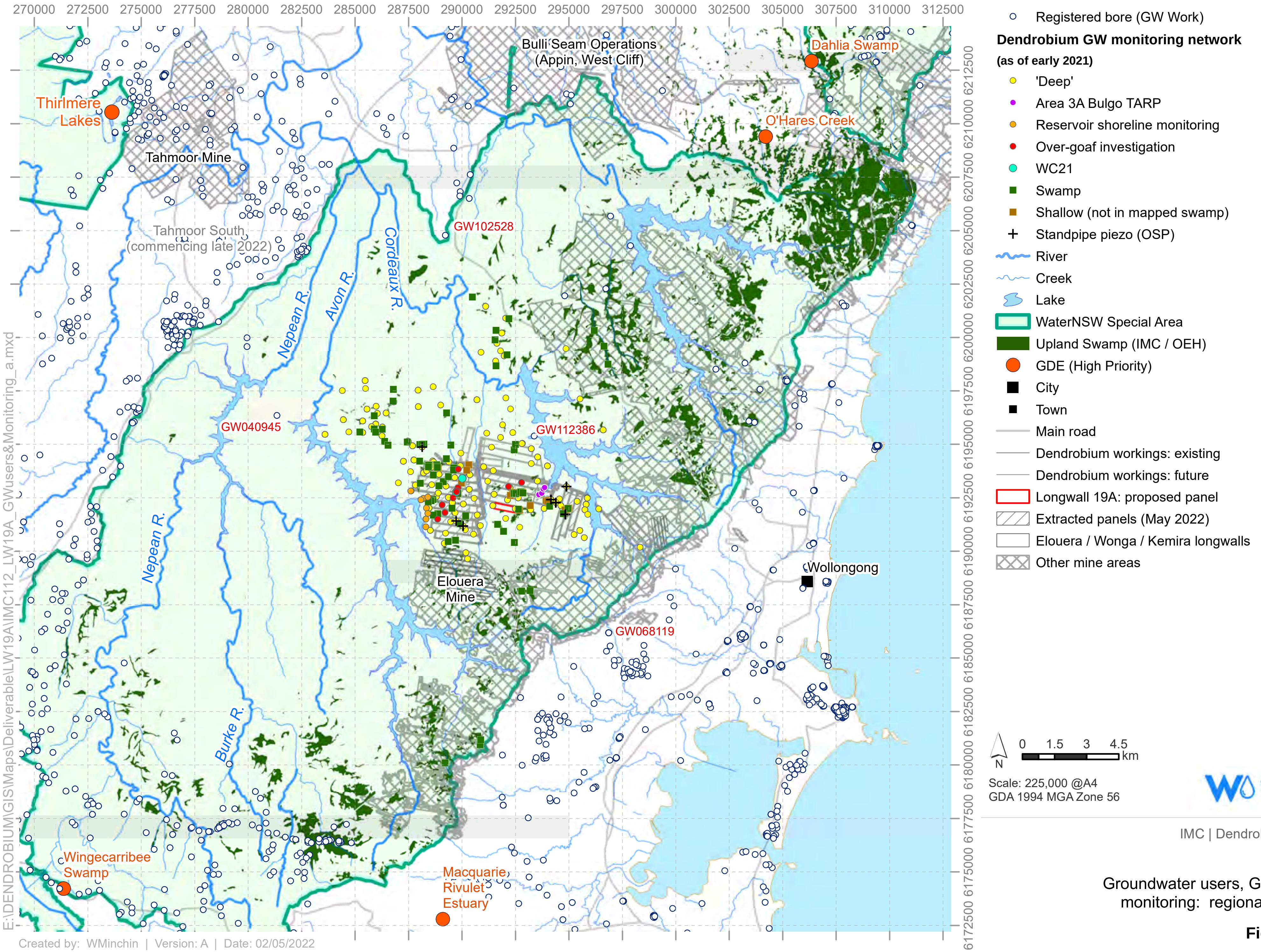
Figure 3-1 shows the location of monitoring sites around Dendrobium. The monitoring network is significant, one of the largest in NSW, and is regularly expanded in terms of size and scope. There are already a number of monitoring sites around Area 3A (**Figure 3-2**).

Groundwater level monitoring at Dendrobium Mine is conducted via:

- Multi-level vibrating wire piezometers (VWPs) installed within 'deep' bores. While there are questions about the absolute accuracy of VWPs, they do allow monitoring at multiple levels within a single bore, meaning they maximise the ability to monitor groundwater pressures in 3-dimensions and allow the vertical distribution of pressure, and therefore of drawdown, to be monitored. There are over 160 such bores, with over 860 such instruments, at Dendrobium, and this constitutes the bulk of the monitoring network and available dataset.
- A small set of standpipe piezometers installed into outcropping sandstone (typically 10-20 m deep). Additional standpipe piezometers will be installed at a selection of locations adjacent to VWP-equipped bores. A comparative study of groundwater levels or pressures recorded at standpipe piezometers and adjacent VWPs will be conducted in the near future.
- A network of shallow piezometers installed into shallow substrate, including swamps (typically 1-3 m deep). There are approximately 100 such piezometers at Dendrobium.
- Within the large network of 'deep' VWP-fitted bores listed above, there are a number of special-purpose bores installed to investigate and monitor pre- and post-mining conditions within the footprint of longwalls or offset from longwalls (**Figure 3-1**). These include:
  - longwall centre-line bores, such as the 'Longwall 9' investigation (Parsons Brinckerhoff, 2015a) and then a number of bores more recently above Longwalls 6, 7, 12, 13, 14, 15, 16 and 17 (HGEO, 2020f, 2021d). More on these is provided in Section 3.6.1.
  - bores drilled between Area 3B and Lake Avon (e.g. S2313, S2314, S2377, S2194 as described in Sections 3.6.3 and 3.7.2).
  - A set of 'shallow sandstone' bores to monitor groundwater levels in the Hawkesbury Sandstone near to shallow swamp piezometers.

Further over-goaf boreholes are planned for other longwalls, e.g. bores S2514 and S2518 are planned for Longwalls 22 and 23 respectively.

Monitoring sites with data displayed in this report (i.e. of relevance to Area 3A) are labelled in purple on **Figure 3-2**, i.e. S1879 (west of Longwall 19A), S1888 (eastern end of LW19A), S1892 (NW corner of Area 3A) and S1870 (to the NE of Longwall 19A and near to Lake Cordeaux).



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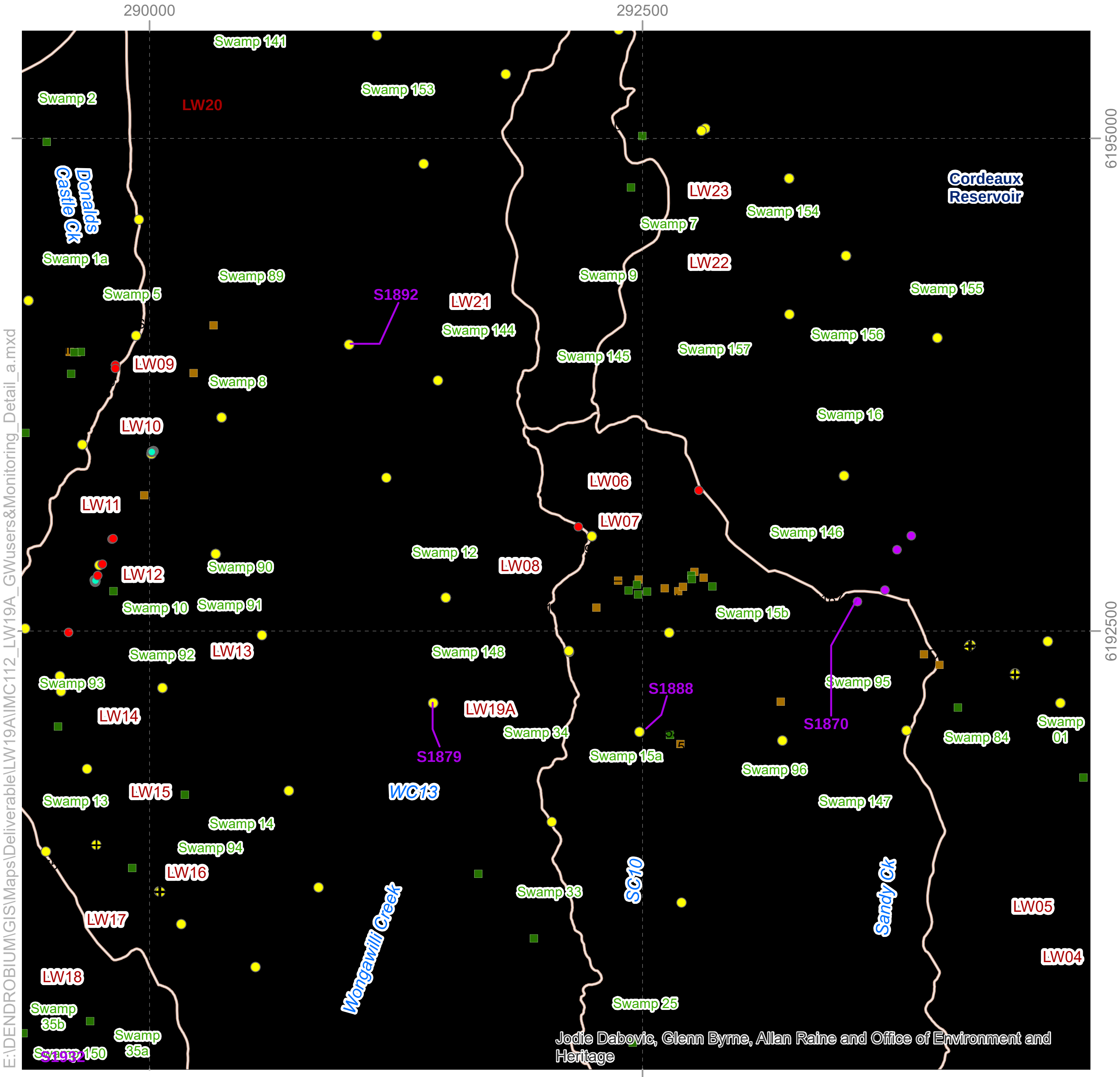
IMC | Dendrobium Mine

Groundwater users, GDEs and monitoring: regional context

Figure 3-1



Dendrobium GW monitoring network
(as of early 2021)

- 'Deep'
- Area 3A Bulgo TARP
- Reservoir shoreline monitoring
- Over-goaf investigation
- WC21
- Swamp
- Shallow (not in mapped swamp)
- Standpipe piezo (OSP)
- River
- Creek

Surface water monitoring site

- Existing / installed
- Approved
- Proposed
- Lake
- Upland Swamp (OEH / IMC)
- GDE (High Priority)

Hawkesbury Nepean

GDE_Probability

- Dendrobium workings: existing
- Dendrobium workings: future
- Mined area
- LW19A void
- Fire Road

0 0.2 0.4 0.6 km
N

Scale: 28,000 @A4
GDA 1994 MGA Zone 56

IMC | Dendrobium Mine

Groundwater users, GDEs and monitoring around Area 3A

Figure 3-2

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3.4 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 DPE-Water, yet exhibit significant variation in their permeability and porosity.

The reason for the 'Highly Productive' classification is the presence of the Hawkesbury Sandstone. This unit is a thick sequence that is primarily sandstone, but with minor 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. Coffey (2012a) showed detailed geophysical logs which showed variable gamma count, where that 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 named as a single stratigraphic unit, it essentially forms a series of layered aquifers, each with a moderate resource potential, tending to higher resource potential where jointing and fracturing (secondary porosity) is more developed.

As a result of the lithological variation, as well as the variable presence of weathering and secondary porosity (i.e. 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.

Bore yields of >5 L/s (which is the threshold for the 'Highly Productive' criteria) are possible, but yield in the area is variable e.g. testing in 2005 of two bores just north of Lake Nepean (Figure 3-1) by the NSW government produced substantially different yields:

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

The deeper units, being the Narrabeen Group and Illawarra Coal Measures, have lower resource potential or productivity.

3.5 Hydraulic Properties – host or natural

The following sections outline pre-mining or 'host' hydraulic properties, and then summarise measurements of post-mining hydraulic properties. Various HGEO and SCT reports, among others, provide more detail on the measurement and analysis of these.

3.5.1 Hydraulic Conductivity (K)

Characterisation of both the horizontal (Kh) and vertical hydraulic conductivity (Kv) has been carried out at Dendrobium. Packer testing is most commonly used to measure Kh in the non-coal strata, while drillstem tests (injection falloff tests, "IFOT") are more commonly used to estimate coal hydraulic conductivity. Laboratory analysis of core samples is used to measure Kv.

Figure 3-3A presents all the available pre-mining packer testing data for Dendrobium showing the depth interval of each test and the stratigraphic unit. Drillstem testing of coals is presented as red squares with an underlying symbol to indicate if the test was from the Wongawilli or Bulli Coal seams. The main observations to be drawn from this are as follows. Kh declines with depth from about 1E-1 m/d down to 1E-4 or 1E-5 m/d. The coal seams are more permeable than rock units (allowing for the different depth profile of these).

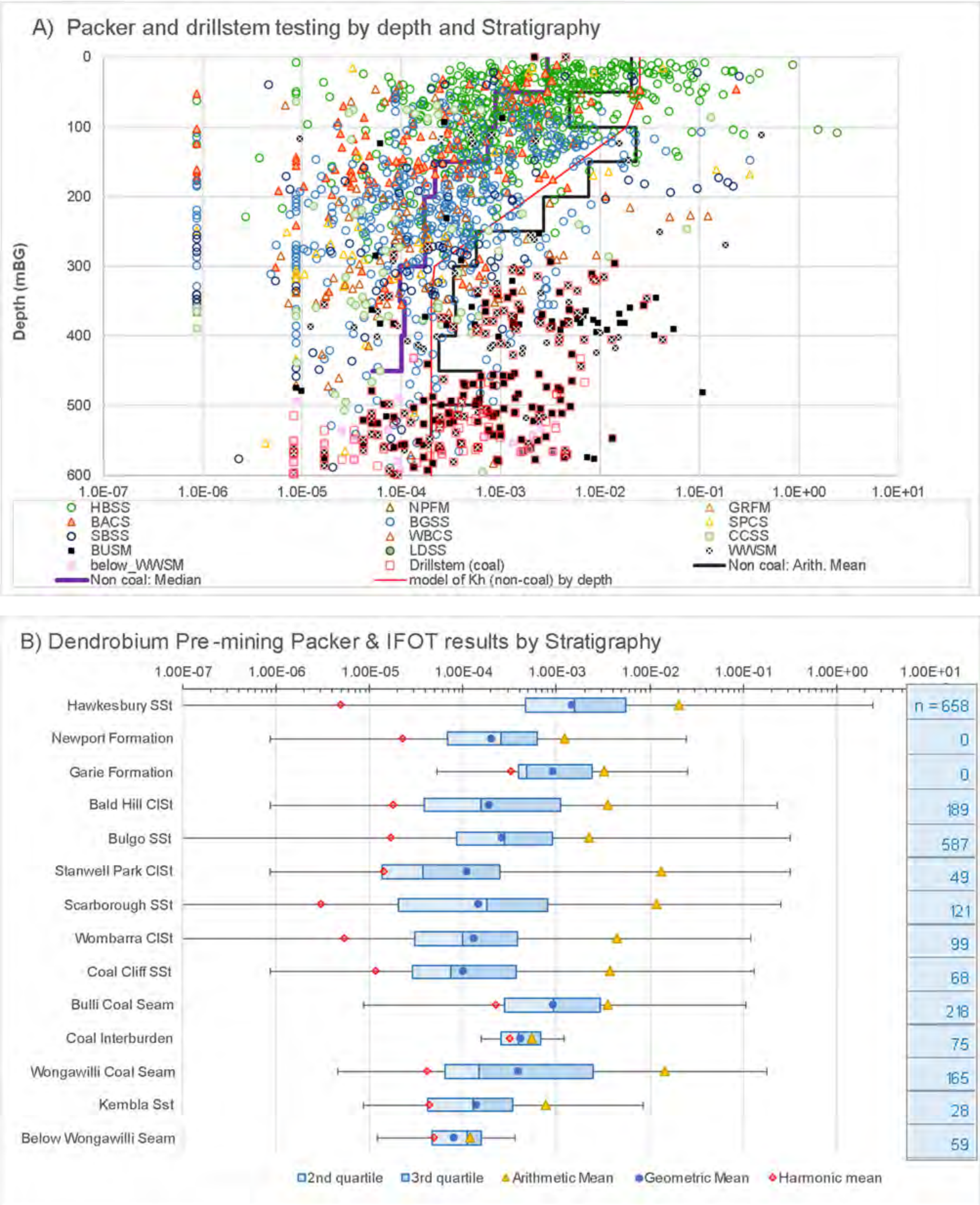

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Figure 3-3 Summary of horizontal hydraulic conductivity (Kh) by depth and stratigraphy

Figure 3-3B presents a summary of the Kh for each stratigraphic unit, ignoring the depth variable. This shows that the claystones (which are shown as triangles **Figure 3-3A**) are often not significantly less permeable (Kh) than surrounding units, e.g. Bulgo Sandstone permeability is typically quite similar to that of the Bald Hill Claystone. Comparison of the variance between stratigraphic units (**Figure 3-3B**) and the relationship with depth (**Figure 3-3A**) suggests that depth is likely more important than lithology.

Further breakdown of the Kh data by stratigraphic unit, depth and also by mining domain is provided in **Appendix A**.

Shaygan et al. (2022) made estimates of saturated hydraulic conductivity (Ksat) for swamps at Dendrobium. That study reported an average Ksat of 0.011 m/d (1.1E-2), with a range of 1E-4 to 5E-2 m/d. Ksat is inversely related to bulk density, which is inversely related to organic matter content, i.e. higher organic matter leads to less dense soil and to higher permeability.

Packer testing estimates the average hydraulic conductivity of the packer-isolated borehole interval but does not provide information on anisotropy. That is, the hydraulic conductivity when measured vertically versus horizontally – or in any other direction. In layered sedimentary rocks, it is common for the horizontal hydraulic conductivity (Kh) to be higher than the vertical hydraulic conductivity (Kv) by one or more orders of magnitude (where “horizontal” and “vertical” are relative to the orientation of the bedding). This is because groundwater can flow preferentially through horizontal layers of relatively high K (e.g. coarse sandstone layers), but vertical flow is impeded by laterally extensive layers of low K (e.g. claystone or siltstone beds). Anisotropy can manifest at scales ranging from centimetres to hundreds of metres (the scale of formations themselves). If the rock mass is fractured, then the preferred flow direction will be largely controlled by the characteristics of the fracture network. Fracture-flow and anisotropy may dominate where the rock mass is affected by mine subsidence (e.g. above the goaf), faulting or jointing.

Aquifer anisotropy can be important in controlling the propagation of groundwater drawdown impacts from mining. In this assessment, vertical anisotropy has been estimated for each major stratigraphic unit using three approaches:

1. Rock core permeability tests, in which Kv and Kh is measured on the same rock core sample in a laboratory. The resulting Kh/Kv ratio relates to the cm scale of the sample.

2. Packer testing results, in which the relevant scale is tens of metres. In addition, the packer test measurements include permeability due to fracture flow, where fractures are present.

3. Borehole Magnetic Resonance survey data (BMR), in which the relevant scale is in the order of metres to tens of metres. BMR is a down-hole geophysical technique that can estimate Kh in a continuous depth profile with a vertical resolution of centimetres.

In the latter two methods, Kv is not measured directly, but is estimated based on the assumption that Kv = Kh at the scale of the measurement. According to literature (Domenico and Schwartz, 1998), for a sedimentary sequence comprising multiple layers, the equivalent Kh and Kv of the sequence is given by the arithmetic mean and harmonic mean of the layer Kh values, respectively. Estimates of vertical anisotropy as expressed by the ratio of Kv/Kh are shown in **Table 3-2**, below.

Estimated Kv/Kh varies depending on the scale and type of measurements used in the calculations. Ratios determined using packer data indicate an average Kv/Kh in the order of 0.01

(range 0.0003 to 0.07)., which is lower than the ratio commonly adopted in groundwater modelling (0.1). Ratios calculated from the BMR data are slightly higher (~0.2, range 0.003 to 0.78). Estimates from core lab measurements vary widely reflecting the high variability at the centimetre scale.

Table 3-2 Estimates of vertical anisotropy in hydraulic conductivity (Kv/Kh)

Unit	Core (range, n)	BMR[1] (average Kv/Kh)	Packer tests (average Kv/Kh)	Representative Kv (m/d)
Hawkesbury Sandstone	3E-5 – 846 (36)	0.02	0.009	1.3E-04 - 2.8E-04
Bald Hill Claystone	0.12 – 12 (3)	0.15	0.003	8.5E-06 - 4.6E-04
Bulgo Sandstone	0.19 – 0.82 (5)	0.003	0.005	7.1E-06 - 1.2E-05
Stanwell Park Claystone	nd	0.09	0.0006	9.7E-06 - 1.5E-03
Scarborough Sandstone	nd	0.10	0.0003	4.1E-06 - 1.4E-03
Wombarra Claystone	nd	0.78	0.003	1.1E-05 - 3.2E-03
Coal Cliff Sandstone	nd	nd	0.002	9.1E-06 - 9.1E-06
Bulli Coal seam	nd	0.58	0.072	6.3E-04 - 5.1E-03
Coal Interburden (Eckersley Fm)	nd	0.27	0.020	1.2E-05 - 1.6E-04
Wongawilli Coal seam	nd	0.01	0.005	5.4E-05 - 1.2E-04
units below WW seam	nd	0.40	0.043	1.9E-05 - 1.7E-04
Cordeaux Crinanite	nd	nd	0.008	4.9E-05 - 4.9E-05
Arithmetic mean (sedimentary)	nd	0.22	0.014	--

Note: 1. BMR = harmonic mean / arithmetic mean using 1 m vertical moving average for each geological unit.
nd = Not determined / no data for specified unit.
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The sedimentary unit-scale estimates derived from packer and BMR data are considered most appropriate for informing groundwater modelling which is vertically discretised at that scale (see Section 6.2). An estimated range of Kv for each unit is provided in **Table 3-2** based on that.

Vertical anisotropy in fractured domains (e.g. above goaf) is estimated based on the assumed dominant orientations of fractures (Sections 3.6.1).

The extensive permeability datasets, compiled from available data from Dendrobium as well as from neighbouring operations (Tahmoor and Appin), that are presented above are more than sufficient for the purpose of informing and constraining the permeability parameters used in groundwater modelling (Sections 6.2).

3.5.2 Aquifer storage (Sy and Ss)

Specific yield (Sy) or drainable porosity has not been measured directly at Dendrobium. Testing of total and effective porosity 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 (the equivalent of the Bulgo Sandstone). 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 3-3** provides total and effective porosity results from laboratory testing of core samples, based on a dataset from Dendrobium and from Appin Mine (Heritage Computing, 2010). This includes average porosity and effective porosity for some geological units, where effective porosity is a reasonable approximation for specific yield.

Table 3-3 Summary of porosity (%) determined from Dendrobium and BSO core samples

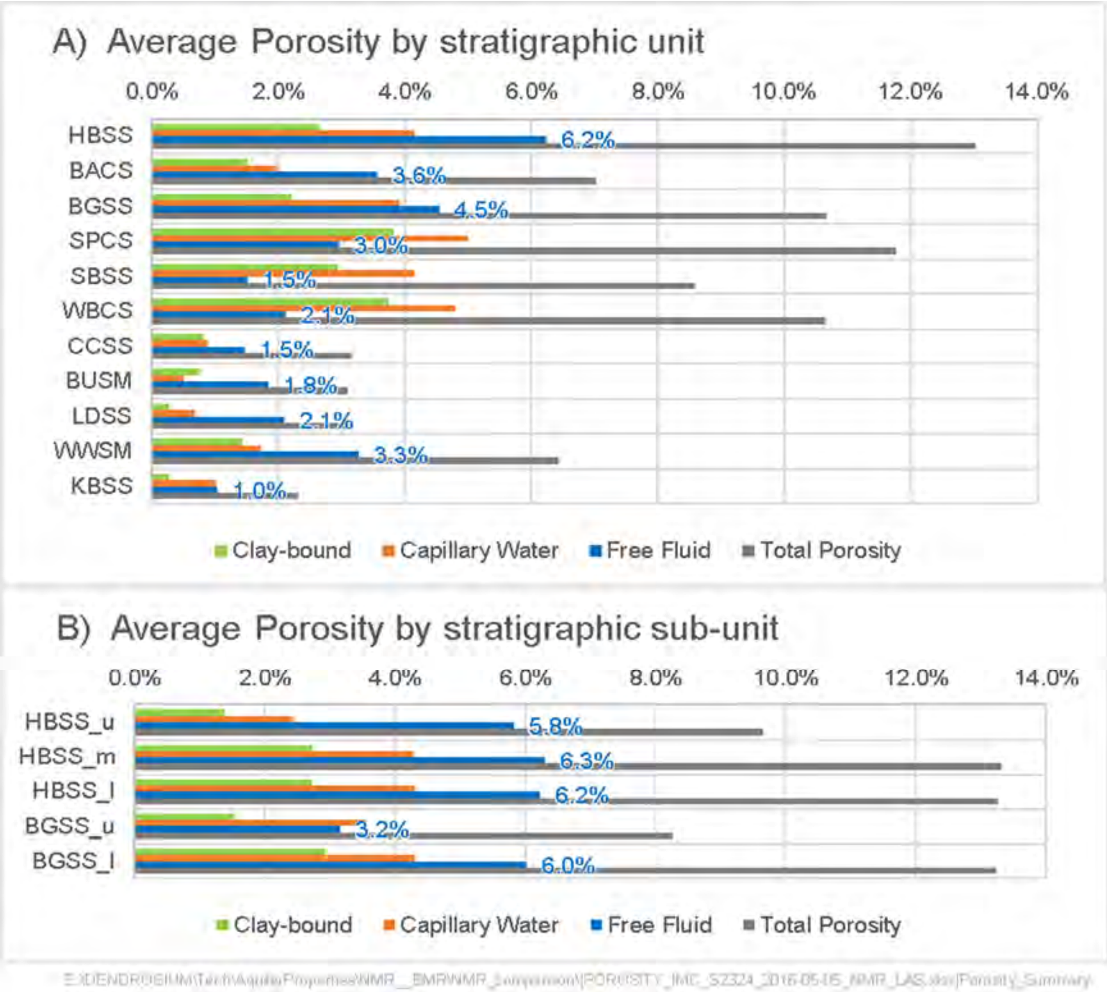
Geological Unit	Total Porosity (%)				Effective Porosity (%)	
	Min	Mean	Max	Count	Mean	Count
Hawkesbury Sandstone	3.8	15.4 (14.9)	23.6	68 (4)	11.2	2
Newport Formation	2	2.4	2.6	3		
Bald Hill Claystone	4.1	6.1	9.9	6		
Colo Vale Sandstone	3.7	9.4	18.1	10		
upper Bulgo Sandstone		(8.2)		(5)	3.3	5
lower 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 Appin Mine. Effective Porosity measurements are from Appin Mine. Source: E:\DENDROBIUM\Tech\AquiferProperties\Packer\Dendrobium_AquiferPropertiesDatabase_20161219.xlsx

As noted in Section 3.5.1, IMC has also used Borehole Magnetic Resonance (BMR) imaging in selected drillholes to provide continuous logging of density, gamma count, porosity and hydraulic conductivity. The BMR 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, where we consider that ‘free water’ is equivalent to drainable porosity or Sy.

Figure 3-4A presents the average of each of the porosity components by stratigraphic unit which correspond to model layers in the subsequent groundwater modelling (Section 5.2.3), 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 3-4B** shows the average porosity for the sub-layers.

The BMR ‘free water’ results indicate that Sy is in the range 1% to 6.3%. For the HBSS, 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 3-3**). The BMR free water values for Narrabeen Group (i.e. BGSS, SPCS, SBSS) are typically higher than the effective porosity values in **Table 3-3**.



(HydroSimulations, 2019)

Figure 3-4 Summary of BMR estimates of porosity components

A review of all the available porosity data shows that this parameter decreases approximately with depth, similar to hydraulic conductivity.

As expected, the values of total porosity, and even the effective porosity from Appin Mine, 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 HBSS (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.

Shaygan et al. (2022) made estimates of porosity and water content for swamps at Dendrobium. From this, we have estimated the specific yield (Sy) as 35% (range 21-48%), with horizons of higher and lower porosity present within each of the six study swamps.

The information from the core tests and NMR and from previous modelling will be used as the basis for the initial parameterisation of the groundwater model (Section 6.2).

Field data or direct measurements of specific storage (Ss) are generally not available. The specific storage of HBSS has been estimated to be approximately 1E-6 m^{-1} in the shallower zones where fracture flow is the dominant flow process (Kelly, Brown and Merrick, 2005) along with similar estimate of 1.5E-6 m^{-1}, for intervals between ground surface and 300 m depth based on pumping tests in HBSS from (Tammetta and Hawkes, 2009).

Estimates of Ss can also be derived from Young's Modulus and porosity, based on calculations in (Mackie, 2009), and methods utilising porosity determined from core testing are recommended (Evans, Campbell and McElvey, 2015). Calculations for strata at Dendrobium suggest that for coal, Ss generally lies in the range 5E-6 m^{-1} to 5E-5 m^{-1}, and interburden from 1.7E-6 (unfractured, fresh rock) to 8E-6 (fractured rock). These estimates are similar to model parameters from other mines in the Southern Coalfield which 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.

As in previous modelling, a trend of generally decreasing Ss with depth is represented in modelling, based on overburden pressure steadily decreasing the 'elastic storage' of strata.

3.6 Hydraulic Properties – post-mining effects

A considerable body of literature has described different aspects of changes to strata due to longwall mining, both in terms of the 3-dimensional extent of changes to strata, and the mode and intensity of these changes. A broad description of these processes is provided in Section 2.6.

Investigation and research by IMC, partly in response to comments and recommendations by agencies (including Dams Safety NSW and WaterNSW), independent review (e.g. PSM (2017)) and the IEPMC, has been targeted at addressing some of the uncertainties with respect to the hydrogeological and hydrological impacts of longwall mining.

The following sub-sections summarise recent work that has focussed on:

- Height of fracturing investigations within the footprint of the longwall, including at longwall centreline boreholes.
- Off-goaf deformation effects, specifically between Area 3B and Lake Avon.
- Surface cracking – recent investigations at Dendrobium and other Southern Coalfield mines have provided useful information.

3.6.1 Fracturing within and immediately adjacent to longwall panels

IMC drilled investigation holes above extracted Longwalls 9 and 12-17 in Area 3B and Longwalls 6 and 7 in Area 3A, allowing assessment of effects above longwalls of different width (305 m and 249 m respectively, including first workings). This program will continue, focussing on early longwalls in successive mine domains.

Domain	Seam	Post-mining boreholes	
		completed	proposed
Area 3A	Wongawilli	2	0
Area 3B	Wongawilli	8	1 (Longwall 18)
Area 3C	Wongawilli	(n/a -no mining in Area 3C)	3

Holes were deliberately located along the centreline of longwalls (and two more deliberately located off-centre) and were drilled to depths of between 280 and 300 m.

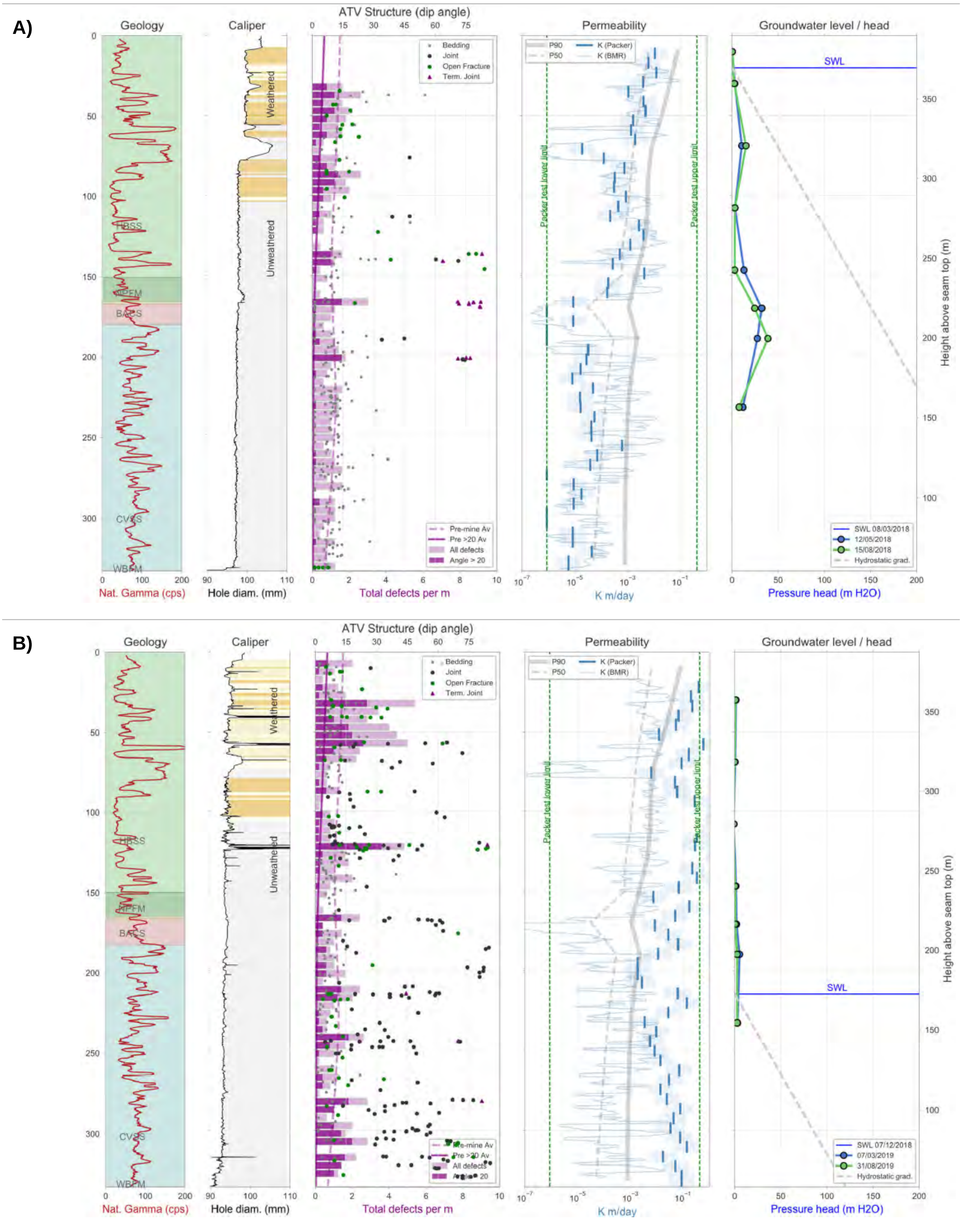
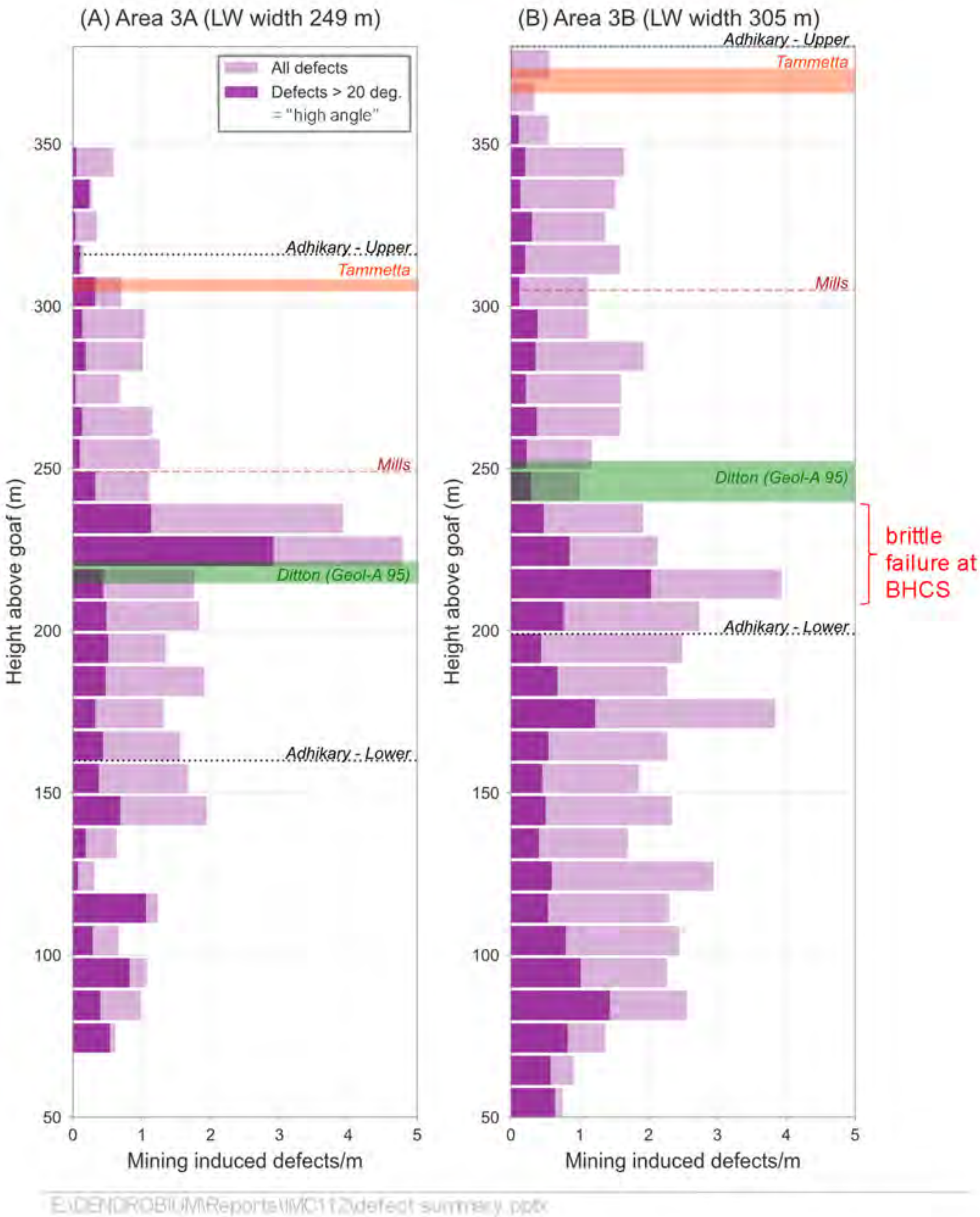


Figure 3-5 Pre- and post-mining conditions above Longwall 14 (boreholes S2398 and S2398A)

Observations from the post mining holes were compared with tests in pre-mining holes at the same drill sites (Parsons Brinckerhoff, 2015b; HGEO, 2020g, 2020e, 2021e).

An example of the pre- and post-mining "goaf hole" bore logs from above Longwall 14 is presented on **Figure 3-5**. This figure shows (A) pre- and (B) post-mining conditions in the centre of a longwall (Longwall 14). This shows, from left to right, the geological log, degree of weathering and calliper survey, the count of all defects and count of 'high angle' defects, packer test results, and groundwater pressures.

Figure 3-6 presents a summary of the defect logging from this investigation, showing the excess mining-induced defects (all defects and high angle defects) with height above the panel.



provided by HGEO

Figure 3-6 Change in fracture mode with height above extracted panel

The main conclusions from the over-goaf investigations are as follows:

- All holes drilled above extracted longwalls show a significant increase in permeability throughout all strata to the surface. Packer tests indicate an increase in permeability of 2-3 orders of magnitude (OM) relative to pre-mining conditions. Above the pillar zone between Longwalls 11 and 12 packer tests indicate distinctly lower post-longwall permeability than the centreline holes throughout all strata.
- In both mine Areas 3A and 3B, mining-induced fracturing, including high-angle (> 20°) fracturing is highly variable but appears to extend to the surface. The frequency of fracturing generally decreases with height above the goaf, with a high proportion of high-angled fractures within ~120 m of the Wongawilli Coal seam (**Figure 3-6**). The intensity of high angle fracturing due to panel extraction generally reduces with height above the extracted panel (the exception to is noted below), while low angle fracturing occurs more consistently to the surface.
- On average, the frequency of fracturing above the 249 m wide longwalls is less than that above the 305 m wide longwalls, although the profiles are variable (**Figure 3-6**).
- Anomalous fracturing is noted at the Bald Hill Claystone in several holes (**Figure 3-6**).
- Changes in vertical permeability cannot be measured directly from packer testing. However the high proportion of high-angle fractures in strata within 120 m of the goaf and general decrease with height implies that the ratio of vertical to horizontal permeability decreases with height above the goaf (whereas horizontal permeability is elevated throughout all strata).
- Assessment of near-surface cracking was beyond the scope of the investigation since vertical drill holes are unlikely to intersect subvertical features. No significant increase in fracture-frequency was noted in the near-surface (~30 m) compared with underlying strata.
- In most over-goaf holes, fractures display a weak preferred orientation parallel to the longwall face within 100 to 200 m above the goaf, transitioning upward to lower-angle or bedding plane fractures. One hole drilled above a longwall pillar shows a weak preferred orientation parallel to the longwall (length), again transitioning upward into lower-angle structures above 100-200 m.
- Vibrating wire piezometers (VWP) indicate that strata are depressurised well-ahead of mining with deeper formations affected before and to a greater extent than shallow units. Following longwall extraction all strata record significant depressurisation, with near-zero pressure heads recorded in most piezometers (**Figure 3-5**). For the initial period after longwall extraction, complete depressurisation is evident throughout the Hawkesbury Sandstone (HBSS) in most holes drilled above goaf.
- Piezometers installed after longwall extraction show evidence for groundwater recovery and perching. The perched horizons are most extensive in strata between the upper CVSS and lower HBSS (> ~220-250 m above the coal seam) and above longwalls extracted three or more years ago (Section 3.7.2 and **Figure 3-12**). The observations imply that rainfall recharge (and stream flow loss), which may be enhanced due to surface fracturing, percolates through the fractured strata and is retarded at certain stratigraphic layers or restrictions in the fracture network. The overall hydraulic gradient remains downward; however, the increasing head trends in some piezometers implies that the rate of recharge exceeds the rate of downward drainage at those perched horizons. Therefore, not all rainfall that infiltrates at the surface above the goaf reports directly to the goaf as mine inflow.

The analysis and data presented in HGEO (2020f, 2021d) have been used to address previous approval conditions set by DPE, and provides the basis for setting up and parameterising the groundwater model. The method of incorporating the above data into the model, in terms of the parameterisation of model inputs and then modifying this during model calibration, is presented in Section 5.4.

3.6.2 Surface cracking

Surface cracking, as described briefly in Section 2.6, extends downwards from the surface and appears to 'overlap' or intersect the 'connected fracture' zone extending upward from the goaf. This conceptual zone was not the focus of HGEO (2020f), although some of the data is relevant. Further data that informs the modelling of this process is available from other studies, e.g. SCT (2016) and SCT (2018).

Both these SCT studies show a substantial increase in packer testing Kh from pre- to post-mining in a zone of 20-40 m below surface. SCT (2016) showed a consistent increase in the count of 'all' defects, consistent with the packer testing, but only a mild increase in the number of >5 degree defects in this zone. This last finding is consistent with the findings to be drawn from the bore logs in HGEO (2020f), which do not show a significant increase in high angle defects in the near surface.

The understanding and model representation of this process is an ongoing focus. Depth (and the intensity) of surface cracking is assumed in subsequent modelling to be related to cutting height but may also be influenced by depth of cover and panel width.

3.6.3 Off-goaf deformation and valley closure

Valley closure relates to valley and horizontal compressive stress. Longwall mining and subsidence causes a redistribution of horizontal in-situ stress, pressure on the valley walls and bedding plane shearing. The contribution of pressure and shear is influenced by the position of nearby longwall panels in relation to the depth of cover and bedding planes.

The occurrence of basal shears, as discussed by various geotechnical engineers (Walsh *et al.*, SCT, PSM), has a potential role in connecting features to the goaf. The mobilisation of such features and enhanced permeability that may result from them might be taken into account by the more general 'off-goaf deformation' or valley closure described above, however given the conjecture about specific or discrete features connecting reservoirs to the connected fracture zone and the goaf, this has warranted additional consideration. Much of the data and discussion below is from investigations near recent mining between Area 3B and Avon Reservoir, however is applicable to future longwalls near Cordeaux Reservoir or to the major valleys/watercourses.

SCT (2015) presented discussion on the presence and behaviour of 'horizontal planar feature' basal shears associated with the Bald Hill Claystone (BHCS) and floors or valleys adjacent to longwall mining. Packer testing of a potential basal shear zone by SCT (2017) indicated a horizontal hydraulic conductivity of about 2E-6 m/s (0.17 m/day) across a 6 m test interval.

Packer testing of pre- and post-mining conditions at a number of boreholes between Area 3B and Lake Avon has indicated a range of post-mining permeabilities (**Table 3-4**). Locations of the relevant 'Avon monitoring bores' are shown on **Figure 3-2**.

Analysis of the above packer testing results led HGEO to conclude that, despite some pre- and post-mining boreholes showing little to no change in Kh, given the small dataset, numerical modelling should use an absolute Kh. Previously this was estimated to be 5E-2 m/d, rather than a multiplier in order to make a conservative estimate of impacts on surrounding waterbodies (e.g. Lake Avon).

This has been changed slightly in this study to 6E-2 m/day based on the results in HGEO (2019b) and **Table 3-4**. This remains unchanged by the recent results from HGEO (2020a).

Table 3-4 Recent pre- and post-mining packer test locations near Lake Avon

Site	Bore(s)	Distance from longwalls	Pre- to post-mining Kh [m/d]	Change	Comment
AD1	S2313, S2331	150 m from LW12	2.9E-03 to 5.00E-03	x 2	
AD2	S2314, S2314A	210 m from LW13	3.04E-02 to 2.10E-01	x 7	
AD3	S2377, S2377B	104 m from LW14	1.20E-02 to 1.50E-01	x 12	Post-mining re-drill in Dec-2017
AD3	S2377, S2377C	104 m from LW14	1.20E-02 to 5.70E-03	x 0.5	Second re-drill in Sept-2018, suggesting further change in Kh.
AD4	S2378, S2378B	105 m from LW15	2.80E-03 to 1.30E-02	x 5	
AD4	S2378, S2378C	105 m from LW15	2.80E-03 to 1.50E-02	x 5	Second re-drill in May-2020; no significant further change in Kh.
AD6	S2314, S2376	10 m from LW13	3.04E-02 to 2.90E-02	x 1	
AD7	S2314, S2435	320 m from LW14	3.04E-02 to 3.10E-01	x 10	
AD8	S2436A, B, C, D	310 m from LW16	5.10E-03 to 1.60E-01	x 30*	*Different test intervals → unreliable. No change in Kh below single shallowest interval.
	General	HBSS within 200 m		→ 5E-2 m/d	HGEO, 2018b

data from Table 2 of HGEO (2019b) and Table 2 of HGEO (2020g).

Based on the data and discussion above, the conceptual model for off-goaf alteration of permeability is:

- There appear to be some transient effects, as at AD3 which has been drilled twice, almost a year apart, following nearby longwall extraction. For conservatism, the apparent reduction in permeability (Kh) inferred from some boreholes could be ignored.
- Enhancement of horizontal permeability could occur up to a maximum of 600 m from longwalls.
- Post-mining Kh declines with distance, based on S2331 vs 2313 and S2314 vs S2314A data, although there is a hypothesis that the effects might be greater at approximately 100-300 m from longwalls, with smaller changes to permeability within 100 m (possibly due to compression above pillars) and beyond 300-400 m.
- Specifically, enhancement to approximately 6E-2 m/d (when averaged over significant thickness, like those of the groundwater model layers) within 300 m.

- Beyond 300 m, Kh change could be an increase of up to 15 times based on testing at S2314A but based on other bores is likely to be an increase of 2-3 times.

PSM (2017) stated that Kh increases of ‘1-3 orders of magnitude’ could occur. However, the upper part of that range is not supported by data from Dendrobium Mine or literature. Numerical modelling could be modified in future if further data supports a change of 3 orders of magnitude, however so far, the data presented above suggests that Kh can change but may only increase by approximately up to 1 order of magnitude or even show no systematic increase.

Given the uncertainty and differences in packer test results, the regional groundwater model has been run multiple times to test the sampled Kh and the potential effects of this on losses from reservoirs. Section 7.2.1 provides additional detail on this.

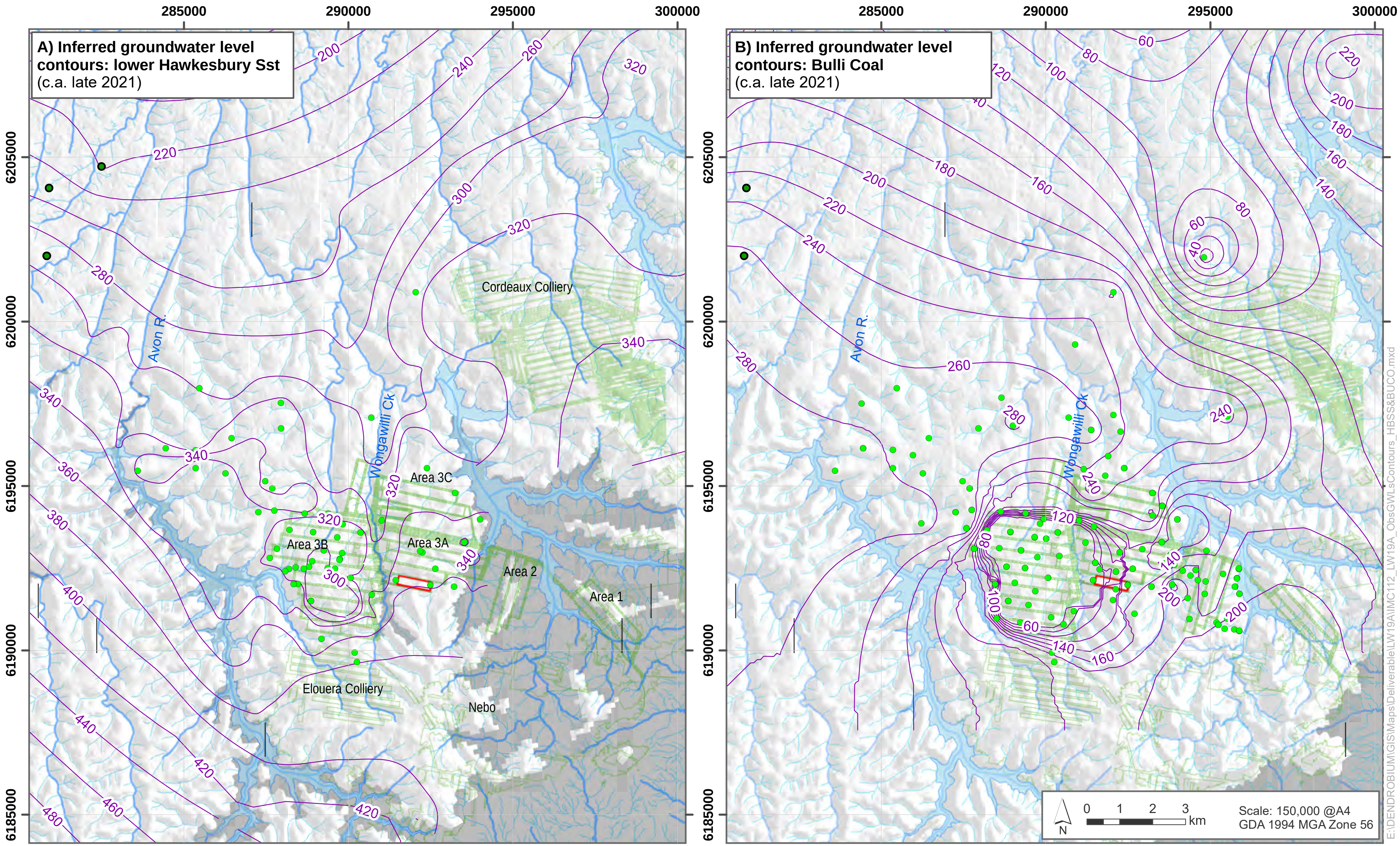
3.7 Groundwater level analysis

Groundwater levels are monitored at numerous sites around the Dendrobium Mine (Section 3.3). The data from many of the bores is analysed regularly as part of the End of Panel reporting process.

3.7.1 Spatial analysis

Groundwater levels contours have been derived from Dendrobium and other mine monitoring sites, and this regional-scale mapping (originally presented in WatershedHG (2022)) is presented on **Figure 3-7**. This shows the water levels from the lower HBSS and the Bulli Coal seam. The contours indicate that regional groundwater flow is broadly to the north, toward the centre of the Sydney Basin. Closer to the escarpment, it is likely that groundwater flow was to the southeast, i.e. discharging at the escarpment.

Water levels within the shallower units, such as the upper or mid-HBSS would be more locally influenced by watercourses and reservoirs which occupy deeply-incised valleys, and so locally may have gradients that diverge from the regional pattern. Groundwater within deeper units, including the coal seams, are much less influenced of surface water features, however can be influenced by the depressurisation effects of mining operations, such as Dendrobium, Elouera, Appin and Tahmoor (**Figure 3-7**).



Rev: A | W Minchin | 03/06/2022

- Major town
- Town
- Lake
- Watercourse
- Tribs
- Mine workings
- LW19A void
- Bore / data point
- GWL contours (c.a 2021)
- Inactive area (strat unit absent)

IMC | Dendrobium Mine

Interpolated groundwater levels:
lower Hawkesbury Sst (HBSS)
and Bulli Coal (BUCO)

Figure 3-6

3.7.2 Temporal trends

Data from a selection of groundwater monitoring bores around Area 3A are presented on **Figure 3-8** to **Figure 3-11**. The bore locations are labelled on **Figure 3-2**.

Bore S1870 (**Figure 3-8**) is located to the north-east of Longwall 19A, near to earlier Area 3A longwalls and Cordeaux Reservoir. Most piezometer pressures are close to or above lake stage in 2007-2010, including the 204m-SBSS piezometer. The early time groundwater pressures in the coal seams ("BUCO" and "WWCO" piezometers) are at 250 mAHD, and below lake stage. The coal seam piezometers clearly show depressurisation in response to Area 2 (Longwalls 3-5) extraction, and more again following Longwall 6 (Area 3A). The SBSS also shows depressurisation of about 100 m since 2011. The BGSS piezometers (149m and 125m) have declined approximately 90 m since 2011, and have declined from being 30 m above lake stage to being 50 m below lake levels. The shallowest BGSS pressures (55m piezometer) have remained just above lake stage, rising from their minimum (302 mAHD) in 2015 to 307 mAHD in 2022. Groundwater levels in the shallower strata (HBSS) have not been obviously affected by mining, but it is possible that 1-2 m of drawdown has occurred in two of the three HBSS piezometers (the other is 2 m above pre-mining levels), and all are well above lake stage.

Bore S1892 (**Figure 3-9**) is located just north of Longwall 6 and near to approved Longwall 21, and 270 m east of Wongawilli Creek. This hydrograph illustrates effects at or beneath the creek, which are relevant to future longwalls in Areas 3A and 3C. These hydrographs show that in 2008, groundwater levels in all monitored units except the LRSS and KBSS at S1892 (within the Illawarra Coal Measures) were similar to or above the level of Wongawilli Creek, indicating groundwater could discharge to the creek and support surface flow. The deepest two piezometers in S1892 clearly respond to mining of Longwall 6, with milder depressurisation evident in the BGSS piezometers. Due to missing data, depressurisation due to Longwall 6 can only be inferred in the SBSS piezometers, although they do show signs of compression effects at this time). At S1892, the upper HBSS piezometer ("8m: HBSS") shows no drawdown, while the 49m piezometer shows about 8 m drawdown, due to both mining and rainfall deficits. The 113m-BGSS piezometer has shown 2 m of recovery since early 2020, while the SBSS pressures have recovered approximately 10 m since 2018.

At S1879 (Figure **3-10**), depressurisation of the BGSS and deeper units has occurred since 2009. This is in the order of 150 m in the coal seams and SBSS, and 50 m in the lower BGSS (piezometer 153.7m) and 13 m in the shallow BGSS (97.4m piezometer). At this last piezometer, 3 m of recovery occurred since 2012, with pressures remaining just below Wongawilli Creek. In the HBSS piezometers, some drawdown is evident in the 48.3m piezometer following Longwall 8, while there are no obvious effects in the shallower piezometers. That water levels in strata near the base of Wongawilli Creek have declined while shallower water levels have remained unaffected or mildly affected (at S1879 and S1892, among other sites) has been described elsewhere (Watershed HydroGeo, 2018; HGEO, 2020d) and similar behaviour is expected to occur along the length of Wongawilli Creek between Areas 3A and 3B (including near Longwall 19A), and likely near future Area 3C longwalls.

Bore S1888 (**Figure 3-11**) is at the eastern edge of the proposed Longwall 19A and adjacent to Swamp 15a. Groundwater pressures in the BGSS and lower units exhibit similar behaviour to those described above. 8m-HBSS pressures show no discernible change due to mining. Pressures in 48m-HBSS show 13 m drawdown since 2010. This piezometer is located 30 m below Swamp 15a, and so interaction between HBSS groundwater levels and swamp has to be inferred from the 8m and 48m piezometers. This suggests that upward flux from the HBSS to the swamp would likely have declined slightly since Longwall 8 was extracted, although an effect on swamp water table at piezometer 15a_06 has not been detected (analysis is restricted by baseline record) (HGEO, 2022b).

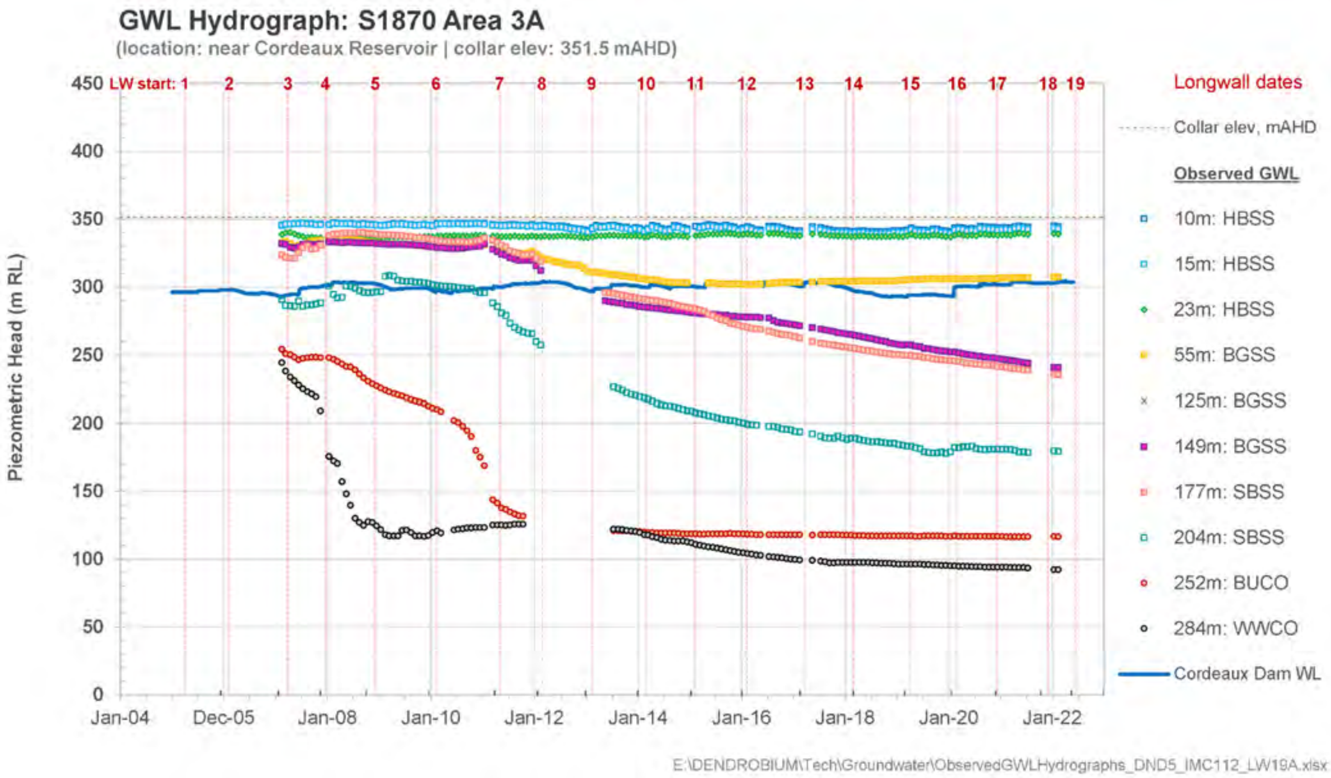


Figure 3-8 Groundwater level trends at bore S1870 (Area 3A, near Cordeaux Reservoir)

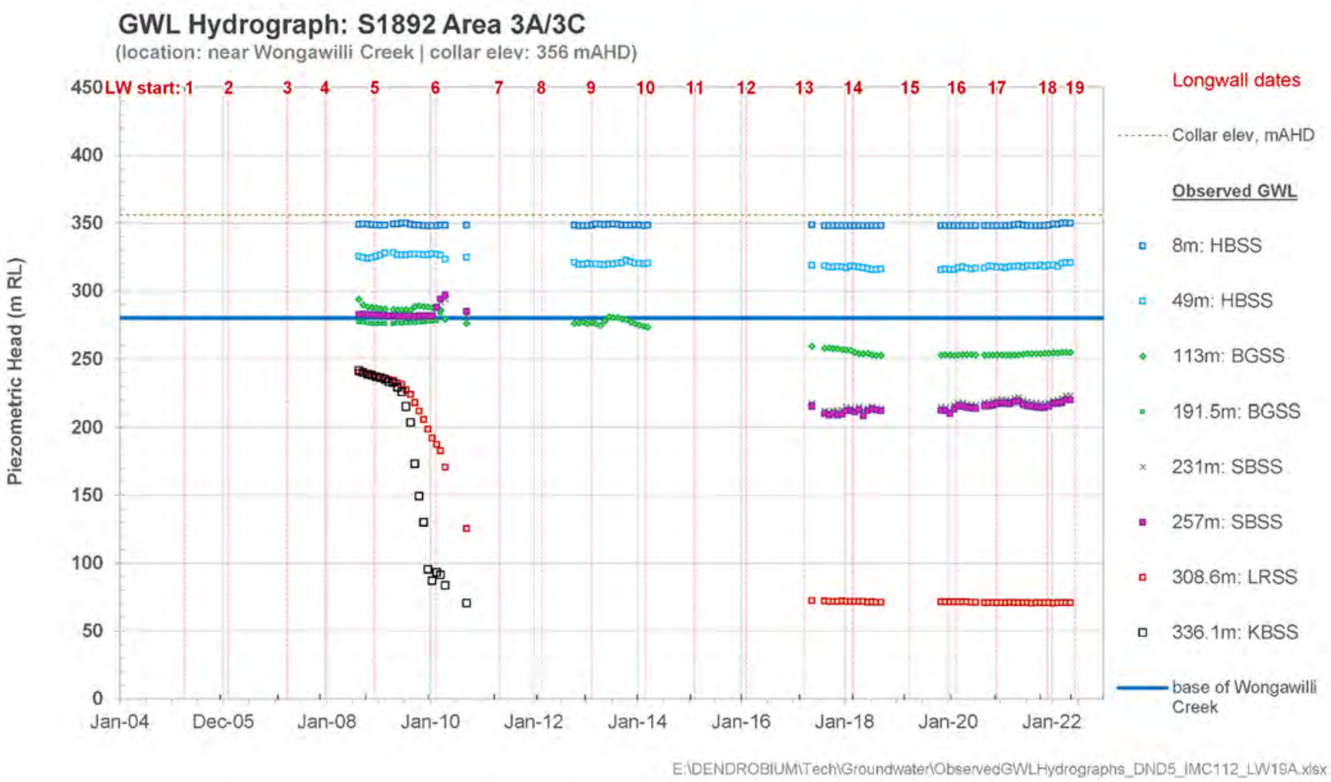


Figure 3-9 Groundwater level trends at bore S1892 (Area 3A, near Wongawilli Creek)

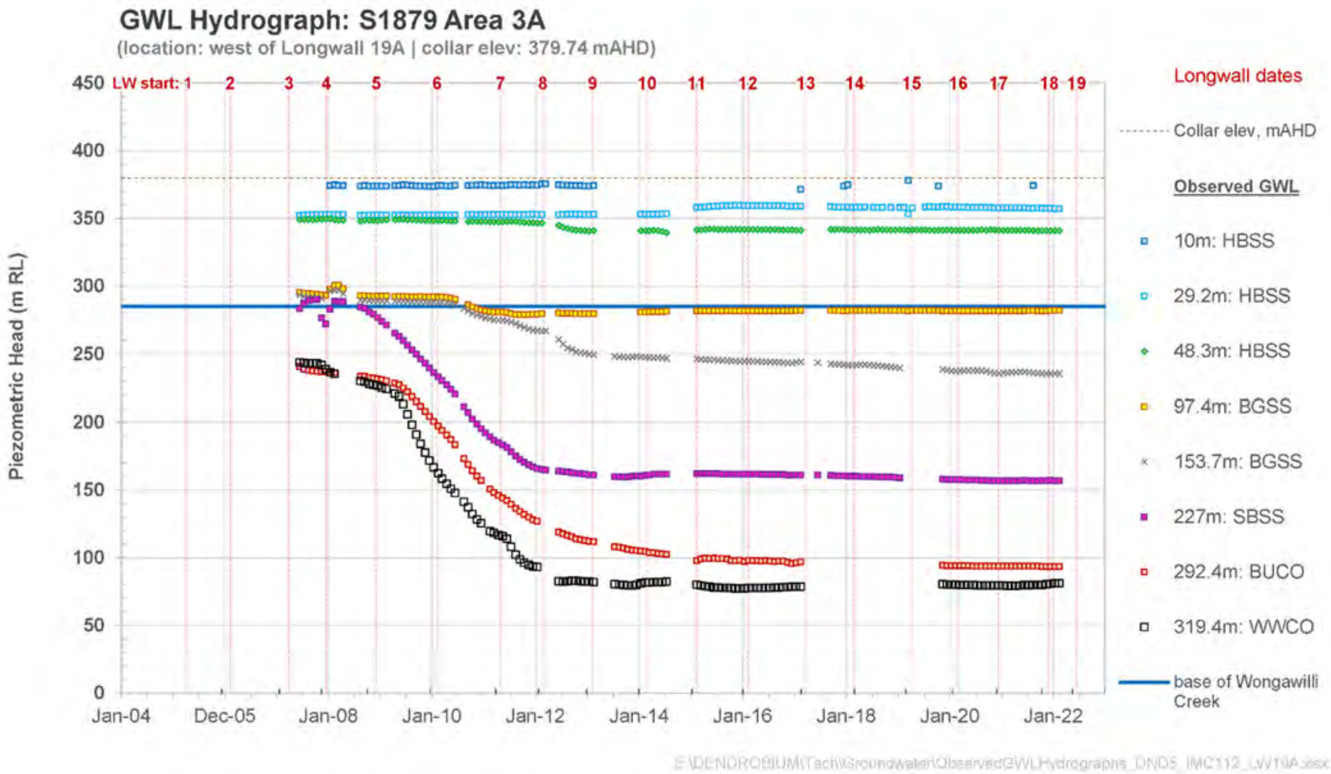


Figure 3-10 Groundwater level trends at bore S1879 (Area 3A, west of Longwall 19A)

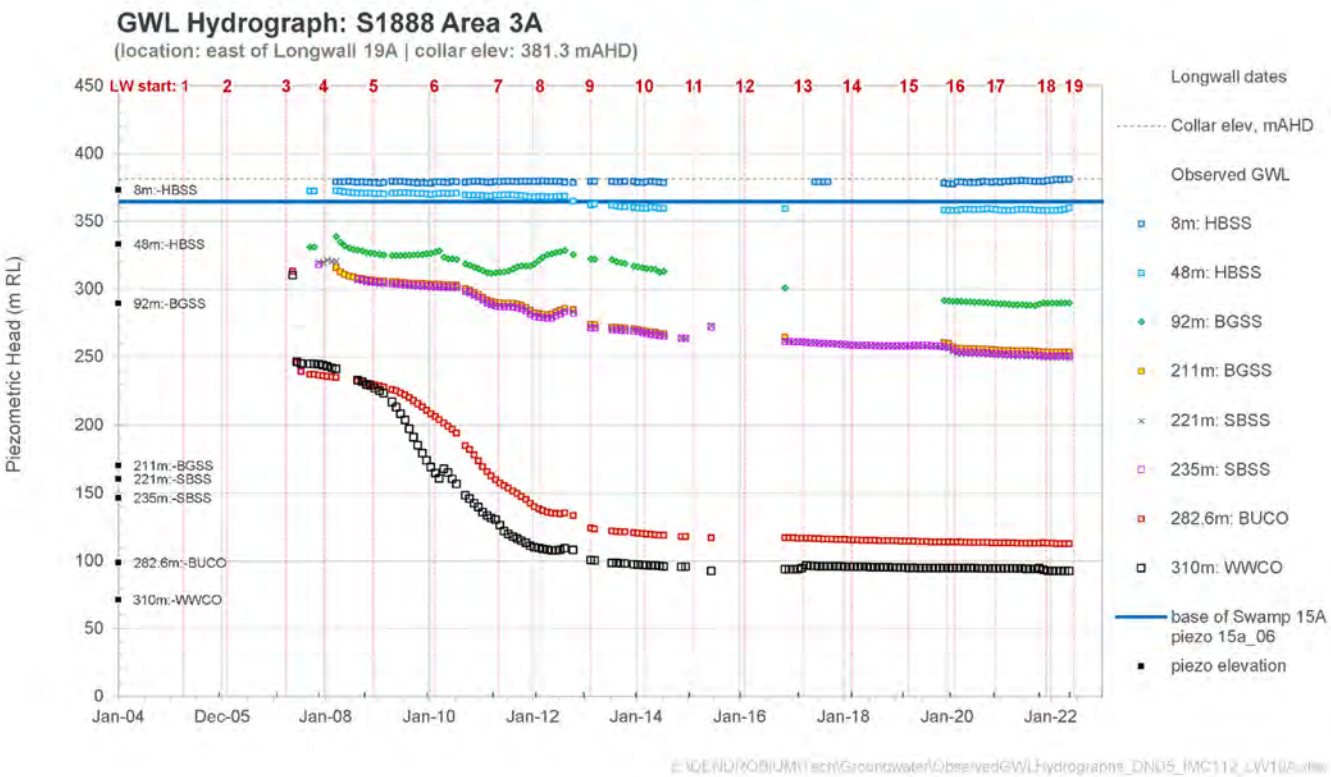


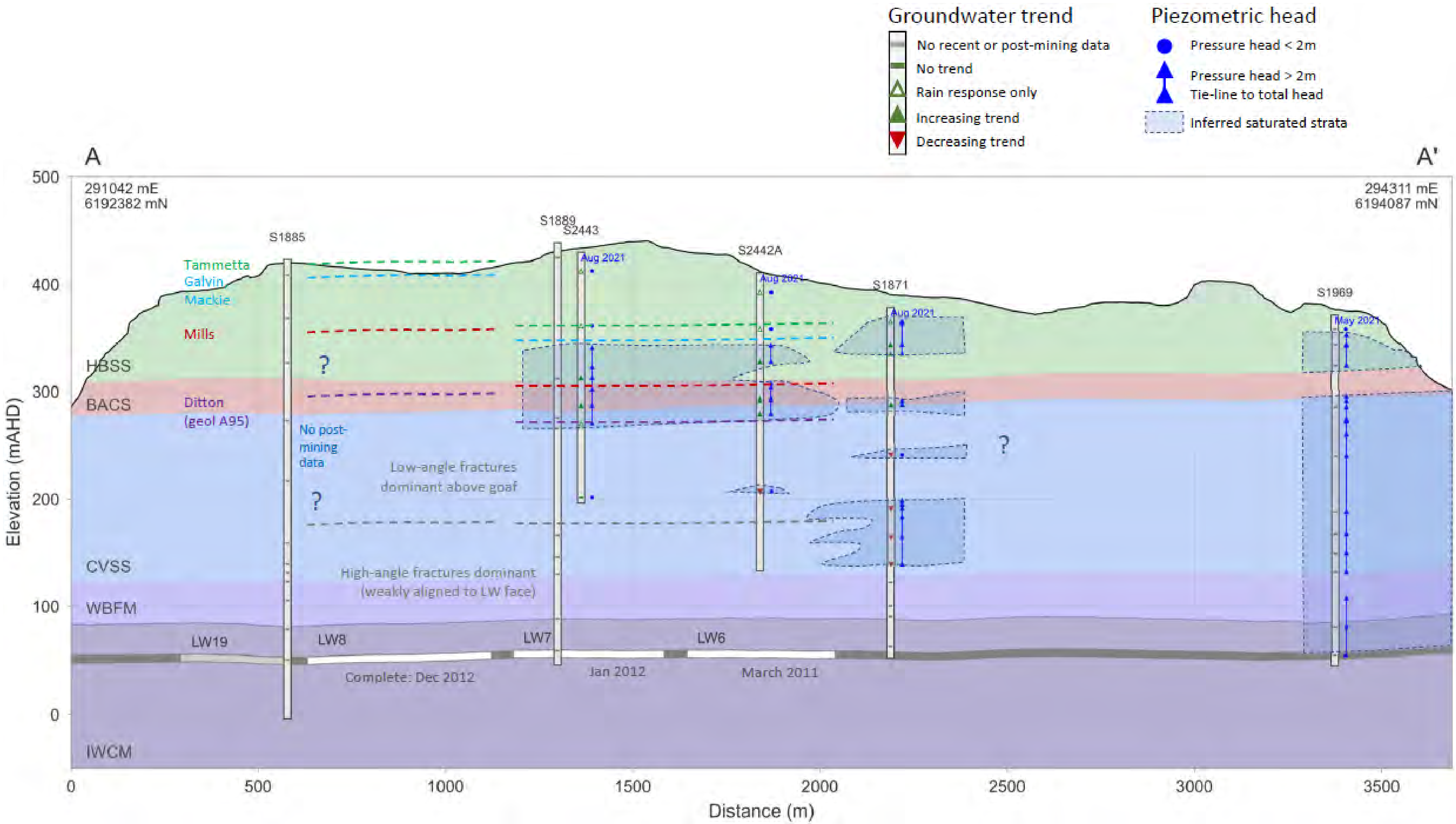
Figure 3-11 Groundwater level trends at bore S1888 (Area 3A, near Swamp 15a)

Based on the above discussion, pressures in almost all strata adjacent to or above longwalls declined following longwall extraction. HGEO developed and continues to update profiles showing groundwater pressures/levels in over-goaf piezometers in Areas 3A and 3B through time in relation to stratigraphic position and height above longwalls (HGEO, 2020f, 2021d). The most recent profile for Area 3A is presented here (**Figure 3-12**), noting that section line used would pass close to the western end of Longwall 19A, but not through the panel itself.

The cross-sections summarise data from numerous individual hydrographs. For each sensor, symbols are plotted that reflect the piezometric head (blue symbols) and the dominant groundwater level trends (green and red triangle symbols). Strata that are inferred to be fully saturated (pressure head >0) are shown with blue shading.

Empirical estimates for the height of fracturing and/or depressurisation are also presented on the figure, namely the models of Tammetta, Ditton and Merrick, Mills, and Galvin and Mackie - see discussion of those, along with some observations of the mode of fracturing made by HGEO based on core logging from these bores (HGEO, 2021e).

Groundwater level monitoring in centre-line holes has allowed observation of groundwater recovery and 'perching' at many sites, typically commencing 2-3 years after longwall extraction, in the upper BGSS (or Colo Vale Sandstone, CVSS), BHCS or into the lower HBSS (HGEO, 2021d). Pressures have generally not shown much, if any, recovery in piezometers below the upper BGSS. This suggests that vertically-connected fracturing does not occur consistently through the profile (Section 4.1). This means that while vertical (downward) flow of groundwater is likely to occur, the rate of this flux may still be relatively low compared to lateral flow and to recharge from above.



HGEO (2021)

Figure 3-12 Groundwater pressure profile (SW-NE) through Area 3A (over-goaf bores)

3.8 Water quality

Almost 3,000 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 water and groundwater chemistry. IMC provides regular reports on water quality data and analysis, and the following discussion is based on that reporting.

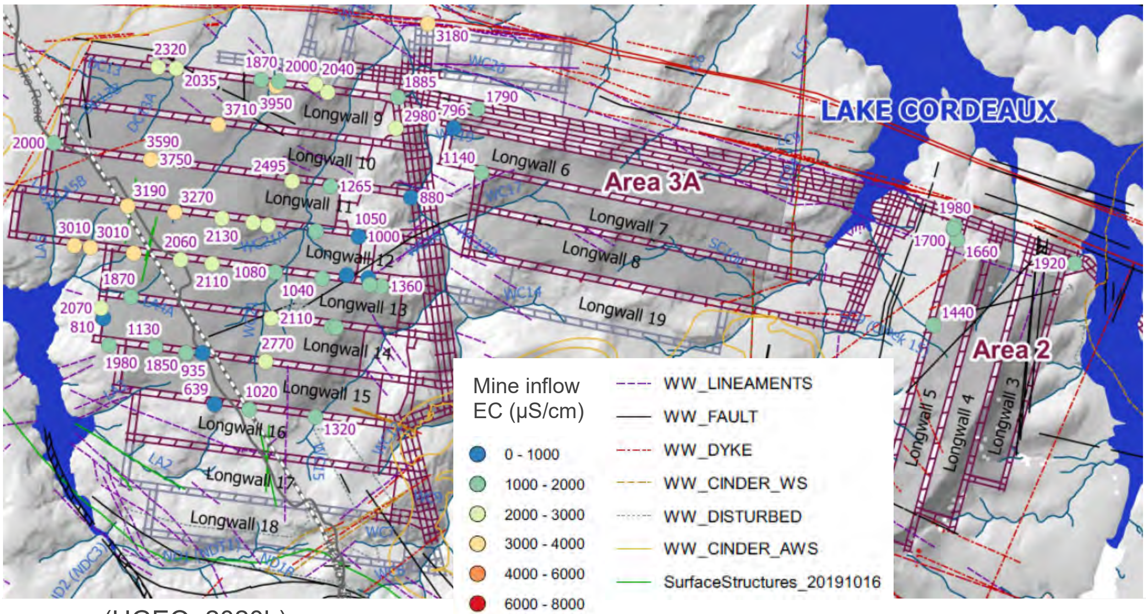
3.8.1 Groundwater quality

Groundwater samples are collected from a set of dedicated bores with installed pumps that sample from the Hawkesbury, Bulgo and Scarborough Sandstones. 'Deep' groundwater samples are collected within mine workings, typically from development roadway roof seepages and mining faces which have not been affected by the formation of the goaf during mining. Roof seepage samples are considered representative of the Wongawilli Coal and adjacent shales. Further samples are collected from goafed areas, and these are a mix of all sources of water entering the mine through the goaf (laterally and from underlying and overlying formations).

Spatial variation in salinity (measured as electrical conductivity, EC) is primarily related to changes in the concentrations of two major ions, Na^+ and HCO_3^-. Spatial variations are evident; the highest salinities are in Area 1 and the western end of Area 3B (HGEO, 2020h).

Based on data from Area 3A and 3B mine workings (**Figure 3-13**), the salinity of roof drippers increases from east to west, i.e. fresher near Longwall 6 (EC = 800-1,800 µS/cm), and slightly more saline in the western sections of Longwalls 9-12 (EC = 3,000-4,000 µS/cm). A trend on the north-south axis through Area 3B is less clear. EC in the southern-most sampling points has been 600-2,000 µS/cm and appears to be freshening slightly to the south.

The salinity recorded nearest Longwalls 19 and 19A are 1100-1360 µS/cm (**Figure 3-13**). Recommendations already discussed with IMC (Section 8.2.1) include further sampling of roof drippers around Longwalls 19 and 19A, and sampling of goaf outflow from Longwall 19 (if it can be assumed that this water is isolated from water re-circulated from elsewhere in the mine, which has been a limitation of sampling in Area 3A).



source: (HGEO, 2020h).

Figure 3-13 Distribution of EC in inflow to mine workings

Groundwater quality is variable depending on sampling depth and the sampled geological formation. There is an increase in the concentration of minor and trace ions with depth, in line with the general increase in EC (HGEO, 2020h).

Table 3-5 and **Figure 3-14** present a summary of electrical conductivity (EC) data. The data shows that groundwater salinity typically increases with stratigraphic age, reflecting the longer residence time in deeper units.

Groundwater within the HBSS is generally fresh (EC <1,000 µS/cm), with a mixed major ion composition. This water quality is indicative of relatively recent rainfall recharge (noting that the HBSS is the main outcropping geology, **Figure 2-3**). Groundwater in older stratigraphic units (such as the BGSS, which is present at outcrop to the east of Area 3A, and SBSS) is generally more saline. Groundwater EC in the workings, even in goafed areas, is reflective of 'deep' groundwater, such as the SBSS and BGSS and of groundwater within the coal measures (which are indicated by the 'seep' samples).

A recent assessment (HGEO, 2020f) of the potential links between structures and water quality within the mine workings found that, except for an apparent correlation between salinity and proximity to mapped dykes, there was no correlation or very poor correlation between water quality parameters, including tritium, to proximity to structures mapped at seam level or at the surface.

Table 3-5 Summary of Electrical Conductivity (EC) Variation at Dendrobium

Sample type (in age/depth order)	Site or Area	Electrical Conductivity (µS/cm)				
		5th %ile	Median	Mean	95th %ile	Count (N)
Rain	Rain	73	90	94	120	40
Surface Water	Wongawilli Ck (FR6)	80	103	111	189	19
	Donalds Castle Ck (FR6)	48	95	112	219	31
	Sandy Ck	66	88	92	118	133
	AR19 (Area 5)	128	209	200	261	24
	CR31 (Area 6)	120	154	163	229	25
	Lake Cordeaux	71	93	93	114	279
	Lake Avon	58	70	69	78	122
Groundwater	Hawkesbury Sst	71	133	174	379	334
	Bald Hill Claystone	153	200	200	247	2
	Bulgo Sst	121	395	520	1575	93
	Scarborough Sst	467	550	556	747	118
Seeps: pre-longwall	Area 1 seep	2981	3340	4543	7907	7
	Area 2 seep	876	1355	1310	1886	231
	Area 3A seep	1029	2240	1956	2791	58
	Area 3B seep	769	1939	2035	3756	70
Goaf: post-longwall	Area 1 goaf	1700	2350	2246	2579	182
	Area 2 goaf	1026	1566	1519	1881	660
	Area 3A goaf	739	862	929	1271	164
	Area 3B goaf	1647	1905	1892	2204	94

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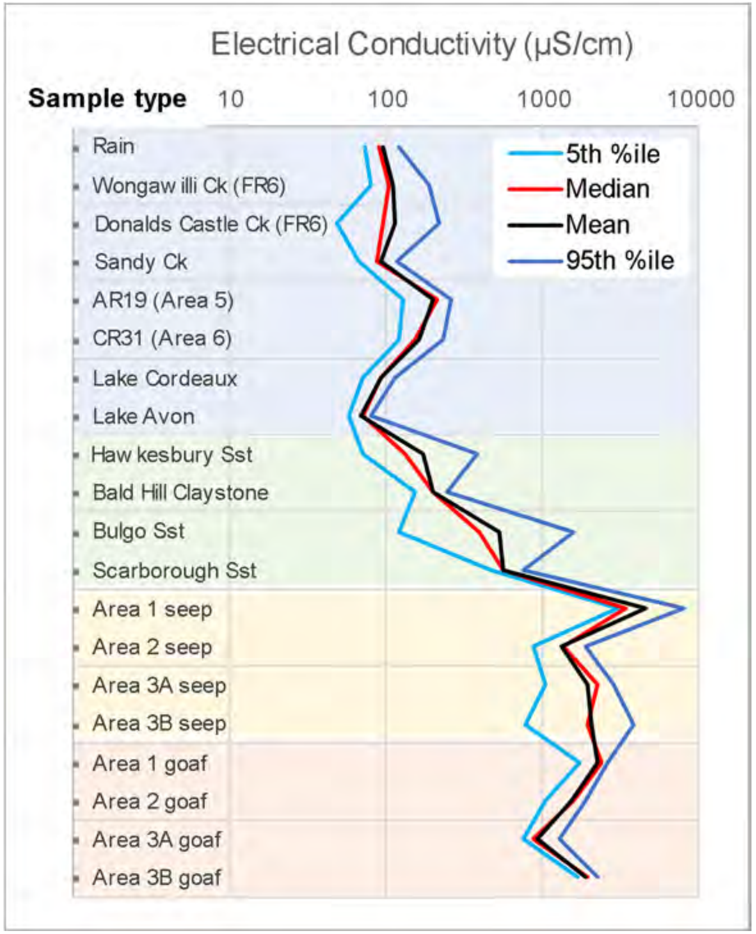


Figure 3-14 Electrical Conductivity (EC) Variation in surface water and groundwater

3.8.2 Water source discrimination

Water quality monitoring at Dendrobium has shown a number of dissolved constituents that can be useful in discriminating ("finger-printing") waters derived from different sources (HGEO, 2017d). Following that review, water samples are routinely analysed for field parameters (pH, EC, Eh and temperature), major ions and minor ions / metals. Stable isotopes of carbon and hydrogen, and radiogenic isotopic tracers of groundwater age (tritium and carbon-14) are analysed at representative sites.

3.8.3 Modern water and mine inflow

As recommended by IEPMC (2019a), the contribution of 'modern' water to mine inflow is the subject of on-going review. IMC's groundwater database currently includes over 700 analyses of tritium at Dendrobium, providing an indication of the presence of modern water (<70 years) in any given sample. Carbon-14 analysis has been conducted more recently at Dendrobium (57 analyses in the database) and indicates the presence of water that is up to 30,000 years old in a sample (Clark, 2015).

A summary of recent analysis is presented in the discussion of mine inflow (Section 3.9.3).

At Area 3B, tritium concentrations have typically been <=0.1 TU, but with an apparent increase to 0.1-0.2 TU since late 2019. Carbon-14 analyses have indicated 2-3 pMC (percent modern carbon), consistent with very low contributions of surface water. Slightly higher surface water contributions are indicated at Area 2 (~0.3-0.5 TU; 4 to 5 pMC), consistent with the much lower depth of cover (140-200 m in places - **Table 1-1**) and consequent stronger correlation of inflows with rainfall events at Area 2 (Section 3.9.3). For comparison, surface water samples have ~1.6 TU (median) and ~95 pMC.

3.9 Groundwater flow processes

Groundwater recharge occurs via infiltration of diffuse rainfall and possibly from leakage from surface water features, mainly from watercourses during and after periods of heavy rainfall. These processes are discussed and, where possible, quantified in Section 3.9.1.

Groundwater discharge occurs via a number of processes. These include:

- abstraction by 'water supply works' or bores (minor in this area, as in Section 3.1);
- dewatering by mines (Section 3.9.3);
- discharge of groundwater to swamps may occur and evapotranspiration in areas where the water table is close to the surface such as swamps but also typically along riparian corridors (Section 3.9.2); and
- discharge to surface water which typically occurs where incised valleys hosting creeks, rivers and lakes intersect groundwater (Section 3.9.4). Springs and seeps may also occur along the escarpment to the coastal plain, where erosion has truncated the stratigraphic units.

3.9.1 Recharge

Groundwater is recharged from rainfall and water bodies, as well as potential downward leakage from overlying strata.

As per the geological outcrop mapping, rainfall recharge primarily occurs to the Triassic Hawkesbury Sandstone or to the outcropping Narrabeen Group (around Areas 1 and 2 and the escarpment), and to the smaller isolated areas of swamp deposits.

Estimates of average or long-term rainfall recharge to surficial strata have been collated from a review of literature and from analysis of Dendrobium field data. According to Advisian (2016), the weight of evidence from multiple studies is that recharge to the Hawkesbury Sandstone is within a range of 0-8.5% of LTA rainfall.

Table 3-6 Summary of Recharge estimates

Reference	Analysis method	Recharge	
		% LTA rain	mm/yr
(URS, 2007)	water table fluctuation ("WTF")	3-10%*	n/a
(Office of Water, 2011)	unknown	6%	n/a
(Coffey, 2012a, 2012b)	Baseflow separation, WTF	2.7 or 6%	n/a
(Pells and Pells, 2013)	unknown	5%	50
(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	
(Crosbie, 2015)	Chloride mass balance in shallow groundwater.	3-8.5%	40-100
(HydroSimulations, 2016)	Chloride mass balance baseflow separation, WTF	6.5%	65
(BoM, 2018)	AWRA-L model (2005 to Apr-2022)	7.6%	92
This study	Soil moisture balance model (2005 to Apr-2022)	6.7%	87

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

A soil moisture balance model that accounts for varying rainfall and evaporation on a daily basis (from SILO), and accounts for soil moisture deficits was described in previous modelling presented in HS (2016 and 2019). This water balance model has been updated for this study.

The series of modelled recharge, as calculated by the water balance model on a daily basis and then aggregated into model stress periods, is presented on **Figure 3-15A**. The average recharge as calculated by the water balance model for the areas of rock outcrop is equivalent to about 6.7% of long-term average rainfall, which matches well with independent estimates made by BoM's AWRA-L model to Apr-2022 (7.2%).

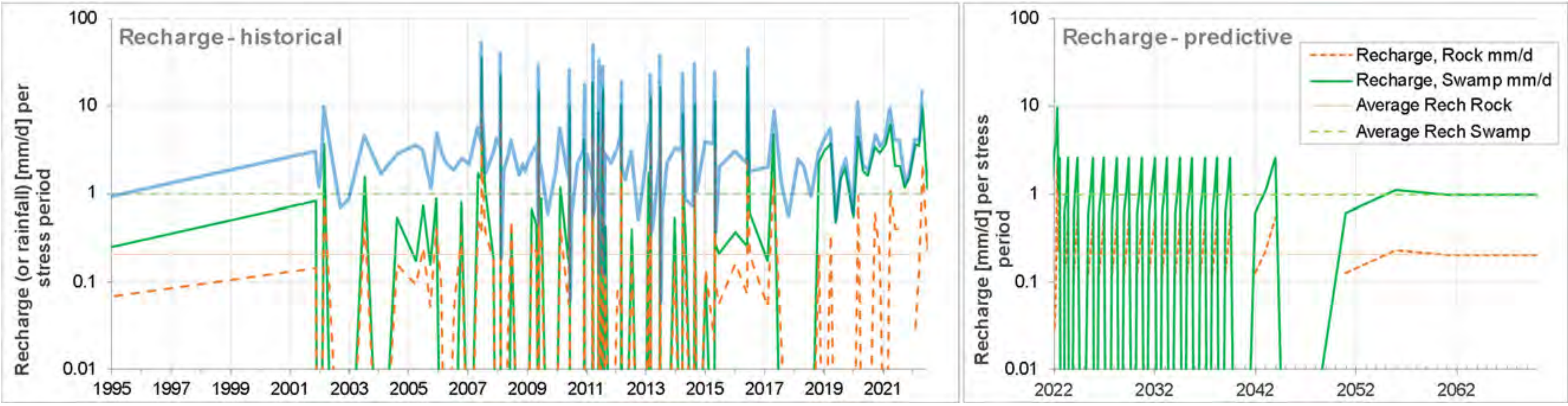
Of note from **Figure 3-15A** is the extended period of low (or no) recharge from mid-2017 to early 2020, followed by higher recharge in response to wet conditions through much of 2020 and into early 2021, and exceptionally high recharge in March and Apri-2022 (Section 2.3.1 and **Figure 2-2B**)

3.9.2 Evapotranspiration

The same soil moisture/water balance model described in the previous section also accounts for the energy balance (i.e. potential evaporation, PE). The model estimates actual evapotranspiration (AE) from the soil zone and keeps account of excess PE. This is calculated on a daily basis and aggregated into model stress periods, as shown on **Figure 3-15B**.

Of note from **Figure 3-15B** is the increase in PE and the resultant increase in potential evaporation demand on shallow groundwater during 2017 to early 2020. This was caused by both a lack of rainfall, and an increase in the PE.

A) **Modelled rainfall recharge**



B) **Modelled potential evapotranspiration from groundwater**

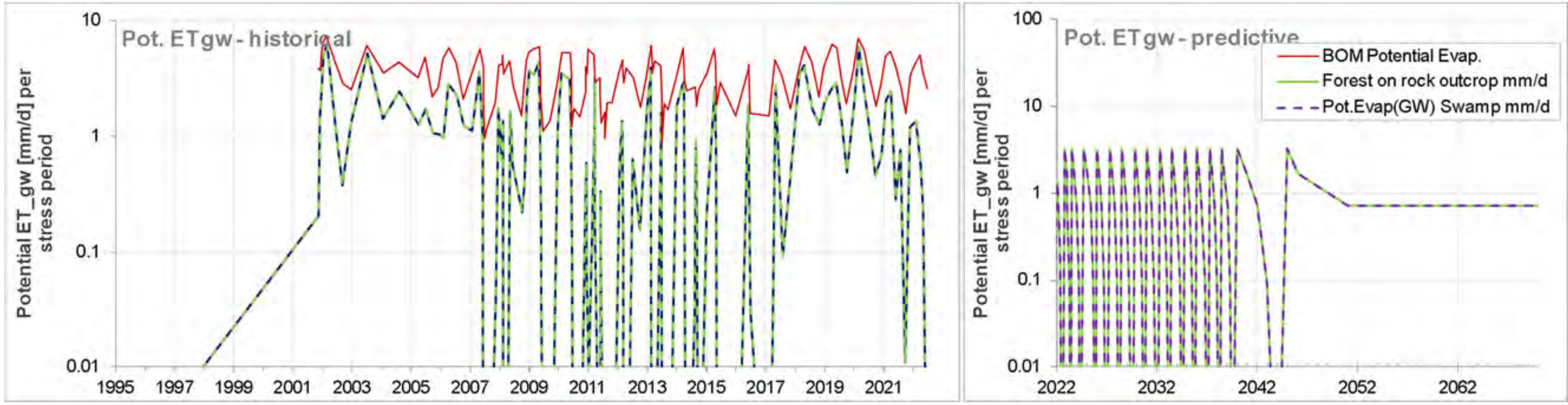


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Figure 3-15 Modelled recharge and evaporation timeseries

Evapotranspiration by vegetation is governed by rooting depth. A review of literature, including Canadell *et al.* (1996), Florabank[3], and Zolfaghar (2013) was carried out. Rooting depth is likely controlled by the geomorphology and depth of soil deposits. 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). Zolfaghar (2013) indicated the rooting depth for sclerophyll forest in the southern Sydney Basin could be up to 9 m.

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. Field work by SMI Environment Centres (2019) found that the vertical extent of roots within swamp deposits was 0.4-0.8 m.

3.9.3 Mine inflow

Groundwater inflow to mine workings cannot be directly measured but is determined through a 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[4]. This detailed water balance accounts for water that enters, circulates and leaves the mine (e.g. air moisture and coal moisture), and groundwater inflow is determined for each mine area.

Table 3-7 summarises the inflow to each area for the 12 months to the end of April 2022. This now includes a record for Area 3C, where first workings commenced in May 2020 – the recent apparent groundwater inflow to that area peaked at 2.6 ML/d, and this seems unreliable given only first workings are present. It is likely that water entering Areas 3A and/or 3B has been measured in Area 3C, which is located down-dip of those other areas. Total accumulated inflow over this period was approximately 2,230 ML, equivalent to a daily average of 6.1 ML/d.

Table 3-7 Dendrobium Mine inflow: 12-month summary for May-2021 to April-2022

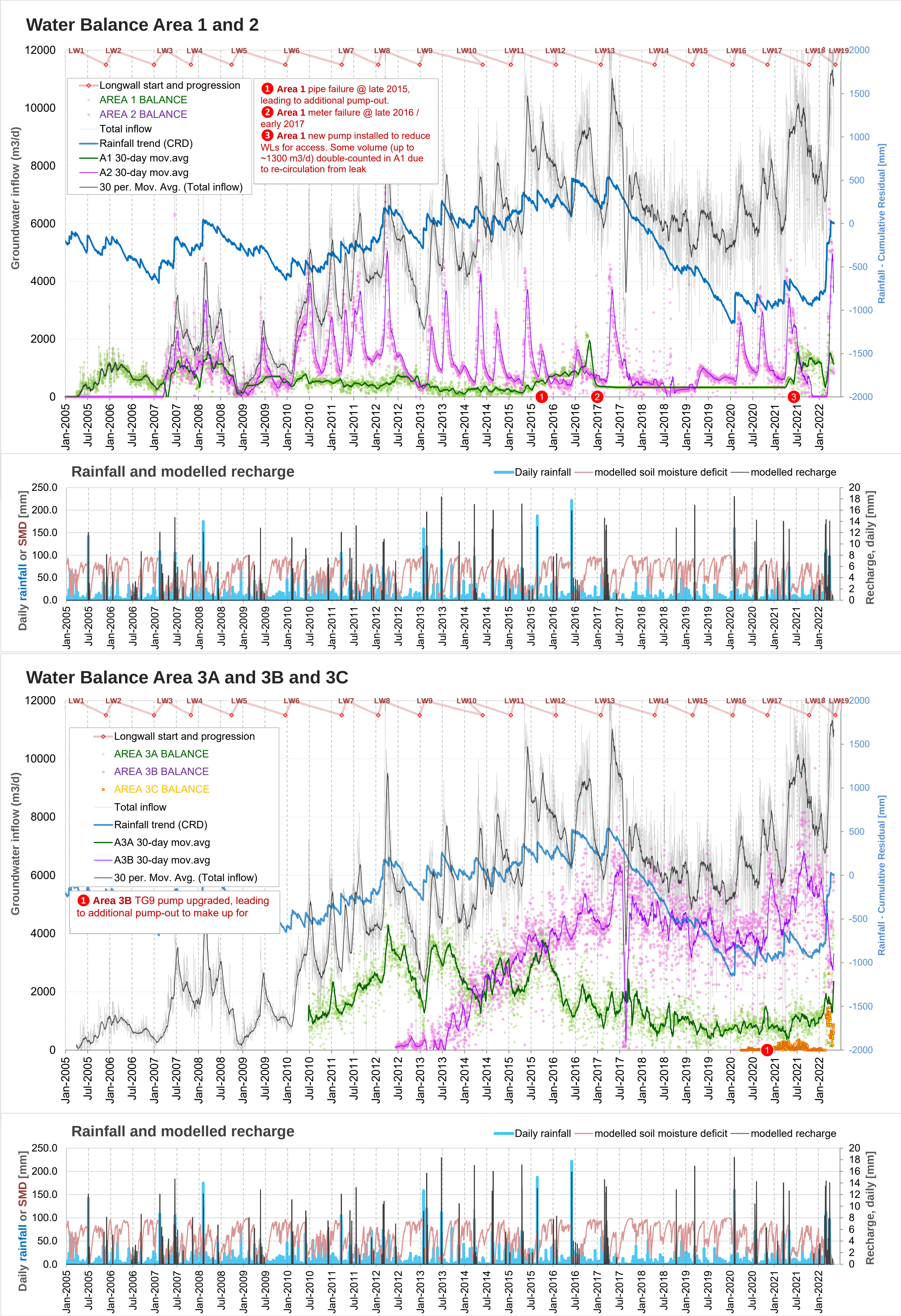
Statistic	Area 1*	Area 2	Area 3A	Area 3B	Area3C	Dendrobium Total
Minimum	0.0	0.01	0.13	0.81	0.00	1.14
Average	1.06	1.16	1.25	5.18	0.20	6.10
Maximum	2.18	6.82	5.77	9.68	2.62	8.18

Units in ML/d. *flowmeter in Area 1 failed in early 2017 → therefore the historical average is reported.

Figure 3-16 plots the record of groundwater inflow to Areas 1, 2, 3A and 3B in the context of longwall timing and rainfall trends (residual mass). IEPMC (2018) commented that there is "*need to consider the runoff-infiltration component in a cumulative way*". Modelled recharge has been included on the charts to show that the infiltration component, which is a function of accumulated rainfall and antecedent soil moisture conditions, is considered in our analysis. The recharge model used here, and for groundwater modelling, is described in Section 3.9.1.

Figure 3-16 shows that since the commencement of Area 3B total groundwater inflow to Dendrobium Mine has ranged between about 4,000-12,000 m3/d (i.e. 4-12 ML/d) (averaging 6.9 ML/d). The highest water-year total was 3,040 ML in 2016-17, however the 2021-22 water year is likely to see a similar total (probably in the range 3000-3200 ML).

[3] http://www.florabank.org.au/
[4] IMC Procedure DENP0049 – Mine Water Balance v4.0.



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Groundwater Inflow Trends by Mine Area **Figure 3-15**

Inflows have generally been greatest in Area 3B, then 3A, then Areas 2 and 1 respectively. In general, this corresponds with the total longwall area extracted. The other thing to note about the specific areas are the different character or shape of the hydrographs.

Area 1 has been consistently low, probably reflective of the presence of some overlying workings (Mt Kembla Mine), and lateral proximity to Kemira workings. Area 2 is most like a surface water hydrograph, responding quickly to short-term rainfall totals of >100 mm (approximately), but with a low ‘dry period’ inflow. Area 3A was also quite variable during the extraction of this area and for a few years after, but the inflow has declined and is a smoother hydrograph since about 2017. It is expected that extraction of Longwall 19 and then Longwall 19A would cause an increase in groundwater flow to this domain.

HGEO (2020c) reports on methods to identify and quantify rapid ingress of rainfall or surface water vs the inflow from older groundwater storage. These methods include a baseflow separation approach (to filter short- and long-term variation, similar to the approach of Mackie (2016) and finger-printing via inspection of tritium and other isotopes and general groundwater chemistry. **Table 3-8** summarises findings for Areas 2 and 3B, which are considered the ‘end-members’ in terms of inflow behaviour.

Table 3-8 Estimates of the source of mine inflow at Dendrobium Mine

Mine Area	Rainfall contribution from filtering/smoothing	Rapid ingress from baseflow separation	Tritium-based estimate of modern water
Area 2	90%	83%	Median = 21% 90%ile = 32%
Area 3B		13% (8-17)%	Median = 4% 90%ile = 12%
Source	(Mackie, 2016)	HGEO (2020c)	HGEO, pers.comm

Using a baseflow separation method, HGEO (2020c) estimated that the rainfall-induced component of inflow to Area 3B during three recent longwalls was 8-17% of the total (i.e. approximately 0.3-0.7 ML/d). For the first 7 years after commencement, approximately 1-2% of Area 3B inflow was considered to be modern water, with that trend rising over that period. That has risen to 4% considering the last 12 tritium samples (November 2019-February 2021), which would equate to approximately 0.2 ML/d over that period.

Despite potential for tritium to be absorbed or lost via diffusion or exchange in strata between the surface and the workings, it is clearly detected in Area 2 (**Table 3-8**) and the contrast, when considering the description of the inflow hydrographs (earlier in this section) is indicative that the contribution of modern water to Area 3B inflow is very limited.

Of note in recent times is the response to the heavy rainfall events in mid-February and in August 2020 (**Figure 3-16**), which were similar in magnitude to the rainfall event in early 2017. Area 2 inflow responded to this rainfall within a week, rising from 0.4-0.6 ML/d to approximately 3 ML/d and declining to <1 ML/, and then responding again (up to 6 ML/d) to record rainfall in March and April 2022 (Section 2.3.1). Until early 2021, Area 3A did not show any response to rainfall that appears to be the result of heavy rainfall events, and it appears to have responded mildly (to 1.5 ML/d) in April 2021, and then more noticeably to 2 ML/d in April 2022.

There was a spike in the Area 3B water balance in late-2020. Advice from IMC staff is that this was due to an issue with pumps in the underground which required increased pumping for a period to make up for an earlier shortfall, and not a true representation of groundwater inflow rates. Otherwise, inflow to Area 3B has not shown a response or spike that is clearly related to February or August-2020 rainfall events. This, therefore, does not support the concept of a rapid surface-to-seam flow path. More recently, heavy rainfall in April 2021 was coincident with the commencement of a rise in inflow to 6-8 ML/d in mid-2021, however the inflow for Area 3B (and 3C) seems unreliable for March and April 2022 (see earlier comment).

3.9.4 Baseflow estimates

Baseflow discharge to watercourses in the Dendrobium area was assessed using flow and EC data at a number of the gauging stations around Areas 3A and 3B. The estimated baseflow indices (BFI), baseflow yield (mm/yr) and % long-term average rainfall are summarised in **Table 3-9**. These estimates of BFI are consistent with the regional average of about 10% concluded by Advisian (2016). This analysis will be extended in future as more data is available from sites in other domains.

Table 3-9 Summary of calculated BFI and Baseflow Yield

Watercourse	Gauge	BFI	Baseflow yield [mm/yr]	%of LTA rainfall
Wongawilli Creek	WWL	10-16 %	31 to 50	2.5 to 4.2%
Donalds Castle Creek	DCU	1-6 %	1.5 to 10	0.1 to 1.0%
Sandy Creek	SCL2	8-20 %	22 to 55	1.8 to 4.6%
AR32	AR32S1	10-16%	5 to 8	0.5 to 0.8%
LA8	LA8S1	2-5%	5 to 12	0.5 to 1.2%

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

The higher porosity of swamp deposits means that these features are considered to supply reliable baseflow to watercourses for an extended period after rainfall. Further work by various agencies and researchers are investigating swamp water balances. 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) and catchment-specific factors (topography, slope, geology, rainfall). The relatively shallow nature of the swamp deposits also limits the volume of water that can be stored in them, despite their higher porosity.

3.9.5 Surface flow depletion

Mining-induced subsidence and depressurisation can result in behaviours such as reductions in low-flows and increase in the duration of cease-to-flow conditions. Reports such as HydroSimulations (2016) and McMahon (2015) discussed that, while the loss of surface flow in headwater streams that have been mined under, such as WC21, DC13S1, DCS2, is discernible on hydrographs for those streams (End of Panel reports for Longwalls 11-17), effects or losses due to mining were not always clear or may not be consistently evident through time. The loss of surface water flow is now better quantified in relation to the hydrology at 'Reference sites' (Watershed HydroGeo, 2019a). The latest End of Panel Reports (HGEO, 2019a, 2020d, 2021c, 2022b) showed that flow reductions due to mining were both clearly evident at headwaters streams WC21, DC13 among others, and could be quantified as being reduction in median flow (Q50) of about 30%, or 60% in the case of DC13, due to mining, along with a clear increase in the number of cease-to-flow days.

At downstream gauging stations which are more distant from longwalls (DCU, WWL) changes in surface water flow remain difficult to discern from natural variability (HGEO, 2019a, 2020d, 2021c, 2022b). At the end of Longwall 15 through to the end of Longwall 17, DCU shows a mild increase in the number of cease-to-flow days due to mining, but no effects are discerned for Q50 at this site, and no effects are detected at WWL. Similar to DCU, SCL2 on Sandy Creek (downstream of Area 3A) shows a small increase in cease-to-flow days (TARP Level 1), and a small reduction in median flow (small enough that the TARP is not triggered) (HGEO, 2022b). Site SCL2 is downstream from sites on SC10 and SC10C, which both show clear effects of Longwall 8 extraction (e.g. two TARP Level 3 for SC10C, and two TARP Level 1 triggers for SC10).

In the case of WWL, that no losses are detected could be because of gauging accuracy and the relatively small magnitude of loss compared to total flow at the downstream gauging stations. However, that argument is not valid for DCU, where the effects on Q50 at upstream sites DCS2 and DC13 represent a significant proportion of Q50 at DCU.

With respect to effects on Wongawilli Creek, while the recent End-of-Panel reports (HGEO, 2019a, 2020d, 2021c, 2022b) indicate no discernible effect beyond the scale of natural variability at WWL, the reach of Wongawilli Creek adjacent to Longwalls 6-14 experiencing very low flows (discontinuous flow) is likely to have increased. The reach from gauging station WWU to the confluence with WC21 (or the northern edge of Areas 3A and 3B) is termed here as ‘mid’ Wongawilli Creek. In the last few years, there has been a periodic cessation of continuous flow through this reach during very dry periods (including an instance identified in the Longwall 15 End of Panel report; HGEO, 2020a). The evidence is that this was not due to creek bed fracturing, as occurs in streams overlying or nearer to longwalls, but most likely by cumulative groundwater drawdown and depressurisation from the longwall areas located on the eastern and western flanks of the creek. This drawdown results in baseflow loss or capture of the residual ‘dry weather’ flows in the creek (Watershed HydroGeo, 2018).

The lack of significant effects at DCU or WWL, despite clear effects on hydrology in their headwaters, is consistent with both the findings on longwall-induced alteration of habitat by the NSW Scientific Committee and work at Waratah Rivulet (Mclean, Reece and Jankowski, 2010). 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).

This last point appears to be supported by the analysis for End of Panel 17 (HGEO, 2022b), which indicated that while there has been a clear reduction in flow and flow frequency at SC10Cs1 since mining, flows in this creek have recovered to similar to pre-mining behaviour since 2018. This suggests groundwater recovery (Section 3.7.2 and **Figure 3-12**) leading to increased baseflow support to the creek in dry periods.

4 Hydrogeological Conceptual Model

Section 4.1 outlines the conceptual model of the groundwater-related effects of longwall mines in general, refined based on data analysis for Southern Coalfield mines and Dendrobium Mine in particular. The potential effects of geological structures are outlined (Section 4.2), and the primary linkages or risk pathways for effects due to the proposed longwalls are summarised (Section 4.3).

4.1 Effects of longwall mining at Dendrobium

This section follows on from the literature-based review in Section 2.6 and **Figure 2-5**. As described in that section, 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 above longwall and pillar extraction areas. Another conceptual model was provided by the Dept. of Planning (2008) and other authors have developed similar or alternative conceptual schemes.

Based on review of the existing conceptual models (e.g. (Booth, 1986, 2002; Holla and Barclay, 2000; Guo, Adhikary and Gaveva, 2007; Mills, 2011; Tammetta, 2013; Ditton and Merrick, 2014), as well as analysis of data from Dendrobium, and discussion between hydrogeologists, geotechnical engineers and mine geologists, a conceptual model diagram has been developed and adopted for groundwater assessment and modelling, both in terms of the geomechanical behaviour and groundwater response. This conceptual model is described in **Figure 4-1** and **Table 4-1**, and draws in findings from HGEO (HGEO, 2020f, 2021d, 2021a) (Section 3.6) and End of Panel reports, e.g. HGEO (2021b, 2021c).

Table 4-1 is based mainly on the geotechnical zones proposed by Mills (2011), but with consideration of other published works. It is acknowledged that in reality, the conceptual zones are not clearly distinguished, and would occur as a continuum with gradual changes between zones.

The following text in this section describe the conceptual model of 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 4-1**, some of which are also listed in **Table 4-1**.

After panels of coal are extracted the strata immediately overlying the extracted seam collapses into the void (forming a 'goaf'). The strata above the goaf deform and fracture in response, and subsidence occurs at the ground surface, manifesting as a trough along the axis of the extracted panel. At Dendrobium, some mode of fracturing due to mining subsidence occurs from the seam to the surface (**Figure 4-2**).

This surface subsidence reduces the volume available to offset the extracted coal. MSEC (2020) shows subsidence of 0.8 m (above pillars) and approximately 2.0 m (along the longwall centreline) for Longwall 8, with an average subsidence of 1.5 m for a mined height of 3.9 m (about 40%). This leaves a residual void space of 2.4 m (calculated as 3.9 m – 1.5 m).

The strata in the lower parts of the fractured zone ①② shows significantly more low angle and high angle defects than host rock (**Figure 4-2**), and are known to have a substantially higher hydraulic conductivity ⑱ than the undisturbed host rocks ⑤:

- horizontal hydraulic conductivity (Kh) is known, from recent packer testing, to be increased by 2-3 orders of magnitude (Section 3.6.1); and
- vertical hydraulic conductivity cannot be measured directly, but based on the defect logging and presence of intense high angle fracturing, is assumed to be significantly higher than host strata.

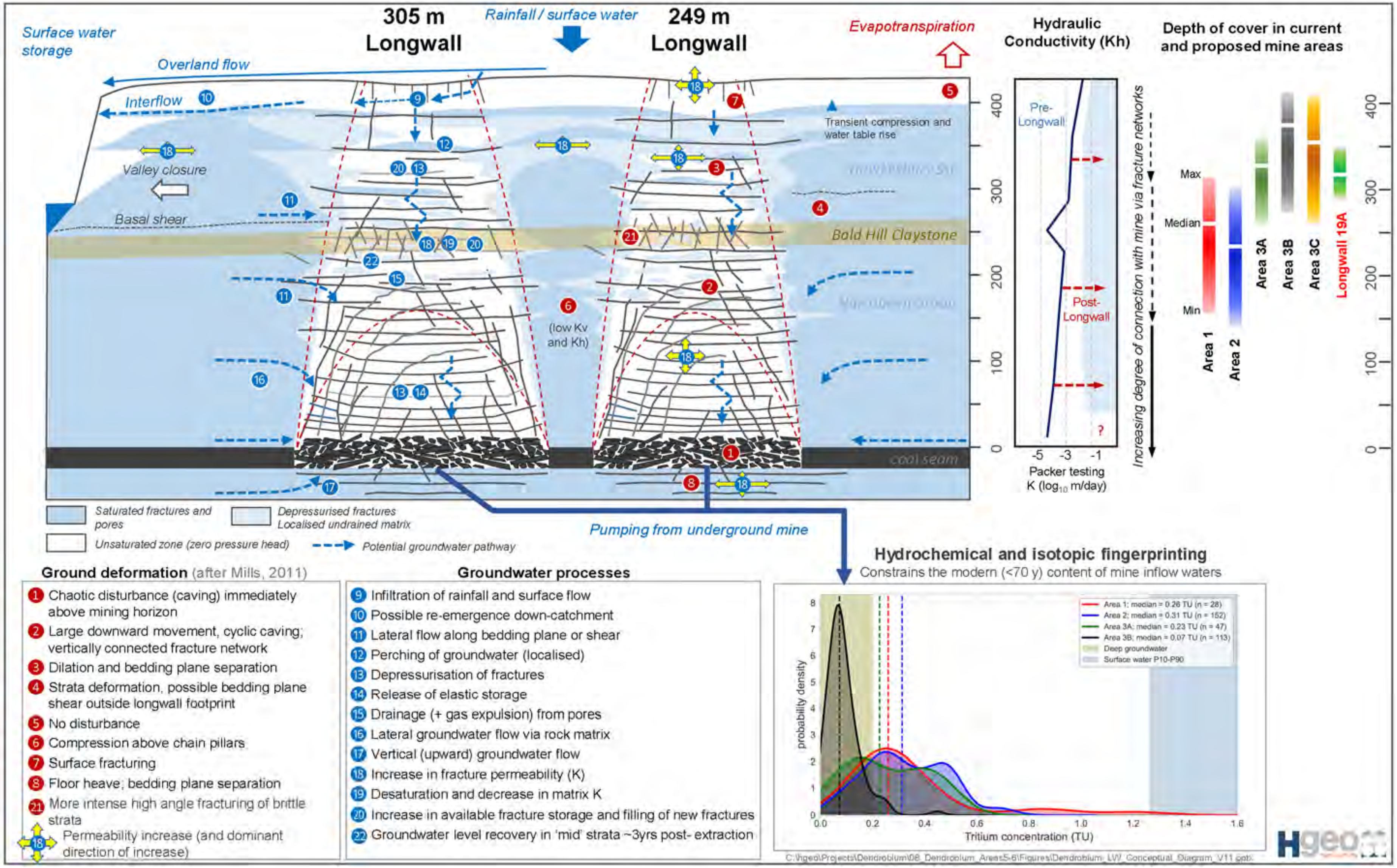


Figure 4-1 Geomechanical and groundwater conceptual model

This fracturing encourages groundwater to move out of storage (elastic storage (S or Ss) and drainable porosity, Sy) and drain downwards towards the goaf ⑬⑭⑮.

The intensity of high angle fracturing due to panel extraction generally reduces with height above the extracted panel, while low angle fracturing occurs more consistently to the surface (**Figure 4-2**).

This declining continuity between separate fractures with increasing height above the seam means that fracturing becomes gradually less well-connected in a vertical sense (i.e.), tending toward being vertically 'disconnected' ③). Kh increases due to the parting of bedding planes by 1-2 orders of magnitude in the upper part of the sequence above a panel, being enhanced more than Kv due to reduced frequency of these high angle fractures to act as vertical pathways.

Table 4-1 Conceptual zones of deformation associated with longwall mining

Conceptual Zone			Mills (2011)	Tammetta (2012)	Ditton (2014)	Geometry
⑦	Surface cracking 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. At Dendrobium, this may occur from the surface down to the Fractured Zone ③.
③	Zones of mostly horizontal shear offset from the longwall panel footprint			Disturbed Zone		Offset from goaf, extending approx. 600 m from longwall edge (but subject to ongoing assessment).
	Constrained Zone		Zone of no disturbance (#5)		C-zone	Based on packer tests, not considered to occur above Area 3B or Area 3A (Section 3.6.1, and Section 3.3 of HGEO, 2020c).
③	Fractured Zone	upper zone dominated by low angle defects ("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); or ▸ H (Tammetta, 2012)*.
②		lower zone of high angle defects ("Connected" Fracturing)	Zone of large downward movement (#2)	Collapsed Zone	A-zone	▸ 1 x panel width (W) (Mills, 2012); ▸ H (Tammetta, 2012)*; 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 seam (extracted panel)					Mined seam thickness (t) listed in Section 1.1
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 4-1**.
***** Tammetta's conceptual model is for groundwater response, not geomechnical changes, so can be applicable to both ② and ③**.**

In these zones where low angle fractures are numerous but high angle fractures much less so, 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, indicating an indirect connection (or a slow or low transmissivity pathway) to the fractured zone and goaf. That is, any high angle fracturing is insufficiently continuous or connected (i.e. insufficiently transmissive) to cause drainage of groundwater from the upper zone toward the mine workings and goaf. Furthermore, the observed significant changes to Kh will cause depressurisation due to lateral drainage.

At distances exceeding approximately 500-600 m from the mine, strata are assumed to be relatively unaffected ⑤ (noting that in different geological settings, such as the Western Coalfield, the effects of geological structure has been shown to result in changes to permeability and effects on environmental receptors to much greater distances (Section 2.5.1.1). This has not been the case for Dendrobium.

Within approximately 600 m of the longwall goaf minor enhancements to Kh may arise at specific horizons due to shearing along 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 and permeability to develop (HGEO, 2020a), and may even reduce Kh in these areas.

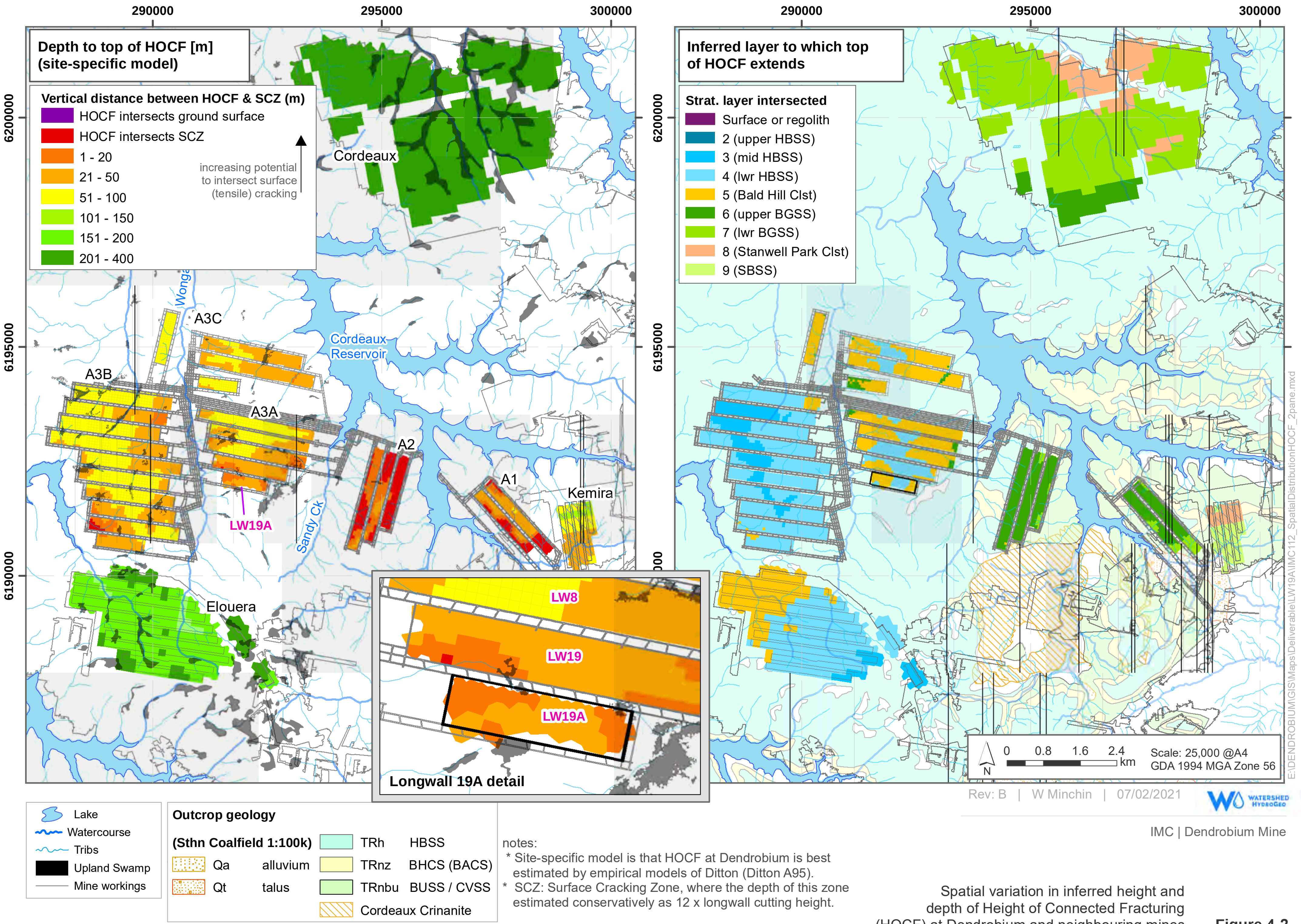
At mines where the depth of cover greatly exceeds the longwall width, strata overlying the fractured zones may sag but not significantly fracture, resulting in a degree of hydraulic isolation of those fracture zones from the surface and near surface (⑦ - see below). This is referred to as the 'constrained zone' by Booth (1986) and others 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. defects and fracturing are observed through the sequence above these longwalls (Section 3.6.1).

Further complicating the situation at Dendrobium is that the Bald Hill Claystone is shown to be more prone to high angle fracturing than adjacent horizons. The concept is that this unit is weaker or more brittle, and less able to resist subsidence and sagging than the neighbouring strata. ㉑

Groundwater level recovery has been observed 2-3 yrs after longwall extraction, occurring in the 'middle' of the column above longwalls (i.e. Bulgo Sandstone to lower Hawkesbury Sandstone). ㉒ This suggests that fracturing in this zone (or immediately below this zone) is not sufficiently connected in a vertical sense to cause persistent drainage, and while fracturing is known to be present, it must be primarily horizontal/sub-horizontal in order to allow this perching effect.

In the surface cracking 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 around the edges of the subsidence trough.

In areas where the connected fracture networks extending upward from the goaf intersect surface cracking extending downward from the surface, there is a significant risk of surface water being able to percolate downward and into the mine workings. The inflow record and water chemistry analysis suggests that this occurs in Area 2. A spatially distributed estimate of the connected fracture zone (CFZ) has been made using the relevant parameters at Dendrobium and at nearby longwall mines using the Ditton Geology Model A95 estimate (Ditton and Merrick, 2014). **Figure 4-2** presents this in terms of the vertical separation between the top of the zone and the base of the surface cracking zone (SCZ), and the stratigraphic unit in which the connected fracturing zone is estimated to extend to.



notes:

* Site-specific model is that HOCF at Dendrobium is best estimated by empirical models of Ditton (Ditton A95).

* SCZ: Surface Cracking Zone, where the depth of this zone estimated conservatively as 12 x longwall cutting height.

Spatial variation in inferred height and depth of Height of Connected Fracturing (HOCF) at Dendrobium and neighbouring mines

Figure 4-2

Figure 4-2 shows that the CFZ and SCZ are potentially connected (red shading) in Areas 1 and 2, and a small area of the western part of Longwall 17 in Area 3B, and a localised point in Longwall 19. Apart from these areas, there is variation in the mapping of the vertical separation between Areas 1, 2, 3A and 3B, with separation ranging 1 m (orange) to 100 m (yellow).

Noting that we have used a conservative cutting height of 3.9 m for Longwall 19A (see Section 1.2.3), the vertical separation distance is likely to be greater than >20 m in Longwall 19A, with areas under the tributaries at either end (east and west) of the panel having a separation of 1-20 m. The CFZ is estimated to extend to within the BHCS or the lower HBSS. The potential for seam-to-surface connection in Longwall 19A is therefore similar to previously mined areas at Dendrobium.

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, Donalds Castle Creek to DCS2, 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, such as impacts observed at LA4 (HGEO, 2017). MSEC indicate that the furthest observed effect was at 290 m from Dendrobium longwalls. Based on the experience along Wongawilli Creek between Areas 3A and 3B, MSEC (2022) assessed the potential of subsidence fracturing within the bed of Wongawilli Creek resulting in surface water diversion: "the likelihood … is low" due to Longwall 19A.

Where such surface fracturing occurs, it is likely to result in persistent or permanent changes to hydrology ⑨, such as the effects analysed in headwater streams around Area 3B which include 20-60% reduction in median flow and 15-40% increase in the average number of cease-to-flow days (HGEO, 2020d, 2021c, 2022b).

Surface water that is redirected into and through near-surface fractures ⑨ may either migrate downwards towards the goaf ⑬, be lost to some other process such as evapotranspiration, be returned to surface drainage somewhere down-gradient ⑩, or some combination of these. In the case of returned flow, net loss from the catchment is minimal. Recent analysis (Section 3.9.5 and HGEO (2020d, 2021c, 2022b)) indicates that the return of surface flows is very plausible, i.e. the strongest evidence for this appears to be in the Donalds Castle Creek catchment (the DCU gauging station), despite significant localised flow reductions immediately above extracted longwall panels (at DC13, DCS2). Leakage of water and transmission through the surface fracturing zone and re-emergence downstream can result in effects on water quality (McNally and Evans (2007), and HGEO (2020d, 2021c, 2022b)), especially in areas where groundwater levels recover to re-saturate freshly fractured strata.

Figure 4-3 shows a comparison of distance from each longwall to Wongawilli Creek and the 'frontage', which is a measure of the length of the nearest longwall edge to the creek.

Comparing these two parameters, Longwall 19A are likely to have effects on Wongawilli Creek that are similar to those of previous longwalls in Area 3B, and likely a lesser effect than others in Area 3A, noting the earlier comment and assessment by MSEC (2022) regarding surface fracturing. A comparison of the panel width/depth of cover (W/D) relationship indicates that same concept, although indicates that the W/D ratio is greater than for Longwalls 6 and 7, similar to 19, but less than for Longwall 8 in Area 3A, while at a greater distance compared to all of Longwalls 6, 7, 8 and 19.

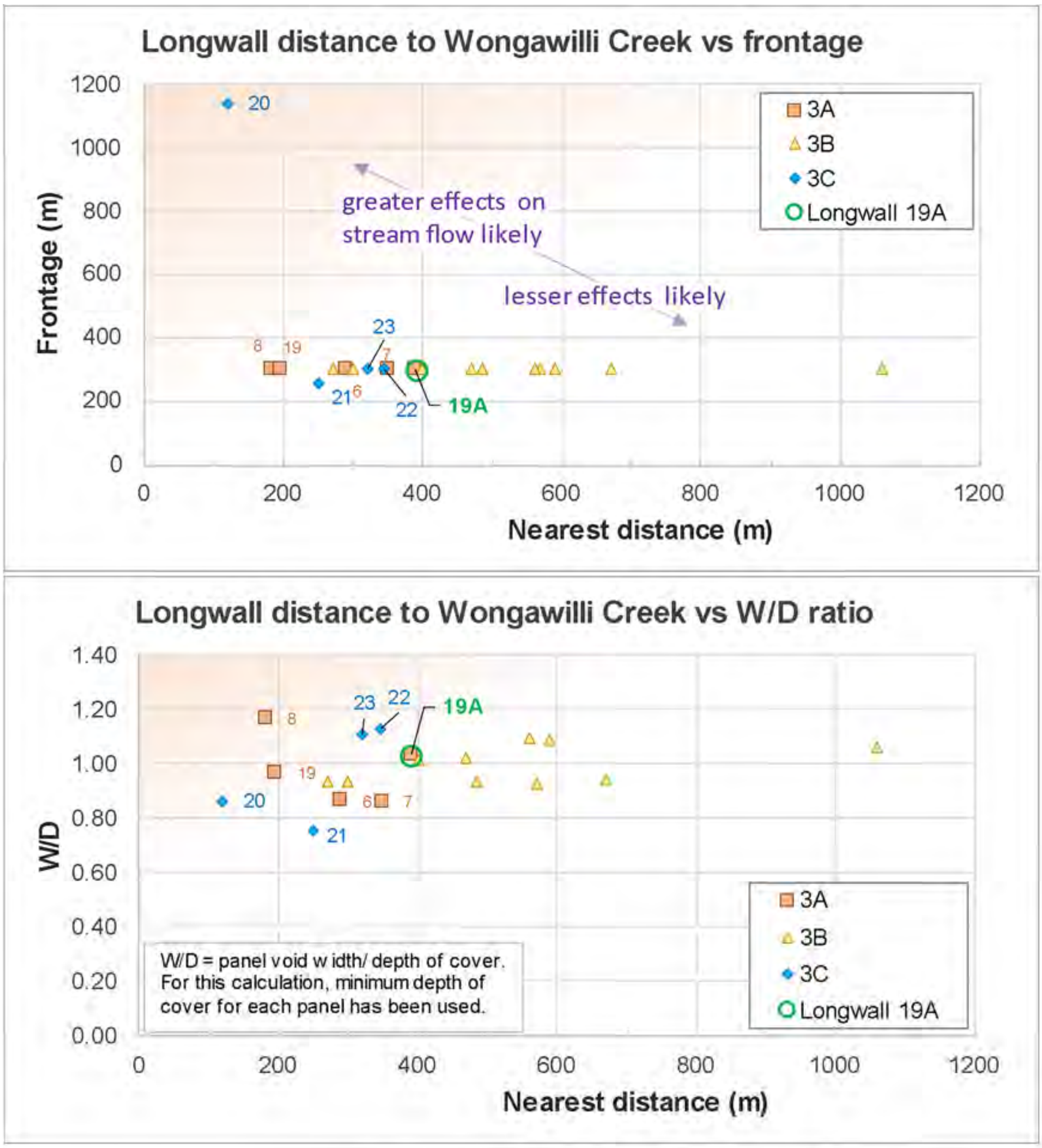


Figure 4-3 Distance and risk of flow reduction in Wongawilli Creek

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).

High angle fractures that are directly connected to the goaf and mine workings would form a pathway for seepage of pore water downwards towards the goaf and so rapidly depressurise. However, this does not mean that these areas contain no groundwater, but that there can be free drainage through the 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 4-1** is a schematic representation of monitoring data of post mining strata conditions at Dendrobium Mine and the conceptualised ‘likely’ case for longwalls in Areas 3A, 3B and 3C. There are a number of models for estimating the height of the zone of connected fracturing ② (discussed briefly in Section 2.6 and in PSM (2017) and IEPMC (2019a)). Observations of perching and recovery above extracted longwalls in Areas 3A and 3B is counter to the conceptual model of Tammetta (2013), which states “*This zone is severely disturbed and is completely drained of groundwater during caving. It is subsequently unable to maintain a positive pressure head. It will behave as a drain while the mine void is kept dewatered*”. The combination of defect logging (Section 3.6.1) and groundwater level response (Section 3.7.2) has led to the position that the Ditton Geology Model A-zone (or A95, as a slightly more conservative estimate) is the most suitable of currently available models to estimate the height of this zone of persistently draining strata.

There are also methods and schemes for estimating change in K (Tammetta, 2014; Guo, Adhikary and Gaveva, 2007). Significantly, the recent post-mining investigations have provided good quantitative data on the changes to Kh, and some ‘soft’ information on how Kv is enhanced (Section 3.6.1). The height of conceptual zones and K are tested during groundwater model calibration (Sections 5.4 and 6).

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 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 potentially providing a rapid and transmissive pathway for surface water to enter the mine. It is unclear at what distance from the fractured zone above the goaf these shear planes might be able to extend. 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.

Recent testing at the Lake Avon monitoring bores (SCT, 2017; HGEO, 2019b) did not consistently detect highly permeable discrete zones in the pre- or post-mining strata. SCT detected one at S2314, although “it is not considered to be a significant conduit for flow from the reservoir into the mine” (SCT, 2017). The development and/or enhancement of shear planes resulting from mining is the subject of ongoing research at Dendrobium.

Aside from the discrete basal shear features ⑪, there is potential for the modification 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, 2015). Hydraulic conductivity testing at bores located between Area 3B longwalls and Lake Avon suggests that Kh might be enhanced 2-3 times, or more, the host (pre-mining) value (~0.3 log units) (Section 3.6.3). However, this is not definitive and possibly not significant as often the post-mining permeabilities measured at Lake Avon monitoring sites have been within the expected range of (pre-mining) Kh.

Although the degree of enhancement of Kh in areas offset from a longwall is unclear and subject to on-going investigation, it is considered prudent that the effects of an increase in Kh are modelled

(Section 5.4.4). For the purpose of modelling, it is assumed that this effect could occur with declining significance to about 600 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. Upward flow through the floor is observed around the mine, and this is likely exacerbated by the deformation within the floor of the workings ⑧⑱.

This conceptual framework is in broad agreement with observed chemistry trends. Estimates of the modern water content for each mine area (see graph in **Figure 4-1**) 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 (Sections 3.8.3)) 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), such that the connection with surface water systems has not been observed or inferred from water fingerprinting and it follows that a slower, less transmissive connection exists between the goaf and surface water systems. Depth of cover at Longwall 19A, which is approximately 330 m on average is similar or slightly less than that of recent Area 3B panels, and has a 'minimum' depth of cover that is similar or slightly greater than most other recent panels (**Table 1-1**).

The greatest drawdown effects occur in the strata within or 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. The Bald Hill Claystone is also potentially within this 'connected' zone due to the brittle failure of the unit. The drawdown is often >50 m, or the strata become completely depressurised (pressure head is zero). Above the connected fractured zone is the disconnected fracture zone (i.e. where fracturing is poorly connected or disconnected ③), the degree of drawdown becomes less towards the surface. Drawdown can still be significant, e.g. 50 m or more in the lower Hawkesbury Sandstone, typically about 10-20 m in the mid-Hawkesbury Sandstone, and in the shallower horizons of the Hawkesbury Sandstone it has been observed to be approximately 5-10 m (e.g. at S2192-S2220 directly overlying Longwall 9 and in the 23-26 m pre- and post-mining piezometers in S2335/S2335A). However it is likely that groundwater can recover after a period of months to years, although this recovery may not be complete (i.e. back to pre-mining levels).

Groundwater drawdown in all units decreases with distance from the extracted panels. For example, and most importantly given the value of this aquifer compared to the other units in this area, within the lower Hawkesbury Sandstone drawdown is approximately 5-10 m at a distance of 1 km from the longwall (e.g. observed from bore S2009, among others). Deeper in the sequence, e.g. the Bulli Seam, 5-10 m drawdown occurs at about 2-3 km from extracted longwalls. 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.

Within Dendrobium Mine there are no domains or areas where inflow has ceased, although 'baseline' inflow to Area 2 is approximately 0.5 ML/d and inflow is clearly declining in Area 3A (down from approximately 2 ML/d to less than 1 ML/d in recent years) (Section 3.9.3). It is expected that drawdown would persist until after inflow ceases, and the mine re-fills and an equilibrium is re-established. The equilibrium groundwater levels may be at different levels to pre-mining conditions (either lower or higher), given the changes to permeability and porosity and consequent changes to recharge/discharge pathways or characteristics, as well as due to post-closure management (e.g. including the type and location of any bulkheads within the workings or the continuation of dewatering).

Some effects will persist, possibly for decades or even permanently. Most significantly, surface cracking effects in the bed of undermined watercourses or streams adjacent to longwalls, will likely persist in the long-term. Rehabilitation is a possibility, and trials are being planned at Dendrobium (WC21) and have been carried out at Tahmoor (Myrtle and Redbank Creeks) and other areas. The effectiveness of these schemes is mixed. If such measures are ineffective, persistent flow losses in creeks that are mined under, such as those estimated in recent End of Panel assessments (HGEO, 2020d, 2021c, 2022b), are likely to continue. Losses that occur to drawdown are more likely to be transient; these might be short-lived if caused by increased strata porosity, but if caused by drawdown within and around zones of connected fracturing they may persist long after dewatering ceases.

4.2 Structure

Geological structures are mapped on **Figure 2-3** and discussed in Section 2.5.1.

4.2.1 Lineaments

At Dendrobium, lineaments are rarely successfully correlated with a structural feature (fault, dyke) at seam level. Further, they have not caused difficulties to mine operations at Dendrobium, nor are mapped lineaments known to interact with water features (e.g. swamps, waterfalls) in a manner that suggest they exacerbate the risk of mining to such features or exacerbate the distance to which impacts manifest themselves (Section 2.5.1.1).

As described in SRK (2020) and Hebblewhite (2020), the Western Coalfield is different to the Southern Coalfield, and the experience at Dendrobium is different to that identified by IEPMC (2019a) at Springvale Mine. MSEC (2019) has indicated that subsidence anomalies along or around lineaments are obvious at Springvale Mine (in the Western Coalfield), with LiDAR mapping showing up to 30% more subsidence along these features, but enhanced subsidence around lineaments beyond the edge of longwall panels is not evident at Dendrobium.

Based on the interpretation above, and the current mapping of lineaments around Longwall 19A, there is no need to explicitly represent lineaments in the regional groundwater model.

4.2.2 Faulting

In terms of groundwater or hydrological effects, the key properties of the faults are:

- Current condition with respect to transverse transmissivity;
- Current condition with respect to longitudinal transmissivity;
- Potential for fault reactivation and possible changes to hydraulic conductivity.

In general terms, transmissivity across the fault plane (i.e. transverse connectivity) is governed by stratigraphic units that are adjacent across the fault plane, including any juxtaposition of these due to offsets (**Figure 4-4**), and the presence and properties of any fault gouge within the core of the fault.

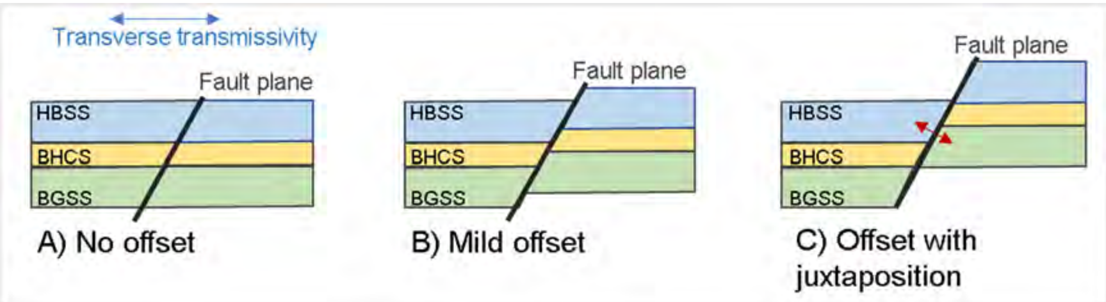


Figure 4-4 Conceptual models of transverse transmissivity and offset strata

These are addressed in the following paragraphs.

There are no faults mapped near Longwalls 19 and 19A (Section 2.5.1). This means there is minimal potential for faulting to juxtapose differing strata, and therefore transverse transmissivity is considered to be the same as un-faulted strata. This conclusion ignores the potential role of any fault gouge in the core of the fault; the presence of such material is likely to further reduce transmissivity in this direction.

Longitudinal transmissivity, i.e. along the plane of the fault, in the current environment will be governed by permeability within the fault zone. Because of the lack of faulting near Longwalls 19 and 19A, there is little evidence for movement that would result in fracturing and deformation that would enhance permeability. Therefore faults are not considered a likely risk in terms of connecting mine workings or goaf to significant environmental features (swamps, creeks, reservoirs).

The extraction of longwall panels changes the stress regime in the ground surrounding the panel, and in this case, there is concern that the extraction of longwalls could alter stress conditions in a way that reactivates faults. Given the lack of mapped faults in this area, this is not considered to be a risk around Longwall 19A.

4.2.3 Dykes

NNE-SSW trending dykes that are mapped in Longwalls 8 and 19 (Section 2.5.1 and **Figure 2-3B**) are present within the Wongawilli Seam. These dykes are not mapped in the roadways adjacent to Longwall 19A, so are unlikely to be present within the proposed panel.

Some degree of igneous intrusion and heat effected coal are likely to be present along the southern edge of Longwall 19A.

The strata above the coal measures are not thought to be intruded by the dykes and intrusions, so are not affected by these features. Therefore drawdown from the Longwall 19A would be transmitted within the Scarborough, Bulgo and Hawkesbury Sandstones and intervening claystones in a manner similar to that observed elsewhere around Dendrobium longwalls (see hydrographs in Section 3.7.2).

4.3 Mine closure

Following mine closure and the cessation of mine dewatering, groundwater levels will recover and flood the workings.

The deepest parts of the mine will flood first (currently that is Areas 3C and 3B), followed by Area 3A, then Area 2. SLR (2022) describes the plan for closure, including the emplacement of bulkheads between Area 1 and 2 to modulate discharge from the mine toward Area 1 and the portals at the escarpment. The simulation of mine closure is presented in Section 5.3.7, with forecasting of groundwater levels and fluxes presented in Sections 7.3 and 7.4.

Eventually groundwater levels above and surrounding the mine will reach a new equilibrium. The equilibrium groundwater levels may be at different levels to pre-mining conditions (either lower or higher), given the changes to permeability and porosity and consequent changes to recharge/discharge pathways or characteristics, as well as due to post-closure management.

Recovery and flooding of the workings has the potential to result in discharge of groundwater in two broad areas:

1. within the Special Area above Dendrobium Mine (including Longwall 19A), if groundwater levels rise to levels above topographic elevations.
2. at the Illawarra Escarpment:

- via Dendrobium Mine portals;
- through natural discharge locations in the coal seams and adjacent strata along the escarpment, eventually to watercourses along the coastal plain; and
- through neighbouring and adjacent mine workings (i.e. Nebo/Wongawilli Mine, Kemira and Mt Kembla), eventually to watercourses along the coastal plain.

Estimates of impacts related to post-mining groundwater discharge are presented in Section 7.4.3. It is not expected that extraction of Longwall 19A would have a discernible effect on water quantity or quality effects in the short- or long-term following mine closure.

4.4 Risk pathways

Based on the data analysis and conceptual model, the primary risk pathways whereby longwall mining at Longwall 19A, could or would interact with environmental or water features are summarised below. The potential pathways are considered, with reference to risks due to faults (IESC, 2021), the structures mapped and described in Section 2.5.1, and in the context of literature, e.g. Tonkin and Timms (2015), and experience at Dendrobium and in the Southern Coalfield in general.

- Groundwater drawdown at Wongawilli Creek, reducing baseflow and leading to a reduction in surface water flow in the creek, which is likely to manifest itself as an increased duration or frequency of 'cease-to-flow' events in this creek, and extending the length of the creek that this effect occurs, noting that this effect was observed between Areas 3A and 3B during the significant drought periods in 2018 and 2019 (Section 2.3). This effect could be exacerbated by ground movement in strata along the flank or the base of Wongawilli Creek valley (beyond the panel footprint), similar to that observed around Avon Reservoir shoreline and Area 3B. There are minor lineaments mapped to the southwest of Longwall 19A. There are no faults mapped that indicate a pathway or increased connection between Longwall 19A and Wongawilli Creek.

- Similar processes could affect tributary SC10, which is the main tributary to Sandy Creek. Because it is closer to Longwall 19A than Wongawilli Creek is, it is more likely that fracturing and water table decline would occur and affect this creek, with resultant effects of reduced flow (detected via changes to median flow) and increased low-flow and cease-to-flow frequency and duration.

- Direct subsidence beneath parts of tributary SC10B (flowing over the pillars of Longwalls 19 and 19A), and minor subsidence effects and drawdown at tributaries SC10A (south of Longwall 19A), WC13 (southwest of Longwall 19A) and WC14 (west of Longwall 19A). Cracking is likely to occur at SC10B, and groundwater drawdown would occur near all of these, leading to reduced surface water flow and increased cease-to-flow frequency above and adjacent to the longwalls. There is no faults identified that are relevant to these tributaries (Section 2.5.1). Surface cracking effects at SC10B would result in loss of flow in that creek (Sections 3.6.2 and 3.9.5). Other than the minor lineaments near to WC13 (southwest of Longwall 19A), there are no structures, particularly no faults, associated with the other features listed here.

- Groundwater drawdown or pressure reduction around many longwalls at Dendrobium has or would cause reduced baseflow and/or result in leakage from adjacent water supply reservoirs. However it is considered that leakage from Cordeaux Reservoir (or Avon) would not occur as a result of Longwall 19A due to the distances involved, as indicated in **Figure 4-5** (and quantified from modelling in Section 7.4.4). This conclusion is made considering geological structures and potential pathways related to these:

- Longwall 19A is adjacent (200-300 m south of) a set of SSW-NNE trending dykes (“DD38” and “DD39”) that extend (from the neighbouring Longwall 19) toward Sandy Creek near Cordeaux Reservoir. These dykes are not considered a pathway for groundwater transmission, and the distance to the reservoir (approximately 1.5 km) is significant.
- There are no faults mapped near Longwall 19A that intersect or are oriented toward the reservoir.

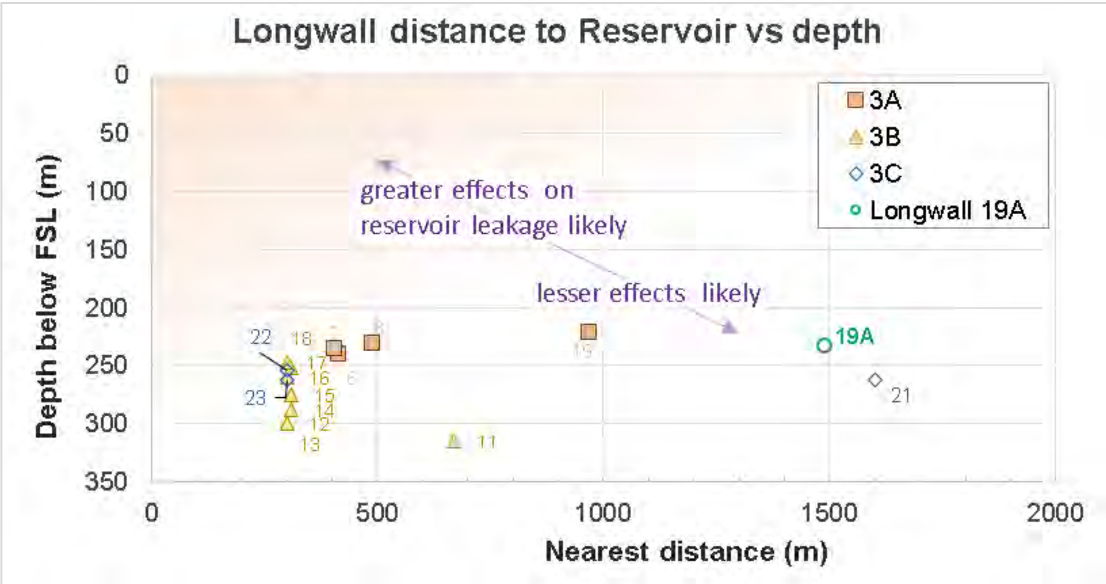


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Figure 4-5 Distance and risk of effects on adjacent reservoirs

- Direct subsidence beneath the most upstream part of Swamp 148, the satellite swamp at the top of tributary SC10B, and the upper part of Swamp 34; surface cracking leading to loss of baseflow, or more likely, increased leakage from these surficial deposits. The Surface Water Assessment (HGEO, 2022a) has more detail. There are no faults (or lineaments) mapped at or near these swamps, or Swamp 15a which is offset from Longwall 19A.

5 Numerical model development and history-matching

As noted in Section 1.5, numerical groundwater modelling has been carried out for Dendrobium since 2007. As IEPMC (2019a) indicate, over this time the requirements of the modelling and the complexity of modelling undertaken has advanced considerably. In response to a recent request by WaterNSW, a brief summary of the history of groundwater modelling at Dendrobium is provided in **Appendix B**.

The groundwater modelling for this study builds on the modelling for the recent DMEP EIS for proposed Area 5 (Watershed HydroGeo, 2022). The following sections are brief, for the purpose of an SMP application. They focus on the key aspects of the modelling and recent modifications.

5.1 Model objectives

The groundwater modelling is required to inform IMC and regulators as to the potential effects of Longwall 19A, in the context of other approved and proposed Dendrobium mine workings. This includes providing incremental and cumulative impact estimates of:

- Groundwater inflow to Dendrobium Mine workings;
- Groundwater head responses (drawdown and possible recovery);
- Changes to surface water flow in nearby watercourses;
- Induced leakage from water supply reservoirs; and
- Discharge from Dendrobium portals following mine closure.

5.2 Model implementation

5.2.1 Software selection

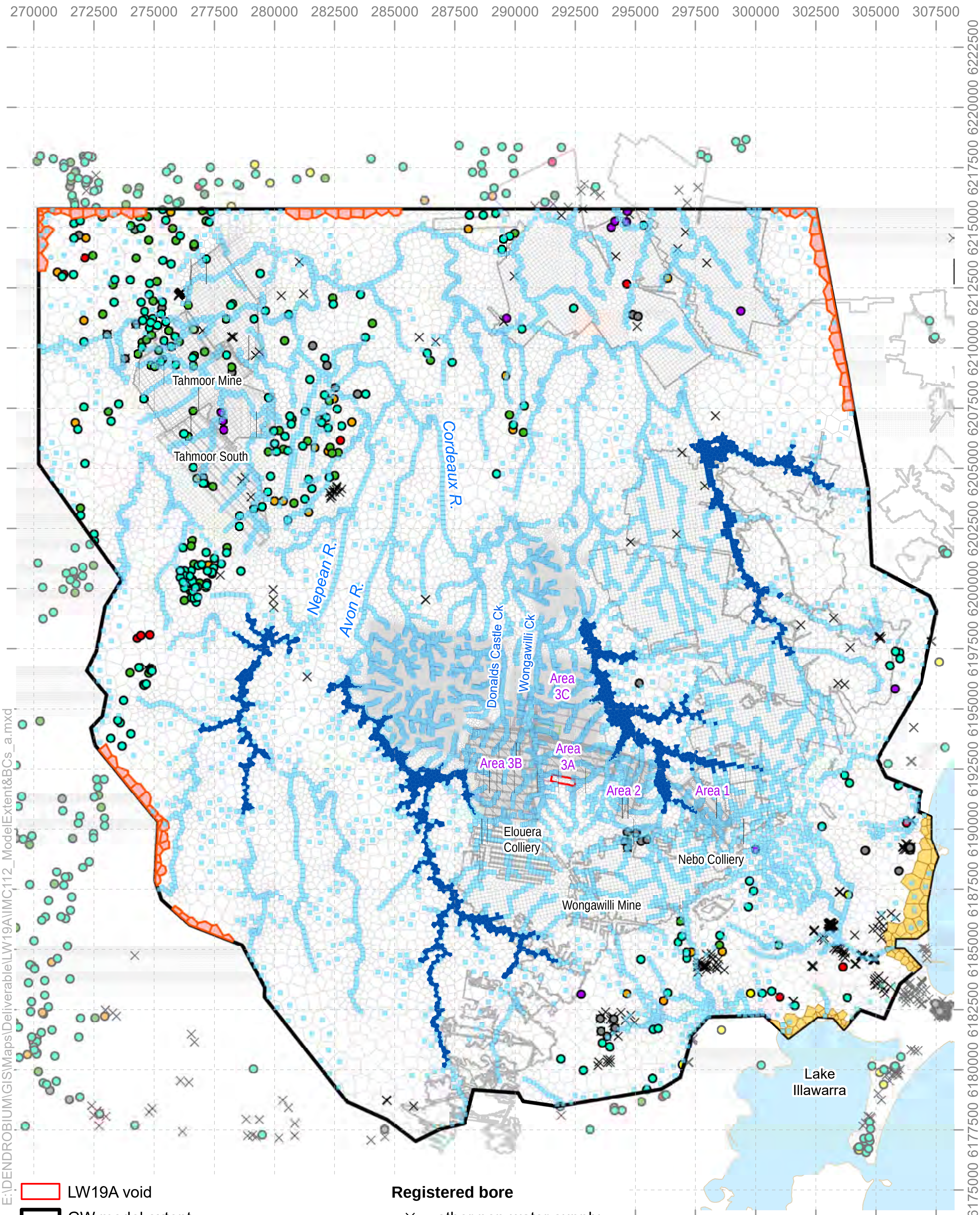
As described in more detail in **Appendix B**, over time the numerical modelling has progressed from 2-dimensional (2D) 'slice' modelling in GHD (2007) to 3D models of Coffey (2012b) and subsequent. Coffey and HydroSimulations (up to and including 2014) used MODFLOW-SURFACT. Later models rely on MODFLOW-USG (Panday *et al.*, 2013), which has come to be the industry standard in Australia. This version of the Dendrobium groundwater model, like other recent versions, uses the enhanced version of MODFLOW-USG, sometimes referred to as MODFLOW-USG-beta or MODFLOW-USG-Transport (Panday, 2022). The current software version is USG-T v.1.10.0.

The model uses the 'upstream weighting' method for simulating unsaturated conditions (similar to the 'pseudo-soil' function in MODFLOW-SURFACT), as per recent modelling. Some earlier versions of the Dendrobium groundwater model have used Richards' equation (e.g. HS, 2014; 2016). The head closure criterion specified in the MODFLOW-USG SMS solver was set at 0.02 m, which is appropriate for the objectives and has not affected the model mass balance error (Section 6.3).

5.2.2 Model mesh and spatial discretisation

The model mesh utilises the 'unstructured' capability of MODFLOW-USG and primarily uses the Voronoi style model mesh, meaning that model cells can be almost any shape and with variable dimensions. Also, layers do not have to be fully extensive across the model domain.

The model mesh was created using AlgoMesh Software v2.0 (HydroAlgorithmics, 2020). Greater cell refinement was applied to areas of interest, such as mine footprints and watercourses. Cells within the mining footprint were given a regular grid structure (i.e. square cells) oriented as consistently as possible with longwall panels. **Figure 5-1** shows the model mesh geometry as well as indicating the boundary conditions applied to the model.



LW19A void
GW model extent
Stream (SFR) boundary condition
Lake (RIV) boundary condition
General head (GHB) boundary condition
Constant Head (CHD) boundary condition

Registered bore

× other non-water supply

Purpose

- Water Supply
- Commercial and Industrial
- Irrigation
- Stock and Domestic
- Other
- Unknown
- Dewatering

Scale: 210,000 @A4
GDA 1994 MGA Zone 56

N

0 1.5 3 4.5 km

WATERSHED HYDROGEO

IMC | Dendrobium Mine

Groundwater model extent and boundary conditions

Figure 5-1

Cells used to represent the mining areas at Dendrobium (Areas 1-3B) are given a uniform width and length of 60 m, while those for future domains (Areas 3C, and 5) are assigned uniform width and length of 50 m. The recent addition of Longwall 19A to the mine plan means that this panel is not simulated with a regular mesh in the groundwater model. The 49 model cells used to simulate Longwall 19A have an average dimension of 75 m, as shown on **Figure 5-2**. Importantly, there are at least four model cells between Longwall 19A and Wongawilli Creek, and at last one cell between the panel and the nearest point on tributary SC10, and this is appropriate for the simulation of drawdown effects.

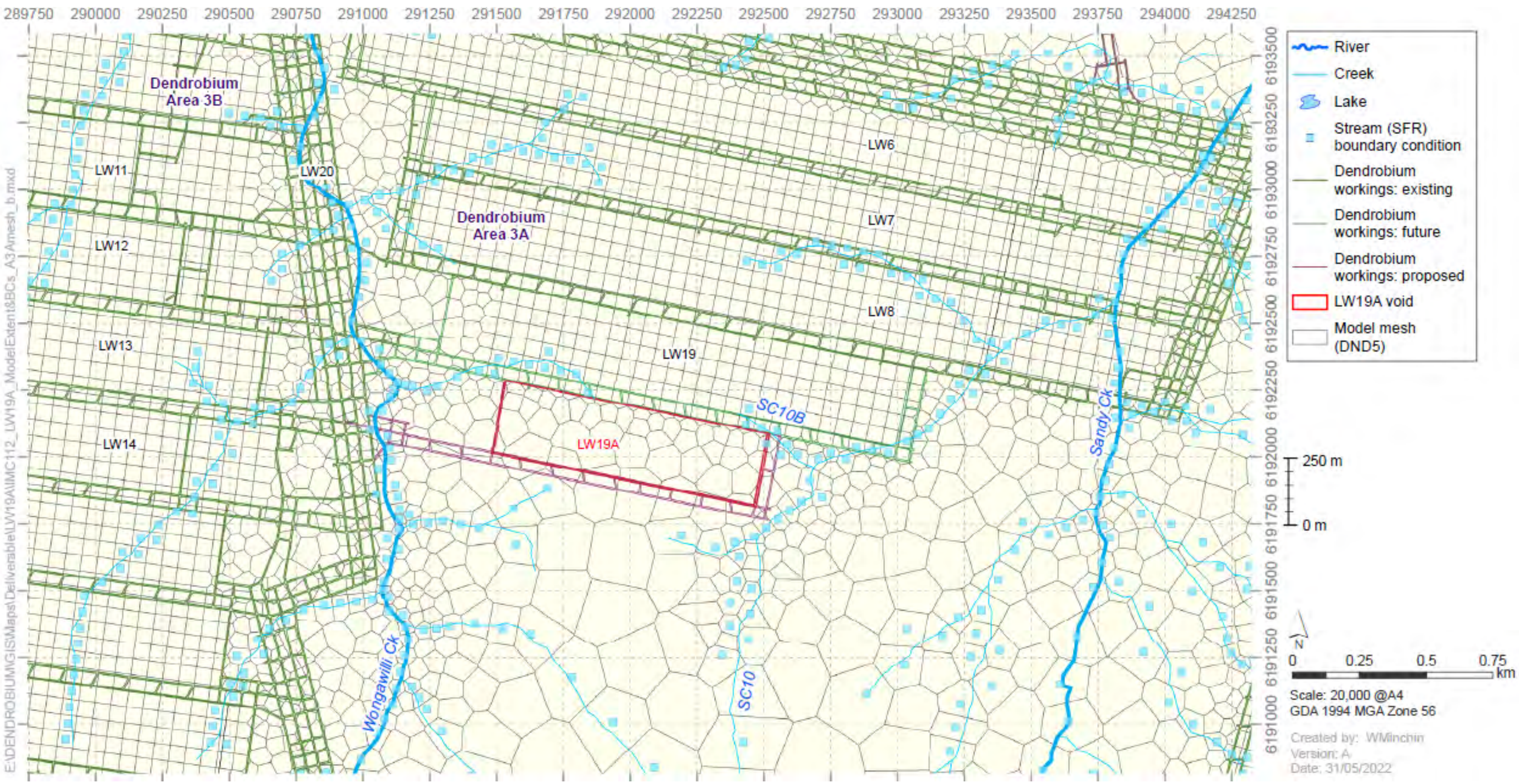


Figure 5-2 Detail of model mesh and cell size in Area 3A

The model consists of 17 layers (as per the DMEP EIS model; WatershedHG, 2022, and recent SMP assessments). Each layer has a maximum of 47,359 cells. The 'pinch-out' functionality was used for this model and removed any cells where the thickness was calculated as less than 0.1 m. This results in a total of 741,889 active cells.

5.2.3 Hydrostratigraphy and model geometry

Table 5-1 summarises the stratigraphy framework for the 17 layers adopted in this project. This is the same as in modelling for Dendrobium since 2019. The geometry of the model layering is based on the geological model supplied by IMC, which is defined by hundreds of exploration drill logs. Layers have a variable thickness across the model domain, but the average thickness across the model domain and the typical thickness at the centre of Longwall 19A are described in **Table 5-1**.

Table 5-1 Model layer assignment

Layer	Stratigraphy	Secondary Lithology	Thickness [m], mean	Thickness, Longwall 19A
1	Regolith	Swamp deposits	Regolith: 5, swamp: 2	Regolith: 5
2	Hawkesbury Sandstone (upper)		24	0
3	Hawkesbury Sandstone (middle)		40	35
4	Hawkesbury Sandstone (lower)	Crinanite (Area 2)	33	40
5	Bald Hill Claystone	plus overlying Garie and Newport Fms / Crinanite (Area 2)	27	32
6	Bulgo Sandstone (upper)	Colo Vale Sandstone (Area 3B) / Crinanite (A2)	53	51
7	Bulgo Sandstone (lower)	Colo Vale Sandstone (A3B) / Crinanite (A2)	40	51
8	Stanwell Park Claystone	Colo Vale Sandstone (A3B) / Crinanite (A2)	17	16
9	Scarborough Sandstone	Colo Vale Sandstone (A3B) / Crinanite (A2)	35	40
10	Wombarra Claystone	Crinanite (A2)	25	25
11	Coalcliff Sandstone	Wombarra Formation (A3B)	11	16
12	Bulli Coal Seam		2.3	2.0
13	Eckersley Formation	Includes Lawrence and Loddon Sandstones	28	28
14	Wongawilli Coal Seam	(working section)	4.2	4.1
15	Kembla Sandstone		19	20
16	lower Permian Coal Measures		24	25
17	Shoalhaven Group and older		100	100

Thickness from E:\DENDROBIUM\GIS\Data\Model\AlgoMesh\Output\DND5v1\DND5v1.shp

5.2.4 Model temporal discretisation

The model stress period schedule is included as **Appendix C** to this report, along with annotations of longwall extraction and rainfall events mentioned below. The stress period schedule has been modified slightly for this study from that used in modelling for the recent DMEP EIS (Watershed HydroGeo, 2022).

The modelled time period, covering 1940 to 2200, is discretised into a total 218 stress periods:

- 132 stress periods for the historical period, 1940 to April-2022, including a steady state stress period in stress period 1 to initialise groundwater levels in response to model hydraulic properties and recharge.
- 86 stress periods for the predictive period, May-2022 to 2200, including the remaining approved/proposed mining in Areas 3A and 3C (see **Table 1-1**), and then the post-mining period (post-closure) to 2200, selected as a nominal year in the "long-term future".

Stress periods are set at a fine resolution for the duration of historical, approved and proposed mining at Dendrobium so that each longwall was typically represented by 3 or 4 stress periods. This allows simulation of the progressive changes to the groundwater system in response to longwall extraction.

Furthermore, to attempt to simulate the dynamics of very high rainfall periods, such as those leading to the 'inflow' events observed in Area 2 (Section 3.9.3), the key events have been identified. A series of shorter stress periods of a few days or a week have been defined to capture the intense rainfall event and the following period where the bulk of the inflow occurs. Fifteen such high rainfall/inflow sequences or events are included in the model time period (**Appendix C**).

5.3 Boundary conditions

Almost all the boundary conditions remain identical to the modelling presented in recent modelling (Watershed HydroGeo, 2021a, 2022). A summary of the boundary conditions is presented below, with emphasis on any changes.

5.3.1 Rainfall recharge

Rainfall recharge is simulated using the MODFLOW Recharge (RCH) package consistent with previous modelling (e.g. WatershedHG (2022)).

The model domain is divided into three zones representing broad 'average rainfall' zones, aligned with BoM long-term average rainfall contours, with higher rainfall and recharge at the top of the escarpment, declining to the west (away from the coast), consistent with estimates by AWRA and Crosbie (2015). These are then sub-divided into two zones based on outcrop geology: unconsolidated (swamps) and rock units. The recharge rate for the area immediately around or above Dendrobium mining areas (Zones 3 and 6, **Figure 5-3**) is the subject of the calculations described below, and then the recharge to the inland and escarpment areas (which are generally drier and wetter, respectively) has been weighted by comparison with the results of Crosbie (2015).

Temporal variation in rainfall recharge to the area above Dendrobium mining areas has been calculated based on a water balance calculated on a daily timestep and accounting for runoff, soil moisture deficit and recharge based on inputs of rainfall and potential evaporation (Section 3.9.1). Rainfall and potential evaporation data are available from several sources:

- Dendrobium site data for the Centroid, Area 3B, Area 1-2 and Area 5 stations; and
- SILO Data Drill records for a location situated approximately in the middle of all Dendrobium areas (Lat. -34.4, Long. 150.7).

This water balance has been calibrated against literature values, especially Crosbie (2015) and AWRA model estimates by BoM (Section 3.9.1). The modelled estimates of recharge were then aggregated across model stress periods (**Figure 3-15**). Estimates of rainfall recharge to unconsolidated deposits within swamp areas are not available but are conceptualised as being more than that of the rock outcrop. As a result, average modelled recharge of about 330 mm/year is assumed, equivalent to 25-30% of long-term average rainfall. On-going research by universities may improve on these estimates in future.

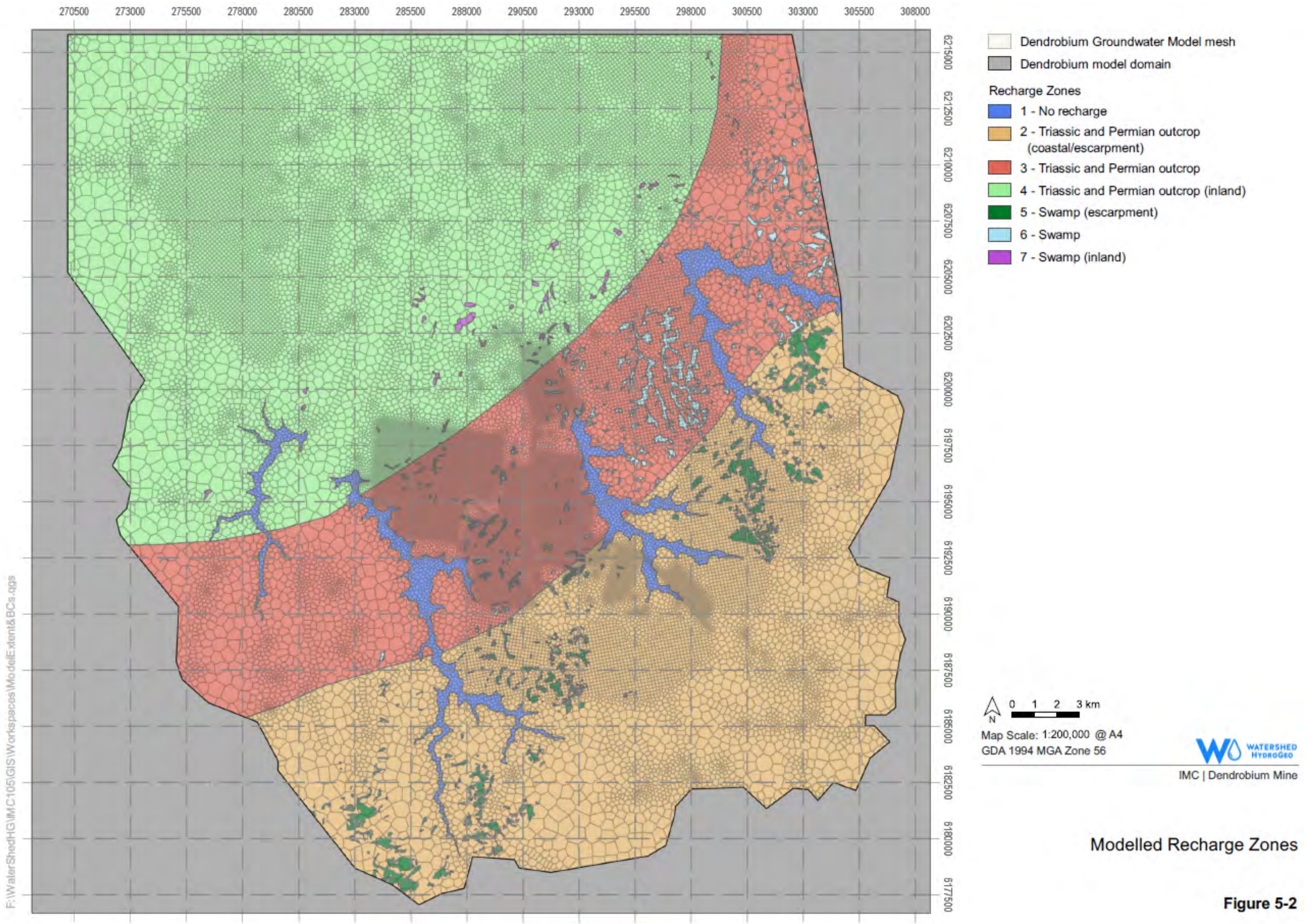


Figure 5-3 Model recharge zones

The groundwater model simulates variable recharge rates until model stress period 132 (equivalent of April 2022), and then a repeated sequence of recharge at 10th/30th/50th/70th/90th percentiles of the annual averages as calculated from the period to end 2021 has been utilised to simulate recharge for stress periods 133-212 (year 2050). This is used to provide some understand of effects under variable weather conditions. Average recharge rates (2000-2022) are used for the remaining period 2051-2200.

5.3.2 Evapotranspiration

The water balance model outlined in the previous section provides estimates of evapotranspiration in the soil zone. Where there is an excess of potential evaporation (PE) on a day during the sequence, this excess PE is then averaged across model stress periods and applied to the MODFLOW model via the Evapotranspiration (EVT) package. The potential rate of evapotranspiration from groundwater was modelled at approximately 700 mm/yr for the outcropping rock at Dendrobium, and approximately 300-400 mm/yr for swamps. No evapotranspiration is simulated from lake or reservoir areas.

Rooting depths ('extinction depths') were set at 4.5 m for areas on outcropping rock, which are primarily sclerophyll forest. This is based on literature (e.g. Zolfhagar, (2013)), but then modified based on previous modelling at Dendrobium. The vertical extent of roots within swamp deposits is likely to be in the range of 0.4-0.8 m, based on information in SMI Environment Centres (2019), and 0.8 m has been adopted in the model.

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

5.3.3 Reservoirs

MODFLOW 'River' boundary conditions have been employed to represent the reservoirs or lakes, as in previous modelling. The historical record of water levels in the Avon and Cordeaux Reservoirs has been employed as in previous modelling but updated to include recent data. The predictive modelling uses the reservoir FSL as the stage. These are 320.18 mAHD for Lake Avon, and 303.76 mAHD for Lake Cordeaux (Section 2.4.2).

These boundary conditions are set in model layer 1, with bed conductance estimated based on model cell area and a hydraulic conductivity of 1E-3 m/d (similar to the geometric mean of Hawkesbury Sandstone Kh). Resultant modelled conductances are 1 to 36 m^2/d, governed by the dimensions of the relevant cells.

5.3.4 Watercourses (creeks and rivers)

Watercourses are represented using the MODFLOW 'Stream-flow Routing' (SFR) package as per the 2022 DMEP EIS model. The spatial distribution of these are shown on **Figure 5-1** and **Figure 5-2**.

The model simulates variable stream stages based on simulated runoff conditions where runoff volumes have been obtained from BoM's AWRA-L model. The SFR package then accounts for the accumulated flow to each SFR cell or "reach", i.e. [runoff] + [gains to that reach] – [losses to that reach]) along the watercourse network. This means that historical weather conditions to stress period 132 (April 2022 – **Appendix C**) are reflected in the modelled stream flow and stage.

For the predictive period, a cycle of quickflow volumes is applied to 5 stress periods and then repeated. This cycle is the 10th, 30th , 50th , 70th , 90th percentiles, where those percentiles are calculated from the stress period averages applied in the historical period. This cycle is simulated for stress periods 133-212 (mid-2022 to 2050 – see **Appendix E**, with the aim allowing the model to provide information on the future effects on or during low, moderate and high flows. The average estimate of runoff is applied to the longer stress periods 213-218 at the end of the simulation (2050 to 2200).

Stream boundary conditions are all set within model layer 1. Bed conductance has been estimated as 2-268, averaging 22 m^2/d. This is based on an assumed hydraulic conductivity of 0.01 m/d, assumed watercourse widths (1.5 to 25 m), and cell “lengths” (calculated as the square root of the cell area).

The model simulates variable stream stages based on the accumulated flow to each SFR reach, based on a user-specified channel width and Manning’s roughness. The channel widths are set based on the hierarchy of streams in the LPI watercourse mapping, with the widths ranging from 1.5 to 25 m based on IMC Environmental Field Team (IMCEFT) mapping of stream features and review of aerial photography.

Watercourses (Streams) are all set within model layer 1. Stream bed permeability was initially set to 0.01 m/d for rock outcrop, but subsequently modified to an assumed hydraulic conductivity of 0.05 m/d (rock outcrop) and 0.2 m/d (swamp areas). The hydraulic conductivity values are chosen to be slightly higher than the relevant K applied to the groundwater flow equation. These values were not modified transiently in response to mining and associated subsidence effects, but the higher K (0.05 m/d) was required to improve calibration to stream flow losses (Sections 6.6 and 7.4.6).

The channels are assumed to be rectangular, which is a simplification of the real cross-section of these watercourses. Mannings roughness is specified as a uniform value of 0.4, which is a deliberate over-estimate of the more realistic value of 0.04 (USGS, 1998) that corresponds to streams that are ‘clean, winding, some pools and shoals’ (roughness = 0.04) to streams with “Sluggish reaches, weedy, deep pools” (roughness = 0.07). The modelled value is selected to compensate for the rectangular cross-section assumed in the SFR package is applied to improve the simulated magnitude and variation in stage (water depth).

5.3.5 Regional groundwater flow

General Head Boundaries (GHB) are set around parts of the model domain where regional groundwater flow is conceptualised as being into or out of the model (rather than predominantly ‘parallel’ to the edge of the model). Inflow is conceptualised as occurring along the southwestern boundary to represent northward groundwater from the Southern Highlands entering the active model domain, while outflow occurs along the northern boundary to represent the continued northward flow toward the centre of the Sydney Basin (Section 3.7.1).

In these areas GHBs are set to allow groundwater flux in the more transmissive parts of the hydro-stratigraphic sequence, typically layers 2, 3, 4, 6, 7, 9, 10, 12 and 14 (Section 5.2.3). The elevation or stage of these is based on nearby groundwater levels from observation bores (where available), otherwise extrapolated levels from contouring or previous modelling.

5.3.6 Mine dewatering

MODFLOW ‘Drain’ boundary conditions are used to represent mining, specifically simulating the dewatering of the workings. Drains were activated to fit the scheduling of all mining areas, but focussing on Dendrobium, as outlined in **Table 1-1** and **Appendix C**.

Drains are set at 0.1 m above the base of the mined seam to simulate dewatering of the workings. Conductances were set as summarised in **Table 5-2**, although may vary slight based on cell size.

Table 5-2 Model Drain parameters

Mine	Coal Seam	Model Layer	Drain Cell Conductance (m^2/day)
Dendrobium			
Longwalls - Areas 1 to 3C + 6	Wongawilli Coal	14	2.5
Longwalls - Area 5	Bulli Coal	12	2.5
Mains and roadways		12 and 14 (by Area)	0.025
Other mines			
Longwalls (e.g. Kemira, Elouera)	Wongawilli Coal	14	10
Longwalls (e.g. Appin/BSO, Cordeaux, Tahmoor, Mt Kembla)	Bulli Coal	12	10
Bord and pillar / partial extraction (e.g. Kemira, Elouera)	Wongawilli Coal	14	8
Bord and pillar / partial extraction (e.g. Appin/BSO, Cordeaux, Tahmoor, Mt Kembla)	Bulli Coal	12	8

5.3.7 Mine closure

Although not strictly a boundary condition, the simulation of the proposed mine closure method (SLR (2022) and summarised briefly in Section 4.3) requires a clear description.

At the cessation of mining operations, the Drain boundary conditions that simulate dewatering (Section 5.3.7) are inactivated, with the exception of those located at the portal entrances near Mt Kembla – these remain active.

At the same time, the Time-varying Material properties (TVM) package of MODFLOW-USG is used to simulate the installation of low permeability bulkheads inbye of Area 1. Given the scale of these bulkheads compared to the model cells in this area, the hydraulic conductivity of these cells is returned to the permeability of the coal seam (approximately 2E-2 m/d) to simulate the transmission of groundwater through the intact coal seam surrounding the bulkheads. This is in contrast to the hydraulic conductivity of 5E+4 m/d (**Table 5-3**) used to simulate the open tunnels (roadways) of the mine that connect the mine workings back to the portals.

5.4 Modelled subsidence and strata deformation

Background to this section is provided in Sections 2.6 and 0. Simulation of mining-induced changes to the hydraulic properties of rock strata within and above longwall panels has typically been limited to simulating the 'connected fracture zone'. Previous modelling at Dendrobium has employed, at different times, three different methods of simulating the fracturing and deformation processes, which were summarised in HydroSimulations (2019), SLR (2020) and IEPMC ((2019b):

- Transient of time-varying material ('TMP' or 'TVM') properties;
- 'Stacked Drains';
- Connected Linear Networks (CLN).

Each of these have their strengths and limitations.

Given the need to simulate post-closure hydrology and from the availability of data and interpretation from Dendrobium's centreline bore investigations (Section 3.6.1), the use of time-varying material properties (TVM) functionality in MODFLOW-USG has been adopted for this modelling. We consider that this equivalent porous media approach to simulating fracturing and deformation is superior because it is an appropriate scale for comparison to observations such as the centreline bore packer testing data. The TVM method (or its equivalent in MODFLOW-SURFACT) was previously used at Dendrobium in 2013/2014 model variants (**Appendix B**) and is also used at other sites in the Southern Coalfield (e.g. Tahmoor, Appin and Metropolitan mines).

Surface flow reductions predicted by the groundwater model presented in some of the earlier models (for EIS and SMP approvals during 2017-2019) had been overly conservative compared to flow losses that have been estimated in the recent End Of Panel reports (HGEO, 2019a, 2020d, 2021c, 2022b) via the water loss / TARP calculations described in WatershedHG, (2019a) and the latest Area 3A, 3B and 3C WIMMCP documents.

However, calibration of this revised model, thus far using TVM alone, has not yet simulated surface water reductions that sufficiently match the historical losses estimated in those recent End of Panel assessments. 'Stacked Drains' have been implemented in conjunction with TVM (Section 5.4.5). As with other components of the modelling, improvements on methods will be the continued subject of further work (Section 8.2.2).

5.4.1 Modified hydraulic properties

The conceptual "zones" of deformation and fracturing are represented in the model via enhanced hydraulic properties. Some commentary on specific zones is provided below, along with a schematic (**Figure 5-4**) showing the application of the zones across and above modelled longwall panels.

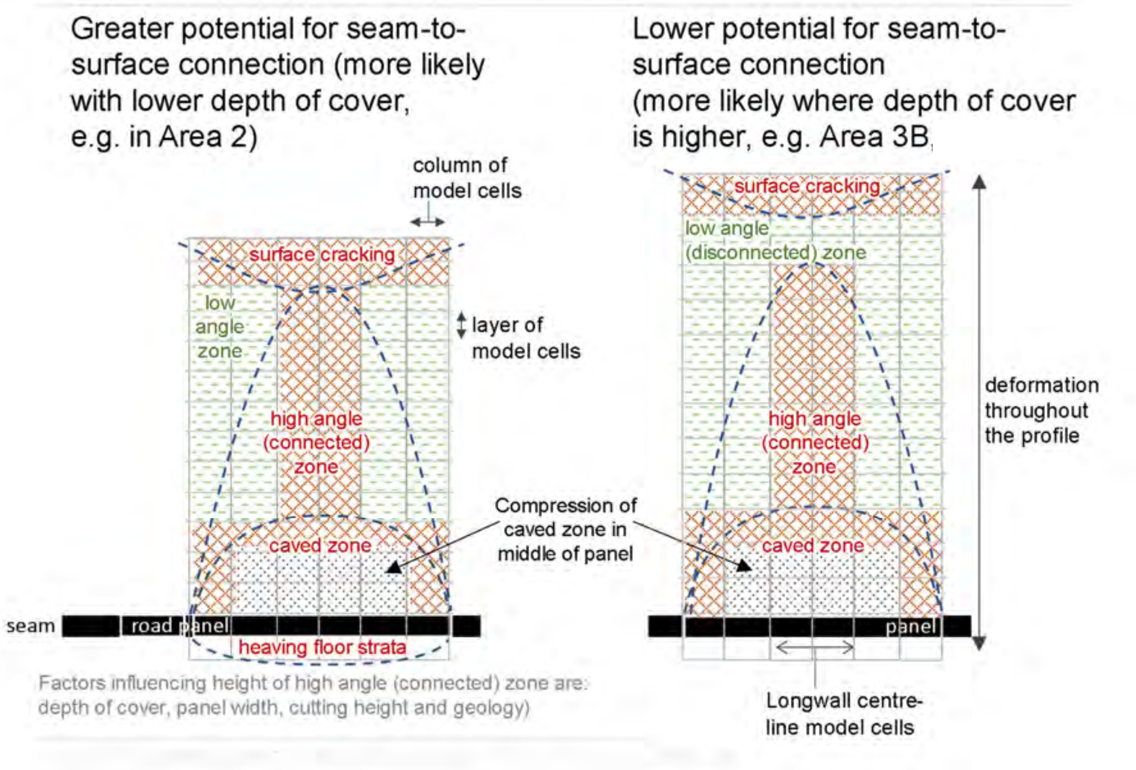


Figure 5-4 Model representation of conceptual property zones above the goaf

The height of the high angle or vertically-connected fracture zone is estimated using the Ditton Geology Model A95 estimate, which relies on panel (void) width, cutting height and depth of cover, as well as an assumed "spanning beam thickness" (*t'*) of 14 m (Ditton and Merrick, 2014).

Hydraulic conductivity

Hydraulic conductivities (Kh and Kv) are modified within these conceptual zones. **Table 5-3** summarises these changes or enhancements, both within the longwall footprint and outside or off the goaf. **Figure 5-5** presents the modelled profiles of hydraulic conductivity against data from the recent over-goaf investigations (Section 3.6).

Table 5-3 Summary of enhanced hydraulic conductivities used in the TVM package

Feature	Model representation		Comment
within footprint	Kh (post-mining)	Kv (post-mining)	
Surface cracking zone	Max of: host x 5 and 1.3E-1 m/d	X 20	
Low angle fracture zone	host x 20	x 2	Within low angle zone, BACS host Kv multiplied by x 5 to simulate brittle fracture.
Seam-to-surface (where high angle/connected zone intersects surface cracking (e.g. Area 2)	Max of: host x 5 and 6E-2 m/d	Max of: host x 20 and 1 m/d	Applied to where high angle/ connected zone intersects surface cracking zone.
High angle (connected fracture) zone	Max of: host x 150 and 1E-2 m/d	Max of: x 50 and 2E-3 m/d	Applied to centre-line model cells, based on comparison of Longwall 12 bore investigations.
Caved zone: edge of panel	3E-1	1E-2	
Caved zone: centre-line	3E-2	1E-3	
Longwall (seam)	100	10	
Underlying floor	host x 5	x 2	
Roadway / partial extraction	5.0E+4	1E-2	Extremely high Kh to simulate free drainage (re: mine closure)
outside footprint			
Off-goaf <100m	host x 4	host x 2.0	Absolute values of 6E-2 up to 2.5E-1 m/d also appropriate.
Off-goaf <300m	host x 3	host x 1.2	
Off-goaf <600m	host x 2	no change	
Closure			
Bulkhead (flow modulation)	2E-2	9E-5	Applied after cessation of mining

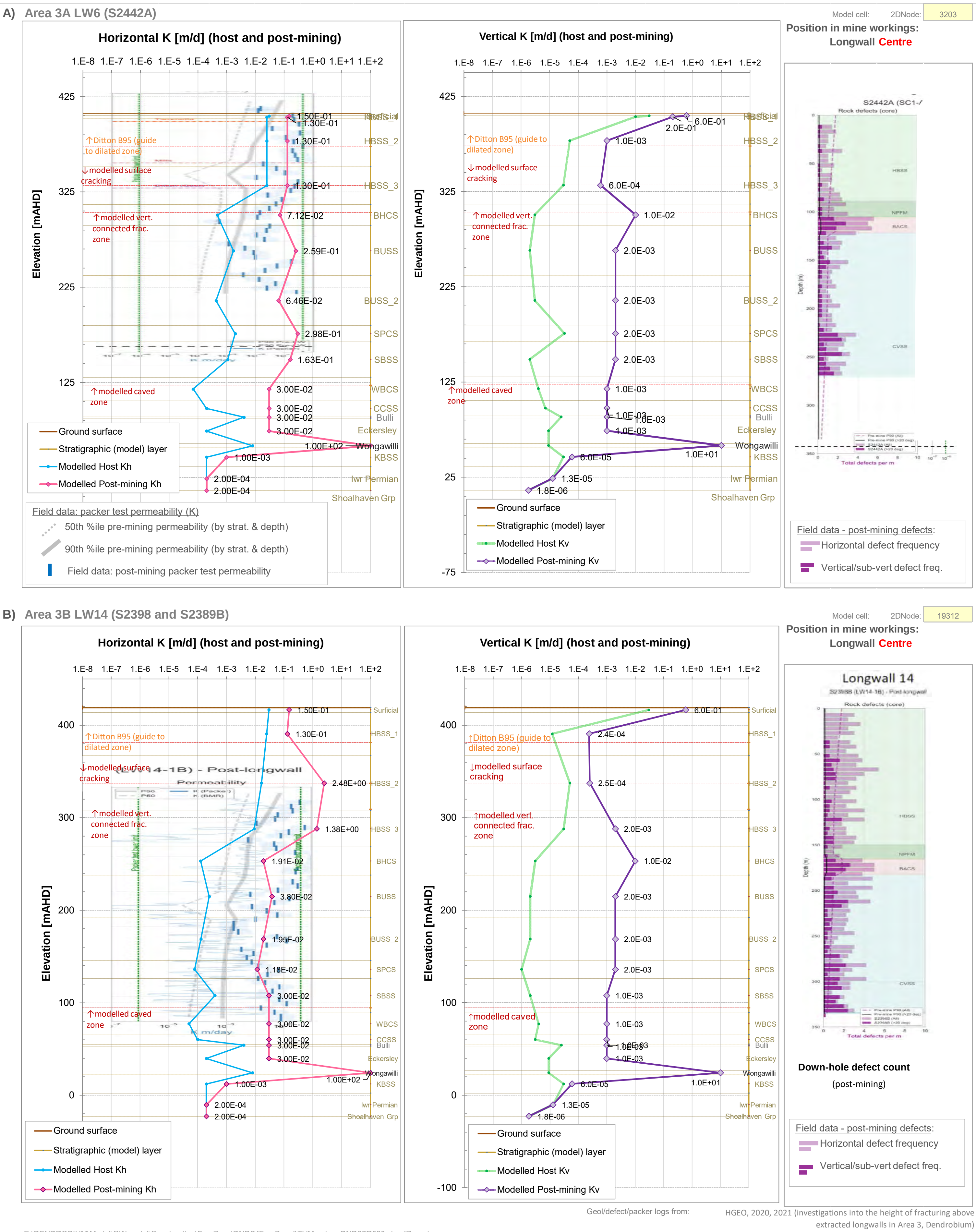
TVM parameters from: \Model\GWmodel\Construction\FracZone\DND6\FracZone&TVMmaker_DND6TR030.xlsm

5.4.2 High angle ('connected') and low angle fracture zones

The results of model calibration to mine inflow, suggested that along with modification of the hydraulic conductivity, differentiation of model cells that are along the centre-line of panels and those that are off-centre should be adopted (**Figure 5-4**). **Figure 5-5a,b** show modelled profiles along centre-line locations in Areas 3A and 3B where over-goaf investigations have occurred. Profiles at additional locations are available on request. **Figure 5-6a,b** shows the modelled Kh and Kv at representative locations within the centreline of Longwall 19 and proposed Longwall 19A

5.4.3 Surface cracking zone

Surface cracking effects, extending down from the surface, were not the focus IMC's over-goaf investigations, although some of the data is relevant. Further data that informs the modelling of this process is available from other studies, e.g. defect logging and packer testing in the Longwall 9 boreholes (Parsons Brinckerhoff, 2015a; PSM, 2017), as well as from SCT (2016, 2019).



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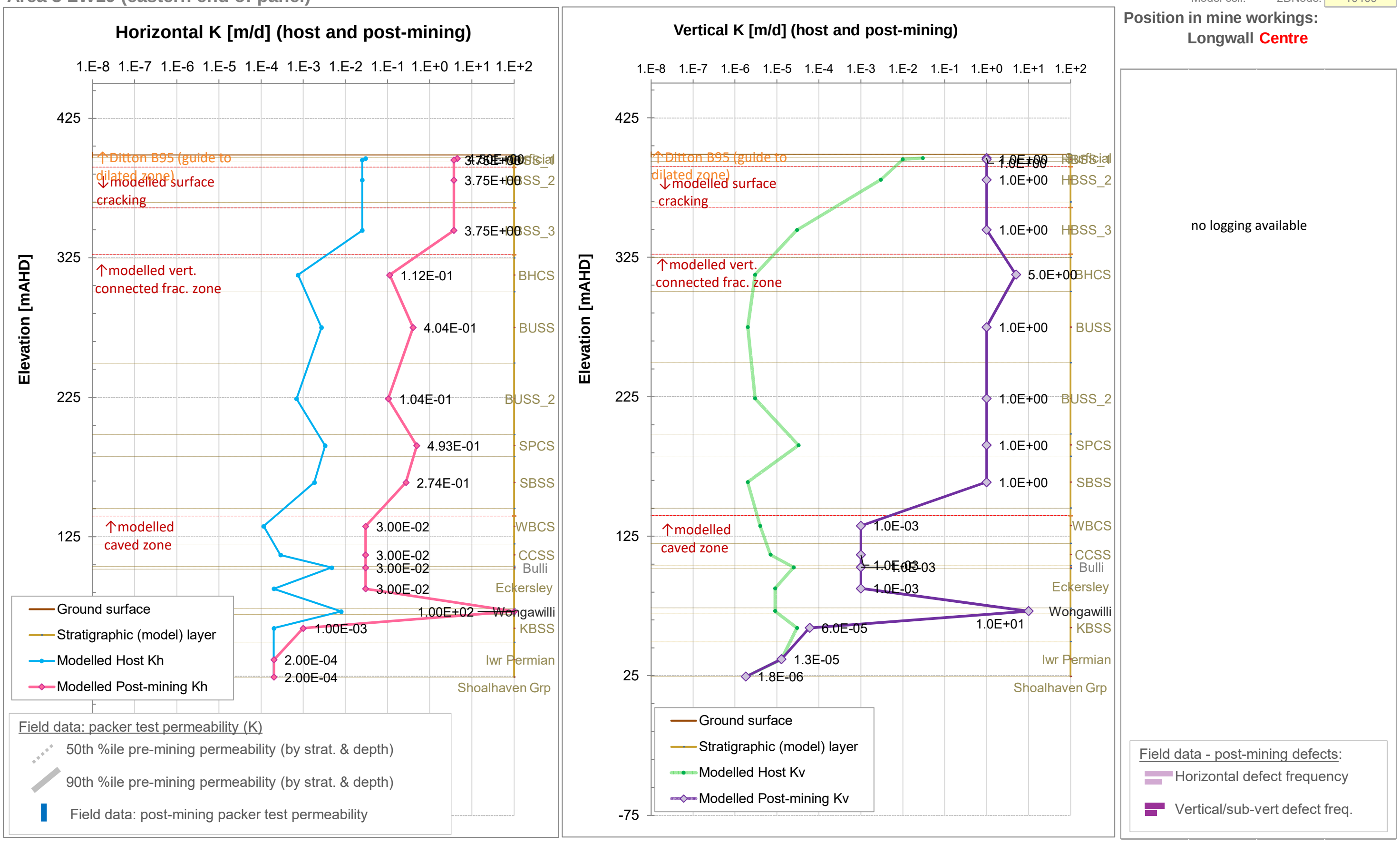
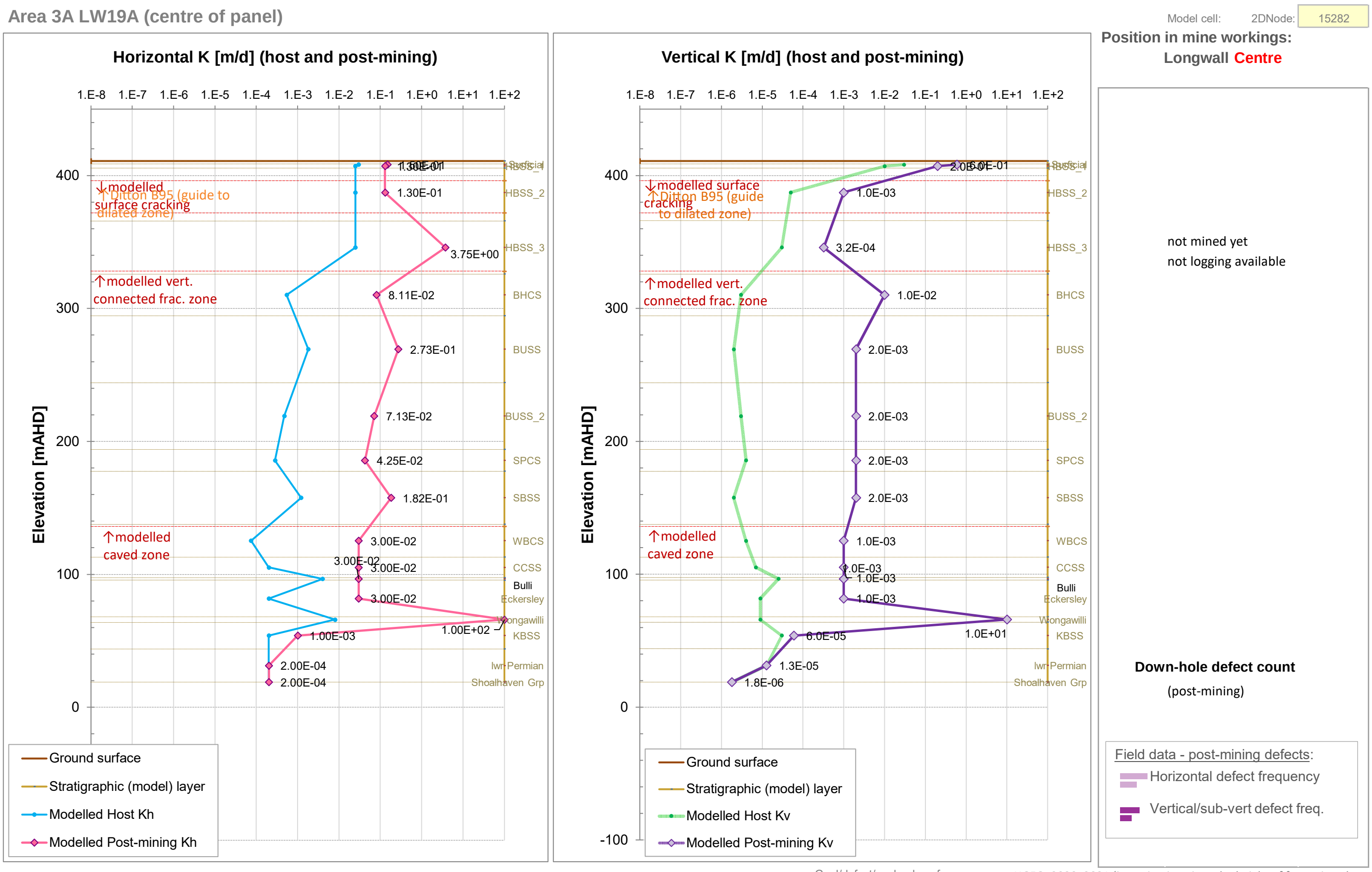
Profiles illustrating modelled Kh and Kv compared against field data

Figure 5-5

A) Area 3 LW19 (eastern end of panel)



B) Area 3A LW19A (centre of panel)



Geol/defect/packer logs from: HGEO, 2020, 2021 (investigations into the height of fracturing above extracted longwalls in Area 3, Dendrobium)

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Modelled deformation and fracturing profiles - sites without field data

Figure 5-6

These studies include data that show fracturing through the vertical profile, with no separation between fracturing from the panel and from the surface (i.e. no 'Constrained zone'). Overlapping of upward extending 'connected fracturing' and downward extending surface cracking means that estimation of the depth of the surface influenced (unconfined) cracking zone is difficult (Advisian, (2016) also noted this complication).

We have assumed that the depth of the surface cracking zone is approximately 10 x cutting height (t). This depth estimate (10 x t) is based on data and experience from Appin, Tahmoor, and Metropolitan mines. As noted in Section 3.6.2, it is acknowledged that the depth is likely related also to depth of cover and panel width.

The representation of this surficial and near-surface process has been the primary focus of recent calibration effort. The profiles on **Figure 5-5** and **Figure 5-6** show the currently modelled Kh and Kv in the near-surface zone(**Figure 5-5** includes a comparison to field data from HGEO (2020b, 2021d)).

5.4.4 Off Goaf (Valley Closure and Strata Deformation)

This process has been 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 (<100 m from the longwall, 100-300 m and 300-600 m from the nearest panel edge) and assigning a K multiplier to each buffer area, with the multiplier declining with distance from the longwall.

Initially, the Kh multipliers selected were x15, x5 and x3 (for areas <100 m, <300 and <600 m from panels, respectively), however given the issues during calibration in previous studies to do with enhanced permeability flattening the inflow hydrograph, lower Kh factors of x4, x3 and x2 were simulated, along with some small increases to Kv. HGEO revised the estimates of how Kh enhancement should be simulated in order to carry out a conservative assessment of the potential connection between Lake Avon and the goaf (HGEO, 2019b, 2020a, 2021a). As a result of these, absolute values of 6E-2 (representative) to 2.5 E-1 m/d (conservative/maximum) for model cells lying within 300 m of a panel edge is also viewed as alternatives to using multipliers (Section 7.2.1).

Kh enhancement is simulated in the strata from the base of the nearest valley, e.g. in the lower Hawkesbury Sandstone and Bald Hill Claystone around the Cordeaux Reservoir shoreline east of Area 3C or in the Hawkesbury Sandstone along Wongawilli Creek between Areas 3A, 3B and 3C.

5.4.5 Stacked Drain parameters

As noted in Section 5.4, 'Stacked Drains' were eventually re-adopted for the purpose of this Groundwater Assessment. The simulation of inflow and groundwater drawdown using TVM alone was appropriate, especially in the Illawarra Coal Measures and Narrabeen Group strata, but the simulated reduction in surface water was not matching that assessed from field data. Further investigation into modified hydraulic conductivities and porosities (specific yield) should be carried out to improve modelling in the future.

In the current model, 'Stacked Drains' were set in 2 layers – the layer at the top of the estimated high angle (connected) fracture zone and in the layer above this. These Drains were set to have a stage 0.1 m above the bottom of the layer.

In earlier modelling for Area 3 SMP applications the 'Stacked Drains' had been set with a conductance that declines with height above the mined seam, with conductances varying, as a result of calibration, from 13 m^2/d above the seam down to 2 m^2/d. HydroSimulations (2019) described a more advanced method of estimating the conductance of the stacked drains using the Thiem equation in a similar fashion to how it can be applied for the 'CLN' package of MODFLOW-USG (Panday *et al.*, 2013).

Further details of the calculations are available in HydroSimulations (2019), but the conductances used in this modelling are derived from that, having been also used in the SMP Groundwater Assessments for Longwall 18 and Longwalls 22 and 23. The conductances applied are listed below, and have been the subject of calibration for drawdown and surface water losses:

Layer	Strat. unit	drain conductance		Layer	Strat. unit	drain conductance
2	HBSS upper	0.01 m2/d		**6**	BGSS upper	0.17 m^2/d
3	HBSS middle	0.23 m2/d		**7**	BGSS lower	0..09 m^2/d
4	HBSS lower	0.31 m2/d		**8**	HBSS upper	0..02 m^2/d
5	BHCS / NPFM	0.03 m2/d				
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In terms of the representation of groundwater responses, which was previously a concern of the IEPMC, the results in Sections 6.4.2 (groundwater pressures and drawdown), 6.5 (mine inflow) and 6.6 (surface water losses) indicate the Stacked Drains and TVM properties are appropriate.

5.4.6 Aquifer storage

The extraction of the longwall results in an increase in porosity (storage) in the subsurface. i.e. the removal of approximately 3.9 m of coal initially leaves a void, which then collapses in the workings. Subsidence at the surface reduces the volume available (left-hand columns in **Table 5-4**). The subsequent deformation in the strata between the seam and the surface results in re-distribution of that porosity through the sequence.

In the current model, the drainable porosity (Sy) increase has been concentrated in the mined seam, and the caved zone, as outlined in the right-hand columns of **Table 5-4**. This is based on Advisian (2016) summary of this process as: "In areas nearer the zone of extraction, such as the caved zone, both vertical and horizontal cracking is thought to be substantial and therefore significant increases in vertical and horizontal permeability are expected, as well as increases in porosity." PB (2015b) stated that the greatest strain occurred below their lowest extensometer (i.e. below the Bulgo Sandstone).

Table 5-4 Modelled Enhancement of Porosity / Specific Yield

Void space calculation		
Parameter	Value	
Mining height	3.9	m (Table 1-1)
Subsidence	1.2	m, above pillar#
	2.6	m, centre-line#
	1.9	m, averaged
Void space created	=3.9-1.9	
	=2.0	m **(#1)**
Depth of Cover [m]	330	average in panel
Average increase in porosity	= (3.9-1.9) / 330 = 0.6%	

Modelled porosity enhancement					
Layer	Thick-ness (m)*	Host		Post-mining	
		Sy	Void (m)	Sy	Void (m)
					2.0 m **(#1)**
Wombarra Fm (L11)	16	0.004	0.06 m	0.011	0.61 m
Bulli Seam (L12)	2.0	0.016	0.03 m	0.023	0.10 m
LRSS (L13)	28	0.005	0.14 m	0.04	1.13 m
Wongawilli Seam (L14)^	4.1	0.015	0.06 m	0.15	0.60 m
Total			0.3 m		2.46 m
Porosity or void space difference			= 2.46 - 0.23 = 2.23 m		

from MSEC, 2022 (Longwall 19A Subsidence assessment); * example thickness within panel; ^ working section only

Table 5-4 shows good agreement between the calculated void space created and the modelled distribution of void space. While it is likely that porosity can be created higher in the profile, and possibly in a non-systematic fashion (Parsons Brinckerhoff, 2015b), we consider that most of the Sy enhancement will occur in the zones nearest the mined seam (as per Advisian, above). As long as the model approximates the total porosity enhancement, then the role of this in delaying groundwater level recovery would be taken into account. Specific storage (Ss) has not been modified from host values.

5.4.7 Other Workings

Roadways (gate roads and mains) and bord and pillar areas are simulated with the parameters set out in **Table 5-3**. The extremely high Kh (5E+4 m/d) applied to the roadways and mains is necessary to simulate free drainage, which was required for assessing closure options in the development of Dendrobium's Closure Concept Plan (SLR, 2022).

6 Model history-matching or calibration

6.1 Approach

Calibration is focussed on replicating observed mine inflow and groundwater levels, while constraining the pre-mining hydraulic conductivity with the large dataset of permeability testing results available at Dendrobium and supported by data from neighbouring mines (Appin, Tahmoor). The aim of this is to improve confidence in resultant forecasting (Section 7), especially in relation to those forecasts for which historical data is available (groundwater levels and drawdown, mine inflow and surface water losses).

Calibration targets are 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 (Appin, Tahmoor). There is now the further constraint of newly available post-mining permeability (Kh) data and defect logging from the extensive field investigations that are briefly summarised in Section 3.6.

The modelling relies on many available values of hydraulic conductivities and storage parameters (Section 3.4), review of independent estimates of recharge (Sections 3.9.1 and 5.3.1), 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 (Section 6.2), and the vertical hydraulic conductivity of deformation zones, with the aim of matching observed data.

Replicating groundwater levels at bores in Areas 3A and 3B has been a particular focus, with particular attention on water levels near the main watercourses (Wongawilli Creek, Sandy Creek and Donalds Castle) and the two reservoirs (Section 6.4) because of the need to represent groundwater processes near these features. Model calibration has also considered groundwater levels within Area 3C, although the stresses there have been less than in historically mined domains. Calibration has been attempted for inflow to each of Areas 1, 2, 3A and 3B (Section 6.5). This is important due to the different character of inflow at each area, especially in Areas 2 and 3B.

6.2 Calibrated parameters

Model parameters have been assigned based on ranges of hydraulic properties produced in the analysis of the packer, drillstem and core testing databases (Section 3.5). The parameters adopted in the modelling are well-constrained by that field data. They are generally between the arithmetic mean and median values for horizontal hydraulic conductivity (Kh), while the vertical hydraulic conductivities (Kv) are generally close to or within the range between the harmonic mean of the packer testing dataset (with comparison against available core testing). As noted by the IAPUM (**Table 1-5**), the core testing represents primary porosity, while comparison against packer testing accounts for any secondary porosity. Calibrated model parameters are tabulated by modelled hydrostratigraphic unit in **Appendix E** of this report and should be considered alongside **Figure 3-3** and **Table 3-2**. The model parameters do not represent a marked departure from previous modelling.

Figure 5-5 presented a comparison of modelled and observed hydraulic parameters for three over-longwall bore locations. Two of these are centreline bores positioned over Longwall 6 (S2442A) and Longwall 14 (S2398-S2398B), while the final location is an off-centre bore positioned over Longwall 12 (S2411). The pre- and post-mining field data presented in **Figure 5-5** has been sourced from the recent compilation and analysis of this data in HGEO (2020f, 2021d). The pre- and post-mining Kh field data is well matched by the model for all stratigraphic units simulated in the model, although possibly slightly too high in the lower Hawkesbury Sandstone. Kv cannot be measured *in situ* (unlike

Kh), but the model configuration is guided by the post-mining Kh data, the relative change in the occurrence of high angle defects through the sequence, and by calibration to drawdown and inflow.

6.3 Water balance

The modelled regional groundwater balance is summarised in **Table 6-1**, which presents the average water balance for 1990 to April-2022. This includes Dendrobium (up to the end of Longwall 18), historical mining around Dendrobium (e.g. Nebo, Elouera, Wongawilli, Kemira etc.), and the parts of Appin, Tahmoor and Cordeaux Mines within the active model domain (**Figure 5-1**).

Table 6-1 Modelled Water Balance for Calibration Period (1990 to early 2022)

MODFLOW component	Conceptual process	In [ML/d]	Out [ML/d]
Recharge	Infiltration recharge	195.2	0.0
Stream Leakage	GW-SW interaction w/	190.2	22.9
River Leakage	Groundwater exchange w/	2.0	6.3
Evapotranspiration	Evapo-transpiration from GW	0.0	336.1
Drains	Mine inflow/ dewatering	0.0	19.0
Head Dep Bounds	Regional groundwater flow	19.3	1.8
Constant Head	flow to ocean, estuaries	0.0	0.0
Storage	groundwater storage	143.6	164.2
Total (ML/d)		550.3	550.3

Units are ML/d. Stress periods 3 to 132, model run DND6TR030D.
E:\DENDROBIUM\Model\Gwmodel\Runs\DND6\DND6TR017\Proc\ZoneBudget\WaterBalance\MassBalance_LST_dTR030D_calib&predict.xlsx.

In general, the largest inputs of recharge and stream leakage are expected. These are balanced by evapotranspiration. Net groundwater storage change is close to zero but negative for this period, representing a slight rise in modelled groundwater levels across the model for the period, which is likely associated with the wet conditions in 2020-22 have reduced that effect somewhat. The model simulates historical mine inflow for all mines in the model domain equal to approximately 10% of the rainfall recharge and 5% of all simulated inputs to the groundwater system.

Groundwater mass balance error was computed by MODFLOW to be less than 0.01%, which is well within the 1-2% error recommended by the Australian Groundwater Modelling Guidelines (Barnett *et al.*, 2012a).

6.4 Groundwater Levels

6.4.1 Summary

In accordance with earlier SMP conditions, A large dataset of groundwater levels has been collated across a total of approximately 800 target instruments (bores, piezometers) at which over 1.3 million daily groundwater level observations have been used to derive “calibration targets”. The locations of boreholes and piezometers used for groundwater level calibration are mapped on **Figure 3-2**.

Of those sites/piezometers, over 790 are piezometers in ‘deep’ bores. From the sub-daily or daily data recorded at those sites, the data have been converted into over 27,200 targets using a progressive approach executed via a script. This approach initially attempts to use the value on the last day of the model stress period, and if there is no (appropriate data), then the median value for the last week of the stress period is used, or then it calculates the median value over the last month for each model stress period. This approach maximises the use of groundwater data in cases where data gaps coincide with the end date of the stress period.

Data quality assessment of these sites has been conducted via three main steps:

- Piezometer elevations and their recorded stratigraphy have been checked against the geological/groundwater model layering. Where there is agreement, a weighting of 1 has been assigned (69% of instruments). Where there is disagreement by 1 layer, a weighting of 0.5 has been assigned (26% of instruments), 0.25 for 2 layers (4%), and a weighting of 0 assigned where there is disagreement by more than that (<1%). This process has also led to some correction of assigned stratigraphic units This step has been added to address previous comments by DPIE-Water.
- The size of the dataset has meant that data ‘cleaning’ or the application of ‘weights’ cannot be carried out rigorously. Clearly erroneous data has been removed (e.g. groundwater levels >600 mAHD).
    - Some suspect data has been assigned a weighting <1, based on a review of hydrographs, but identifying suspect data is not always possible in this environment.
    - As a result more than 65% of the dataset is weighted as a ‘1’ for inclusion in the calculation of calibration statistics, and 28% is weighted 0.5 (likely to reasonable data, but not reliably attributed to the stated stratigraphic unit). Approximately 5% is weighted ‘0.1’ or ‘0.25’, representing suspect data that cannot be categorically classified as incorrect. Approximately 1.0% is weighted as ‘0’, i.e. considered to be bad data.

The overall weighting for a transient observation (‘target’) is then calculated as the product of the piezometer weighting and the data weighting.

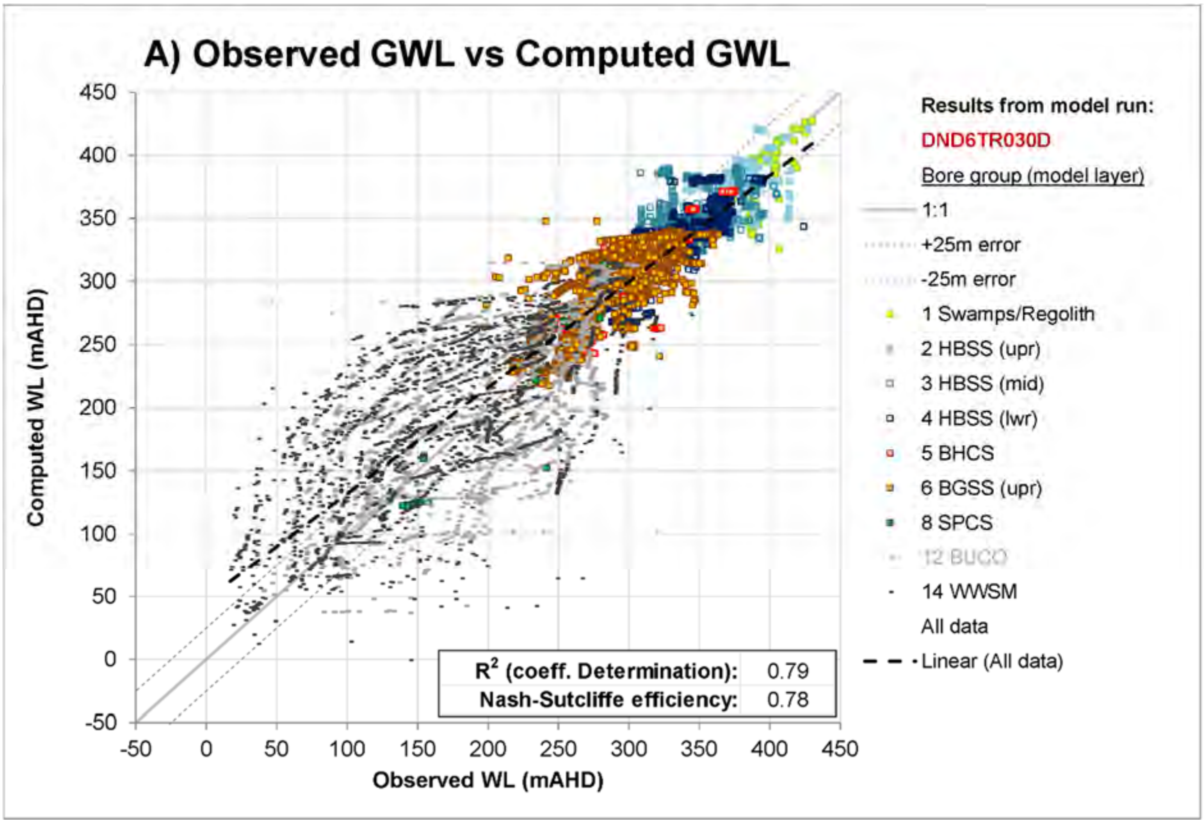
Added to this ‘deep’ dataset are recorded elevations from the shallow swamp and regolith piezometers at Dendrobium. This means there are an addition >2,500 water table targets.

The modelled heads are plotted against the observed head targets on **Figure 6-1**.

The key reasons for the variation between observed and modelled heads on the X:Y plot are:

- 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 out by 100 m or more because it either draws down too quickly or too slowly compared to observed (examples of this are on the later hydrographs, e.g. **Figure 6-3** and **Figure 6-4**);
- longwall progression and commencement of significant impacts at a monitoring point occurs over small time increments compared to model stress periods;
- potentially incorrect layer assignment. Some VWPs located in the mid-Bulgo Sandstone (BGSS) may be assigned to the lower BGSS but could be validly assigned to the upper BGSS;
- incorrect or suspect data which has not been identified or cannot be confirmed as incorrect;
- incorrect or imperfect parameterisation of the model re: K and S parameters, either on a local or larger-scale; and
- overestimation of drawdown by the model in areas above the goaf occurs, as seen by the vertical series of “Layer 1 Swamps/regolith” (and other shallow layer) targets on the upper-

right of **Figure 6-1**. This shows that the model overestimates drawdown at some of these shallow piezometers (although this behaviour has improved in recent modelling).



E:\DENDROBIUM\Model\GWmodel\Runs\DND6\DND6TR030\Proc\Heads\MOD2OBS\[DND6v1_Targets_SP_end_V02_DND6TR030D.xlsx]CalibCalcs&Plo

Figure 6-1 Summary X:Y plot of modelled vs observed groundwater levels

The SRMS error for the correlation between observed data and the transient model groundwater levels is 6.8%. This value is within the often-quoted example of 10% (MDBC, 2000; Barnett *et al.*, 2012b), and, and 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. The mean residual groundwater level is -2.2 m, R^2 = 0.79, and a Nash-Sutcliffe efficiency = 0.78 for the whole dataset. Each of these statistics suggest that the model simulates heads to an appropriate degree.

6.4.2 Temporal trends (hydrographs)

A subset of calibration hydrographs is presented in **Figure 6-2** to **Figure 6-5**, while a larger set of hydrographs are provided in **Appendix F**. On these figures, the observed groundwater levels are plotted as coloured symbols, with the corresponding modelled series in a solid line of similar colour. These hydrographs have recently been re-formatted based on previous comments by DPE-Water.

These include groundwater levels at S1892 in Area 3A near Wongawilli Creek (**Figure 6-2**), at S1870 between Area 3A and Cordeaux Reservoir/Sandy Creek (**Figure 6-3**), water levels at S1888 between Longwall 19A and SC10 (**Figure 6-4**) and S1879 (west of Longwall 19A - **Figure 6-5**). Of these locations, S1879 and S1888 are closest to Longwall 19A.

The match between modelled and observed hydrographs is generally good, with the relative drawdown with depth (i.e. drawdown of >150 m in the coal seams, drawdowns of approximately 50 m or more in the Bulgo Sandstone and Scarborough Sandstones, and lower magnitude of drawdown (tens of metres or less) in the Hawkesbury Sandstone) being represented well.

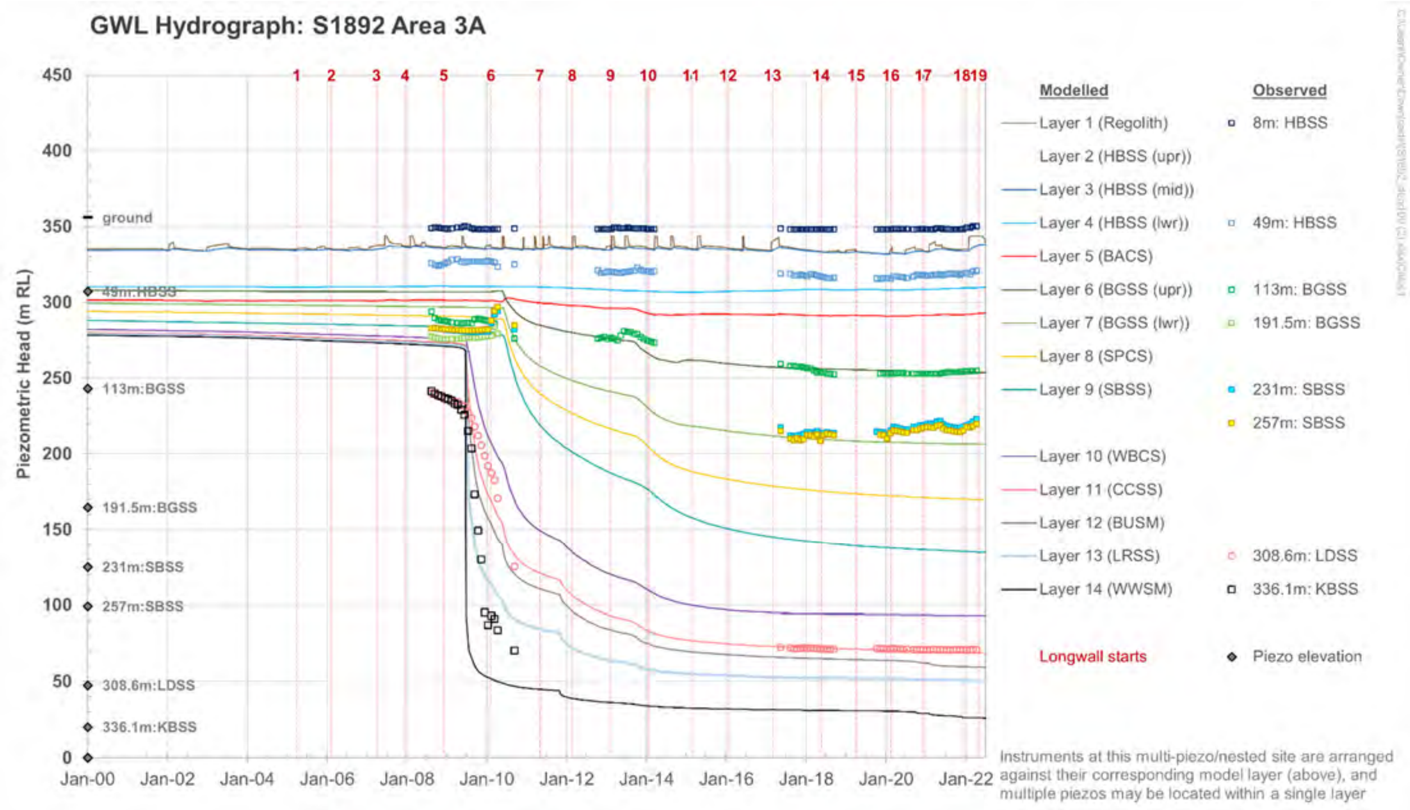


Figure 6-2 Modelled vs observed groundwater levels: S1892

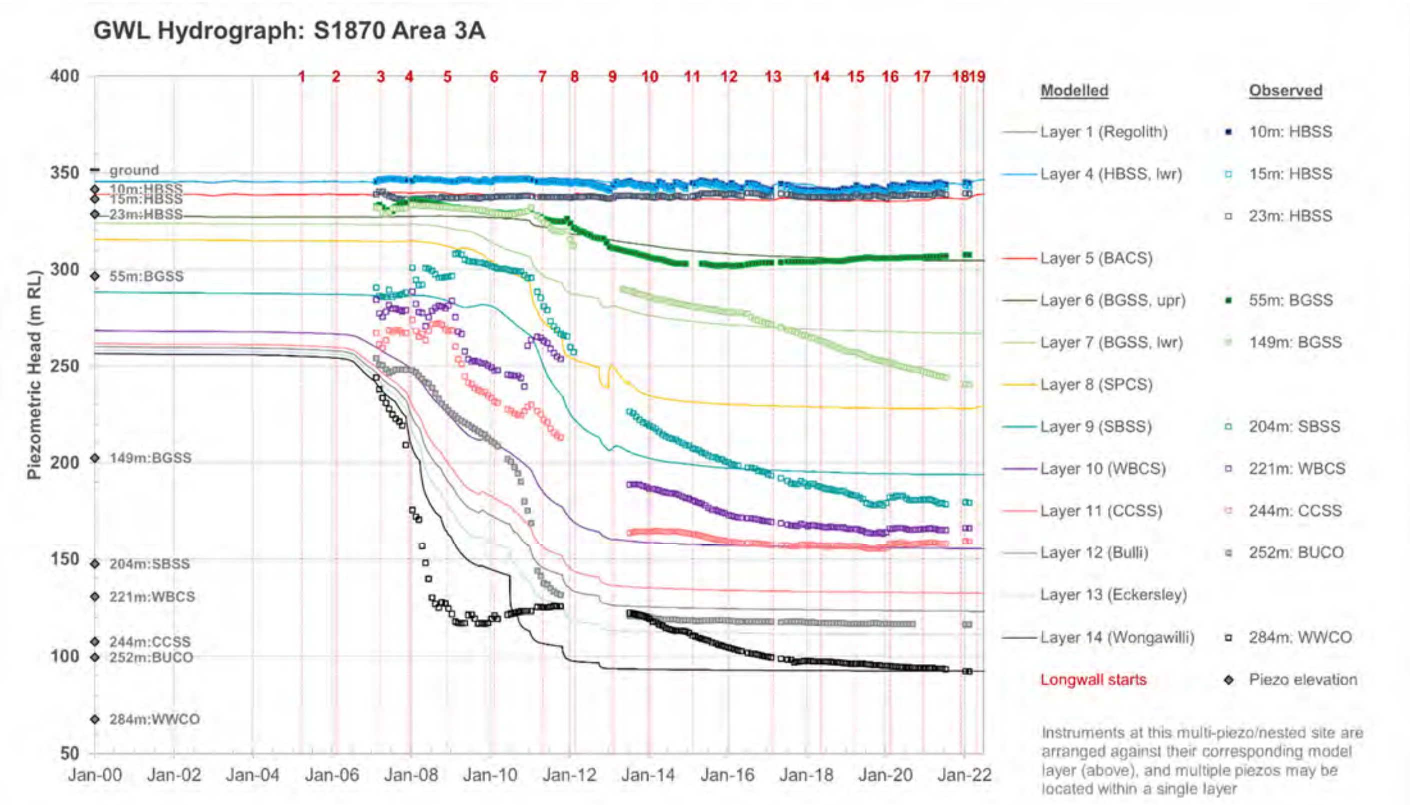


Figure 6-3 Modelled vs observed groundwater levels: S1870

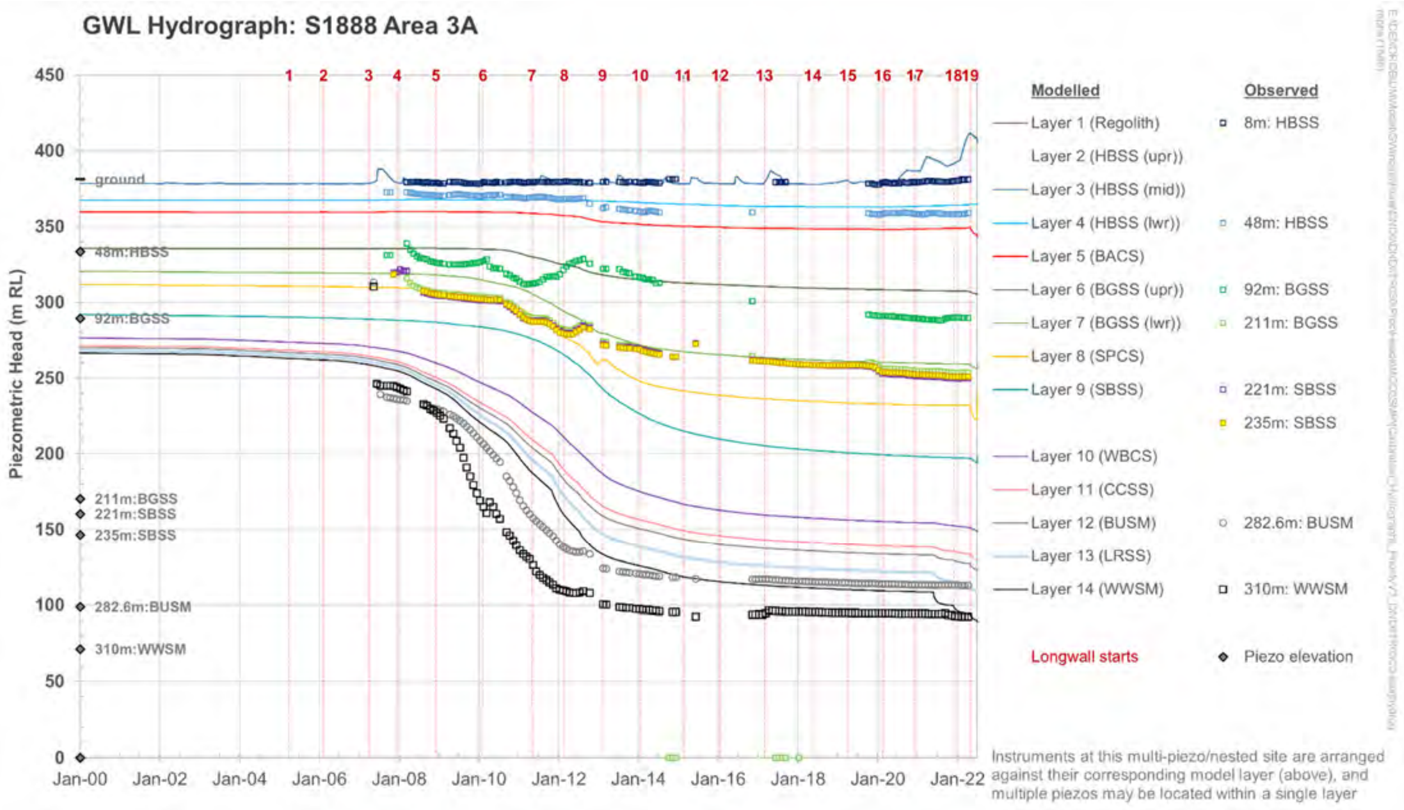


Figure 6-4 Modelled vs observed groundwater levels: S1888

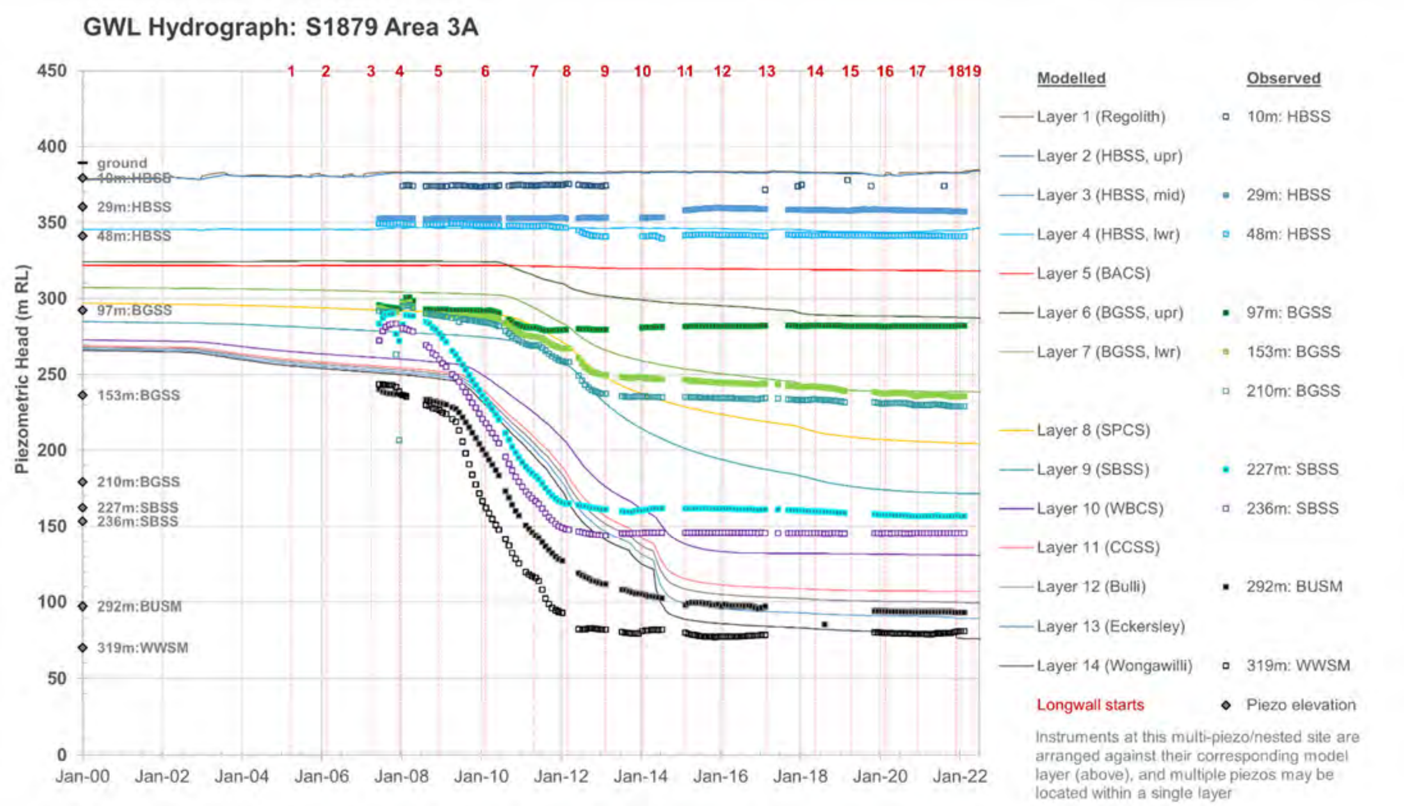


Figure 6-5 Modelled vs observed groundwater levels: S1879

For example, at S1892, the model responds well to drawdown in the deepest piezometers (KBSS and LDSS, both close to the mined seam). The model replicates the trends in drawdown in the shallow units, including the upper Bulgo (113m-BGSS) and lower HBSS (49m-HBSS)including the relationship of those layers to the stage in nearby Wongawilli Creek, which is at approximately 282 mAHD).

The main weakness evident in the hydrographs is that while the overall scale of drawdown is often quite well represented, the timing of drawdown is not always matched, and this can lead to large residuals in the statistical assessment of calibration. This could be due to the real timing of mine development versus the timing of model stress periods but is more likely related to local-scale variation in permeability and porosity properties (e.g. specific storage), or geotechnical behaviour that cannot be captured in a regional model, e.g. multiple caving/subsidence events related to extraction of (multiple) longwalls.

6.4.3 Spatial distribution of heads

A series of groundwater level contour plots are provided in **Appendix G**. These maps show modelled groundwater level elevation on the left-hand pane and, as following a previous request by the IEPMC, the estimated depth to water on the right-hand pane. These show modelled groundwater levels for:

- the water table;
- lower Hawkesbury Sandstone (model layer 4);
- upper Bulgo Sandstone (layer 6); and
- the Wongawilli Seam (layer 14).

The water levels for these strata are presented for specific time intervals (two historical and two predictive periods):

- the ‘pre Dendrobium’ case (model stress period 3);
- early-2022 (stress period 132), representing ‘recent or current conditions’;
- 2027 (stress period 158) – following Longwalls 19, 21, 19A, 22, 23 and 20; and
- 2200 (stress period 218) – long-term after mine closure.

These are supplied in one series to enable review of changing water levels through time.

Figures G2, G6, G10, G14 (in **Appendix G**) present modelled groundwater level contour plots for model stress period 132(April-2022).

The modelled water table (**Figure G2**) shows the strong signature of local topography and drainage on surface water features. The contours bend around large rivers such as the Cordeaux, Avon and Nepean Rivers, and also other watercourses such as Wongawilli Creek. The reservoirs generally receive groundwater baseflow from the water table as indicated by the higher flow gradient along their margins. Groundwater levels drop steeply over the escarpment to the south and east as the land surface declines towards the coastline. Comparison against **Figure G1** shows how the model has simulated the change from the natural or pre-mining condition to “present day” (early 2022), including drawdown concentrated above longwall panels and the influence of recent extremely wet conditions.

Modelled groundwater levels in the lower Hawkesbury Sandstone (**Figure G6**) also indicate an influence from local topography and surface water features. Mining impacts on the groundwater levels are discernible from the ‘bending’ of contour lines in areas of mining. At Dendrobium this can be observed as occurring over the northern section of Area 3B in the area occupied by Longwalls 9-14, which were extracted between 2013 to 2019, with milder drawdown in Longwalls 15-18 at this time.

Comparison against **Figure G5** shows how the model has simulated the change from pre-Dendrobium condition to early 2022.

Contour patterns indicating mining related drawdown are more discernible in the lower Bulgo Sandstone (**Figure G10**). Tightly grouped groundwater contours are present around the longwall footprints of Dendrobium Areas 1, 2 and 3A, and also in Area 3B, including clearer definition of the drawdown cone developing above Longwalls 15-17 in 2019-2021. Comparison against **Figure G9** shows how the model has simulated the change from the pre-mining condition to 2022.

The Wongawilli Coal Seam (**Figure G14**) shows significant drawdown, as expected of the mined seam for the historical and active workings at Dendrobium. The extent of the drawdown footprint is influenced to the south of Areas 3A and 3B by mining activity at the Wongawilli (Elouera) and Nebo Colliery. Comparison against **Figure G13** shows how the model has simulated the change in pressures as mining at Dendrobium has advanced.

6.4.4 Verification: groundwater drawdown

HGEO reported on model predictions of groundwater level compared to observed groundwater pressures (see Section 3.4.1 of HGEO, 2021b). This concluded that the model provides a reasonable estimate of groundwater level and drawdown, with a slight bias to over-estimating drawdown.

6.5 Mine Inflow

Mine inflow or dewatering rates represent one of the key history-matching targets, given that inflow is a function of the hydraulic properties and height of the zone of connected fracturing above the longwalls, as well as of the adjacent (unfractured) strata.

Mine inflow is calculated using the IMC site water balance, which is a key target for calibration. Groundwater model estimates of inflow to each mine area have been calculated considering time-weighted averages, with reference to model output times in each stress period. **Figure 6-6** and **Figure 6-7** compare the 'observed' and modelled inflows to each mine area and Dendrobium as a whole, respectively.

Noting that previous longwalls in Areas 3A and 3B are most similar, in terms of depth of cover and stratigraphic sequence to Longwall 19A, the following points are made for each area (**Figure 6-6**):

- Area 1: modelled inflows are over-estimated during through the mining period (2005-2007), and then decline to more realistic rates, although still high compared to the rates for much of the period. This is considered appropriate for considering long-term (post-mining) behaviour.
- Area 2: modelled inflows are well matched during Longwall 3 (2007) and then over-estimated during through the mining period (2008-2010). Following that, the average inflow is well matched, however the model is not simulated the variability, including the peaks following high rainfall events, and then decline to more realistic rates, although still high compared to the rates for much of the period. This is considered appropriate for considering long-term (post-mining) behaviour.
- Area 3A: modelled inflows are well matched during Longwalls 6 and 7 (2010-2012) and then slightly underestimates peaks for the years 2013-2015 following cessation of mining in this area. Following that, the average inflow is well matched.

  Area 3B: modelled inflows are well matched during Longwalls 9 and 17 (2013 to present day). This modelling represents the best match to Area 3B inflow compared to previous modelling for Dendrobium, including the rise in inflow to 2017, subsequent plateau (even slight decline) to late 2020, and rise through 2021.

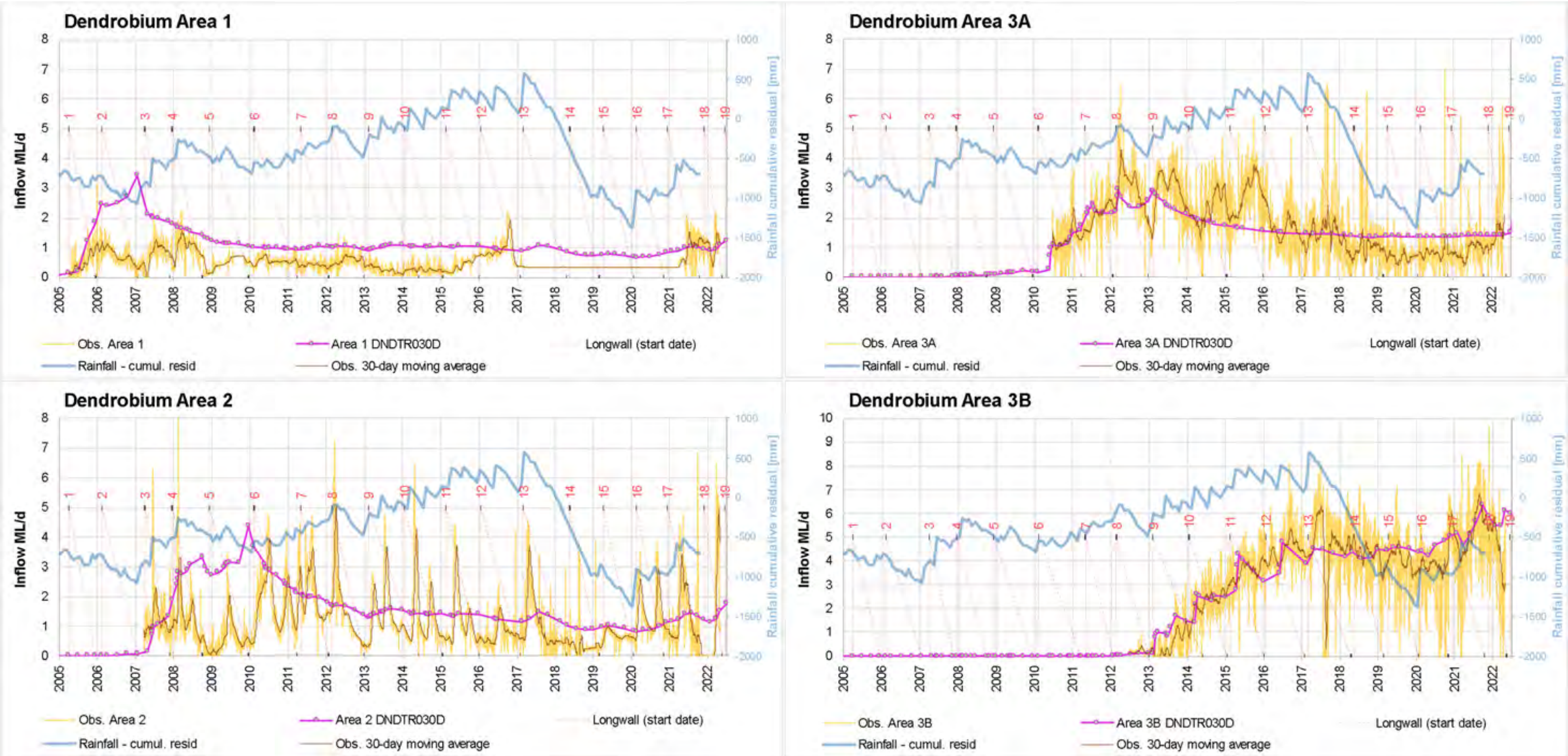


Figure 6-6 Modelled vs observed mine inflow: by area

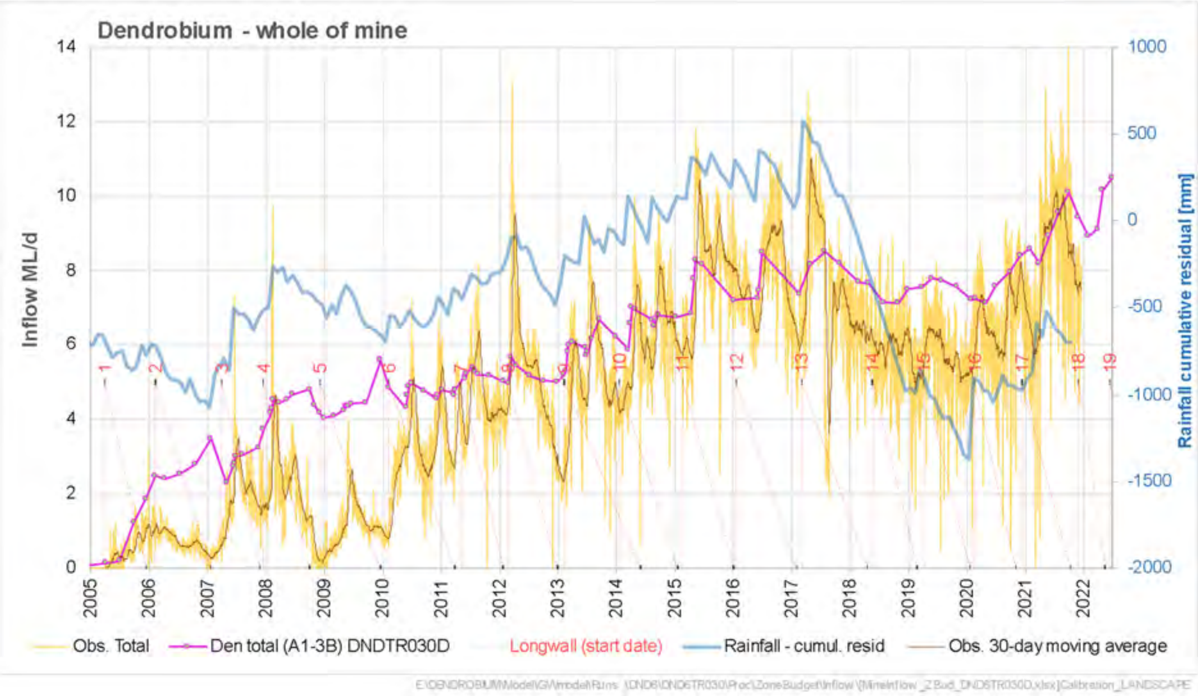


Figure 6-7 Modelled vs observed mine inflow: Dendrobium total

A comparison of modelled and calculated inflows to the whole of mine (**Figure 6-7**) shows it is an appropriate match for the purpose of understanding the effect on the water balance of this groundwater system. The modelled inflows generally provide a slightly conservative estimate of the calculated inflows during mine progression.

Overall, the ability of the model to capture the variability of inflows to each mine area is sufficient to constrain the water balance and provide reasonable estimates of the water balance effects of future development.

Versions of the model tested during calibration had lower and higher rates of inflow (to Area 3B, most importantly), however did not appropriately simulate losses from surface water systems, so the current model has been favoured, with then main weakness being the lack of inflow variability in Area 2.

6.6 Surface water flow loss

The charts in the previous section show that the model is capable of simulating appropriate magnitude of surface water flow along the watercourses above the mine. However the forecast of primary interest in this area is the potential reduction in surface water flow in WaterNSW's Special Area.

As noted in Section 3.9.5, regular compliance reporting (End of Panel reports) document the estimated change in flow, specifically the mining-related change to cease- to-flow frequency and the change in median flow at the surface water gauging sites in Areas 3A and 3B (and in Area 3C and potentially Area 5, in future). The methods for this analysis are documented, and are independent of groundwater modelling conducted at Dendrobium (Watershed HydroGeo, 2019a).

By comparing the modelled historical scenario and a no-mining scenario during the calibration process, the ability of the model to estimate flow losses can be assessed. A summary of the modelled changes to surface water flow compared to the results in the latest End of Panel report (HGEO, 2022b) is presented on Figure 6-8. This shows that, with the exception of the Donalds Castle Creek sites (DC13S1, DCS2 and the downstream site DCU), the model is good at replicating the observed losses, and tends to slightly over-estimate the losses (the primary exception being LA3S1).

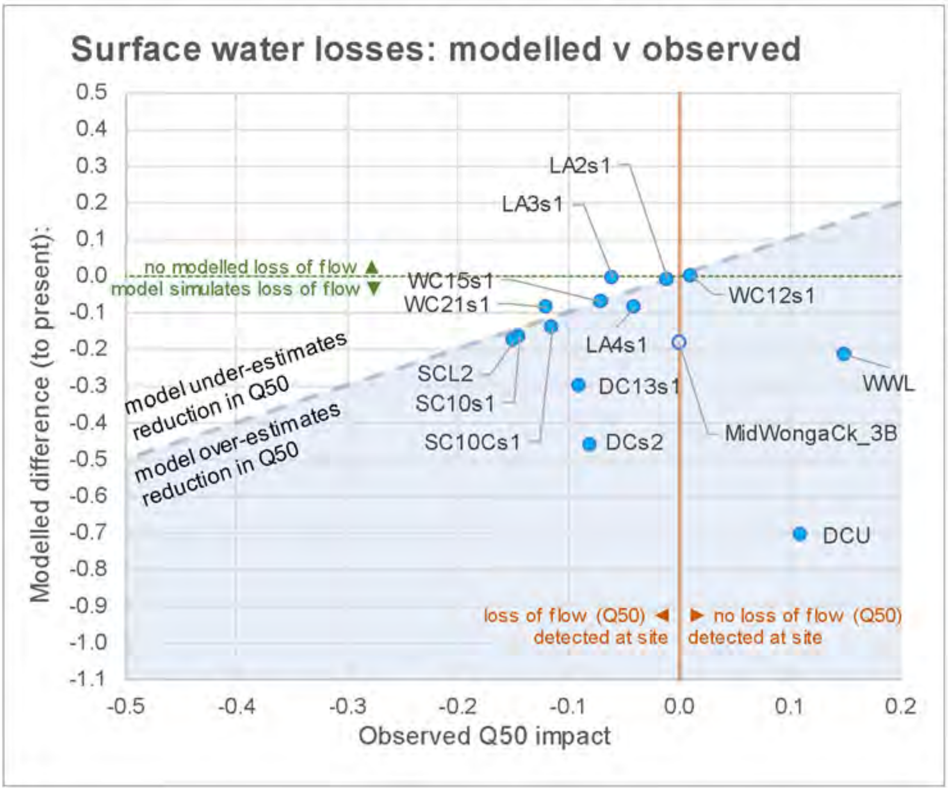


Figure 6-8 Summary of modelled surface water effects (losses)

On the whole, considering all the sites where the field-based estimates of loss are made, the comparison below shows that the model provides realistic, yet slightly conservative estimates.

Sites	Total observed loss (ML/d)	Total modelled loss (ML/d)	% difference
All sites (Area 3A and 3B)	-0.88	-1.49	70%
All sites except Donalds Castle sites	-0.71	-0.73	3%

There is only one site where the model significantly under-estimates historical losses (LA3S1), for which the field-based estimates of loss are less reliable due to a much shorter baseline periods than for the other sites, and also possibly in the middle reach of the Wongawilli where a reliably quantified loss cannot be made (no suitable site for a gauging station). At WC21, the simulated losses are a reasonable approximation, albeit are 30% lower (0.04 ML/d) than observed. At all other sites, the model is a good match or over-estimates the losses determined from field data.

IEPMC (2019a) stated that "*groundwater models should not be relied upon to give accurate estimates of future surface water losses. Complementary approaches should be investigated. This may include adjusting groundwater model results according to their under- or over-estimation of losses for previous LWs.".* With regard to the first part of that statement, and acknowledging that will be uncertainties associated with model parameters, model structure (time and spatial discretisation), and in the measurement and analysis of flow data collected in the field. This revised groundwater model does provide reasonable estimates of historical losses and is considered suitable.

6.7 Model performance and suitability

The regional model takes approximately 8 hours to run for the calibration or historical model (stress periods 1-132), with a further 10-14 hours for the predictive period (stress periods 133-218), depending on whether in parallel with other model runs.

6.7.1 Model 'Confidence Classification'

The Australian Groundwater Modelling Guideline (Barnett *et al*, 2012) includes a 'Confidence Classification'. This has been populated and is presented in **Appendix D**.

The modelling presented here is generally a Level 2 confidence model, with a number of aspects of Level 3 confidence. This is appropriate for impact assessment purposes, and reflective of the amount of data gathered, the analysis carried out for this site, as well as the magnitude of future stresses (i.e. those from the proposed Longwall 19A) being similar to the historical observed and simulated stresses.

6.7.2 Peer Review

The conceptualisation of the site and the numerical modelling have been the subject of Peer Review by Brian Barnett (Jacobs). This review was carried out in early 2022 for the DMEP EIS, and the modelling for that study is almost identical to that carried out for this SMP assessment.

7 Model forecasting

This section describes the forecast model scenarios carried out for impact assessment and presents the results of these. Given the amount of model output that could be generated, only the key results, notably fluxes, have been discussed in detail in the following sections.

Section 7.1 briefly outlines the model set up for predictive scenarios, while Section 7.2 describes the 'resource development' scenarios used to carry out the quantitative impact assessment. Some additional deterministic scenarios (Section 7.2.1) have been carried out to quantify the effects of uncertain features of the hydrogeological systems.

Section 7.3 presents predicted effects on groundwater levels via a number of methods, as per previous SMP conditions (**Table 1-3**).

Section 7.4 presents flux results, including mine inflow, losses from reservoirs and losses from watercourses. There is also a sub-section on surface water take from the water supply catchments that are within the model domain (Section 7.4.7), to meet a recommendation by the IEPMC (2018). These results are typically presented for Dendrobium as a whole as well as the incremental effects of the proposed Longwall 19A.

7.1 Forecast model configuration

The calibrated or base case model is used as the basis for forecast modelling, specifically the hydraulic conductivity and storage parameters, the representation of subsidence and deformation (fracturing) and the boundary conditions. The key features of the forecast modelling that are different to the historical period are:

- The predictive period does not include variation in rainfall recharge, although the rates simulated is the average based on the calculated historical patterns.
- Generally, stress periods are set at 4-6 per year for the predictive mining period, lengthening to yearly or longer periods after the simulated end of mining (**Appendix C**).
- Mining scenarios (i.e. MODFLOW Drains to represent dewatering) and specific parameters to describe fracturing and deformation are described in Section 7.2.

7.2 Model Scenarios

The mine plan and schedule are presented in **Table 1-1** and **Appendix C**. Model forecast scenarios, which are summarised in **Table 7-1**, have been carried out to provide a forecast of the effects of the proposed Longwall 19A and of Dendrobium Mine as a whole.

7.2.1 Uncertainty Analysis

A series of deterministic scenarios, as per the IESC Uncertainty Guidelines (Middlemis and Peeters, 2018) have been carried out to help assess the uncertainty associated with particular predictions. These scenarios consider potential changes to hydraulic conductivity associated with valley-bulging and focus on predictions of mine inflow, losses from the reservoirs and effects on watercourses that might be caused by mining at Dendrobium. A summary of these is as shown in **Table 7-1**.

Unlike in a previous SMP groundwater assessment (specifically that for Longwall 18; WatershedHG (2020)), structural features are not considered a significant risk pathway for Longwall 19A (Section 4.3), and therefore not considered explicitly in uncertainty scenarios. The scenarios below are focussed the potential effects on watercourses Wongawilli Creek and SC10 (tributary of Sandy Creek).

Table 7-1 Summary of modelled mine development and uncertainty scenarios

Scenario	Run	Name	Dendrobium	Connected fracture zone method	Other Mines	Comment
B	DND6TR30B	Baseline	No Dendrobium	TVM	All	Baseline condition Comparison against D isolates effects of Dendrobium.
C	DND6TR30C	Dendrobium, no LW19A	All Areas 1, 2, 3A, 3C (LW 20-23) and all 3B, except LW 19A	TVM + Stacked Drains	All	Comparison against D isolates effects of LW 19A.
D	DND6TR30D	Full Development	All Areas 1, 2, 3A (including Longwall 19A), 3C (LW 20-23) and all 3B	TVM + Stacked Drains	All	
Deterministic uncertainty scenarios						
D	DND6TR31D	Full Development: Offgoaf 1	as for D	as for D	as for D	Greater off-goaf permeability (Kh 6.5E-2 m/d) based on Section 3.6.3).
D	DND6TR32D	Full Development: Offgoaf 2	as for D	as for D	as for D	Greater off-goaf permeability (Kh 2.5E-1 m/d) based on Section 3.6.3).

7.2.2 Model Performance

All predictive runs had overall mass balance errors of <0.02% which is acceptable based on the recommended threshold of 1-2% of Barnett *et al*. (2012). Some timesteps, typically those at the beginning of a stress period, have higher mass balance errors. This is due to the enhancement of hydraulic properties in many cells and activation of 'Stacked Drains' in those periods.

7.3 Forecast groundwater level response

The following sections present groundwater level responses to mining via:

- Modelled groundwater level contour maps for key stratigraphic units, as well as the estimated depth to groundwater, for a set of key times.
- Modelled groundwater level hydrographs to illustrate trends in pressure/drawdown through time in a number of stratigraphic units.
- Profiles/cross-sections of pressure head.
- Predicted groundwater drawdown at the nearest water supply works (bores).

7.3.1 Contour maps – groundwater levels

A series of groundwater level contour plots are provided in **Appendix G** (as discussed in Section 6.4.3). These maps show modelled groundwater level elevation on the left-hand pane and the estimated depth to water (or piezometric level expressed as depth below ground level) on the right-hand pane. These show modelled groundwater levels for:

- the water table;
- lower Hawkesbury Sandstone [HBSS] (model layer 4);
- upper Bulgo Sandstone [BGSS] (layer 6); and

- the Wongawilli Seam [WWSM] (layer 14).

The water levels for these strata are presented for specific time intervals including modelled historical groundwater levels in 1990 and early 2022 (**Figures G1-2, G5-6, G9-10 and G13-14**) to enable review of changing water levels through time. **Figures G3, G7, G11 and G15** present the results 2027 (stress period 158), after proposed and planned Longwalls 19, 21, 19A, 22, 23 and 20), while **Figures G4, G8, G12 and G16** present results for 2200 or approximately 175 years after mining (stress period 218). This last time period (2200) now accounts for the simulated closure process described in SLR (2022) and Section 5.3.7.

The figures in **Appendix G** indicate that significant drawdown would occur within the WWSM (in the order of 200-300 m from pre-mining conditions within the footprint of the Area 3A and 3C longwalls), upper BGSS (approximately 80-120 m) and lower HBSS (40-100 m). The water table is also predicted to be disturbed by about 100 m in some locations along the centreline of Longwall 19A, and by 5-10 m just outside of these panels.

Drawdown or depressurisation is predicted to occur at some distance outside the footprint of the longwalls (e.g. at a point approximately 1 km east of the Longwall 19A (near to Sandy Creek), simulated pre-mining heads in the lower HBSS (Layer 4) are about 365 mAHD (**Figure G5**) and are simulated to be steady through to 2027 (**Figures G6-G7**). At the same location, the depressurisation in the BGSS (Layer 6) is also simulated to show a 15 m decline in groundwater levels, falling from 335 mAHD (**Figure G9**) to 320 mAHD (**Figure G11**). The drawdown in the WWSM is about 150 m at the same point. The water table is not predicted to be affected at this distance.

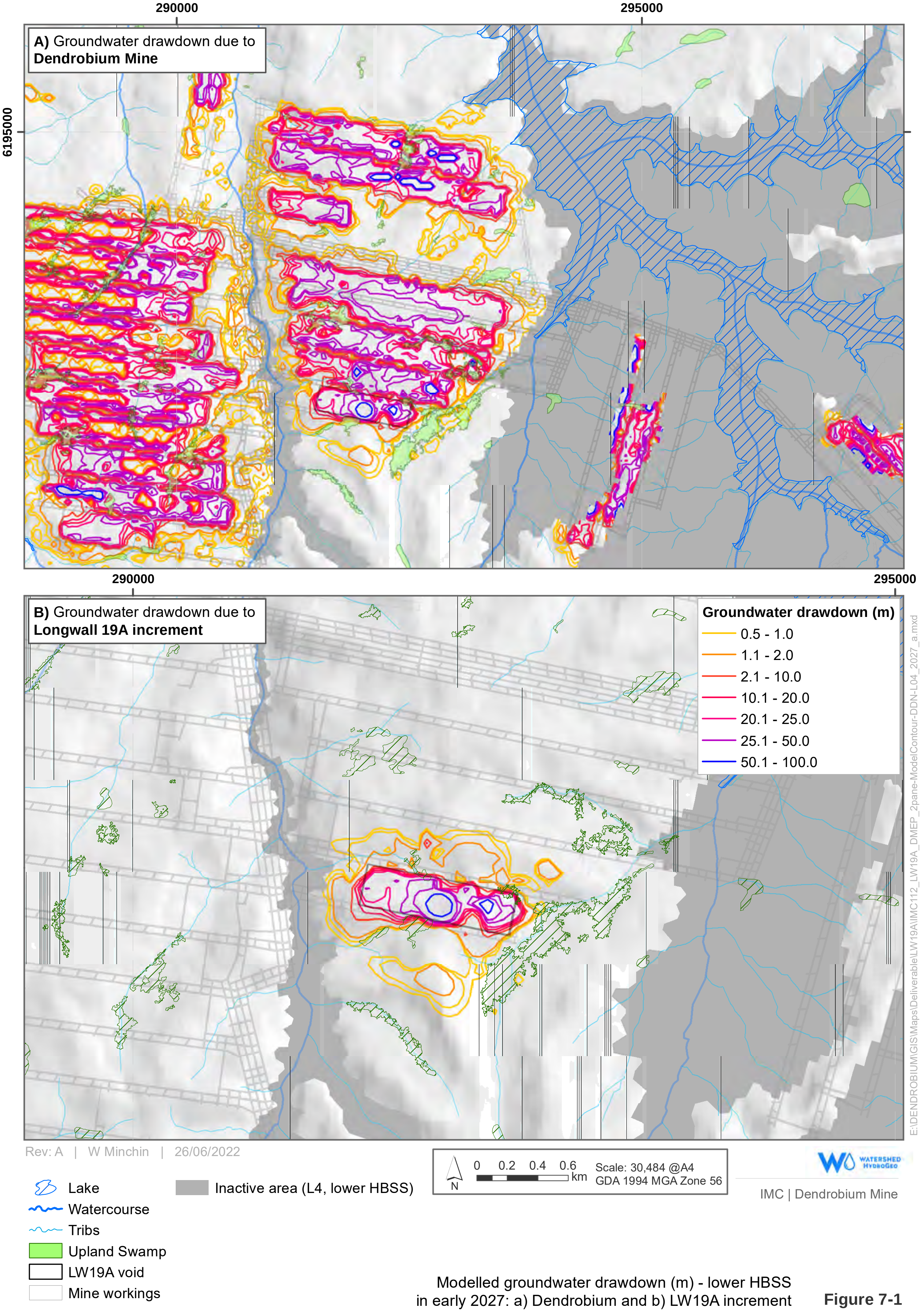
Comparison of groundwater levels well into the future (**Figures G4, G8, G12 and G16**) with pre-mining conditions (**Figures G1, G5, G9 and G13**) suggest that water levels in the lower HBSS, as well as the water table, could recover after mining to be 5-20 m below pre-mining levels around much of Longwall 19A, primarily due to changes in permeability in the shallow strata. Water levels in the BGSS are predicted recover to above pre-mining levels in the area of Longwall 19A compared to pre-mining conditions. The model indicates that groundwater pressures in the Wongawilli Seam would recover to near or above pre-mining levels around Longwall 19A.

More on the drawdown and recovery is presented in Sections 7.3.2 and 7.3.3 in alternative formats.

7.3.2 Groundwater drawdown

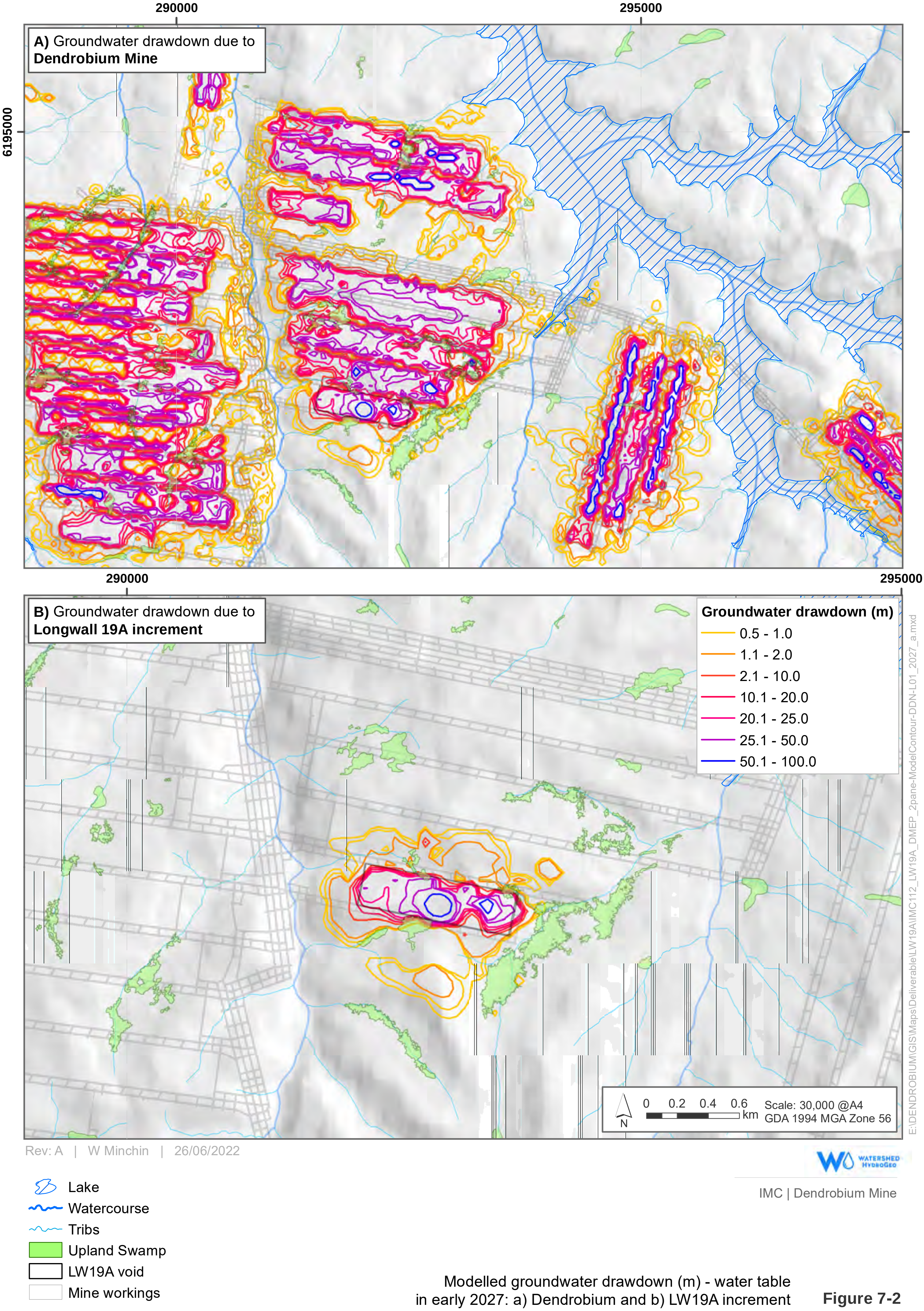
For clearer comparison of the effects of Longwall 19A, and of Dendrobium as a whole, the drawdown in 2027, which is approximately 3 years after Longwall 19A is to be extracted, has been mapped on **Figure 7-1** (lower HBSS) and **Figure 7-2** (water table). These have been calculated as the difference between the Full Development scenario (Scenario D) and the scenario without Longwalls 19A (Scenario C) as in **Table 7-1**.

Figure 7-1A shows that the predicted drawdown due to Dendrobium as a whole is extensive in the lower HBSS above and just outside the footprint of longwalls, especially to the south of Longwall 19A and to the north of Longwall 23 where there are no geological or hydrological features to restrict the cone of depression. Significant drawdown (<50 m) is predicted along the centre-line of Longwalls 17, 8, 19, 19A, 22 and 23. Near Area 3A, drawdown extends to Wongawilli Creek or close to it, and under tributary SC10, as well as under Swamp 15A (east of Longwall 19A) and Swamp 33 (south).



Modelled groundwater drawdown (m) - lower HBSS in early 2027: a) Dendrobium and b) LW19A increment

Figure 7-1



Modelled groundwater drawdown (m) - water table in early 2027: a) Dendrobium and b) LW19A increment

Figure 7-2

Figure 7-1B shows the incremental drawdown in the lower HBSS due to Longwall 19A. The cone of depression is focussed on the panel, extending a little to the north (over Longwall 19) and to the south, east and west. To the east, it extends under SC10 and parts of Swamp 15a, and to the west to Wongawilli Creek – this will likely reduce baseflow discharge to those hydrological features for a period of years or decades (see Section 7.3.3). Swamp 34 to the immediate south of the panel would be affected similarly, while Swamp 33 to the south might be affected by very mild reduction in baseflow.

Figure 7-2A shows the Dendrobium-related drawdown in the water table in 2027. Surface cracking can lead to significant drawdown within parts of the panel footprint, and generally the water table drawdown is very restricted around the panel footprint. Milder drawdown of <=2 m extends to some areas outside the panels.

Figure 7-2B show the incremental water table drawdown due to Longwall 19A. As with other panels, most of the drawdown is restricted to the panel footprint. Of note, is the water table drawdown extended toward Swamp 15A – the actual drawdown in the swamp is buffered by the availability of water within the swamp, but suggests a reduction in baseflow in the swamp (as with Swamp 34). Water table drawdown at Wongawilli Creek is predicted to be <0.5 m.

7.3.3 Hydrographs – groundwater levels

A series of hydrographs are presented to illustrate predicted groundwater trends at a number of representative locations around Longwall 19A. Broadly these figures show the degree of drawdown due to mining and illustrates the recovery of water levels is predicted to be partial (in many cases), recovery being relatively quick in the upper layers in these locations which are outside longwall areas but selected because of their proximity to features around the relevant Area 3A longwalls.

Groundwater levels at monitoring bore S1888, within the footprint of Longwall 19A, are presented on **Figure 7-3.** The effects of mine dewatering on pressures in the WWSM are clear: the simulated effects of mining, including Area 3A, are evident as >200 m drawdown by 2014. The simulated effects of Longwall 19 (to the immediate north) and then Longwall 19A are shown in 2021-24, with a further decline from 110 mAHD to 70 mAHD. Subsequent recovery in the WWSM is indicated to be to levels about 30 m above pre-mining levels, due to simulated connection with overlying strata. In the upper Bulgo Sandstone, maximum drawdown is predicted to be up to about 75 m, and the incremental drawdown due to Longwall 19A is approximately 20 m.

Maximum drawdown in the lower HBSS is predicted to be almost 27 m. Drawdown in the water table at this location is predicted to be approximately 35 m due to surface cracking, resulting in the water table no longer being perched in the near-surface but residing in the lower HBSS. Water levels in the HBSS are predicted to recover approximately 6 years after Longwall 19A extraction. Water levels in the lower HBSS are predicted to recover to near pre-mining levels (within 1 m), however the surface cracking effect would mean that perching in the near-surface directly above the panel may not occur.

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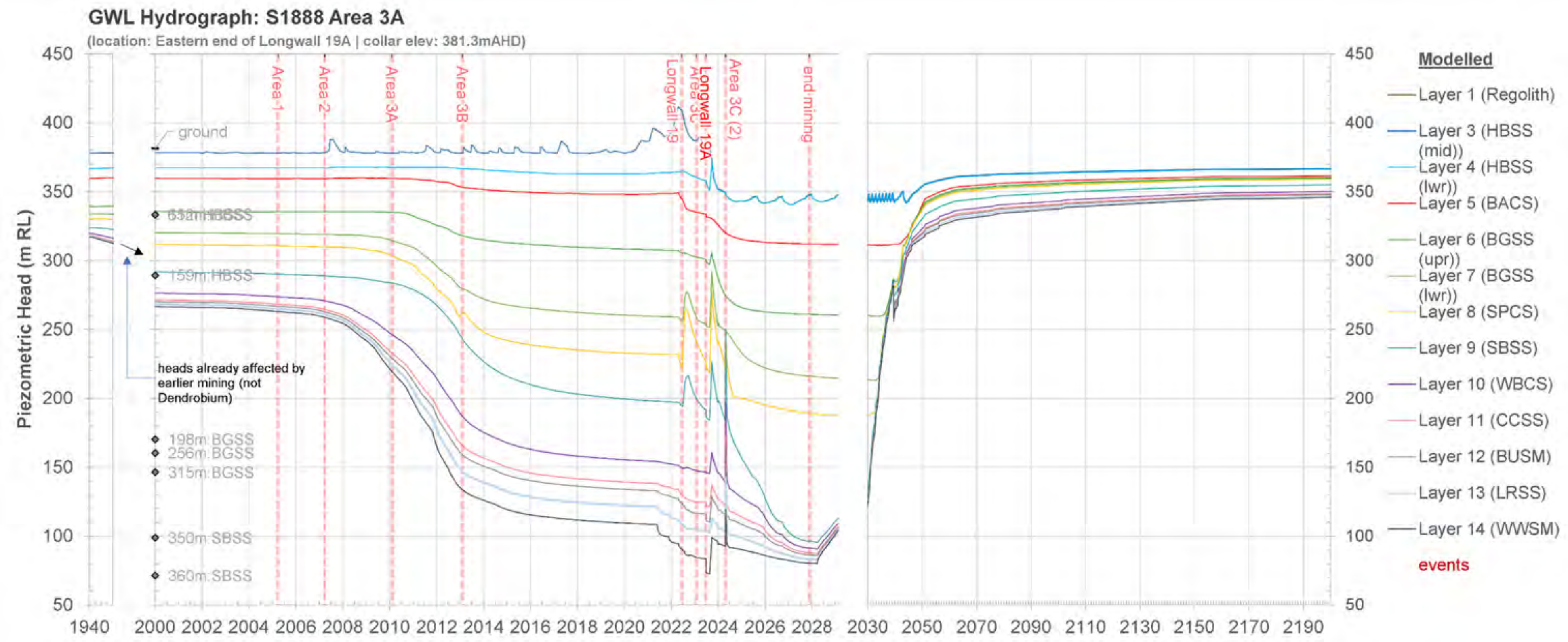

Figure 7-3 Modelled groundwater levels at S1888 (within the footprint of LW19A)

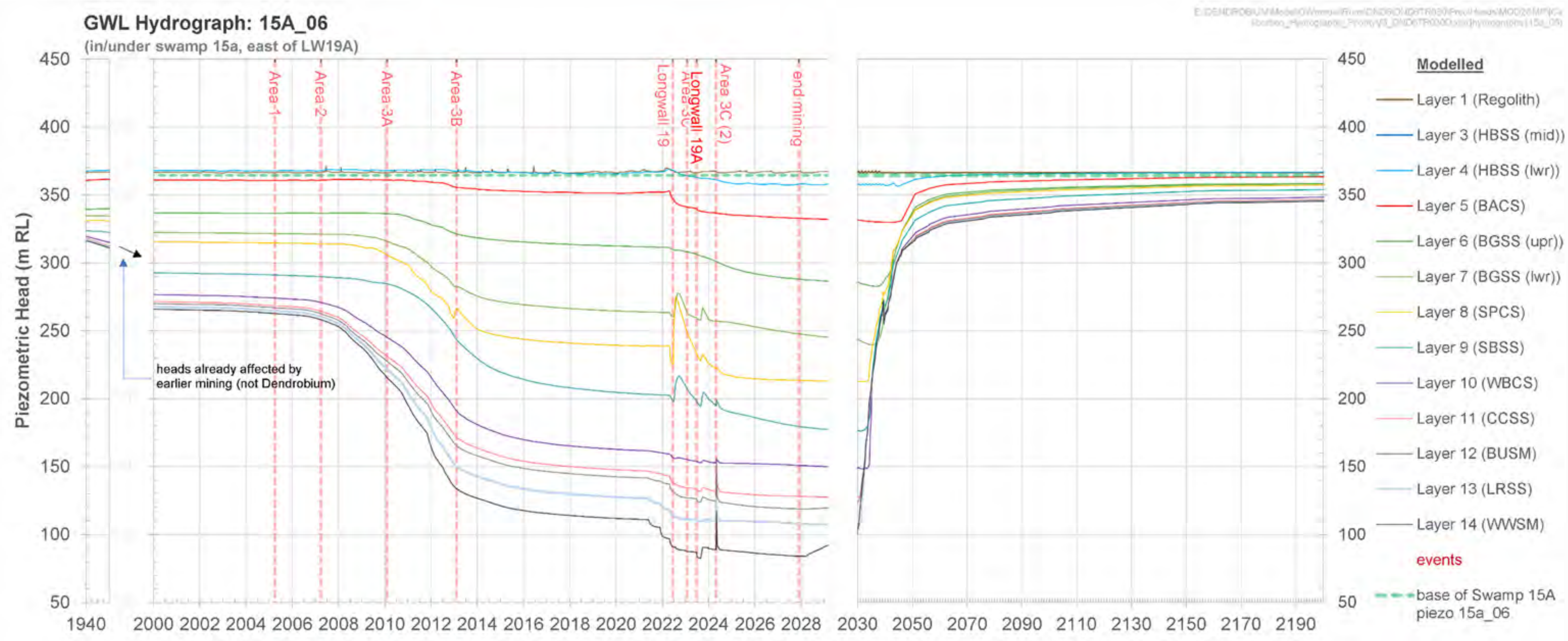

Figure 7-4 Modelled groundwater levels at (under) Swamp 15a

Groundwater levels at piezometer 15a_06 and beneath this location in Swamp 15A are presented on **Figure 7-4**. This site is approximately 225 m east of Longwall 19A. Drawdown from historical workings at Dendrobium are similar to that at S1888 (above). The model simulates historical drawdown of about 200 m in the WWSM with a further 30 m by the end of Longwall 19A. Drawdown in the upper BGSS is predicted to be 20-25m by the end of Area 3B, followed by a further 28 m following extraction of Longwall 19A.

The model predicts almost no drawdown in the HBSS due to earlier mining at Dendrobium, but 10 m following Longwall 19A extraction. Perched water tables at this location, i.e. within the swamp, are predicted to be drawn down by approximately 0.5 over time.

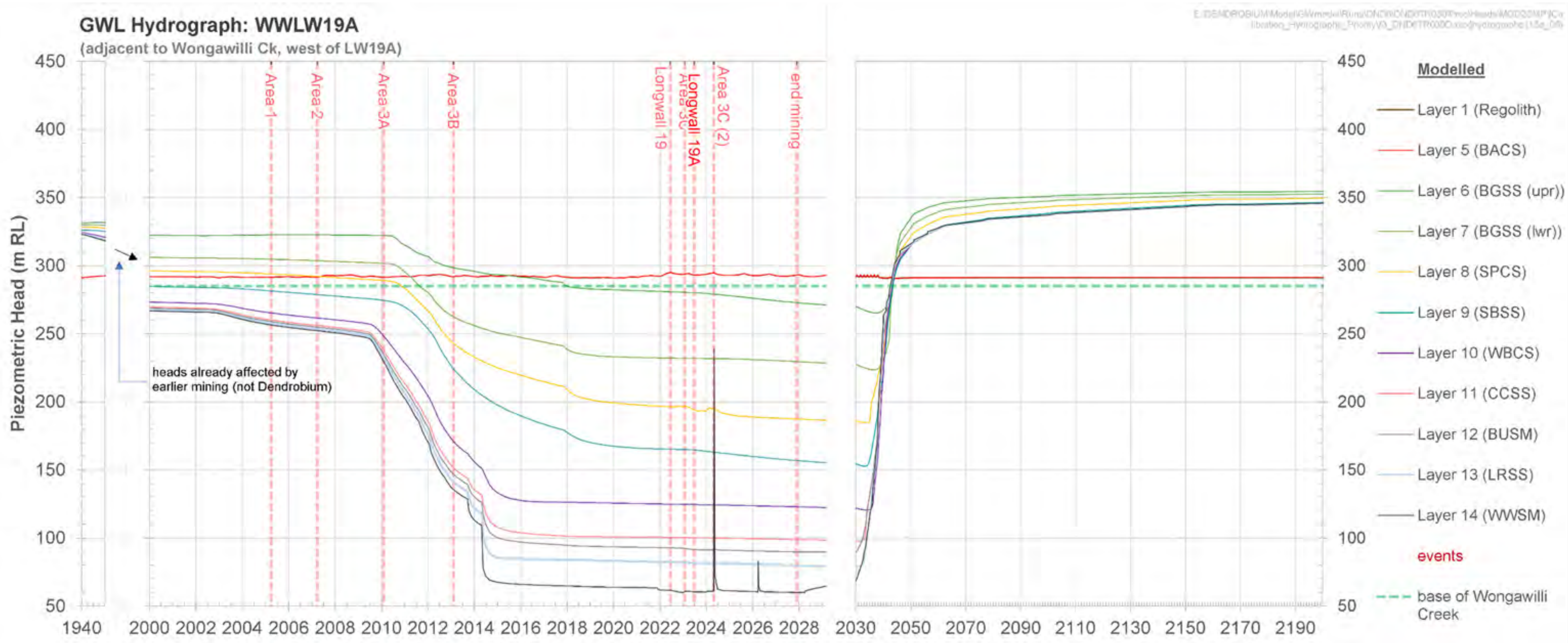

Figure 7-5 Modelled groundwater levels at Wongawilli Creek near Longwall 19A

Groundwater levels at a location adjacent to Wongawilli Creek to the west of Longwall 19A (approximately 400 m west of the longwall) are presented on **Figure 7-5**. The HBSS is eroded away at this location, and the Bald Hill Claystone is present within the base of the creek (**Figure 2-3B**). As at S1888, drawdown of approximately 150 m was simulated in response to extraction of Longwalls 6-8 in Area 3A, followed by further drawdown of 50 m due to Area 3B. Longwall 19A is not predicted to cause further depressurisation of the seam here. Recovery is predicted to above pre-mining conditions.

BGSS water levels drawdown of approximately 30 m due to early Area 3A operations, declining a further 20 m due to Area 3B, including a decline to below the creek level. Longwall 19A is predicted to cause a further 10 m decline. The Bald Hill Claystone levels (the water table at this location) is predicted to be affected by <0.5 m. The upper BGSS pressures are predicted to recover to above pre-mining levels, due to part to changes in permeability in off-goaf areas.

The key behaviour here is that baseflow to Wongawilli Creek is likely to be reduced after 2010, especially after 2017, and remain weakened until 2030-2040 until BGSS pressures recover. Effects on surface water flows in the creek were observed in the most recent drought (Watershed HydroGeo, 2018) and the extraction of Longwall 19A would extend the period over which baseflow will be reduced and the chance of pool water level declines occurring.

7.3.4 Groundwater drawdown at groundwater bores

The nearest Groundwater Works from the NSW government database are described in Section 3.1. Of those bores, the nearest of them (GW112386) is a monitoring bore, not a water supply work, and there is no requirement under the AIP to assess drawdown at monitoring bores.

The maximum estimated drawdown at each water supply bore is listed in **Table 7-2**. The AIP states that the threshold for 'minimal harm' is 2 m of drawdown. The modelling indicates that none of the nearest bores would be adversely affected by the extraction of Longwalls 19A, or by the currently existing or proposed Dendrobium Mine as a whole.

Table 7-2 Maximum Predicted Drawdown at Groundwater Works

GW Works #	Depth	Stratigraphy	Layer	Predicted Max. Drawdown (m) due to:	
				Dendrobium A1-3C	Longwall 19A increment
GW040945	110-170 m	HBSS	4	0.0	0.0
GW068119	9-19 m	Shoalhaven Group	17	0.0	0.0
GW102528	17-169 m	HBSS	3, 4	0.0	0.0

7.4 Forecast changes to water balance and fluxes

In the following sections, predicted changes to fluxes as a result of further mining at Dendrobium, including proposed Longwalls 22 and 23, are presented. These fluxes include:

- regional mass balance;
- mine inflow to Dendrobium;
- mine inflow to Elouera (considered for the purpose of assessing the behaviour or role of Elouera Fault);
- losses from Avon and Cordeaux Reservoirs; and
- reduction in surface water flows in watercourses ('incidental surface water take').

7.4.1 Regional groundwater mass balance

The modelled regional groundwater balance is summarised in **Table 7-3**, which presents the average water balance for 2021-2060, which is consistent with DPIE's condition requesting model estimates of specific fluxes for a period to 30 years after the proposed end of mining.

The groundwater balance includes simulated mining at Dendrobium (including Longwalls 19, 21, 19A, 22, 23 and 20), historical mining around Dendrobium, and the parts of the approved Tahmoor Mine and the Appin Mine that lie within the active model domain.

Rainfall recharge is the dominant input, while evapotranspiration and baseflow to watercourses/springs/reservoirs are the dominant outputs. The model simulates future mine inflow for all mines in the model domain equal to approximately 4% of recharge. During the reported period, there is a net increase in groundwater storage (i.e. groundwater level recovery), which follows the simulated decline due to the simulated mining (e.g. Dendrobium to 2028 and the remainder of Tahmoor Mine).

Table 7-3 Modelled Water Balance for Predictive Period (2022-2060)

MODFLOW component	Conceptual process	In [ML/d]	Out [ML/d]
Recharge	rainfall recharge	188.15	0.00
Stream Leakage	GW-SW interaction w/ watercourses	260.11	22.21
River Leakage	Groundwater exchange w/ Reservoirs	1.25	3.58
Evapotranspiration	evapotranspiration	0.00	425.02
Drains	mine inflow	0.00	7.59
Head Dep Bounds	regional GW flow	7.16	1.92
Constant Head	flow to ocean, estuaries	0.00	0.03
Storage	groundwater storage	113.4 (decline in GWLs)	109.7 (rise in GWLs)
Total		570.1	570.1

Units are in ML/d. Results are from model run DND6TR30pD: SP133-214.
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7.4.2 Forecast groundwater inflow

Inflow to Area 3A: Modelled inflow to each mine domain, including Area 3A (with and without Longwall 19A) is presented on **Figure 7-6**. The difference between the red and green series indicates the incremental contribution of Longwall 19A. Note that the model stress periods are typically 2-3 months long, so the model cannot capture short-term peaks (i.e. days-weeks) that might occur.

Figure 7-6 shows that inflow to Area 3A is likely to peak at approximately 3 ML/d at the end of Longwall 19, with a slight recession while mining moves to Longwall 21 (Area 3C), and a further peak at 3.5 ML/d when mining occurs at Longwall 19A in 2024. This latter peak is similar to peaks that occurred during Longwall 8.

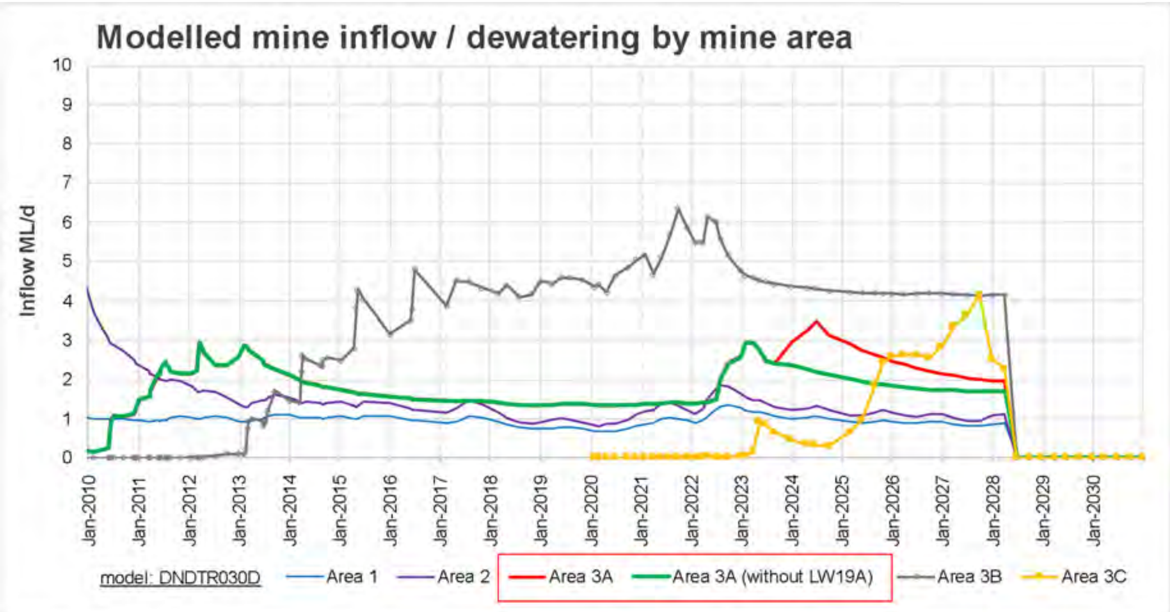

Figure 7-6 Modelled groundwater inflow by mine domain (with and without Longwall 19A)

The model suggests that the incremental inflow to Area 3A due to Longwall 19A would be up to 1.2 ML/d.

Inflow to Dendrobium: The current model is a useful tool when It comes to estimating the total inflow to Dendrobium (Section 6.5). The model forecasts that inflow could rise just over 12 ML/d (**Figure 7-7**) by the end of Longwall 23 and 20 in Area 3C.

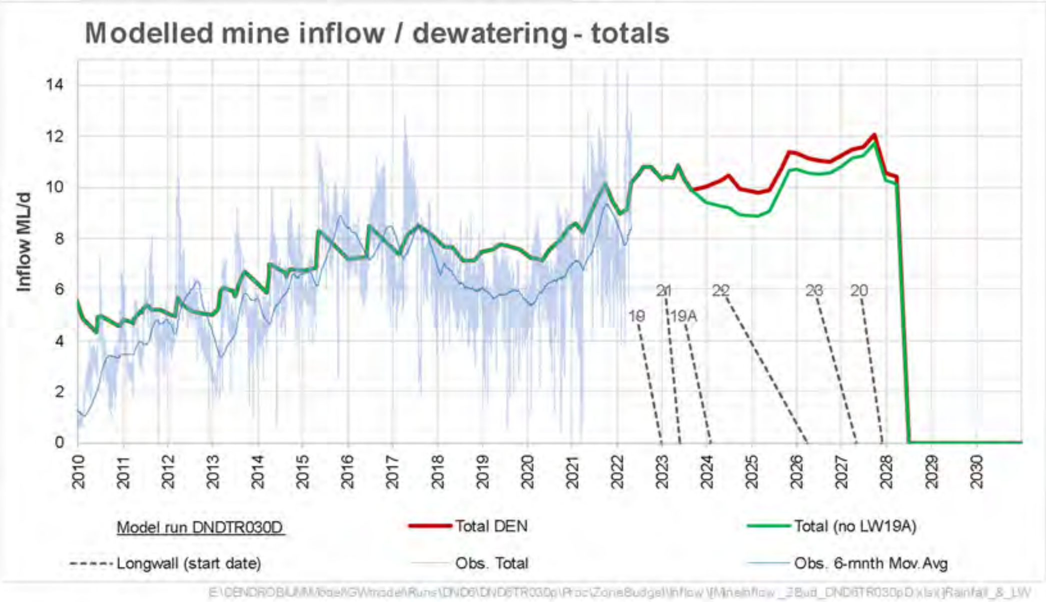

Figure 7-7 Modelled total groundwater inflow to Areas 1-3C

The difference in peak inflow cause by the inclusion or exclusion of Longwall 19A is shown by the difference in the red and green series on the chart below. The difference in peak inflow is predicted to be very small; 12. ML/d compared to 11.7 ML/d without Longwall 19A, even though the peak incremental take during the extraction of Longwall 19A is greater (1.2 ML/d approximately during late 2024).

Annualised inflow is forecast to reach approximately 4400 ML/yr in 2027-28, yet this will remain below the current annual groundwater entitlement held for Dendrobium Mine (9,185 ML/yr or >25 ML/d).

7.4.3 Forecast discharge after closure

The most direct pathways for mine water egress is via the Dendrobium portals (specifically the Kemira Valley portal, due to its elevation), via abandoned mine headings and portals along the Illawarra Escarpment, and natural discharge points, all of which are located outside WaterNSW's Special Area.

Groundwater flux from Areas 2, 3A, 3B and 3C would be limited by both the bulkheads proposed (SLR, 2022), and by the elevation gradients from those areas toward the portal. Water will pass through the coal seam around the bulkheads and into the mains or Area 1 workings. Inflow to Area 1 will drain to the portals.

Numerical modelling indicates that egress from the mine portals would be low initially at the time of mine closure, from <0.1 ML/d (**Figure 7-8**) rising to 0.5 ML/d within a few years. Once workings in Areas 2 and 3 flood and water levels recover to above the elevation of the bulkheads, then the volume of discharge would increase over time, reaching approximately 1 ML/d and then rising slowly to 1.2 ML/day), as shown on **Figure 7-8**. The error bars included here are from recent uncertainty scenarios (Watershed HydroGeo, 2022), and the range in long-term discharge is 0.95 to 1.5 ML/d.

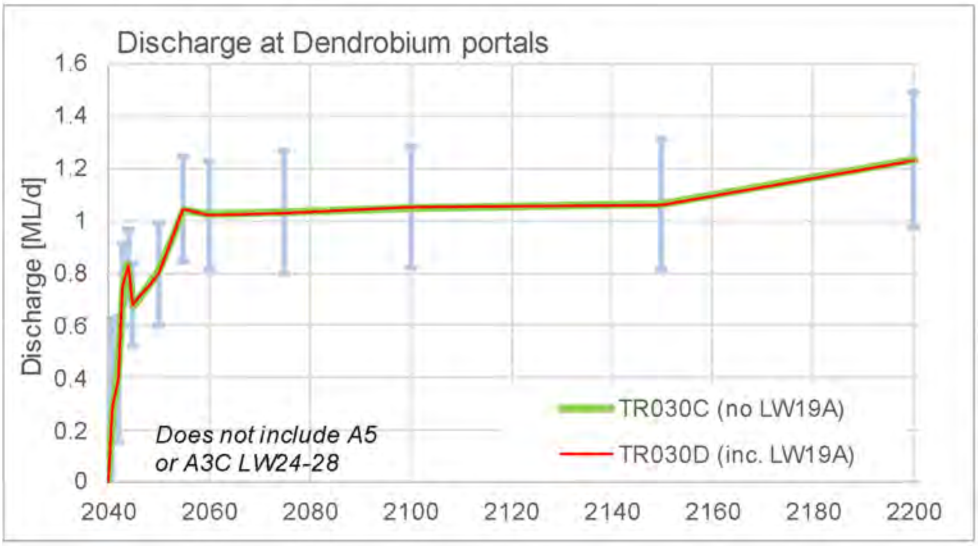

Figure 7-8 Modelled discharge at Dendrobium portals

This long-term flux has been reviewed for both model Scenario D (red series - Full Development, which includes Longwall 19A) and Scenario C (green series - Dendrobium without Longwall 19A). The model results indicate that the difference in this discharge rate between the scenarios is <1%. That is, the simulated mining in Longwall 19A makes almost no difference to this flux compared to the flux from the remainder of Areas 1-3C.

7.4.4 Simulated Leakage from Cordeaux Reservoir

Based on the scenarios outlined in **Table 7-1**, the range in simulated maximum leakage from Lake Cordeaux due to Dendrobium operations averages 0.12 ML/d, but could be up to 0.30 ML/d considering the extreme off-goaf fracturing scenarios. This range is similar to previously reported estimates of 0.14 ML/d (HS, 2019a), 0.08 ML/d (HS, 2019b), and 0.1 ML/d (SLR, 2020a), noting that they did not include Longwalls 22 and 23. The upper estimate from the modelling presented here (0.36 ML/d) is lower than the prescribed tolerable limit for Lake Cordeaux (1 ML/d).

This estimate appears reliable given the improved calibration to Bulgo Sandstone groundwater levels in Area 3A, as well as the fact that recent 'baseline' inflow to Areas 1, 2 and 3A (which are located around Lake Cordeaux) totals approximately 1.5-2 ML/d.

Leakage from Cordeaux Reservoir due to Longwall 19A is related to the predicted drawdown in Section 7.3.2. The predicted incremental leakage is summarised in **Table 7-4**, which shows that Longwall 19A is predicted to have a negligible effect on Cordeaux Reservoir.

Table 7-4 Maximum predicted leakage [ML/d] from Cordeaux Reservoir

	Longwall 19A	Dendrobium Areas 1-3C
Maximum leakage	<0.01	Mean 0.12, up to 0.30 ML/d
Nearest distance from reservoir	1.5 km	220 m (Area 1)

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7.4.5 Simulated Leakage from Avon Reservoir

The maximum leakage from Avon Reservoir as a result of cumulative mining at Dendrobium has been estimated from the deterministic scenarios, and is predicted to be between 0.09 and 0.45 ML/d, with an average of the scenarios being 0.13 ML/d. More discussion of these results is presented in WatershedHG (2020), which focusses on the potential effects of longwalls in Area 3B.

The model estimates that the incremental leakage from Avon Reservoir due to Longwall 19A is zero.

7.4.6 Simulated 'Incidental Take' from Watercourses

Previous approvals included a requirement to provide estimates of surface water losses in 5-yearly intervals out to 30-years after the proposed completion (of Area 3B). We have revised that approach as follows:

- consider three time periods, one from the start of Longwall 19A to 3 years after completion of that panel (essentially to 2028), and period to approximately 30 years after mining (2060 – consistent with the previous approval requirement), and the simulated period after that date to 2200;
- include two statistics from the predicted and annualised losses (mean and maximum annual loss) for the two earlier periods, and an average loss for the long-term estimate. These are reported from the calibrated of Base Case model (model run TR030D –see **Table 7-1**).
- additionally, the maximum loss from the uncertainty scenarios is included as a third statistic (in brackets in the following tables) (see **Table 7-1**).

The reason for doing this are twofold. First, this should simplify the reported losses into a more user-friendly and intuitive set of results. Secondly, the model uses an user-specified weather pattern to simulate low, moderate and high flow periods. While we present a timeseries of losses graphically for a selection of sites, the weather is not predictable, so statistical summaries of generally broader periods seems more useful and appropriate.

The results from MODFLOW budget files have been extracted from the predictive scenarios, and net difference, the 'take' from surface water, has been calculated for a number of sites (both gauged and ungauged). **Appendix H** presents charts showing whole-of-mine effects on watercourses around Dendrobium (the selection presented are those most relevant to Longwall 19A; SC10B, SC10, WC13 and Wongawilli Creek Lower). These charts show a range of surface water losses for the annualised periods, and show the change in losses over time.

Results for the watercourses near to and most affected by Longwall 19A are tabulated in **Table 7-5**. Results (and charts) for other watercourses can be provided but are not tabulated in this report.

The tables below show that the effects of Longwall 19A are greatest on SC10A and downstream SC10, and WC13 (leading to Wongawilli Creek). Losses on baseflow discharging directly to Wongawilli Creek are relatively small. The effects of uncertainty scenarios (i.e. the degree of off-goaf fracturing and enhanced permeability) are variable between the sites over time, but in the short-term term, all these scenarios suggest higher losses could occur if the more extreme degree of fracturing was to happen.

In the long-term, losses generally decline, however in the case of SC10B, losses are predicted to be more persistent, owing to this watercourse's proximity to the panel footprint and the associated surface cracking effects.

The modelling suggests recovery to pre-mining flows or possibly greater than pre-mining in the long-term at some sites (i.e. an increase of X ML/d). This is plausible, but we have reported as "0 to X".

Table 7-5 Predicted annualised change in surface water flow (ML/d): Longwall 19A increment

Period	Statistic	SC10A	SC10B	SC10	Sandy Ck (SCL)	WC13	WC14	lower Wongawilli Creek (WWL)
Longwall 19A + 3yrs 2023-2028	Mean & Max (base case)	-0.007 to -0.01	-0.002 to -0.004	-0.012 to -0.018	-0.012 to -0.018	-0.010 to -0.014	-0.003 to -0.003	-0.012 to -0.018
	Uncertainty Max	*(-0.027)*	*(-0.011)*	*(-0.074)*	*(-0.077)*	*(-0.021)*	*(-0.014)*	*(-0.042)*
30yrs post-mining 2029-2060	Mean & Max (base case)	-0.003 to -0.009	-0.003 to -0.008	-0.010 to -0.017	-0.011 to -0.017	-0.010 to -0.014	-0.002 to -0.003	-0.010 to -0.022
	Uncertainty Max	*(-0.021)*	*(-0.015)*	*(-0.0915)*	*(-0.096)*	*(-0.021)*	*(-0.018)*	*(-0.152)*
Long-term 2060-2200	Mean (base case)	0.000	-0.007	-0.009	-0.008	0.000	0 to 0.001	0 to 0.010
	Uncertainty Max	*(-0.004)*	*(-0.009)*	*(-0.029)*	*(-0.029)*	*(0)*	*(-0.002)*	*(0 to 0.01)*

Negative value = reduction in surface water flow. Statistics reported are "MEAN" to "MAX" from the Base Case [calibrated] model, and (*"UNCERTAINTY MAX"*) from deterministic scenarios.
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Table 7-6 Predicted annualised change in surface water flow (ML/d): Dendrobium total

Period	Statistic	SC10A	SC10B	SC10	Sandy Ck (SCL)	WC13	WC14	lower Wongawilli Creek (WWL)
Longwall 19A + 3yrs 2023-2028	Mean & Max (base case)	-0.011 to -0.014	-0.038 to -0.048	-0.292 to -0.363	-0.393 to -0.469	-0.013 to -0.021	-0.071 to -0.092	-0.900 to -1.337
	Uncertainty Max	*(-0.039)*	*(-0.055)*	*(-0.363)*	*(-0.469)*	*(-0.031)*	*(-0.105)*	*(-1.337)*
30yrs post-mining 2029-2060	Mean & Max (base case)	-0.006 to -0.023	-0.026 to -0.054	-0.166 to -0.437	-0.220 to -0.582	-0.016 to -0.032	-0.040 to -0.102	-0.662 to -1.651
	Uncertainty Max	*(-0.057)*	*(-0.063)*	*(-0.437)*	*(-0.582)*	*(-0.042)*	*(-0.119)*	*(-1.651)*
Long-term 2060-2200	Mean (base case)	0.000	-0.020	-0.062	-0.058	0.000	0 to 0.024	0 to 0.905
	Uncertainty Max	*(-0.006)*	*(-0.026)*	*(-0.128)*	*(-0.145)*	*(0)*	*(-0.023)*	*(0 to 0.377)*

Negative value = reduction in surface water flow. Statistics reported are "MEAN" to "MAX" from the Base Case [calibrated] model, and (*"UNCERTAINTY MAX"*) from deterministic scenarios.
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The following section describes the surface water losses due to Dendrobium as a whole, with incidental takes for specific watercourses summarised in **Table 7-6**.

Effects on SC10A and WC13 associated with Longwall 19A (**Table 7-5**) comprise the largest component of the cumulative Dendrobium effects (**Table 7-6**), which is unsurprising given the proximity of Longwall 19A to these watercourses in comparison to other longwalls.

As with the incremental effects, the variability of effects through time, i.e. their persistence, is usually associated with the position of each watercourse in relation to longwalls and associated surface cracking effects (**Table 7-6** and **Appendix H**).

The total predicted take from Wongawilli Creek for the simulated longwalls is approximately 300 ML/yr (0.8 ML/d), but could be up to 600 ML/yr (base case and uncertainty scenario maximum, equivalent to almost 1.6 ML/d). Losses are predicted to declining over time after all longwalls are extracted. Note that analysis of field data has not yet detected a reduction in median flow beyond natural variability.

The total take from Sandy Creek for the simulated longwalls averages approximately 143 ML/yr, but could be up to 212 ML/yr (base case and uncertainty scenario maximum, equivalent to almost 0.6 ML/d).

We consider that the likely impact or take from headwater streams is well represented by the model (Section 6.6), while the predicted losses from downstream sites (e.g. WWL = Wongawilli lower) will be toward the lower end of these estimates (based on comparison against End of Panel surface flow assessment results – Section 6.6). The range of predicted impacts, based on comparison of the modelled and historical losses has been provided in relevant Surface Water Assessments (HGEO, 2022a), noting that future rainfall and flow conditions as well as uncertainties in the groundwater model representation of mining effects, will influence future losses.

7.4.7 Simulated Take from Water Supply Catchments

As recommended in IEPMC (2019a) the groundwater model has been used to estimate the total surface water losses from the catchments to the Avon and Cordeaux Reservoirs.

The surface water catchment to Cordeaux Reservoirs is completely within the active extent of the groundwater model, while about 95% of the catchment of Avon Reservoir is within that domain.

Table 7-7 Predicted reduction in surface water flow to reservoirs (ML/yr)

5 Year Interval	Avon Reservoir catchment		Cordeaux Reservoir catchment	
	Moderate	Range	Moderate	Range
2021-25	-196	-162 to -229	-318	-259 to -365
2026-30	-227	-163 to -442	-380	-345 to -428
2031-35	-190	-157 to -220	-401	-346 to -449
2036-40	-122	-32 to -210	-271	-107 to -468
2041-45	-22	25 to -87	-77	6 to -193
2046-50	-25	-9 to -40	-92	-84 to -101
2051-55	11	22 to -40	-62	-47 to -84

Negative value = reduction in surface water flow.
E:\DEND…\Model\GWmodel\Processing\Zonebudget\SWtake\SWlosses_WatercoursesByCatchment_DND6TR030_SummaryToHEC.xlsx

Taken alongside the results in Section 7.4.6, the revised model suggests that Dendrobium Mine could take approximately 1090 ML/yr of surface water during the period 2021-2040 and declining thereafter:

- 610 ML/yr (range: 140-870 ML/yr) from the water supply catchments; and
- 570 ML/yr (range 225-660 ML/yr) from Wongawilli and Donalds Castle Creeks.

The maximum total take from watercourses is estimated as approximately 1530 ML/yr, equivalent to 4.2 ML/d, noting that there is uncertainty in these estimates, based on the uncertainty regarding future weather conditions as well as uncertainty in model parameters and mining effects.

8 Conclusions

The numerical groundwater model has been revised from previous modelling (see **Appendix B**). This update was carried out following the acquisition of newly available pre- and post-mining data from longwall areas (Sections 3.6 and 5.4).

This model is assessed for calibration against a large dataset of groundwater levels from more than 600 target locations, as required by the conditions of the SMP Approval, as well as against mine inflow in each mine area, while constraining the model to field-derived values of permeability, including the use of a K-depth relationship, which is evident from field data, to parameterise the model.

These new data and modifications have allowed significantly improved model calibration for groundwater levels (as shown in hydrographs in Section 6.4) as well as some improvement to mine inflows. The modelling has also now incorporated calibration against surface water losses calculated in recent End of Panel reporting to attempt to provide more realistic, but still conservative (as per IEPMC, 2019a), estimates of future surface water take as a result of mining operations.

Based on currently available mapping, dykes and the Nepheline Syenite intrusion are the main structural features of note near Longwall 19A. There are very few mapped faults and lineaments, and nearby dykes are shown to terminate outside the footprint of Longwall 19A. Therefore, based on current data, geological structures are not considered a significant risk pathway for Longwall 19A.

The key results from the revised groundwater model and groundwater assessment as a whole are:

- The model matches historical inflow to the Dendrobium Mine with reasonable accuracy for total mine inflow and the dynamic pattern of inflow to individual areas. This provides confidence in assessing associated changes in the catchment water balance.
- Dendrobium Mine inflow or groundwater take is predicted to peak at approximately 12 ML/d after Longwalls 19, 21, 19A, 22, 23 and 20 (not all approved at this time, but simulated here for the purpose of this assessment).
    - The modelling suggests the extraction of Longwall 19A would cause an increase in inflow of up to 1.2 ML/d during the period of extraction, however would have only a very minor effect on the peak inflow for the whole mine.
    - The modelling also suggests that extraction of Longwall 19A would have a negligible effect on the long-term groundwater discharge to the portals after mine closure. The total outflow predicted here is approximately 1.2 ML/d, following extraction of Areas 1-3C and installation of bulkheads inbye of Area 1.
- Simulated leakage from Cordeaux Reservoir is predicted to be less than the prescribed tolerable limit, being up to 0.30 ML/d. The incremental rate of loss due to Longwall 19A is <0.01 ML/d.
- The incremental leakage from the Avon Reservoir due to extraction of Longwall 19A would be effectively zero.
- Incidental surface water capture has been estimated using the groundwater model and tabulated as required in **Table 7-6**. The maximum incremental take due to Longwall 19A across all nearby watercourses would likely be approximately 20 ML/yr (**Table 7-5**).
- A tributary of Wongawilli Creek (WC13) and a minor tributary SC10B (flowing into SC10 and then to Sandy Creek) would be the watercourses most affected by extraction of Longwall 19A. SC10B would very likely be affected by fracturing, resulting in flow losses that persist in the long-term. Other watercourses to be affected would be WC14 and SC10A. Of these, WC14 will mainly be affected by extraction of Longwall 19, rather than 19A, while SC10A, and WC13

will mainly be affected by drawdown, which typically results in a temporary loss of flow. Cracking could occur along these drainage lines, but is unlikely.

- As well as effects to small tributaries, Longwall 19A would cause a reduction in flow in Wongawilli Creek and SC10, most likely due to groundwater drawdown rather than cracking of the creekbed. Based on an empirical comparison of longwall geometry and orientation, and distance to the creek, Longwall 19A is likely to have similar effects to those observed on Wongawilli Creek due to earlier Area 3A and 3B longwalls (**Figure 4-3**).
- The nearest High Priority GDE, as defined in the relevant WSP (Section 3.2.1) is the Macquarie Rivulet Estuary which is approximately 17 km from Dendrobium Area 3A (**Figure 2-1**). No drawdown effects will occur at this location as a result of mining at Dendrobium.
- Effects on Upland Swamps are described more fully in the accompanying Shallow Groundwater and Surface Water Assessment (HGEO, 2022a), however it is likely that cracking due to extraction of Longwall 19A will affect parts of swamps Den34, Den148, and the satellite swamp of Den15a located on tributary SC10B. Drawdown from Longwall 19A will affect each of those swamps as well, as it will Den15a.
- The nearest registered "water supply work" (i.e. private bore) is >4 km south or south-east of Dendrobium Area 1, and over 7 km from Longwall 19A. Drawdown due to Dendrobium operations is predicted to be effectively zero at these sites. No water supply works are predicted to be affected to any degree and none exceed the 2 m threshold in the AIP.

8.1 Assessment against the Aquifer Interference Policy

Table 8-1 Summary of AIP Assessment

Aquifer	**Sydney Basin Nepean Sandstone Groundwater Source, Management Zone 2**	
Category	Highly Productive groundwater	
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.	Minimal impact consideration classification: The relevant Water Sharing Plan is the 'Greater Metropolitan Groundwater Sources' (dated 1 October 2011). **High Priority GDEs** There are no High Priority GDEs listed in this WSP within 15 km of Dendrobium Areas 1-3C. Hence there are no known risks of mine development to such sites. **High Priority Culturally Significant Sites** 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. **Registered Groundwater ("water supply") works** There is minimal risk of drawdown in excess of the water supply work drawdown criterion within the Permo-Triassic or shallow strata (based on the distance to registered groundwater works).	**Level 1**
Water pressure A cumulative pressure head decline of not more than a 2m decline, at any water supply work.	Minimal impact consideration classification: There is a very minor risk of depressurisation in excess of the water supply work drawdown criterion within the Permo-Triassic strata (at GW112386).	**Level 1**
Water quality	Minimal impact consideration classification: Mining-induced changes to the hydraulic properties will cause effects on shallow groundwater and surface water quality. The combined effects of changes to 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**

8.2 Recommendations

Recommendations for future data analysis and modelling are as follows:

8.2.1 Monitoring and analysis

There is no additional surface water monitoring recommended for watercourses around Longwall 19A.

Two over-goaf investigations were conducted over Longwalls 6 and 7 in Area 3A. Further bores are planned for Longwalls 22 and 23 (bores S2514 and S2518 on **Figure 3-2**), and another is planned for above Longwall 21 in Area 3C (Section 3.6.1). These will be packer tested, logged for defects and have piezometers installed to assess pre-mining conditions, similar to the recent over-goaf bore investigations (HGEO, 2020f, 2021d). The over goaf bores are required to be decommissioned prior to mining, and then a similar post-mining bore will be installed. No additional over-goaf bores are recommended for Longwall 19A, given the data already obtained and planned to be obtained for other Wongawilli Seam longwalls.

The evolution of longwall mine plans means that some of the sites identified in the previous version of the long-term monitoring plan will no longer be suitable for long-term monitoring (e.g. bore S2059 in Area 3C). For Area 3A, this is currently not an issue. However, it is recommended that the long-term monitoring plan be reviewed to reflect recent changes to the mine plan, conceptual understanding and closure management.

Future analysis of mine inflow following re-starting of longwall mining in Area 3A. The inflow hydrograph in this domain was quite variable and moderately responsive to rainfall trends up until 2016, and then became much more muted after that time. Recent extreme rainfall (during mid-2022) should provide an opportunity to investigate this further, especially once tracer data is obtained.

IMC should re-commence sampling of water quality within Area 3A workings, noting that this has been difficult given water management procedures in Area 3A (including re-circulation of water from elsewhere in the mine). We recommend that sampling of roof-drippers occur in the areas around Longwalls 19 and 19A (if infrastructure allows), as well as sampling of goaf outflow from Longwall 19 and Longwall 19A (if it can be assumed that this water is isolated from water recirculated from elsewhere in the mine). The parameters analysis should be consistent with those sampled in Area 3B.

The groundwater TARPs stated in **Table 8-2** are those that have been reported against for Area 3A operations previously (South32, 2022). It is recommended that this be continued for Longwall 19A, noting that IMC monitors and reviews the groundwater data for these boreholes on a monthly basis and the results reported in the Monthly Dam Safety NSW Report.

Table 8-2 Deep groundwater TARPs for Area 3A

Secondary TARP 4 – Area 3A Ground Water Monitoring (Bores S1867, 1870, 1992 & 1994)					
	CHARACTERISTICS OF LEVEL	POSSIBLE REASONS	ACTIONS	ACTION BY	NOTIFICATION
Normal	Depressurisation of Scarborough Sandstone to Wongawilli Seam strata Partial depressurisation of Hawkesbury & Bulgo Sandstones	▪ Predicted impact of Longwall on Groundwater	▪ Download Area 3 piezometers monthly ▪ Review data at normal review team meetings	**Manager Approvals**	None necessary
Level 1	Piezometric Head in the Bulgo Sandstone approaches SWL	▪ Water movement commencing towards goaf	▪ Review Team to consider data and review water balance and other monitoring data and determine appropriate actions	**Manager Approvals**	Review Team
Level 2	Piezometric Head measured in one Bulgo Piezometer (within a borehole) drops below Cordeaux Dam SWL	▪ Water movement commencing towards goaf	▪ Review Team as per Level 1 ▪ Increase download frequency of remaining piezometers to weekly	**Manager Approvals**	Review Team
Level 3	Piezometric Head measured in all Bulgo Piezometers (within a borehole) drops below Cordeaux Dam SWL	▪ Water movement towards goaf	▪ Actions in Level 2 ▪ Activate Level 1 Principal Monitoring Alarm	**Manager Approvals**	Review Team, DS and WaterNSW

The location of Longwall 19A away from most other sensitive receptors means that other groundwater-related TARPs are not considered necessary for Longwall 19A.

8.2.2 Modelling

The over-estimation of inflow, especially for recent years in Area 3B and the underestimation of peak inflows in Area 2 requires further investigation. Recent work has improved the simulation of Area 3B inflow while improving surface water loss estimates, but the inflow to Area 2 remains more muted than observed. Additionally, the mis-match between modelled and observed inflow for the post-longwall inflows in Area 3A may be related to the reconsolidation of caved strata, as outlined in Section 2.6.

Further investigation and calibration of Kv (and perhaps Kh) is needed within the deformed zones inside the panel footprint. The difficulty thus far is balancing too much inflow in Area 3B with too little incidental take from watercourses (hence the adoption here of 'Stacked Drains'), as well as trying to increase the response to rainfall in Area 2. Further model testing and calibration should ideally aim to completely remove the 'Stacked Drains' and rely solely on the TVM method of simulating enhanced hydraulic properties as a result of fracturing.

The simulation of enhanced storage properties by MODFLOW-USG affects model calibration of inflow and heads during mining. There needs to be further investigation into the simulation of enhanced storage properties in the deformation zones, specifically those within the longwall footprint, and how best to simulate this without negatively affecting predictions of inflow (especially) but improving the realism of simulated post-mining recovery.

Given the sensitivity of surface water losses to prevailing weather and flow conditions, and the high rainfall that has occurred to mid-2022, further analysis of flow losses occurring during 2022 should be undertaken as soon as flow data is available (as noted previously, access to monitoring sites and availability of data has been restricted during 2022). Following that, further consideration of how to improve the incorporation of extreme wet years (such as the record rainfall in 2022) and use that for model forecasting needs to be undertaken.

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10 Data register

The following data is relied on for the analysis in this report. Data is available on request via IMC.

Data type	Data collected/owned by	File(s):	Updated: 15/06/2022
Geological structures	IMC geologists	ww_faults_dykes.dwg (spatial CAD data)	
Hydraulic conductivity	IMC geologists	Dendrobium_AquiferPropertiesDatabase_20210413.xlsx (summary by WatershedHG)	
Mine inflow	IMC water balance officer	WaterBalanceReadings_Report_20220503.xlsm	
Rainfall and evaporation			
Daily rainfall and PE data	SILO	Obtained from SILO: https://www.longpaddock.qld.gov.au/silo/point-data/	
Daily rainfall data (site)	IMCEFT / consultant (ALS)	CDX_DEN-All_Rainfall_from_2002.xlsx	
Groundwater Levels (“deep”)			
Monitoring details and locations	Consultant (Geosensing)	boredatabase_piezo_Ver2.xlsb	
Transient pressure/level data- by monitoring site, as in main sections of this report	Consultant (Geosensing)	S1879_Dend 92.xlsx S1870_Dend 85.xlsx S1885_Dend 93.xlsx S1888_dend 96.xlsx S1892_dend 99.xlsx	
Summary of data from almost all available sites	Consultant (HGEO)	DEN_VWP_data_compiled_LW16_V04.xlsx (produced from Geosensing’s files)	
Water chemistry (summary)	Consultant (HGEO)	DEN_Mine_EC_field_averages_V02_April2021.xlsx Den_Water_Quality_V18_20200811.xlsx DEN_Dams_Safety_WQ_Feb2022.xlsx	
Groundwater Levels (“shallow”/swamps)			
Monitoring details and locations	IMCEFT	Piezo Installation Data - IMC Master Table.xlsx	
Transient pressure/level data (by monitoring site)	IMCEFT	Multiple spreadsheets (per typically one per shallow piezometer)	
Surface water flows			
Monitoring locations	IMCEFT	MonitoringSiteData.xls	
Transient level/flow data	Consultant (ALS)	288_IMCFT_DEN_CatchmentALSFlowSites_20220609002953.xlsx	
Summary of flow data from all Dendrobium sites	Consultant (WatershedHG)	SWFlowData_Compiled_Wshed_v4_20211217.xlsx	